

Study of charmonia and bottomonia at Belle

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on behalf of the Belle collaboration

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Selected topics

- ▶ Search for $X(3872) \rightarrow \pi^+ \pi^- \pi^0$
- ▶ Search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_S^+ D_S^+ (D_S^{*+} D_S^{*+})$
- ▶ Measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ from $\gamma\gamma \rightarrow \chi_{c2}(1P) \rightarrow J/\psi\gamma$

Belle experiment

Highlights:

- KEK, Tsukuba, Japan
- Operation 1999-2010
- Collected $\mathcal{L} \sim 1 \text{ ab}^{-1}$
- 454 members, 21 countries
- More than 600 publications

Belle Detector

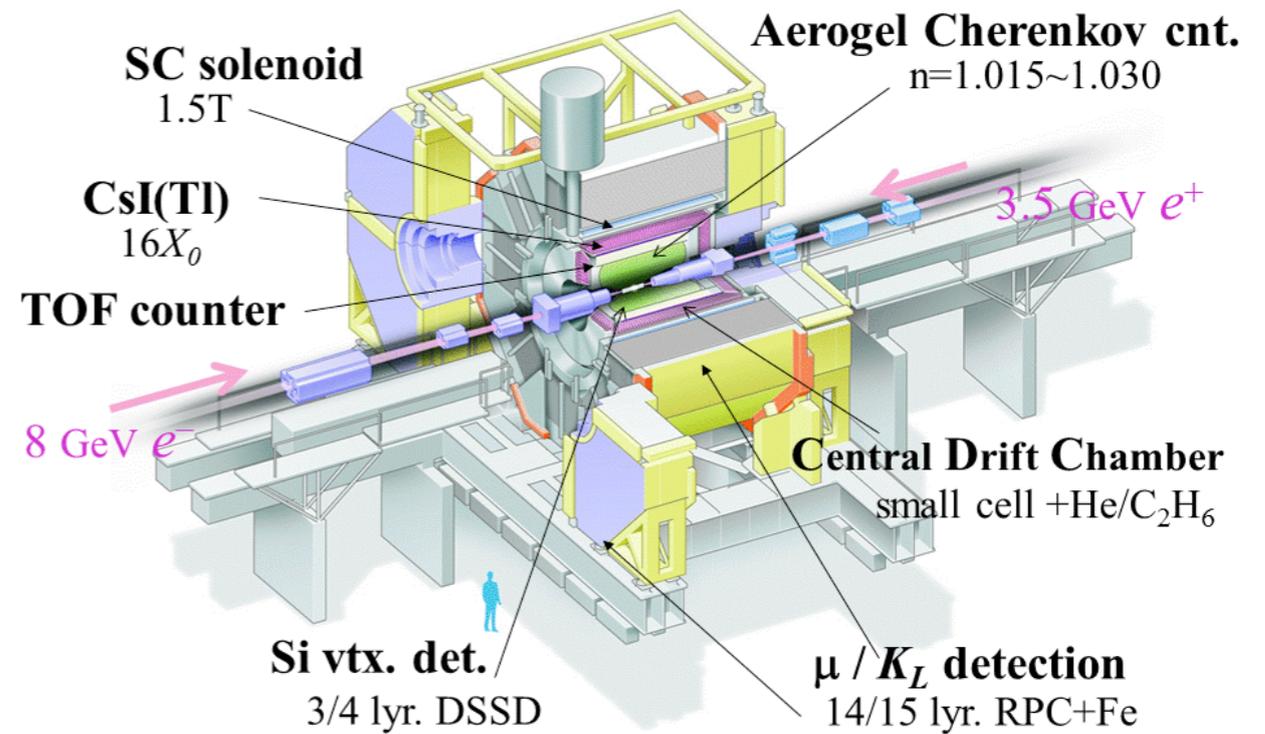


Table I. Summary of the luminosity integrated by Belle, broken down by CM energy.

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of resonances
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$ SVD1	140.0	15.6	$152 \times 10^6 \text{ } B\bar{B}$
$\Upsilon(4S)$ SVD2	571.0	73.8	$620 \times 10^6 \text{ } B\bar{B}$
$\Upsilon(5S)$	121.4	1.7	$7.1 \times 10^6 \text{ } B_s\bar{B}_s$
Scan		27.6	

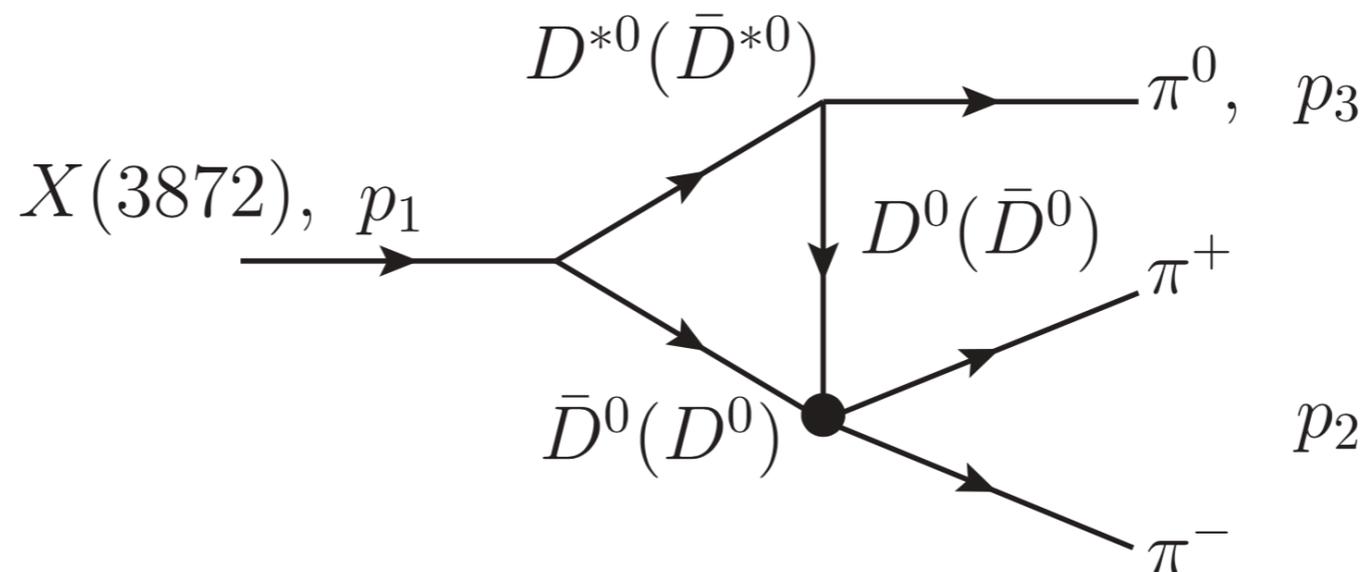
Search for $X(3872) \rightarrow \pi^+ \pi^- \pi^0$

aka $\chi_{c1}(3872)$

$X(3872) \rightarrow \pi^+ \pi^- \pi^0$ theory

► Physical motivation:

- Models in which the $X(3872)$ is a pure charmonium state predict a significant branching fraction for $X(3872) \rightarrow gg \rightarrow$ light hadrons.
- $BR(X(3872) \rightarrow \pi^+ \pi^- \pi^0)$ prediction $10^{-3} - 10^{-4}$
 - Dominant contribution: $X(3872) \rightarrow D\bar{D}^{*0} + c.c. \rightarrow D\bar{D}^0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0$
 - the $\pi^+ \pi^-$ invariant mass peaks close to the $D^0 \bar{D}^0$ threshold
 - [N. Achasov and G. Shestakov, Phys. Rev. D 99, 116023 \(2019\)](#)



$X(3872) \rightarrow \pi^+ \pi^- \pi^0$ strategy

▶ Channels:

- $B^\pm \rightarrow K^\pm [X(3872) \rightarrow \pi^+ \pi^- \pi^0]$

- $B^0 \rightarrow K_S [X(3872) \rightarrow \pi^+ \pi^- \pi^0]$

- $K_S \rightarrow \pi^+ \pi^-$

▶ Dataset: $(772 \pm 11) \times 10^6 \Upsilon(4S) \rightarrow BB$

▶ Presence of a resonant backgrounds with same final state such $B \rightarrow D\rho$, $B \rightarrow K^*\rho$

▶ Study 2 selection:

- Case I: Pions are distributed uniformly in phase space

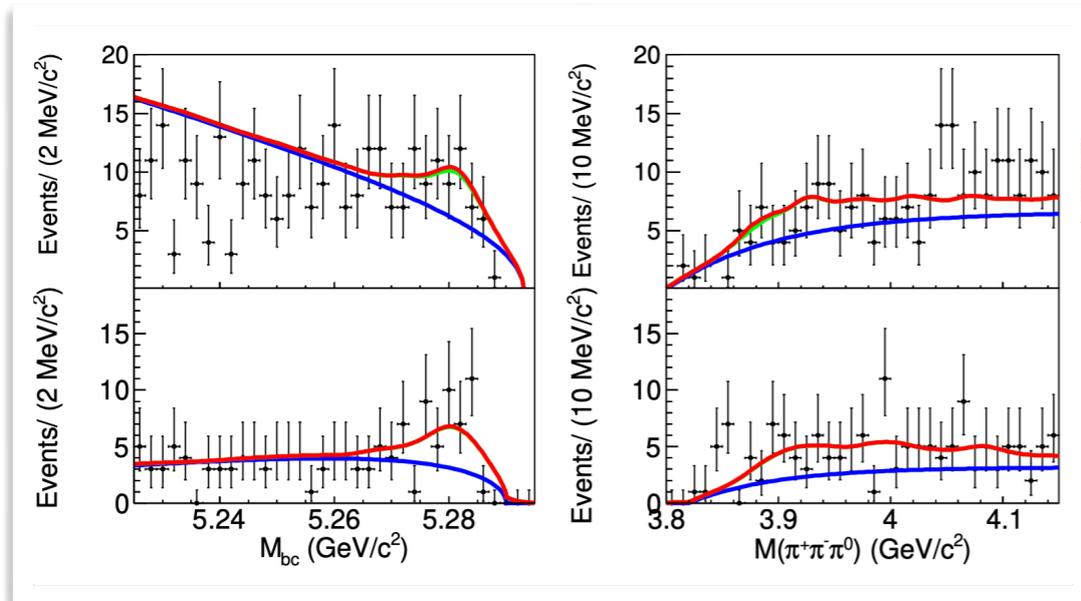
- Case II: Constrain $\pi^+ \pi^-$ invariant mass to peak close to the $D^0 \bar{D}^0$ threshold

▶ Unbinned two dimensional simultaneous fit on the $(M(\pi^+ \pi^- \pi^0), M_{bc})$ distributions

- $M_{bc} = \sqrt{E_{beam}^2 - P_B^2}$

$X(3872) \rightarrow \pi^+ \pi^- \pi^0$ results (90 % U.L.)

Case I : Pions are distributed uniformly in phase space



B^+

$$BR(X(3872) \rightarrow \pi^+ \pi^- \pi^0) < 1.3 \%$$

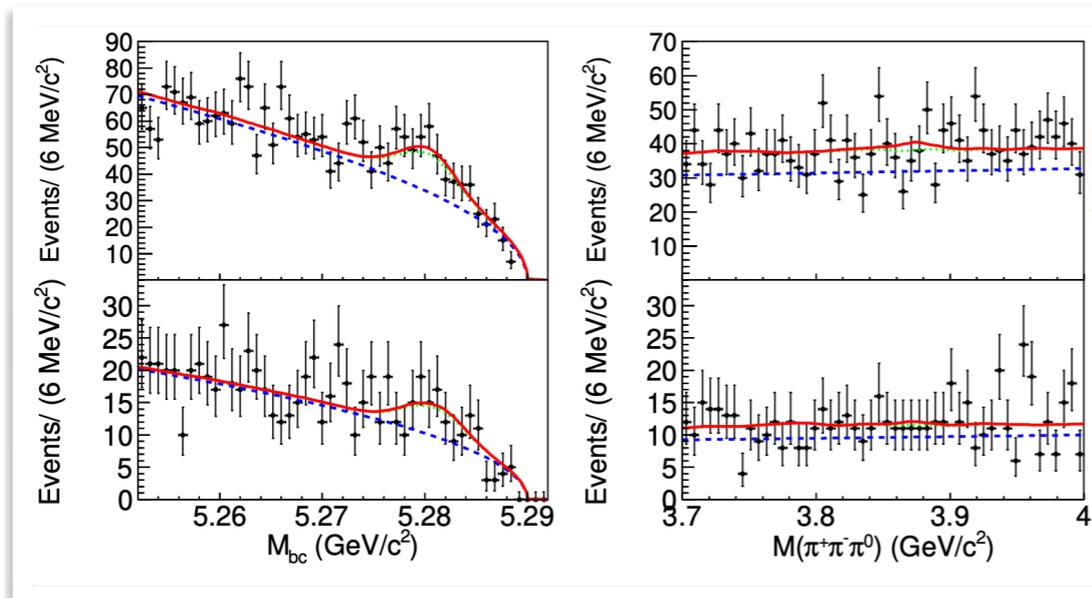
— All

— Combinatorial background

— Combinatorial + resonant background

B^0

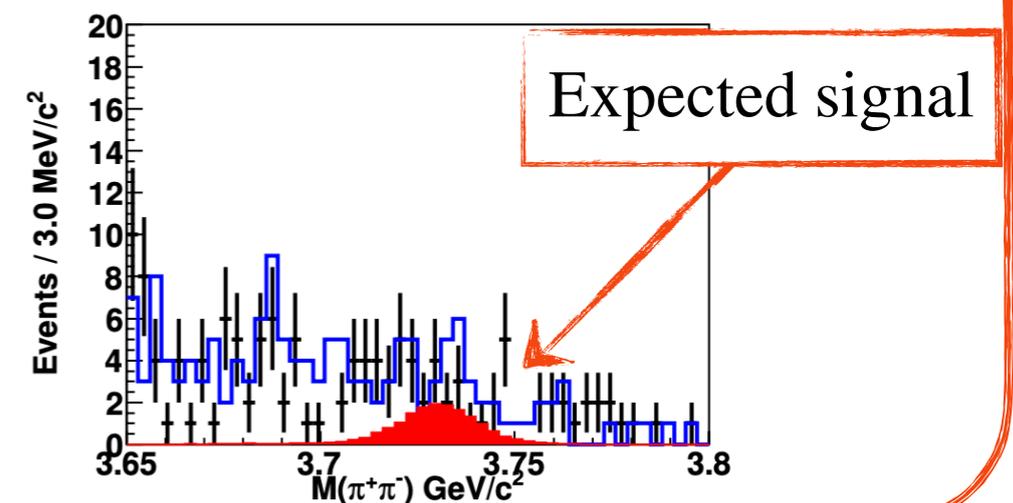
Case II: Constrain $\pi^+ \pi^-$ invariant mass to peaks close to the threshold



B^+

$$BR(X(3872) \rightarrow \pi^+ \pi^- \pi^0) < 1.2 \times 10^{-3}$$

B^0



Search for tetraquark states

$$X_{cc\bar{s}\bar{s}} \text{ in } D_S^+ D_S^+ (D_S^{*+} D_S^{*+})$$

[PhysRevD.105.032002](#)

$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+})$ theory

▶ Double charged state with heavy quark-quark pair of the same flavor.

▶ Prediction of 4 tetraquark resonance states:

● 1 in $D_s^+ D_s^+$ final state

■ $I(J^P) = 0(0^+)$, $M = 4.9$ GeV, $\Gamma = 3.54$ MeV

● 3 in $D_s^{*+} D_s^{*+}$ final state

■ $I(J^P) = 0(2^+)$, $M = 4.85$ GeV, $\Gamma = 10.68$ MeV

■ $I(J^P) = 0(2^+)$, $M = 4.78$ GeV, $\Gamma = 23.26$ MeV

■ $I(J^P) = 0(2^+)$, $M = 4.82$ GeV, $\Gamma = 5.58$ MeV

★ highest observable probability

● [G. Yang, J. L. Ping, and J. Segovia, Phys. Rev. D 102, 054023 \(2020\)](#)

$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+})$ strategy

▶ Channels:

● $e^+e^- \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+}) + \text{anything}$

■ $D_s^{*+} \rightarrow \gamma D_s^+$

■ $D_s^+ \rightarrow [\phi \rightarrow K^+ K^-] \pi^+$

■ $D_s^+ \rightarrow [\bar{K}^*(892)^0 \rightarrow K^- \pi^+] K^+$

▶ Datasets:

● $102 \times 10^6 \Upsilon(1S), \quad 158 \times 10^6 \Upsilon(2S)$

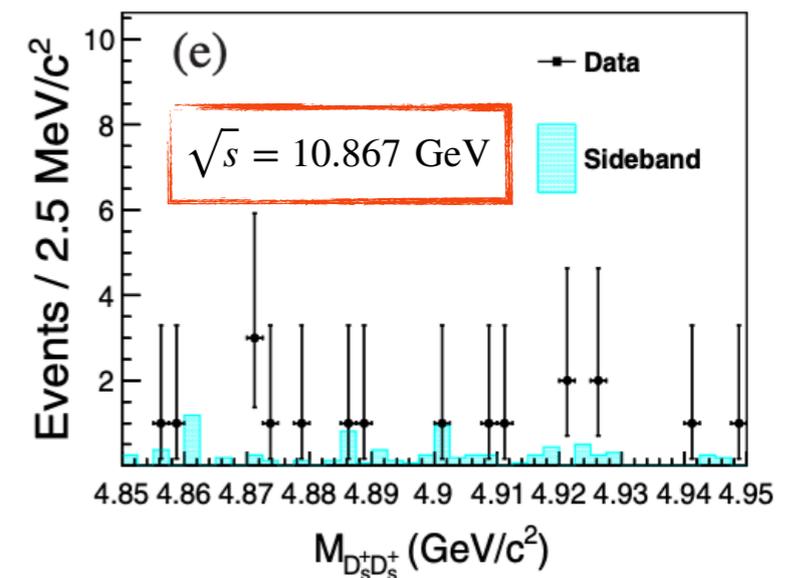
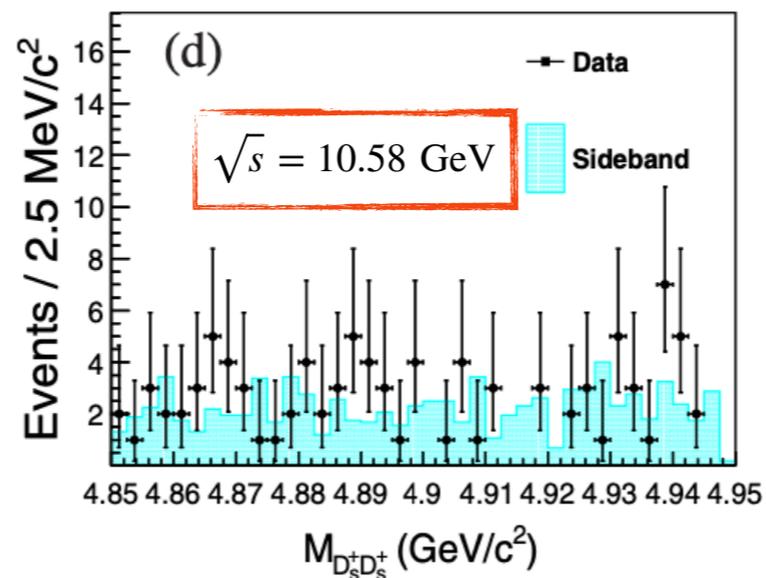
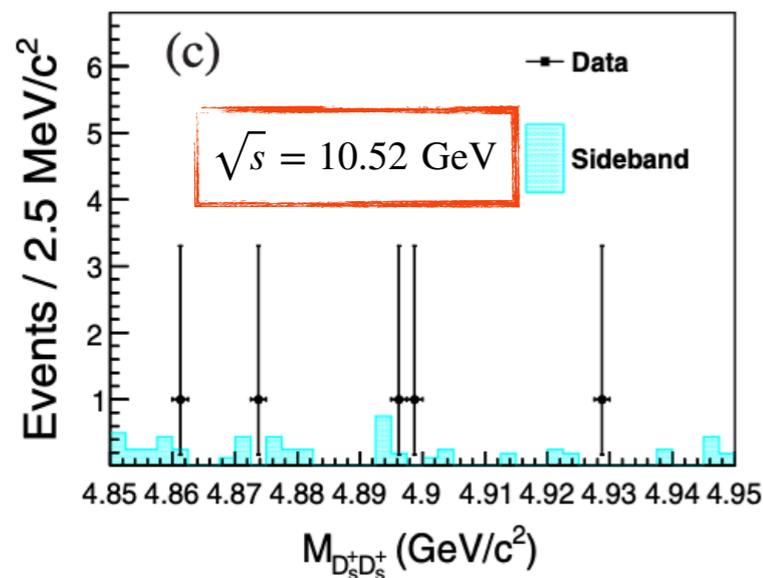
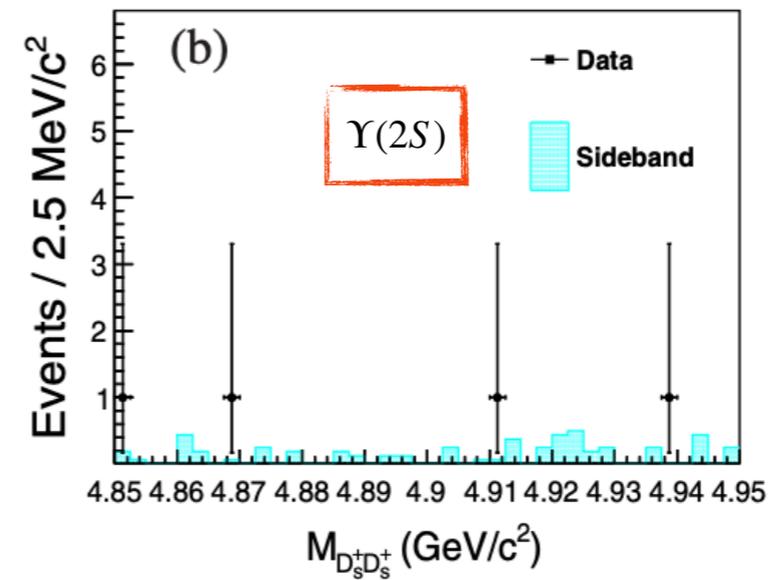
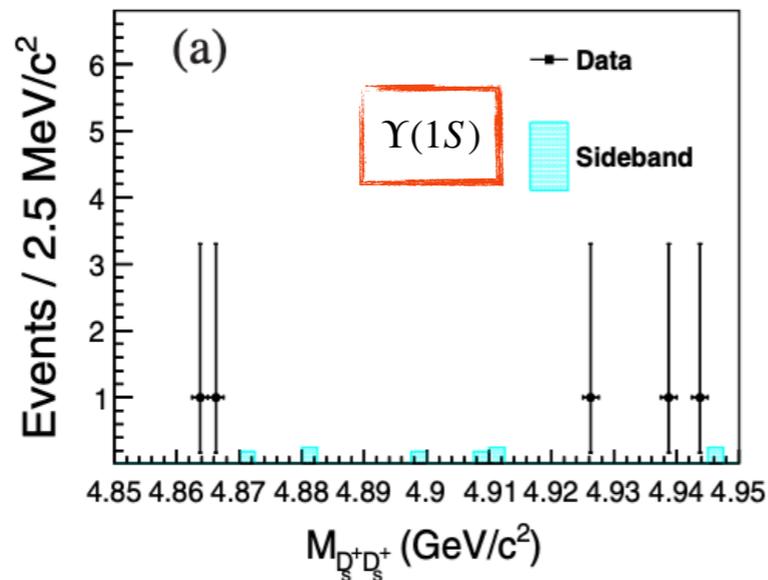
■ Search for $\Upsilon(nS) \rightarrow X_{cc\bar{s}\bar{s}} + \text{anything}$

● 89.5, 711.0, 121.4 fb⁻¹ at $\sqrt{s} = 10.52, 10.58$ ($\Upsilon(4S)$), 10.867 ($\Upsilon(5S)$) GeV

■ Search for $e^+e^- \rightarrow X_{cc\bar{s}\bar{s}} + \text{anything}$

$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+$ results

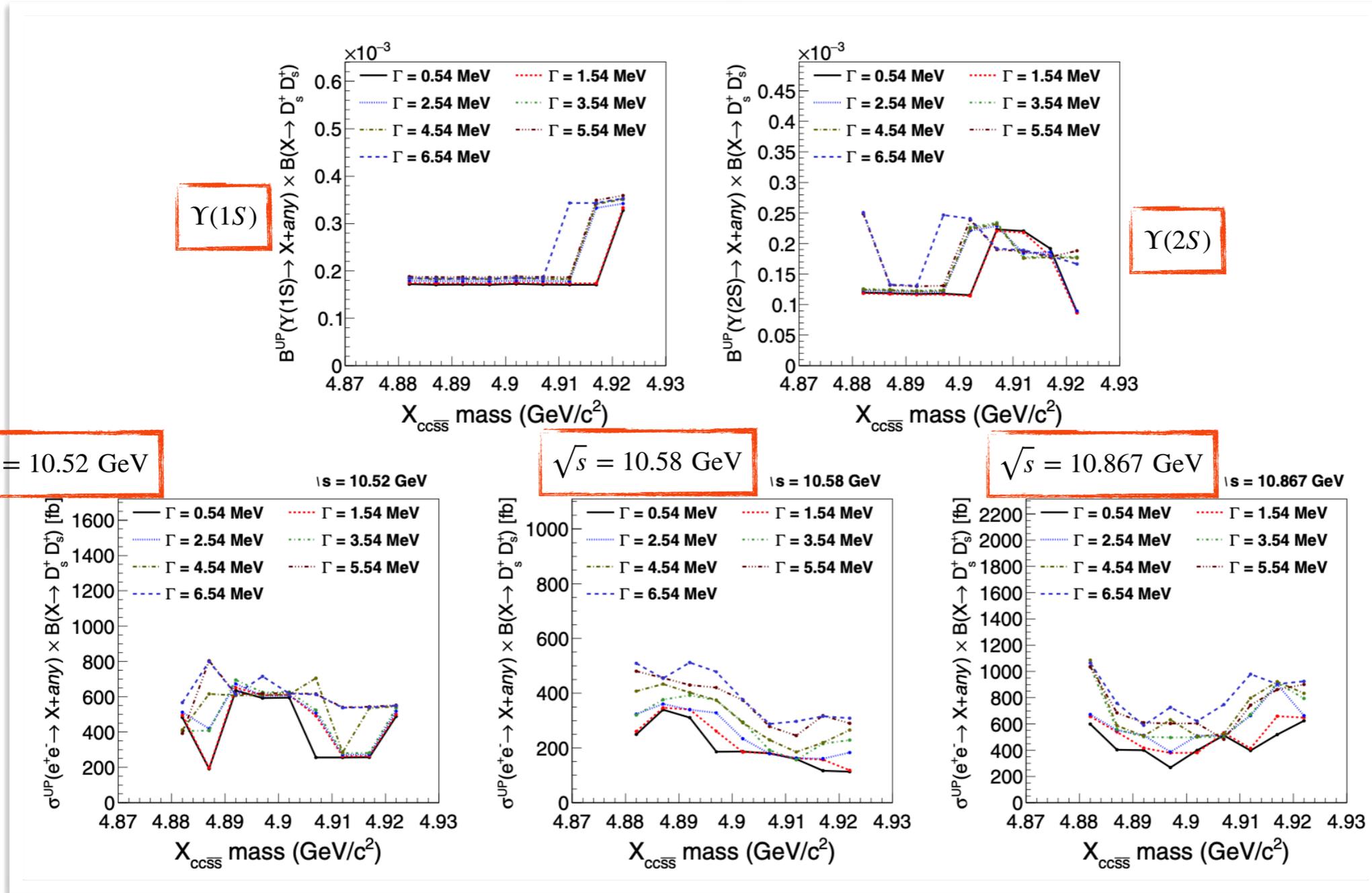
- No clear signals are observed in the invariant-mass spectra.
- Set 90% CL upper limits on the numbers of signal events



$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+$ U.L.

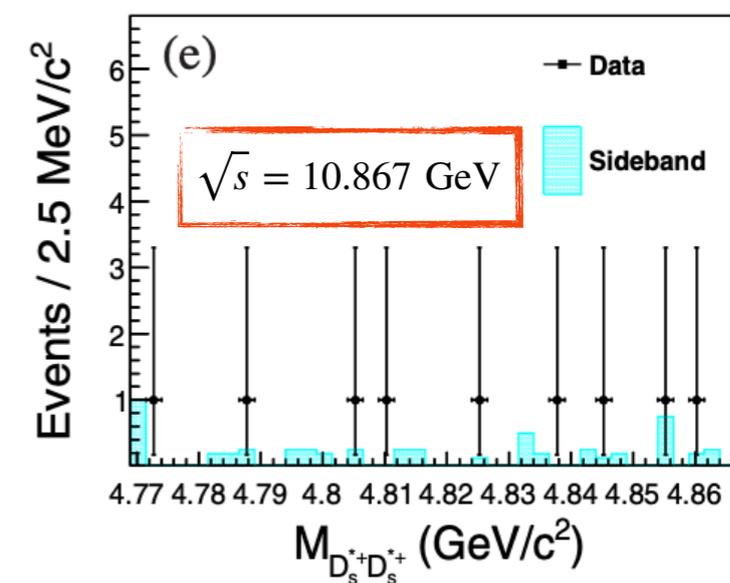
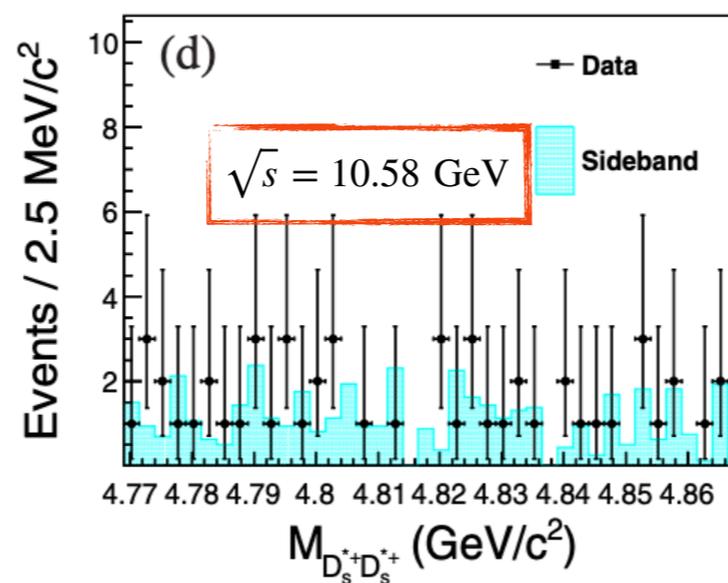
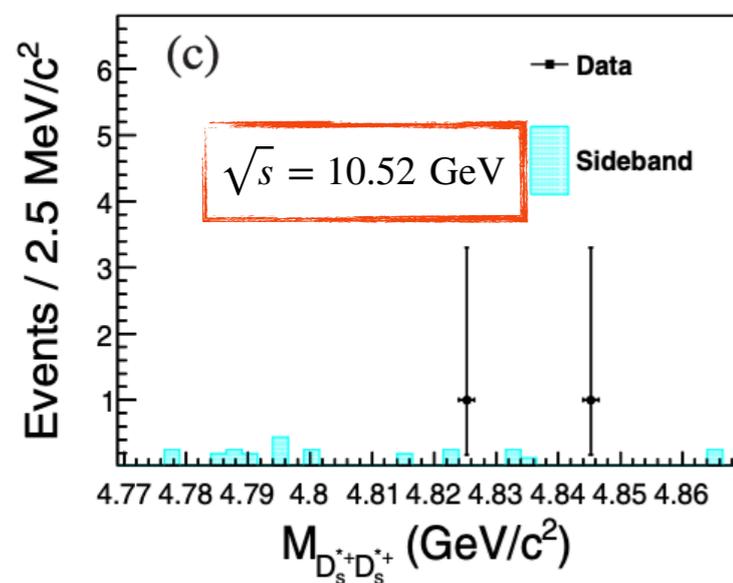
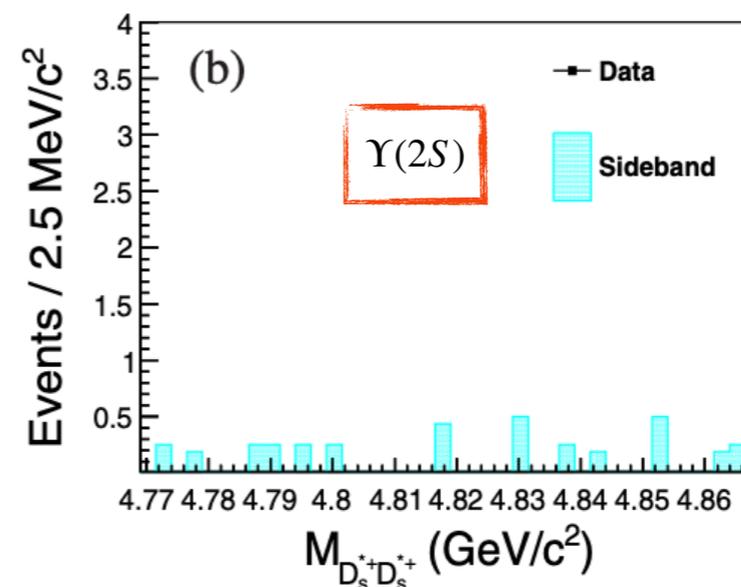
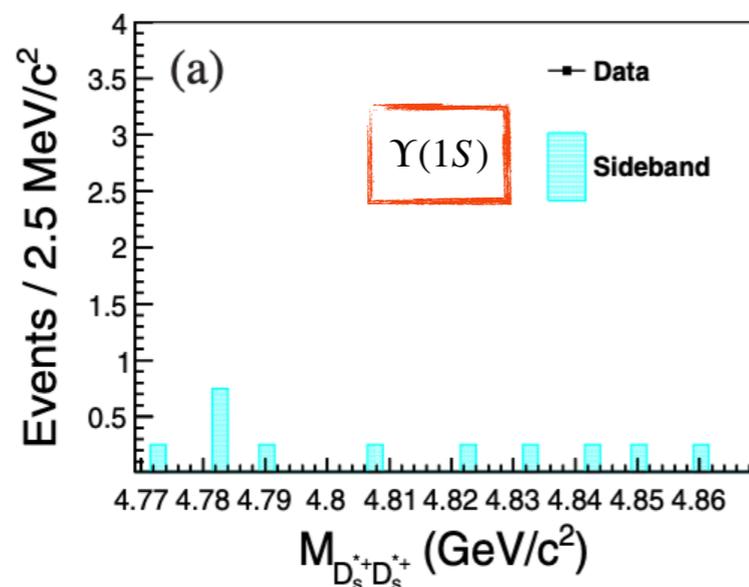
▶ $BR^{UP}(\Upsilon(nS) \rightarrow X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+)$ for $\Upsilon(1S)$, $\Upsilon(2S)$

▶ $\sigma^{UP}(e^+e^- \rightarrow X_{cc\bar{s}\bar{s}} + \text{anything}) \times BR(X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+)$ for $\sqrt{s} = 10.52, 10.58, 10.867$ GeV



$X_{cc\bar{s}\bar{s}} \rightarrow D_s^{*+} D_s^{*+}$ results

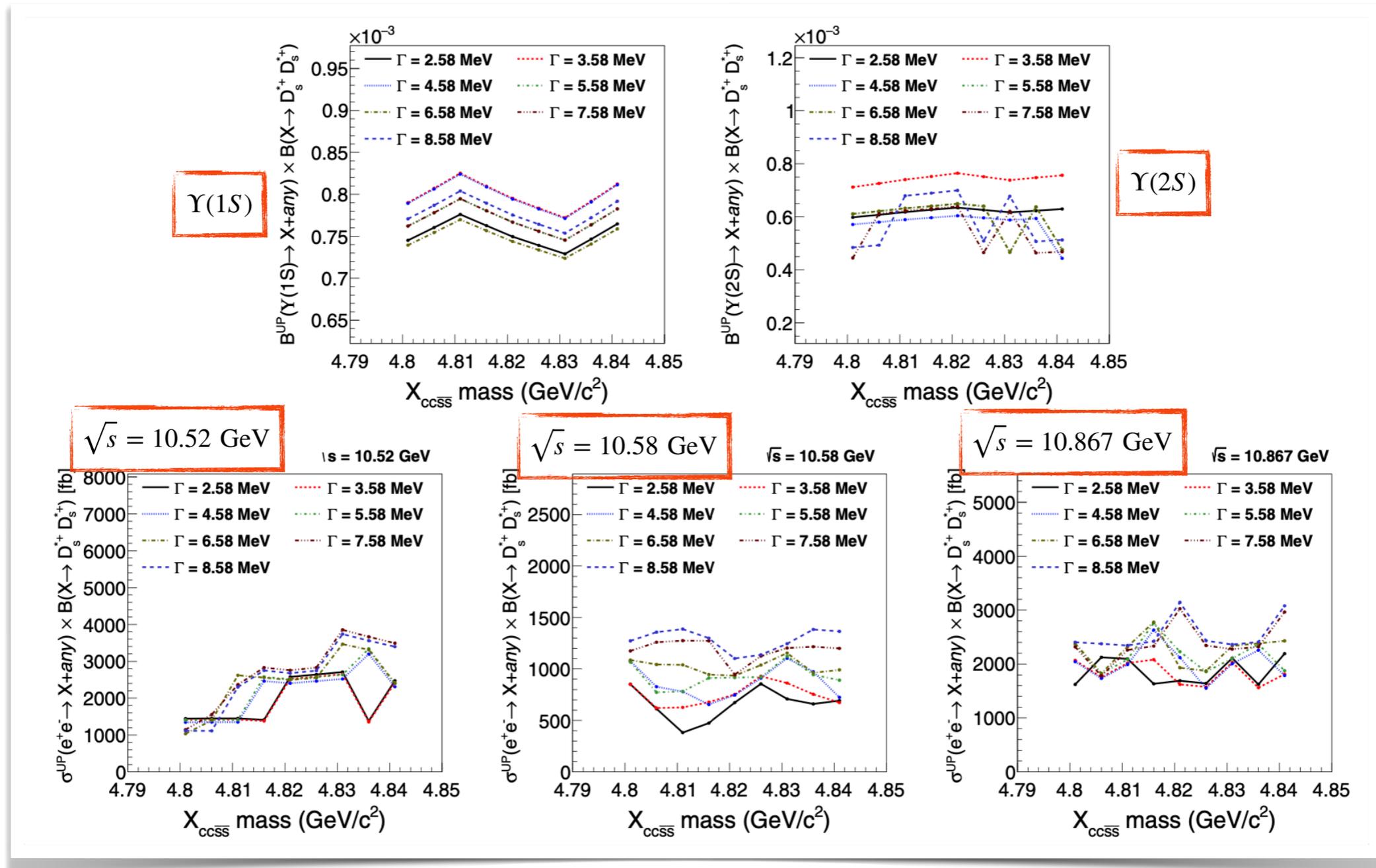
- No clear signals are observed in the invariant-mass spectra.
- Set 90% CL upper limits on the numbers of signal events



$X_{cc\bar{s}\bar{s}} \rightarrow D_s^*+D_s^*+ 90\% \text{ CL upper limits}$

▶ $BR^{UP}(\Upsilon(nS) \rightarrow X_{cc\bar{s}\bar{s}} \rightarrow D_s^*+D_s^*)$ for $\Upsilon(1S), \Upsilon(2S)$

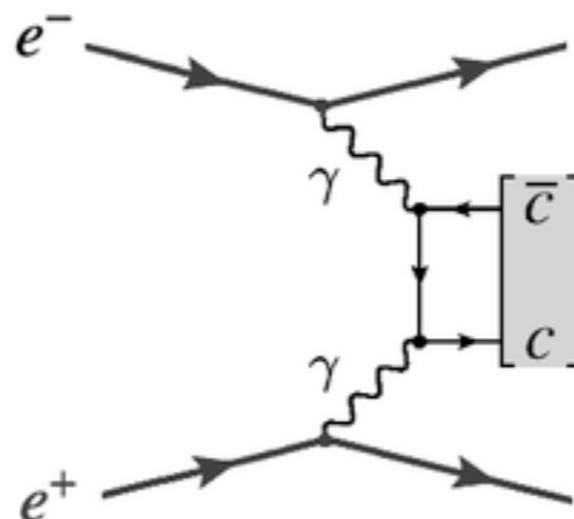
▶ $\sigma^{UP}(e^+e^- \rightarrow X_{cc\bar{s}\bar{s}} + \text{anything}) \times BR(X_{cc\bar{s}\bar{s}} \rightarrow D_s^*+D_s^*)$ for $\sqrt{s} = 10.52, 10.58, 10.867 \text{ GeV}$



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

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

- ▶ The two-photon decay widths ($\Gamma_{\gamma\gamma}(R)$) of mesonic states provide important information for testing QCD models
- ▶ Prediction range from 280 eV to 930 eV
 - List of theoretical model in backup-slides
- ▶ $\Gamma_{\gamma\gamma}(R)$ can be measured from 2 photon decay or from 2 photon collision
 - 2 photon collision has been chosen for this analysis



$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ strategy

▶ Channels: $\chi_{c2}(1P) \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-, e^+e^-$

▶ Dataset: 971 fb⁻¹ collected at or near the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$ and $\Upsilon(5S)$

● Previous Belle measurement done with 32.6 fb⁻¹

▶ Recoiling e^+e^- are left undetected

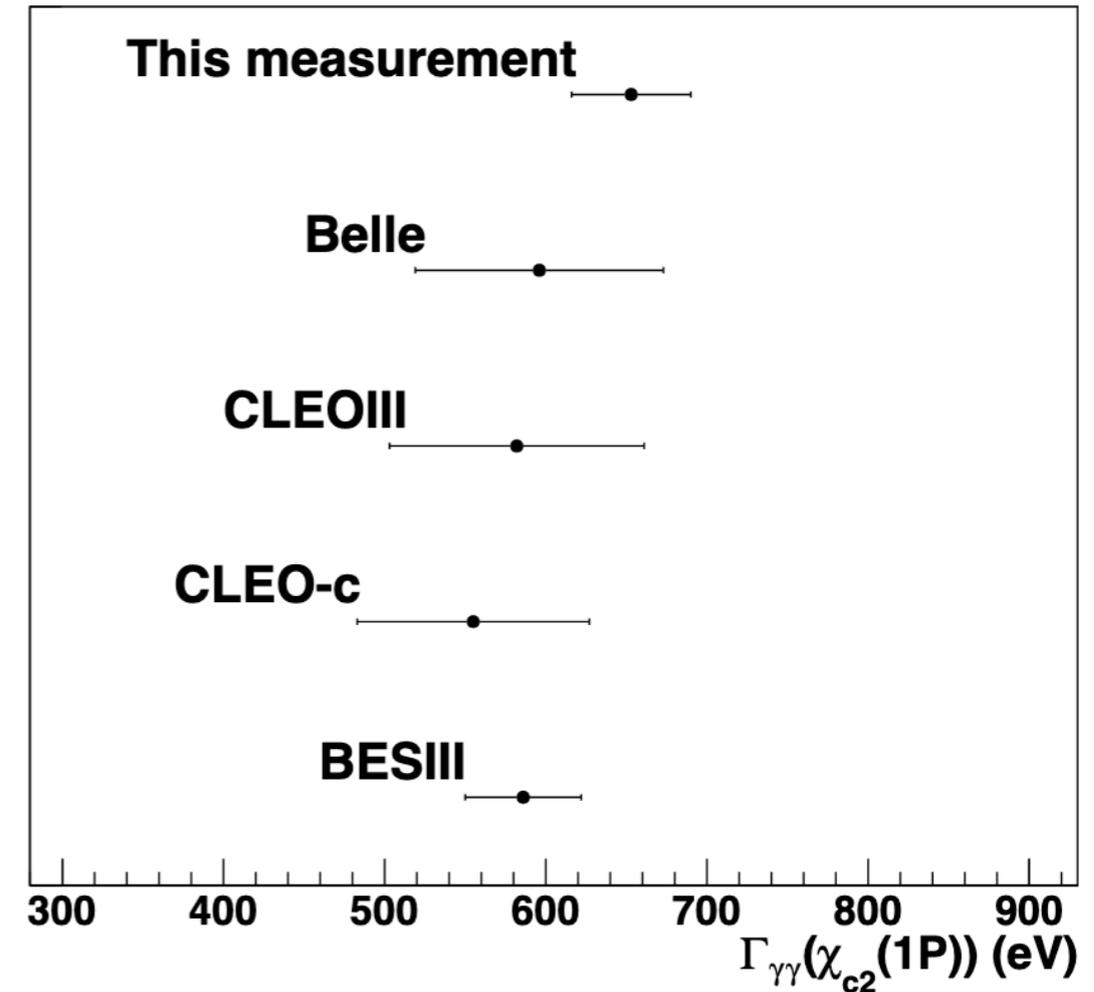
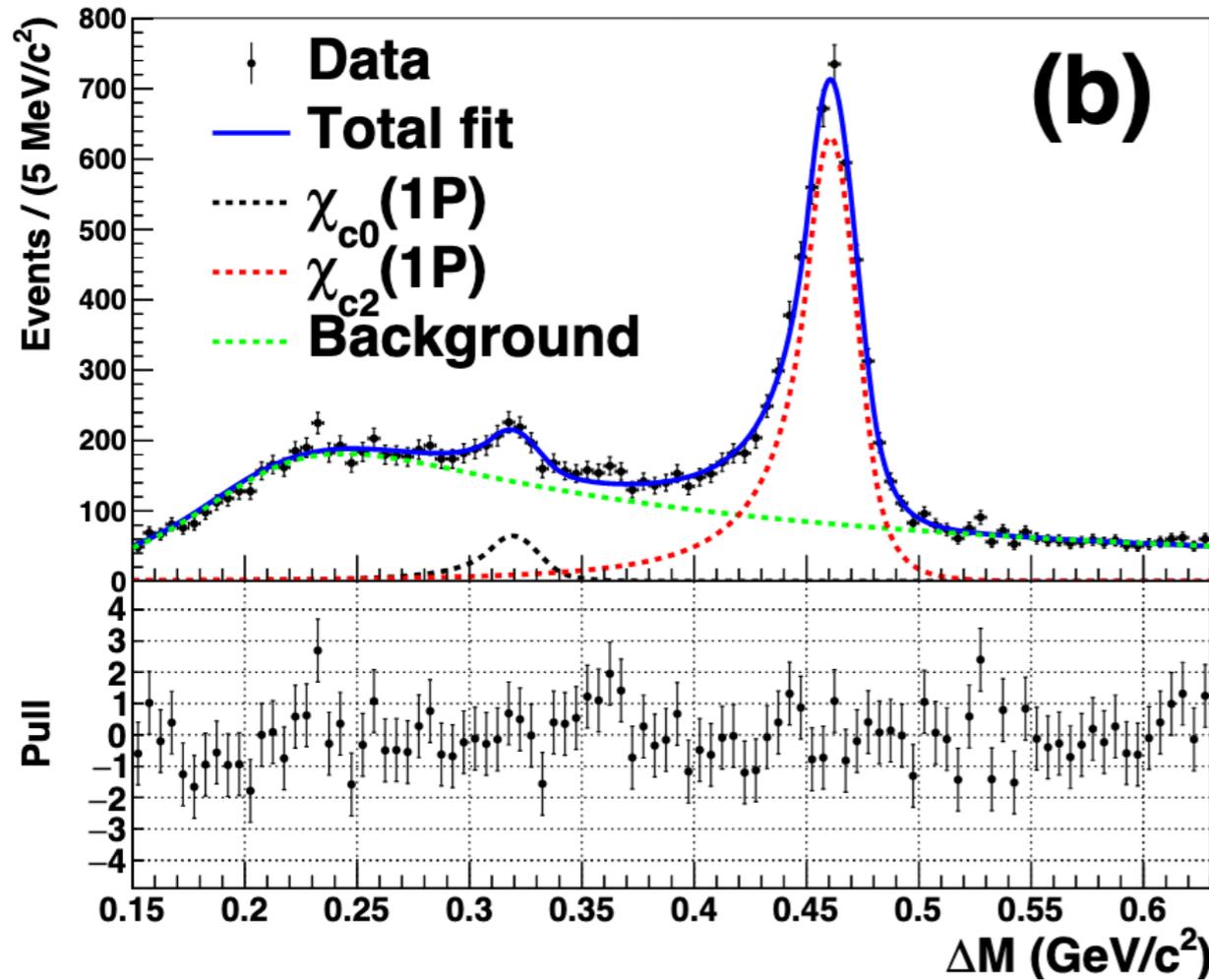
▶ The signal $\chi_{c2}(1P)$ produced in quasi-real two-photon collisions are selected with a \mathbf{p}_T^* -balance requirement.

● $|\mathbf{p}_T^{*\text{tot}}| = |\mathbf{p}_T^{*+} + \mathbf{p}_T^{*-} + \mathbf{p}_T^{*\gamma}| < 0.15 \text{ GeV}/c$

▶ Binned extended maximum-likelihood fit on $\Delta M = M_{\ell+\ell-\gamma} - M_{\ell+\ell-}$

▶
$$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = \frac{m_{\chi_{c2}(1P)}^2 N_{sig}}{4\pi^2(2J+1)(\int \mathcal{L} dt) \cdot \epsilon \cdot L_{\gamma\gamma}(m_{\chi_{c2}(1P)}) \cdot \mathcal{B}(\chi_{c2}(1P) \rightarrow \text{final state})}$$

$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ Results



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]	$\mathcal{B}_3 \times \mathcal{B}_4 \times 10^5 = 2.83 \pm 0.08 \pm 0.06$	$586 \pm 16 \pm 13 \pm 29^{c,e}$

Summary

- ▶ Albeit Belle end operation ~10 years ago, we are still producing exciting results.
- ▶ We report the search for $X(3872) \rightarrow \pi^+ \pi^- \pi^0$
- ▶ We report the search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_s^+ D_s^+ (D_s^{*+} D_s^{*+})$
- ▶ We reported the measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ from
 $\gamma\gamma \rightarrow \chi_{c2}(1P) \rightarrow J/\psi\gamma$



Backup slides



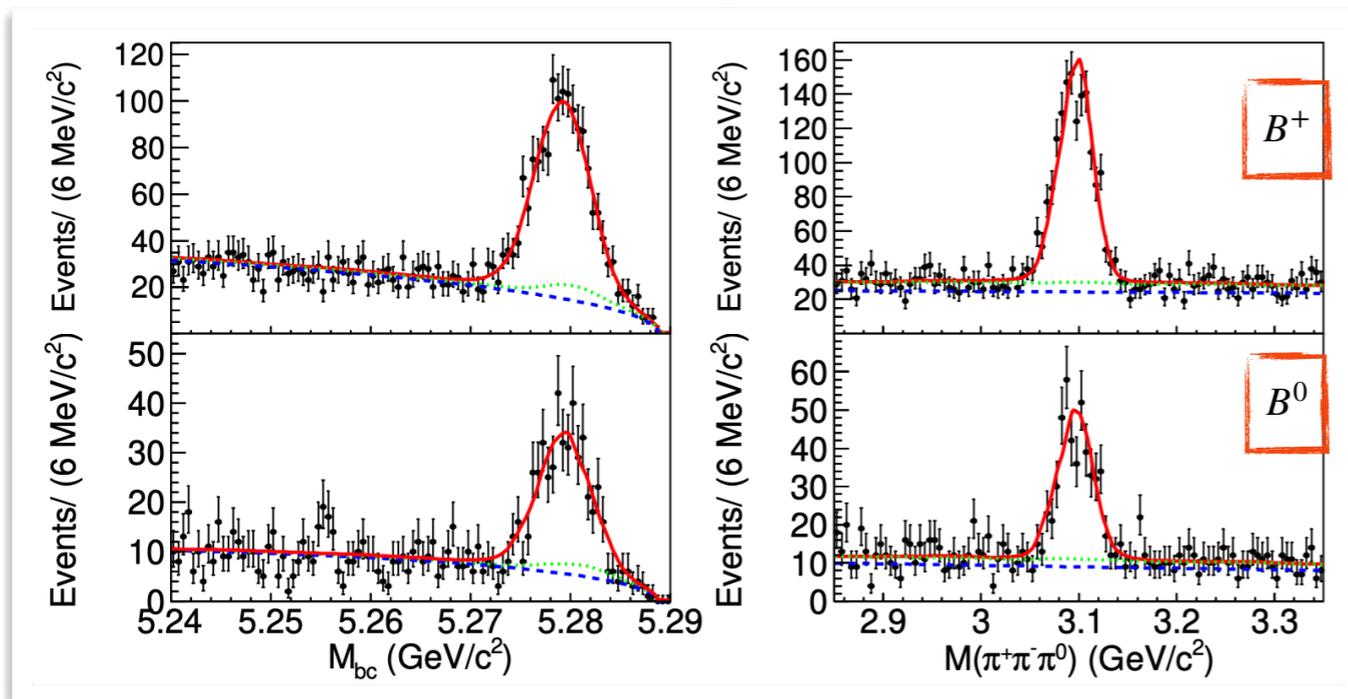
Search for $X(3872) \rightarrow \pi^+ \pi^- \pi^0$

aka $\chi_{c1}(3872)$

$X(3872) \rightarrow \pi^+ \pi^- \pi^0 J/\psi$ Control Region

▶ $M(\pi^+ \pi^- \pi^0) \in [3.0, 3.15] \text{ GeV}$

▶ $M_{bc} > 5.27 \text{ GeV}/c^2$



— All

— Combinatorial background

— Combinatorial + resonant background

Search for tetraquark states

$$X_{cc\bar{s}\bar{s}} \text{ in } D_S^+ D_S^+ (D_S^{*+} D_S^{*+})$$

$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+})$ signal MC

▶ $D_s^+ D_s^+$

- $M(X_{cc\bar{s}\bar{s}})$ in the interval from 4882 to 4922 MeV/c² in steps of 5 MeV/c²
- $\Gamma(X_{cc\bar{s}\bar{s}})$ varying from 0.54 to 6.54 MeV in steps of 1 MeV.

▶ $D_s^{*+} D_s^{*+}$

- $M(X_{cc\bar{s}\bar{s}})$ in the interval from 4801 to 4841 MeV/c² in steps of 5 MeV/c²
- $\Gamma(X_{cc\bar{s}\bar{s}})$ varying from with 2.58 to 8.58 MeV in steps of 1 MeV.

$$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+})$$

$$\triangleright \sigma^{UP}(e^+e^- \rightarrow X_{cc\bar{s}\bar{s}} + \text{anything}) \times \text{BR}(X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+})) = \frac{N^{UP} \times |1 - \Pi|^2}{\mathcal{L} \times \sum_i \epsilon_i B_i \times (1 + \sigma)_{ISR}}$$

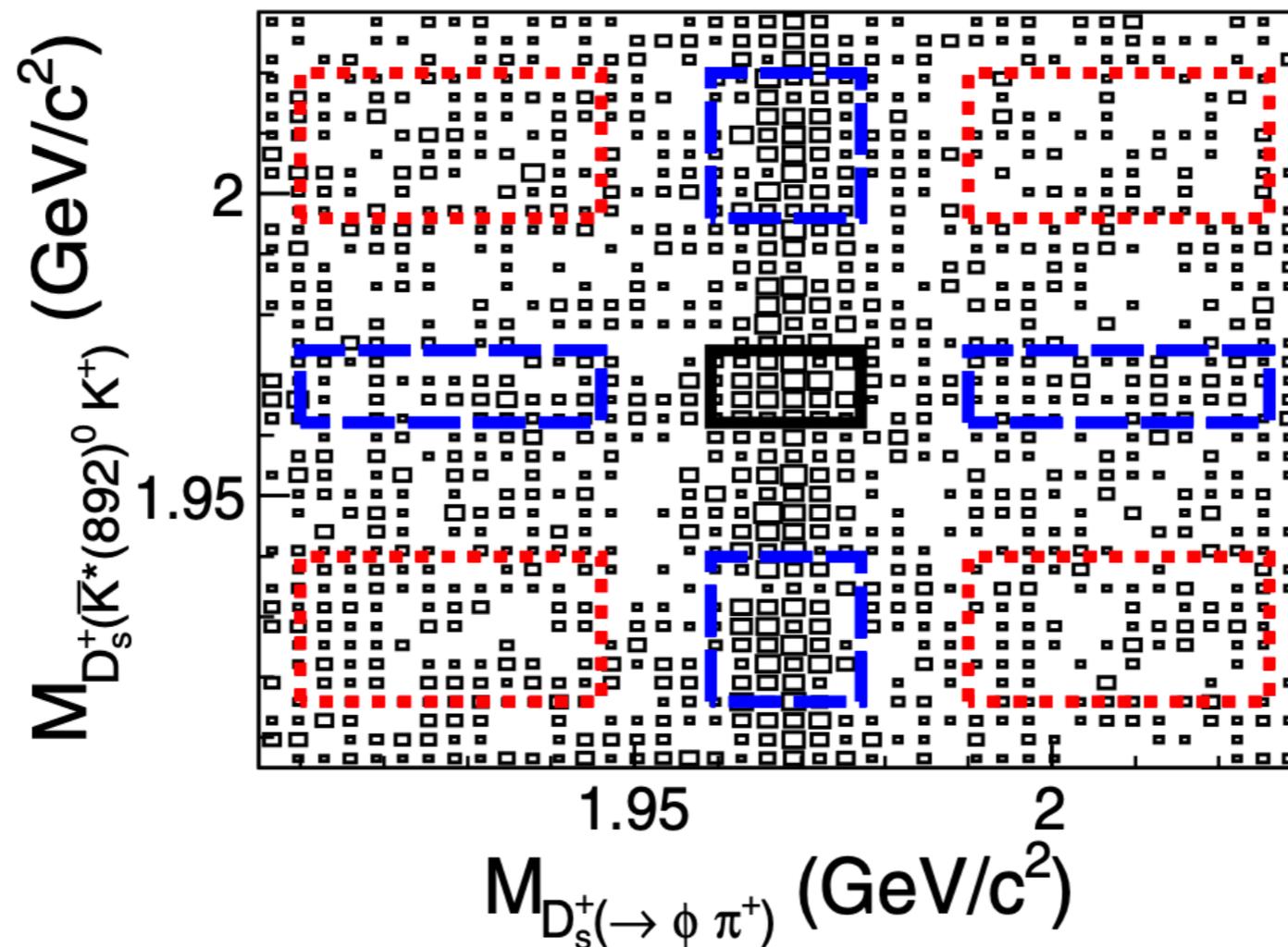
$\triangleright |1 - \Pi|^2$ is the vacuum polarization factor

$\triangleright (1 + \sigma)_{ISR}$ is the radiative correction factor

$$\triangleright \text{BR}^{UP}(\Upsilon(nS) \rightarrow X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+})) = \frac{N^{UP}}{N_{\Upsilon(nS)} \times \sum_i \epsilon_i B_i}$$

$$X_{cc\bar{s}\bar{s}} \rightarrow D_s^+ D_s^+ (D_s^{*+} D_s^{*+}) \text{ Side bands}$$

▶ Black box correspond to signal region



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

$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ theory papers:

- ▶ R. Barbier, R. Gatto, and R. Kögerler, Phys. Lett. B 60, 183 (1976)
- ▶ C.R.Münz, Nucl. Phys. A 609, 364 (1996).
- ▶ S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
- ▶ S. N. Gupta, J. M. Johnson, and W. W. Repko, Phys. Rev. D 54, 2075 (1996).
- ▶ D. Ebert, R. N. Faustov, and V. O. Galkin, Mod. Phys. Lett. A 18, 601 (2003).
- ▶ G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D 46, R1914 (1992).
- ▶ H. W. Huang and K. T. Chao, Phys. Rev. D 54, 6850 (1996); 56, 1821(E) (1997).
- ▶ G. A. Schuler, F. A. Berends, and R. van Gulik, Nucl.Phys. B 523, 423 (1998).
- ▶ H. W. Crater, C. Y. Wong and P. VanAlstine, Phys. Rev. D 74, 054028 (2006).
- ▶ J. P. Lansberg and T. N. Pham, Phys. Rev. D 79, 094016 (2009).
- ▶ C. W. Hwang and R. S. Guo, Phys. Rev. D 82, 034021 (2010).

Production cross-section

$$\triangleright \sigma(e^+e^- \rightarrow e^+e^-R) = \int \sigma(\gamma\gamma \rightarrow R; W) L_{\gamma\gamma}(W) dW$$

● $L_{\gamma\gamma}(W)$ luminosity function

$$\triangleright \sigma(\gamma\gamma \rightarrow R; W) \simeq 8\pi^2(2J+1) \frac{\Gamma_{\gamma\gamma}^R \Gamma_R}{(W^2 - m_R^2)^2 + m_R^2 \Gamma_R^2}$$

▶ For $\Gamma_{\gamma\gamma}, \Gamma_R \ll m_R$

$$\bullet \sigma(e^+e^- \rightarrow e^+e^-R) = 4\pi^2(2J+1) \frac{L_{\gamma\gamma}(m_R) \Gamma_{\gamma\gamma}^R}{m_R^2}$$

$$\triangleright \sigma(e^+e^- \rightarrow e^+e^-R) \mathcal{B}(R \rightarrow \text{final state}) = \frac{N_R}{(\int \mathcal{L} dt) \epsilon}$$

$$\triangleright \Gamma_{\gamma\gamma}^R \mathcal{B}(R \rightarrow \text{final state}) = \frac{m_R^2 N_R}{4\pi^2(2J+1)(\int \mathcal{L} dt) \epsilon L_{\gamma\gamma}(m_R)}$$

Zero tag

▶ Events induced by highly virtual photons (i.e., photons with high- Q^2) are effectively rejected by a strict transverse momentum(p_t) requirement applied to the χ_{c2} daughter particles

- Q^2 is defined as the negative of the invariant mass squared of a virtual incident photon.
- It is approximately equal to $|p_t|^2$ of the virtual photon with respect to the e^+e^- beam axis.
- The signal $\chi_{c2}(1P)$ produced in quasi-real two-photon collisions are selected with a \mathbf{p}_T^* -balance requirement.
- $|\mathbf{p}_T^{*\text{tot}}| = |\mathbf{p}^{*+} + \mathbf{p}^{*-} + \mathbf{p}^{*\gamma}| < 0.15 \text{ GeV}/c$

Selection

- ▶ γ : One cluster in the ECL with an energy $E_\gamma \geq 0.2$ GeV isolated from charged track by an angle $> 18.2^\circ$
- ▶ Tracks: 2 tracks with $E/p \geq 0.8$ for electrons and 2 tracks with $E/p \leq 0.4$ for muons
- ▶ $M_{\text{recoil}}^2 > 5.0$ GeV/c⁴ to remove ISR process
- ▶ Peaking background
- ▶ $e^+e^- \rightarrow \gamma_{\text{ISR}} \psi(2S), \psi(2S) \rightarrow \chi_{c2}(1P)\gamma, \chi_{c2}(1P) \rightarrow J/\psi\gamma, J/\psi \rightarrow \ell^+\ell^-$
 - 3.3 % of the peak

