Study of charmonia at Belle

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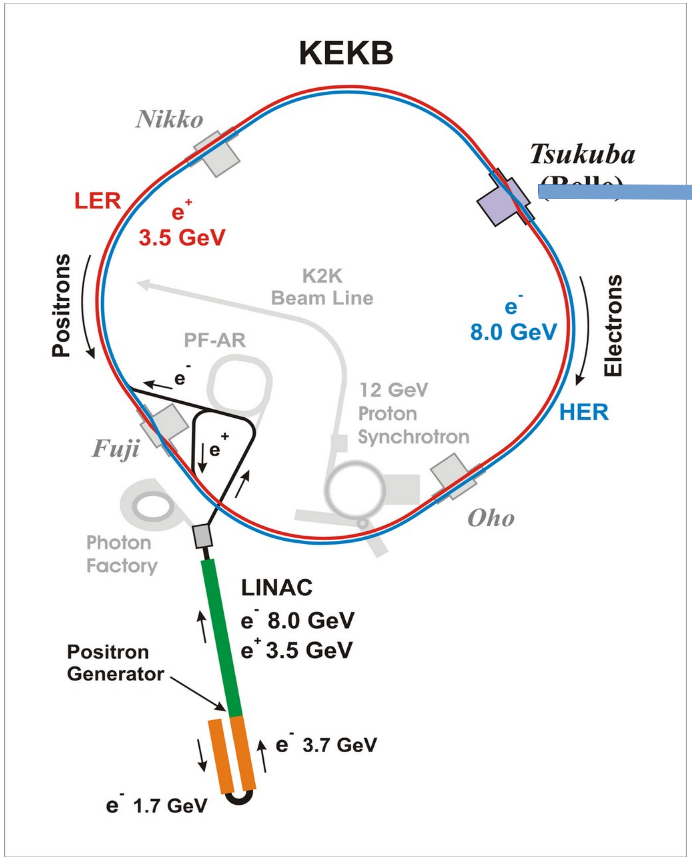
Overview

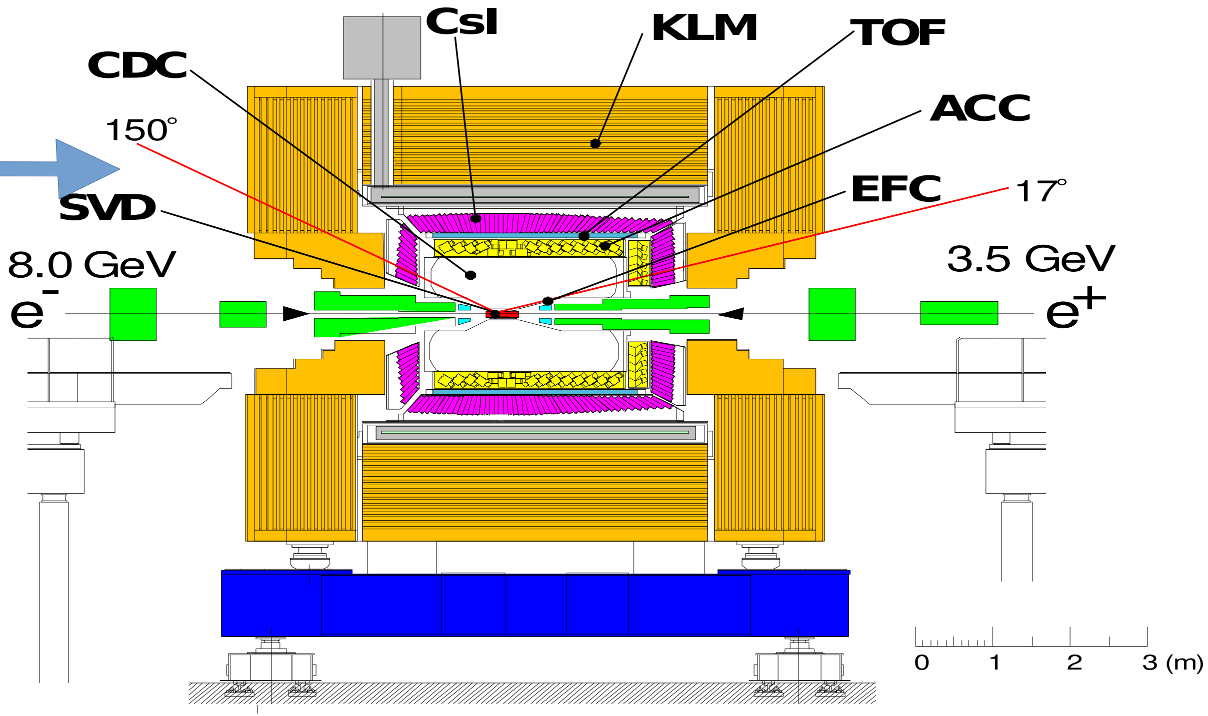
- Search for $X(3872) \to \pi^+\pi^-\pi^0$ at Belle
  [*submitted to PRD, arXiv:2206.08592*]

- Measurement of two-photon decay width of $\chi_{c2}(1P)$ in $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$ at Belle
  [*submitted to JHEP, arXiv:2208.04477*]

- Search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_s^+D_s^+$ ($D_s^{*+}D_s^{*+}$) final states at Belle
  [*PRD 105, 032002 (2022)*]

Belle Experiment





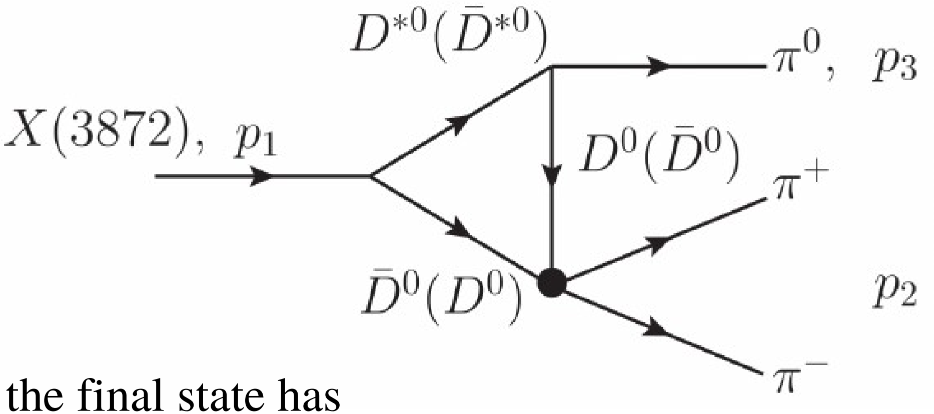
Search for $X(3872) \to \pi^+\pi^-\pi^0$ at Belle

Overview of $X(3872) \to \pi^+\pi^-\pi^0$ decay

X(3872)

- X(3872) was discovered by the Belle Collaboration in 2003.
- Recently, quantum number of X(3872) is defined as $J^{PC} = 1^{++}$ by the LHCb collaboration. Phys.Rev.Lett. 110 (2013) 222001

Phys. Rev. D 99, 116023



- The search for X(3872) with no charmed particle in the final state has remained in great interest.
- Considering X(3872) as a pure charmonium state, X(3872) → gluon+gluon → light hadrons decays has significant branching fraction.
- Considering the molecule picture into account, dominant contribution from:

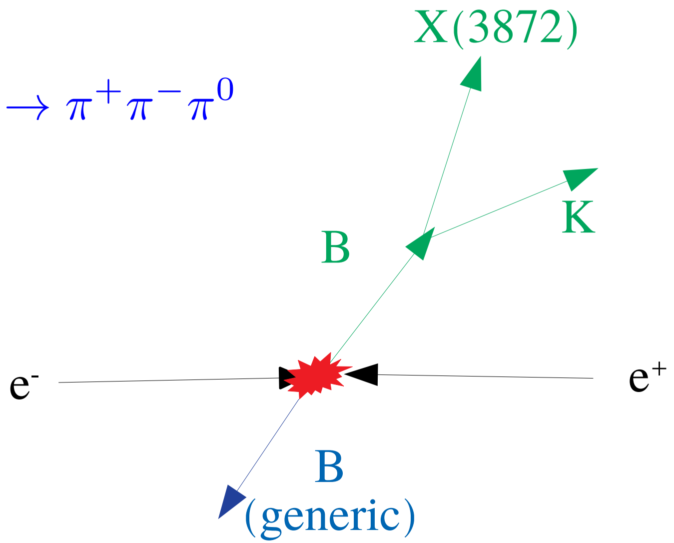
$$X(3872) \to (D^*\bar{D} + \bar{D}^*D) \to \pi^0 D\bar{D} \to \pi^0\pi^+\pi^-$$

$$\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0) \sim 10^{-4} - 10^{-3}$$

Strategy : X(3872)→π⁺π⁻π⁰

- **Decay channel:**

$$\Upsilon(4S) \to B^0\bar{B}^0/B^+B^- \qquad B \to X(3872)K \qquad X(3872) \to \pi^+\pi^-\pi^0$$

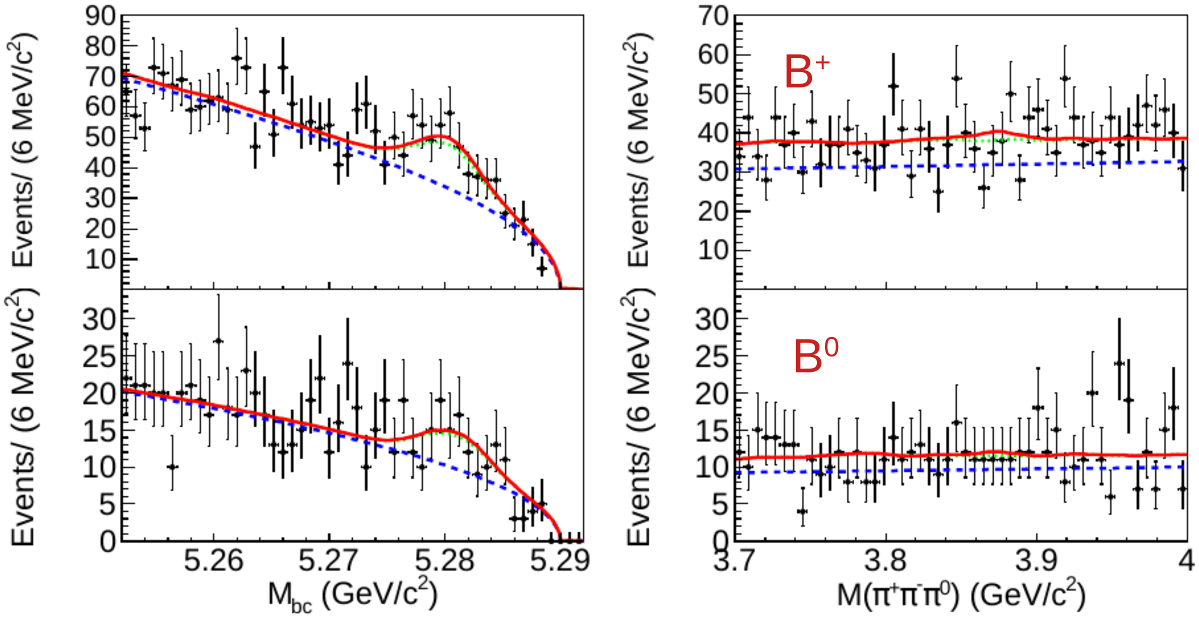


- **Data set**: (772 ±11) million $\Upsilon(4S)$ sample
- Boosted Decision Tree (BDT) has been used to suppress large continuum background.
- Peaking background arises from $B\to D\rho$ and $B\to K^{*}\rho$ decays.
- Signal is extracted from a 2D simultaneous fit to $M(\pi^+\pi^-\pi^0)$ and M_{bc}.
- Calibration mode: $B\to J/\psi K$, $J/\psi\to\pi^+\pi^-\pi^0$ decay.

Studies of two cases

- **Case I (3π phase space):** Pions are distributed over phase space uniformly.
- **Case II ($\pi^+\pi^-$ peaking):** $\pi^+\pi^-$ mass is constrained to peak near $D^0\bar{D}^0$ threshold.

Result : $X(3872)\to\pi^+\pi^-\pi^0$ [Case I (3π phase space)]



Overall fit

Combinatorial BKG

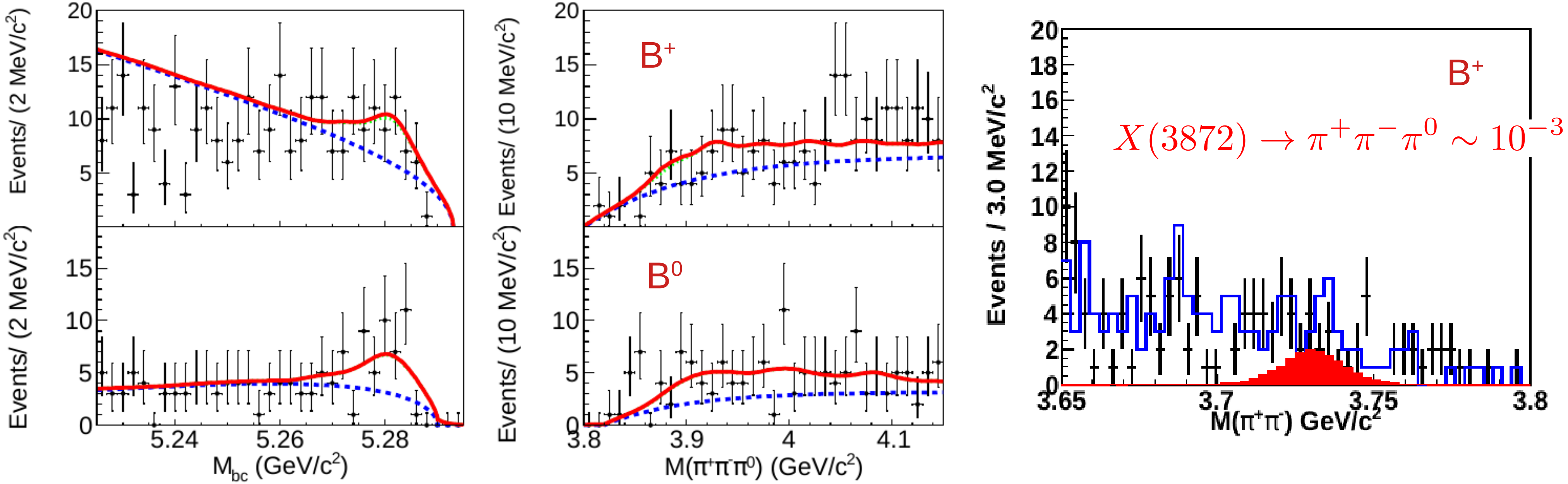
Combinatorial +resonant BKG

$\mathcal{B}[J/\psi\to\pi^+\pi^-\pi^0]=(2.00\pm0.06)\%$

channel	$N_{\rm sig}$	Upper Limit (90% CL)
$B^\pm\to K^\pm X(3872),\ X(3872)\to\pi^+\pi^-\pi^0$	20.3 ± 22.0	$<1.9\times10^{-6}$
$B^0\to K^0 X(3872),\ X(3872)\to\pi^+\pi^-\pi^0$	4.2 ± 4.6	$<1.5\times10^{-6}$
$X(3872)\to\pi^+\pi^-\pi^0$		$<1.3\times10^{-2}$

Phys.Rev.Lett. 124, 152001 (2020)

Result : $X(3872) \to \pi^+\pi^-\pi^0$ [Case II ($\pi^+\pi^-$ peaking)]



channel	$N_{\rm sig}$	Upper Limit (90% CL)
$B^\pm \to K^\pm X(3872),\ X(3872) \to \pi^+\pi^-\pi^0$	25.4 ± 24.0	$< 1.5 \times 10^{-7}$
$B^0 \to K^0 X(3872),\ X(3872) \to \pi^+\pi^-\pi^0$	-6.2 ± 10.6	$< 1.8 \times 10^{-7}$
$X(3872) \to \pi^+\pi^-\pi^0$		$< 1.2 \times 10^{-3}$

Phys.Rev.Lett. 124, 152001 (2020)

Measurement of two-photon decay width of $\chi_{c2}(1P)$ in $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi\gamma$ at Belle

Overview of $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ measurement

- P-wave charmonium states are at the intersection between perturbative and non-perturbative QCD.
- Theoretical prediction of two-photon decay width of $\chi_{c2}(1P)$, $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$, has a wide range: 280 eV to 930 eV. Phys. Rev. D 79, 094016 (2009) Rev. D 82, 034021 (2010)
- $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ can be measured using $\gamma\gamma\rightarrow\chi_{c2}(1P)$ and $\chi_{c2}(1P)\rightarrow\gamma\gamma$ decays.
- $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ can be calculated from the following relation.

$$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = \frac{N_{\mathrm{sig}} m^2_{\chi_{c2}(1P)}}{4\pi^2(2J+1)(\int \mathcal{L}dt)\mathcal{B}[\chi_{c2}(1P) \to J/\psi\gamma]\mathcal{B}[J/\psi \to \ell\ell]\epsilon L_{\gamma\gamma}(\chi_{c2}(1P))}$$

Strategy : $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ measurement

- **Decay channel:**

$$\gamma\gamma \to \chi_{c2}(1P) \qquad \chi_{c2}(1P) \to \gamma J/\psi \qquad J/\psi \to \mu^+\mu^-/e^+e^-$$

- **Data set**: 971 fb^{-1} data collected at $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, and $\Upsilon(5S)$.

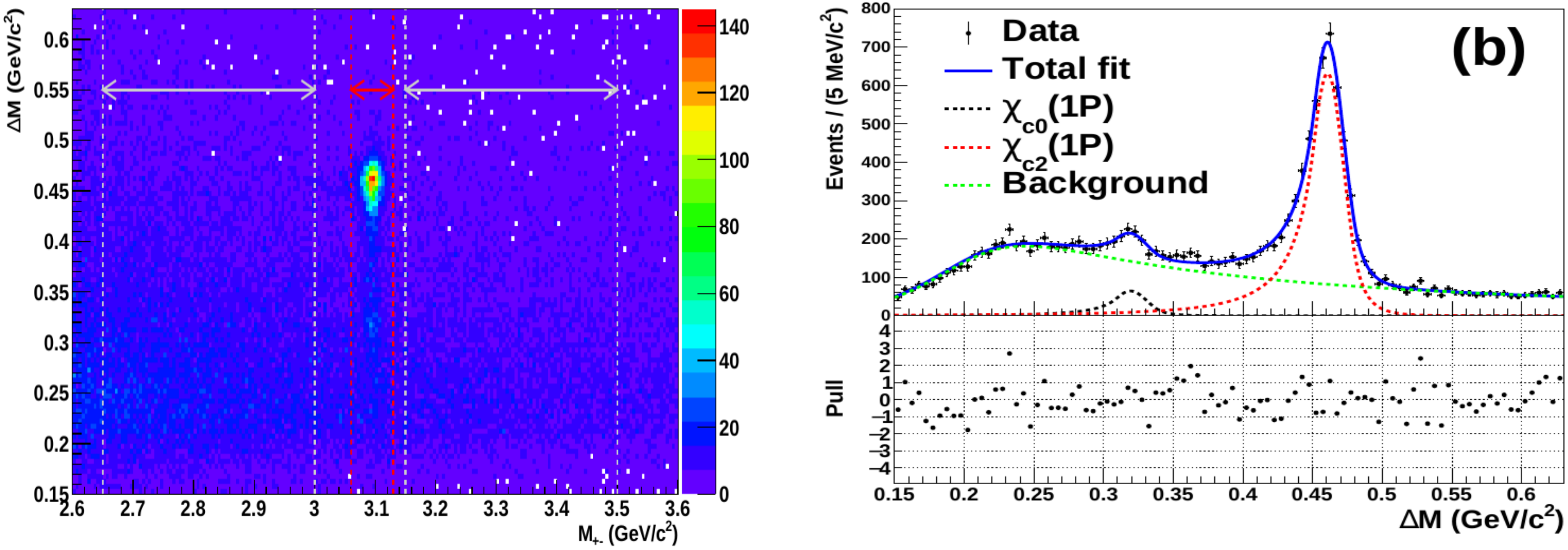
- We use recoil mass of two leptons to reject the ISR photons.

$$M^2_{\text{rec}} = (E^*_{\text{beam}} - E^*_{+-})^2 - |p^*_{+-}|^2$$

- Signal is extracted from a binned maximum likelihood to ΔM.

$$\Delta M = M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-}$$

Signal extraction : $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ measurement

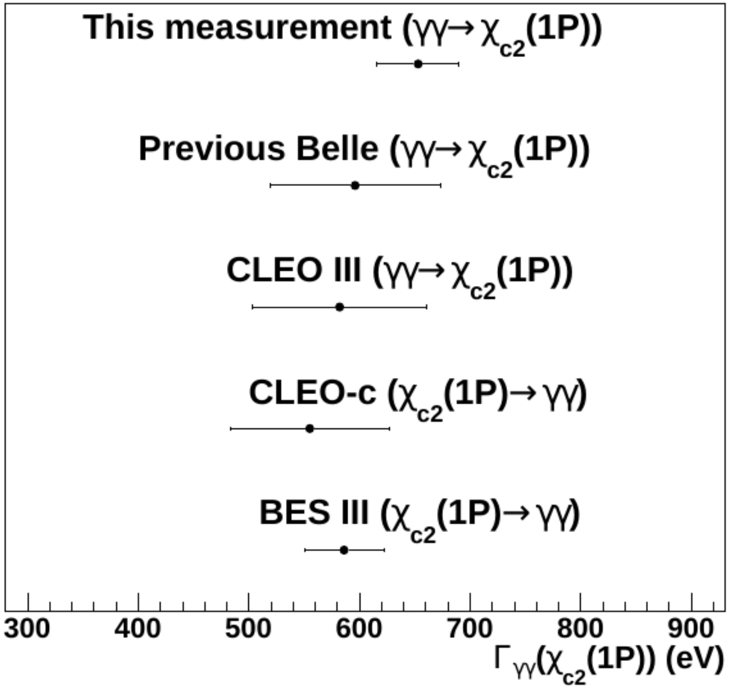


$N_{sig}(\chi_{c2}(1P)) = 4960.3 \pm 97.9$

Reasult : $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ measurement

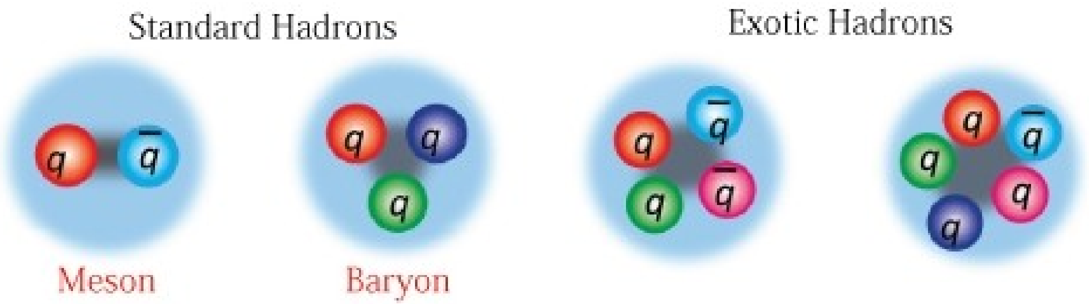
Experiment	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ (eV)
This measurement	$653 \pm 13 \pm 31 \pm 17$
Previous Belle	$596 \pm 58 \pm 48 \pm 16$
CLEO III	$582 \pm 59 \pm 50 \pm 15$
CLEO-c	$555 \pm 58 \pm 32 \pm 28$
BES III	$586 \pm 16 \pm 13 \pm 29$

This measurement is the most precise measurement.



Search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_S^+ D_s^+$ ($D^*_s{}^+ D^*_s{}^+$) final states at Belle

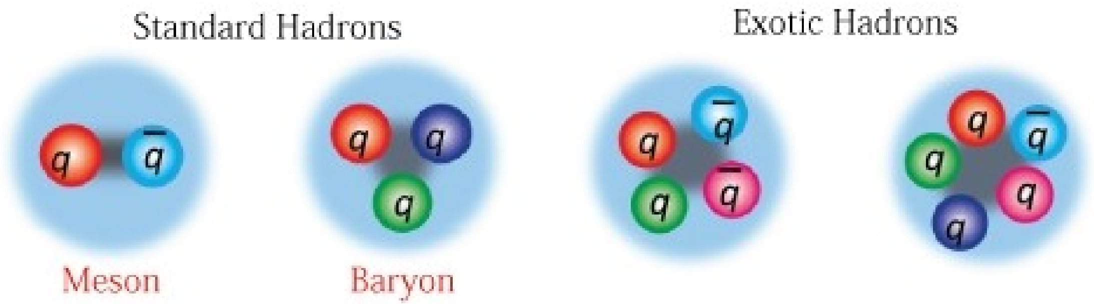
Overview of $X_{cc\bar{s}\bar{s}}$ searches in $D_s^+D_s^+$ ($D_s^{*+}D_s^{*+}$)



Mode	IJ^P	Mass (MeV/c^2)	Width (MeV)
$X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+$	00^+	4902	3.54
$X_{cc\bar{s}\bar{s}} \to D_s^{*+} D_s^{*+}$	02^+	4821	5.58
	02^+	4846	10.68
	02^+	4775	23.26

- Quark model was proposed by Gell-Mann and Zweig in 1964 to understand the nature of hadrons available at that time.
- Recently, the LHCb experiment announced the observation of an open-double-charm state T^+_{cc} in $D^0D^0\pi^+$ mass spectrum.
- Double-heavy tetraquark states (with two heavy quarks and two light quarks) are studied in many scenarios: QCD sum rules, quark models, lattice QCD.
- A QCD inspired chiral quark model gives prediction for $X_{cc\bar{s}\bar{s}}$ with +2 electron charge and $J^P = 0^+, 2^+$. Phys. Rev. D 102, 054023 (2020)

Overview of $X_{cc\bar{s}\bar{s}}$ searches in $D_s^+ D_s^+$ ($D_s^{*+} D_s^{*+}$)



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Strategy : $X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+ \; (D_s^{*+} D_s^{*+})$

- **Decay channel:**

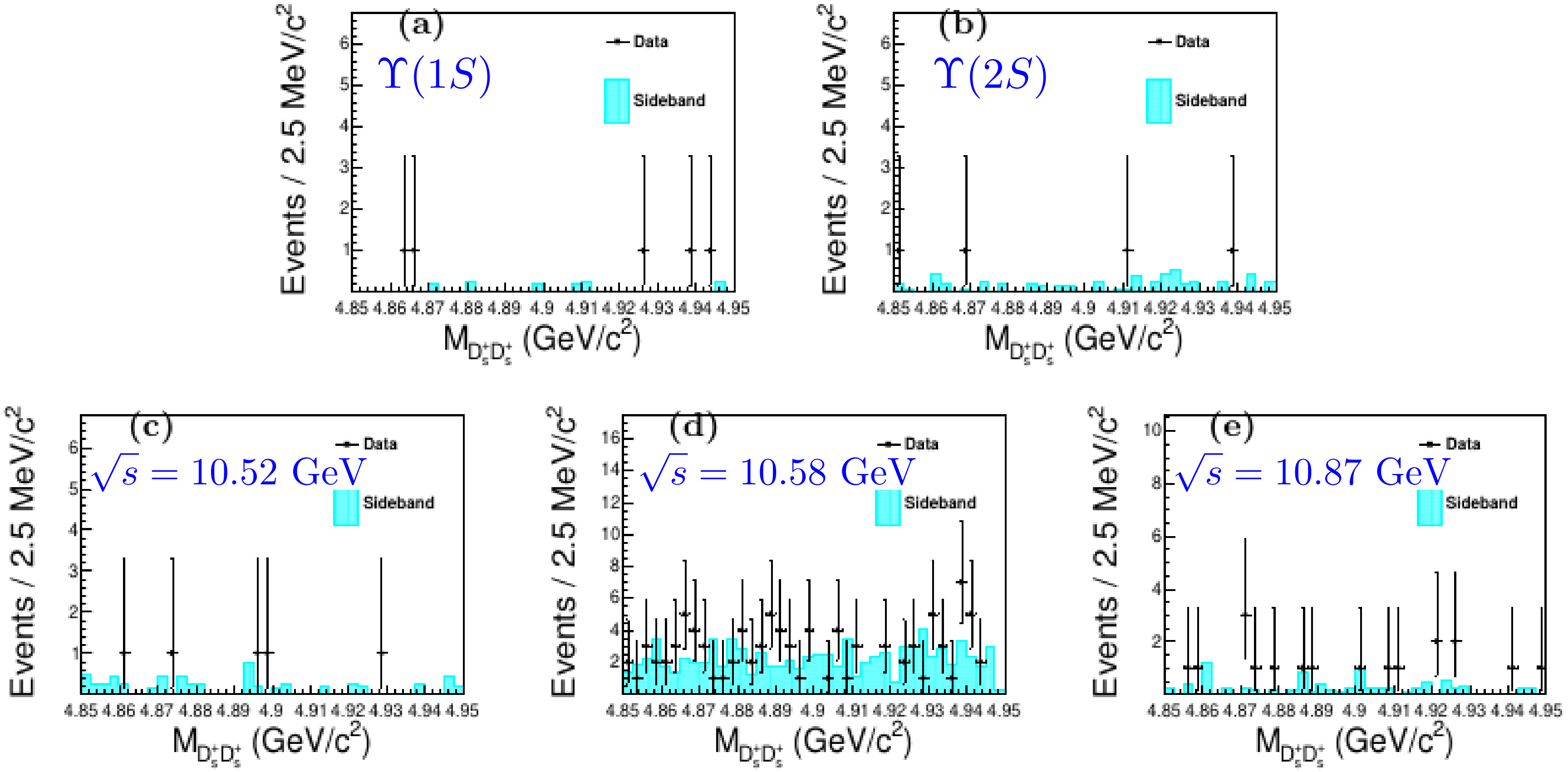
$$e^+e^- \to X_{cc\bar{s}\bar{s}} + \text{anything} \qquad X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+ \; (D_s^{*+} D_s^{*+})$$

$$D_s^{*+} \to D_s^+\gamma \qquad D_s^+ \to \phi(\to K^+K^-)\pi^+, \; \bar{K}^*(892)^0(\to K^-\pi^+)K^+$$

- **Data set**: 6 fb^{-1} $\Upsilon(1S)$, 25 fb^{-1} $\Upsilon(2S)$, 711 fb^{-1} $\Upsilon(4S)$, 121 fb^{-1} $\Upsilon(5S)$, and 89 fb^{-1} at e^+e^- collision at 10.52 GeV.

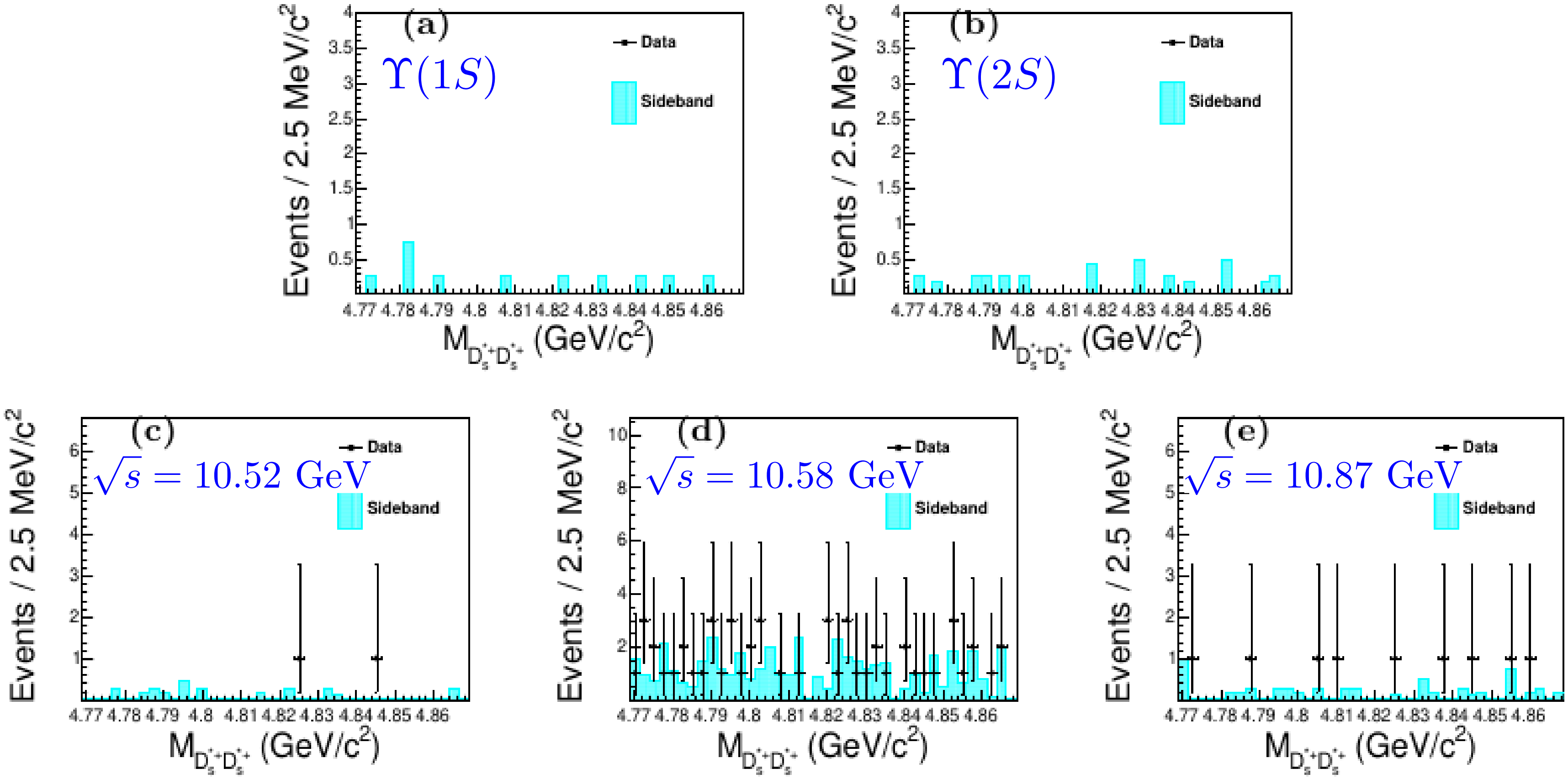
- For $D_s^+D_s^+$ ($D_s^{*+}D_s^{*+}$) channel, we choose the $X_{cc\bar{s}\bar{s}}$ mass window from 4882 to 4992 (4801 to 4841) MeV/c^2 in step of 5 MeV/c^2.

Signa extraction : $X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+$ decay



No significant signal is found

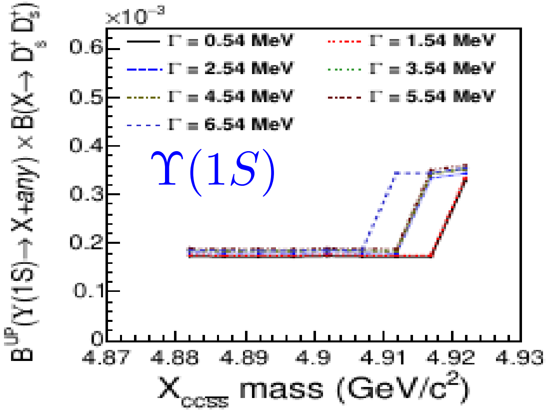
Signa extraction : $X_{cc\bar{s}\bar{s}} \to D_s^{*+} D_s^{*+}$ decay

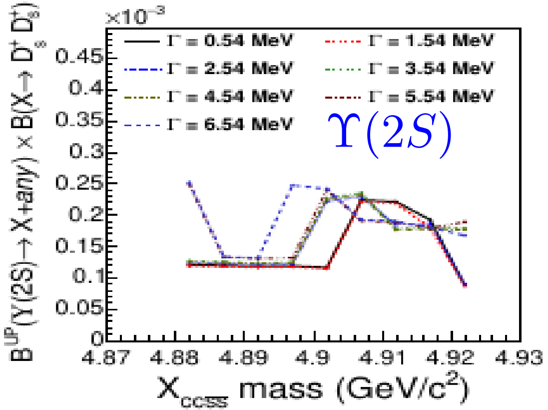


No significant signal is found

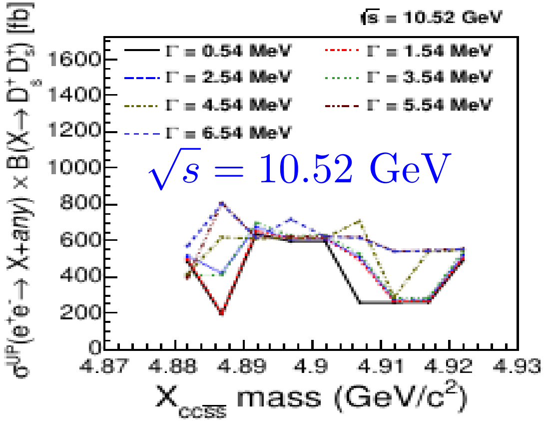
Result : $X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+$ decay

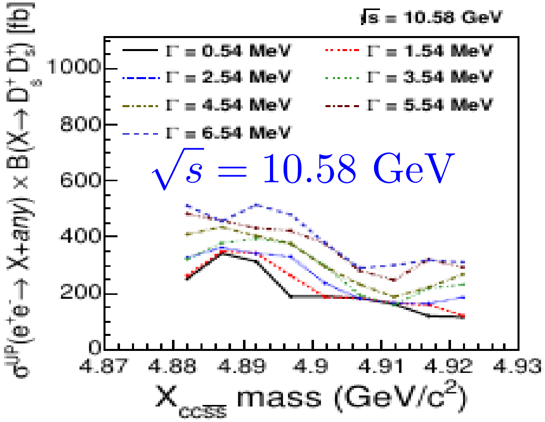
$$\frac{N^{\mathrm{UP}}}{N_{\Upsilon(1S),\Upsilon(2S)} \times \sum_i \epsilon_i \mathcal{B}_i}$$

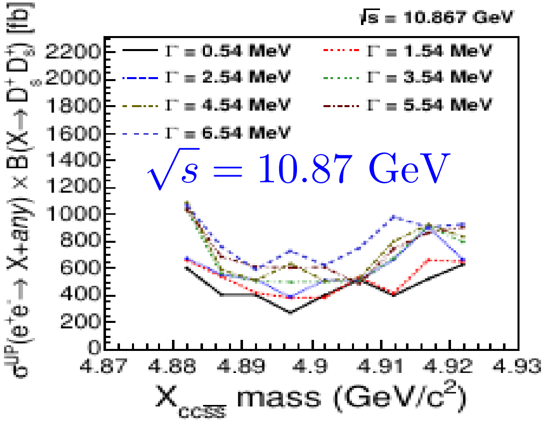




$$\frac{N^{\mathrm{UP}} \times |1-\Pi|^2}{\mathcal{L} \times \sum_i \epsilon_i \mathcal{B}_i \times (1+\delta)_{\mathrm{ISR}}}$$





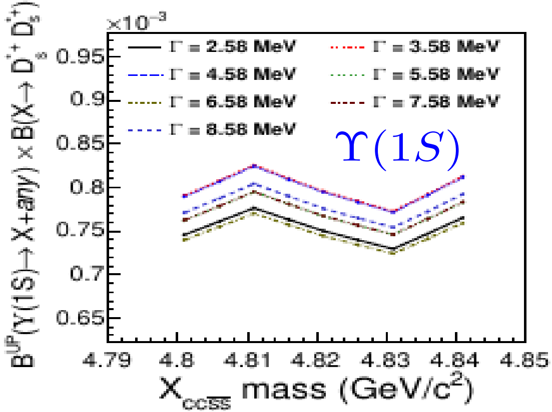


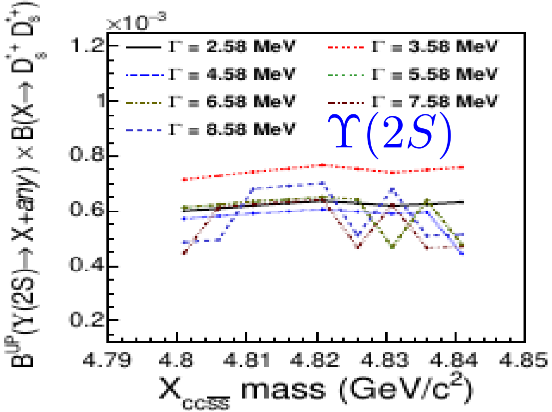
We provide the upper limits at 90% CL

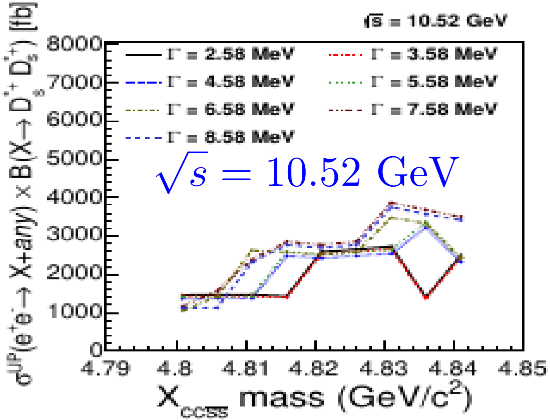
Result : $X_{cc\bar{s}\bar{s}} \to D^{*+}_{s} D^{*+}_{s}$ decay

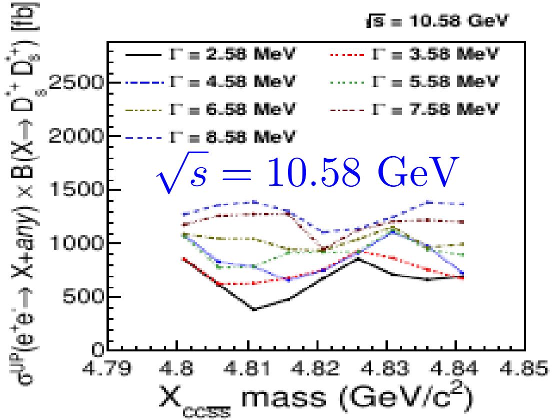
$$\frac{N^{\mathrm{UP}}}{N_{\Upsilon(1S),\Upsilon(2S)} \times \sum_i \epsilon_i \mathcal{B}_i}$$

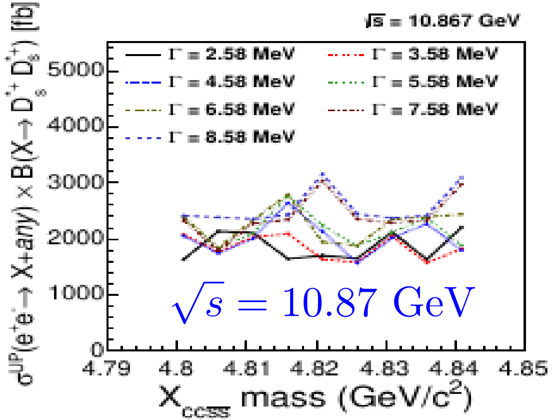
$$\frac{N^{\mathrm{UP}} \times |1-\Pi|^2}{\mathcal{L} \times \sum_i \epsilon_i \mathcal{B}_i \times (1+\delta)_{\mathrm{ISR}}}$$











We provide the upper limits at 90% CL

Summary

- We report the first search for $X(3872)\to\pi^+\pi^-\pi^0$. In absence of significant signal, we estimate the UL at 90% CL. For case I and case II, the ULs are estimated to be 1.3×10^{-2} and 1.2×10^{-3}, respectively.

- We measure the two-photon decay width for $\chi_{c2}(1P)$ in $\gamma\gamma\to\chi_{c2}(1P)\to J/\psi\gamma$ decays. This measurement is crucial for better understanding of QCD models. We report the most precise measurement: $\Gamma_{\gamma\gamma} = 653\pm13\pm31\pm17$ eV.

- We search for double-charm tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_s^+D_s^+$ ($D^*_s{}^+D^*_s{}^+$) decays. In absence of significant signal, we estimate the UL at 90% CL. Estimated ULs for $BR[\Upsilon(1S,2S)\to X_{cc\bar{s}\bar{s}}]\times BR[X_{cc\bar{s}\bar{s}}\to D_s^+D_s^+ (D^*_s{}^+D^*_s{}^+)]$ are in the order of 10^{-4}.

Thanks for your attention