16th International Workshop on Heavy Quarkonium (QWG 2024)

February 26 - March 1, 2024
IISER Mohali, India

Recent
Spectroscopy results from Belle

Jitendra Kumar
IIT Jodhpur

Talk Topics

Spectroscopy

1. Searching double-charmonium state with $\eta_c J/\psi$
   [JHEP 08 2023, 121 (2023)]
2. Two-photon decay width of $\chi_{c2}(1P)$
   [JHEP 01 2023, 160 (2023)]
3. Scan of $e^+e^- \to B_s^0\bar{B}_s^0X$ cross section
   [JHEP 08 2023, 131 (2023)]

Outline

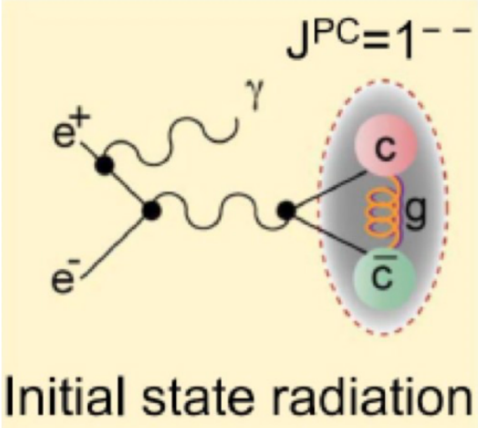
- Understanding of Quarkonium physics;
  - new exotic states, checking agreement with the predictions from theoretical quark model (testing theory)
- Belle (B-factory experiment) offer several advantages in searching for new states and rare decays:
  - full-event reconstruction and offered a clean event environment
  - also complimentary tool for the search for exotic states performed at proton-proton experiments (e.g. LHCb)

1 Searching double-charmonium state with $\eta_c J/\psi$

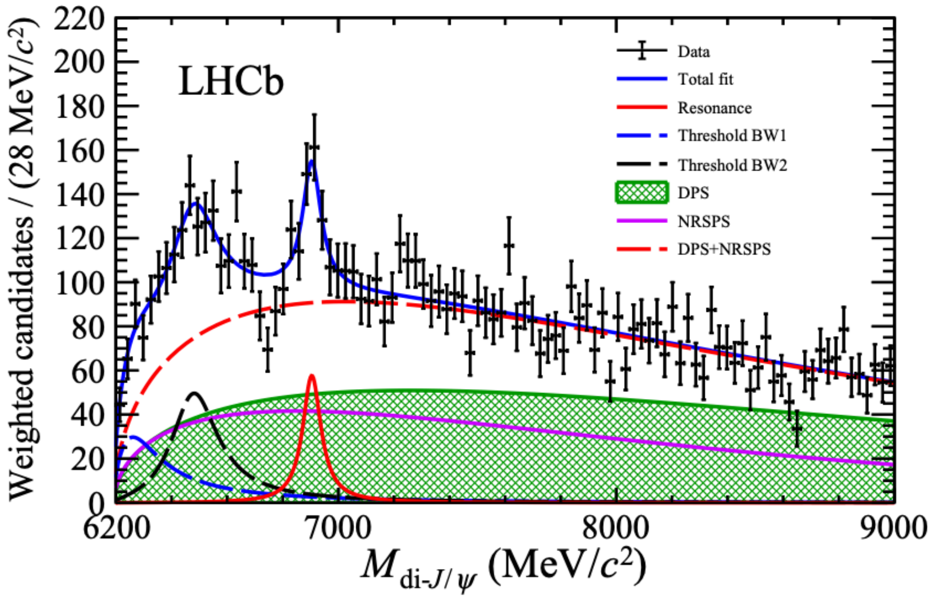
[JHEP 08 2023, 121 (2023)]

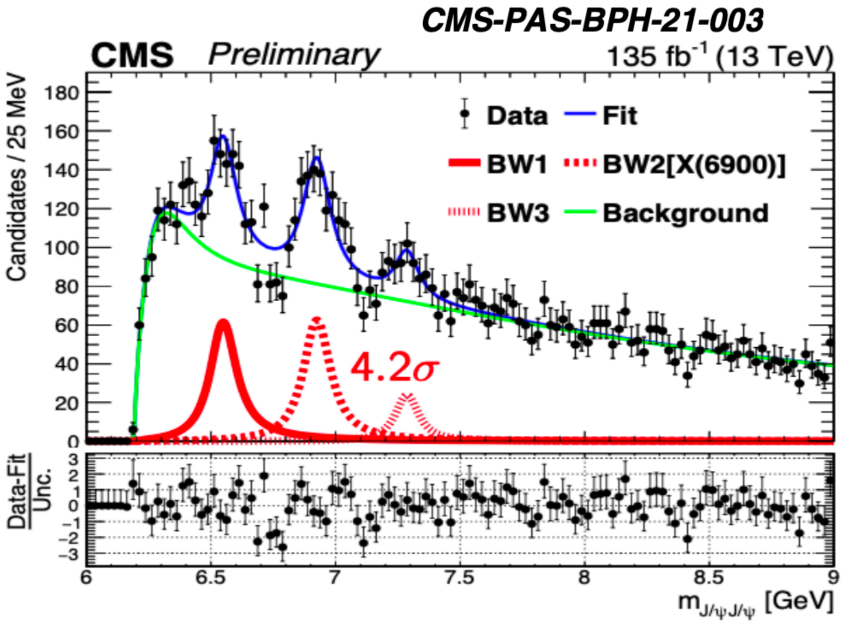
Goal

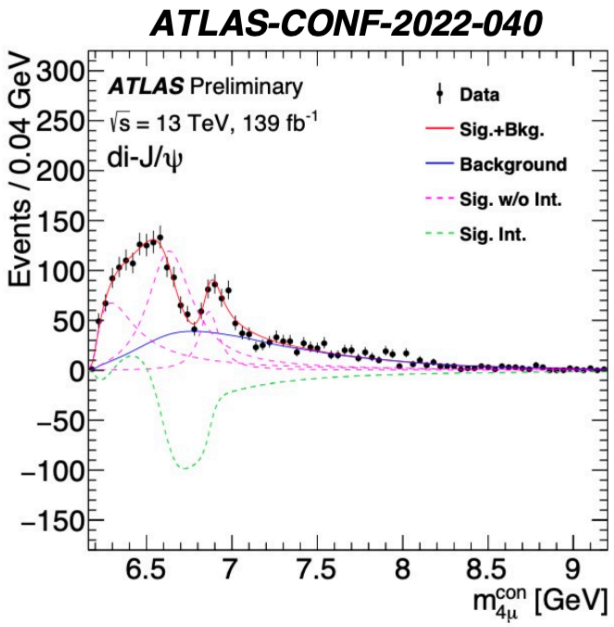
- Search for exotic state ($cc\bar{c}\bar{c}$)
- **Theory**: molecule? bound state? tetra-quark?
    - mass predictions are model dependent..
- **Experiment**:
    - LHCb (in 2020) reported structures in prompt double J/ψ production.
        - an enhancement seen near J/ψ pairs threshold region from 6.2 to 6.8 GeV
        - ..also a narrow peak around 6.9 GeV *X(6900)*
            - .. seen at CMS as well.
    - Belle attempt (this paper)
        - Search for double charmonium state in $e^+e^- \to \eta_c J/\psi$
            - via Initial State Radiation (ISR) near the threshold region 6 to 8.5 GeV



Initial state radiation







1 Searching double-charmonium state with $\eta_c J/\psi$

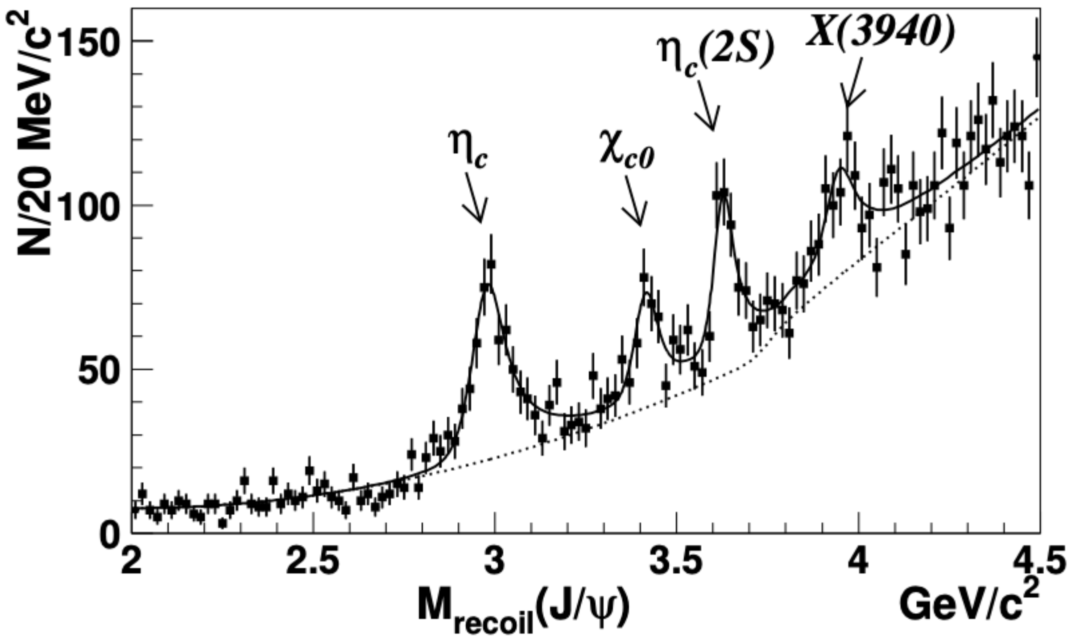
[JHEP 08 2023, 121 (2023)]

Analysis Method

- Search for lowest mass combination of charmonia state decay $\eta_c J/\psi$
  - might have larger branching fraction

Clean observation of J=0 charmonium peaks

Belle PRL **98**, 092001 (2007)



Two reconstruction methods

- **Inclusive reconstruction** of J/ψ and γ_{ISR}
  - selection of mass recoiling against $J/\psi\,\gamma_{ISR}$ in the η_c region
- **Exclusive reconstruction** of $\eta_c J/\psi$
  - in 6 decay modes of η_c: $pp,\ pp\pi^0,\ K_S^0 K^\pm \pi^\mp,\ K^+K^-\pi^0,\ K^+K^-K^+K^-,\ 2(\pi^+\pi^-\pi^0)$

Data Sample and other details

- Data: 980 fb^{-1} full data set for $\Upsilon(nS)$ n=1-5 on/off resonance or near threshold data
- MC: Signal: PHOKHARA and EVTGEN for ISR processes, η_c and J/ψ decays (EVTGEN for continuum background)

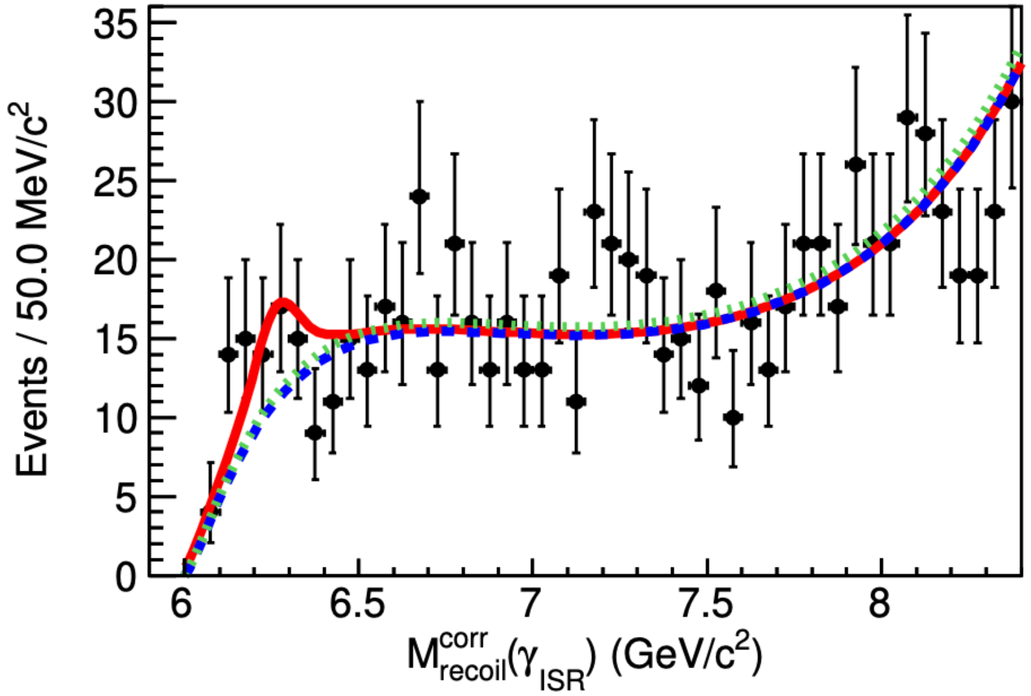
1 Searching double-charmonium state with $\eta_c J/\psi$

[JHEP 08 2023, 121 (2023)]

$e^+e^- \to \eta_c J/\psi$ near threshold

- **Inclusive reconstruction** of J/ψ and $J/\psi\gamma_{ISR}$
  - $M^{corr}_{recoil}(\gamma_{ISR}) = M_{recoil}(\gamma_{ISR}) - M_{recoil}(J/\psi\gamma_{ISR}) + m(\eta_c)$
    - $M_{recoil}(J/\psi) = |p_{e^-e^+} - p_{\eta_c J/\psi}|^2/c^4$
  - Double counting from exclusive is removed

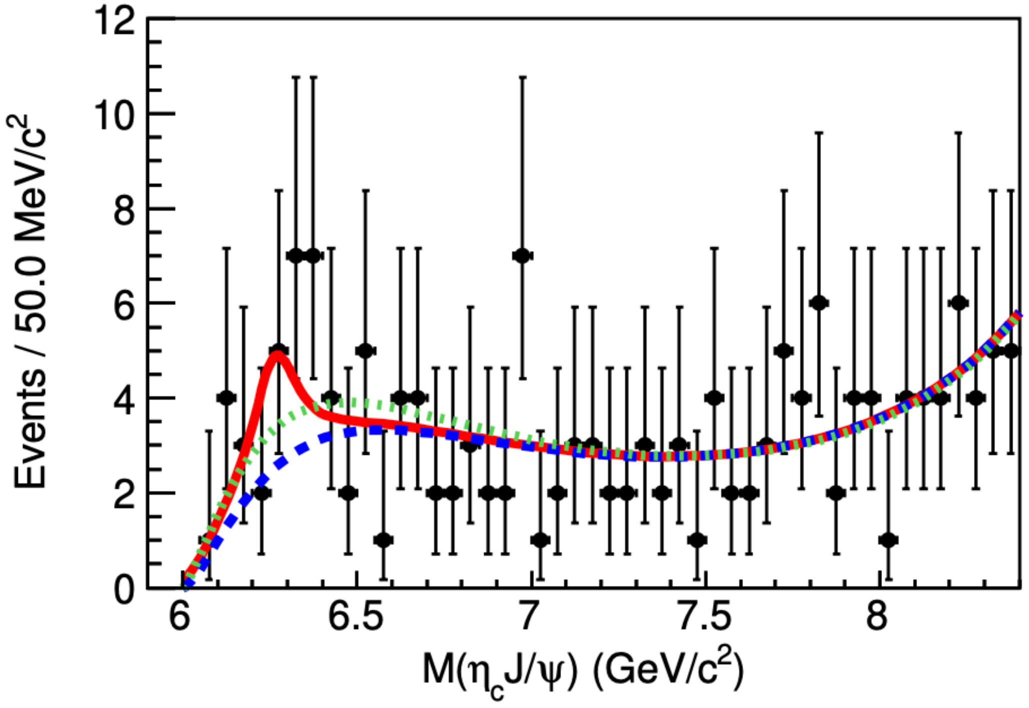
Inclusive



- No evidence of threshold enhancement.
- Expected revisit at Belle II with larger statistics

- **Exclusive Reconstruction** of $\eta_c J/\psi$
  - Invariant mass of $M(\eta_c J/\psi)$
    - Event/track selections + recoil mass squared of $\eta_c J/\psi = |p_{e^-e^+} - p_{\eta_c J/\psi}|^2/c^2$ in [-1, 2] GeV^2/c^4

Exclusive



- 3.3σ evidence of threshold enhancement.
- Expected revisit at Belle II with larger statistics

Signal extraction

- Signal are described Breit-Wigner function (see fits in backup)
  - Mass 6267 ± 43 GeV/c² and Width 121 ± 72 GeV
  - Signal events for exclusive (inclusive) = 9 ± 4 (23 ± 11)

2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

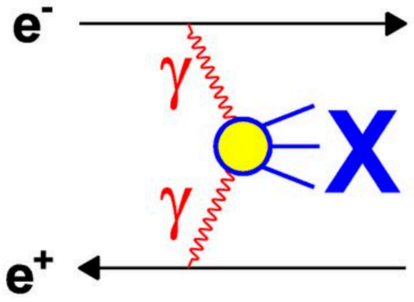
Goal

- Decay width is fundamental and direct observable for probing internal structure of meson ($q\bar{q}$)
- $\chi_{c2}(1P)$ (p-wave charmonium) is even special for probing QCD vs pQCD scenario
    - - Theory models predict $\chi_{c2}(1P)$ mass in wide range 280-930 eV
    - - Previous measurements by Belle (2002), CLEO (2006, 2008) and BESIII (2017)

Method

- Two approach for $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$
    - Study of $\chi_{c2}(1P) \rightarrow \gamma\gamma$ **decay**
        - Adopted by CLEO-c (2008: $\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = 555 \pm 58 \pm 32 \pm 28$ eV)** *Phys. Rev. D 78, 091501(R) (2008).*
        - BES III (2017: $\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = 586 \pm 16 \pm 13 \pm 29$ eV)** *Phys. Rev. D 96, 092007 (2017).*
    - Study of $\gamma\gamma \rightarrow \chi_{c2}(1P)$ **collisions**
        - Adopted by BELLE (2002: $\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = 596 \pm 58 \pm 48 \pm 16$ eV)* *Phys. Lett. B 540, 33 (2002).*
        - CLEO (2006: $\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) = 582 \pm 59 \pm 50 \pm 15$ eV)* *Phys. Rev. D 73, 071101(R) (2006).*
        - **+ Belle this talk:** $\gamma\gamma \rightarrow \chi_{c2}(1P) \rightarrow J/\psi(\rightarrow l^+l^-)\gamma$ *here* $l = e, \mu$

Less precise



Data Sample and other details

- Data: 971 fb^{-1} collected at or near $\Upsilon(nS)$ n = 1-5.
    - ~30x statistics in compare to last 2002 measurement 32.6 fb^{-1}
- MC: TREPS Generator for two photon process and radiative decay of J/ψ through PHOTOS

---

*Recalculated $\mathscr{B}(\chi_{c2}(1P) \rightarrow J/\psi\gamma)$ for = (19.0 ± 0.5)% and $\mathscr{B}(J/\psi \rightarrow l^+l^-)$ = 11.93 ± 0.05 MeV from PDG

**Recalculated $\mathscr{B}(\psi(2S) \rightarrow \chi_{c2}(1P)\gamma)$ for = (9.52 ± 0.20)% and $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ = 1.97 ± 0.09 MeV from PDG

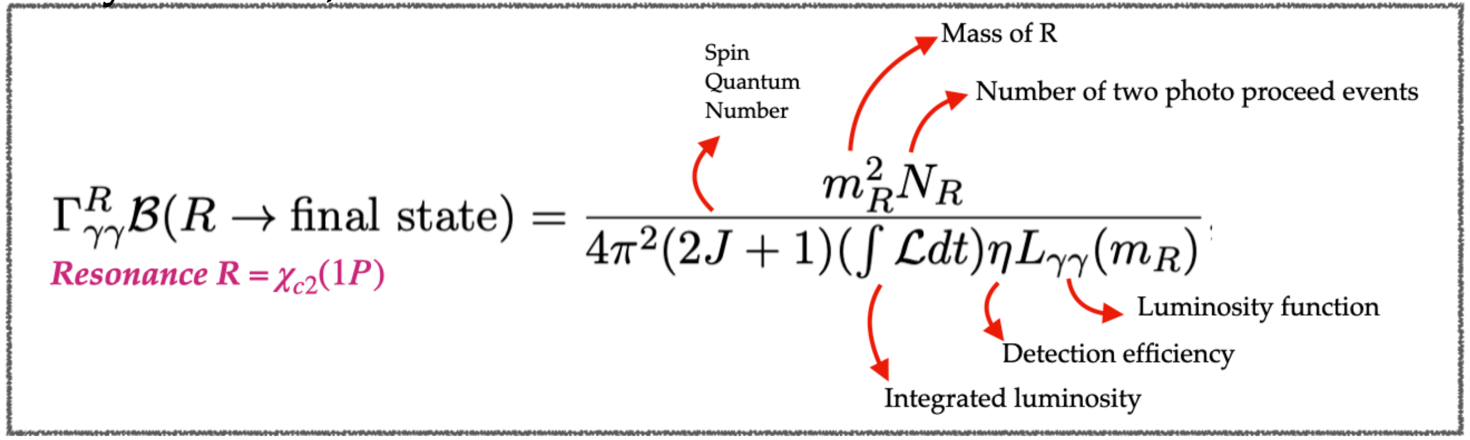
2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

Analysis Method

- Approach #2: Study of $\gamma\gamma \to \chi_{c2}(1P)$ collisions
  - $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi(\to l^+l^-)\gamma$;
  - zero-tag mode $\sum |p_T^*| \sim 0$
    - events from quasi-real two-photon collisions
  - strategy: similar to previous Belle measurement

decay width as;



$$\Gamma^R_{\gamma\gamma}\mathcal{B}(R \to \text{final state}) = \frac{m_R^2 N_R}{4\pi^2(2J+1)(\int \mathcal{L}dt)\eta L_{\gamma\gamma}(m_R)}$$

Resonance $R = \chi_{c2}(1P)$

Spin Quantum Number

Mass of R

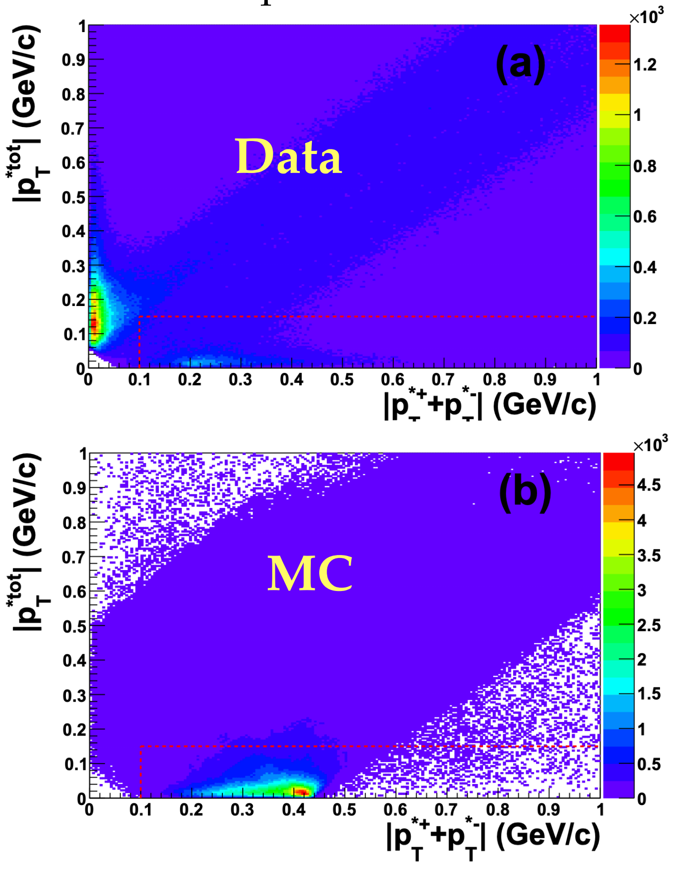
Number of two photo proceed events

Luminosity function

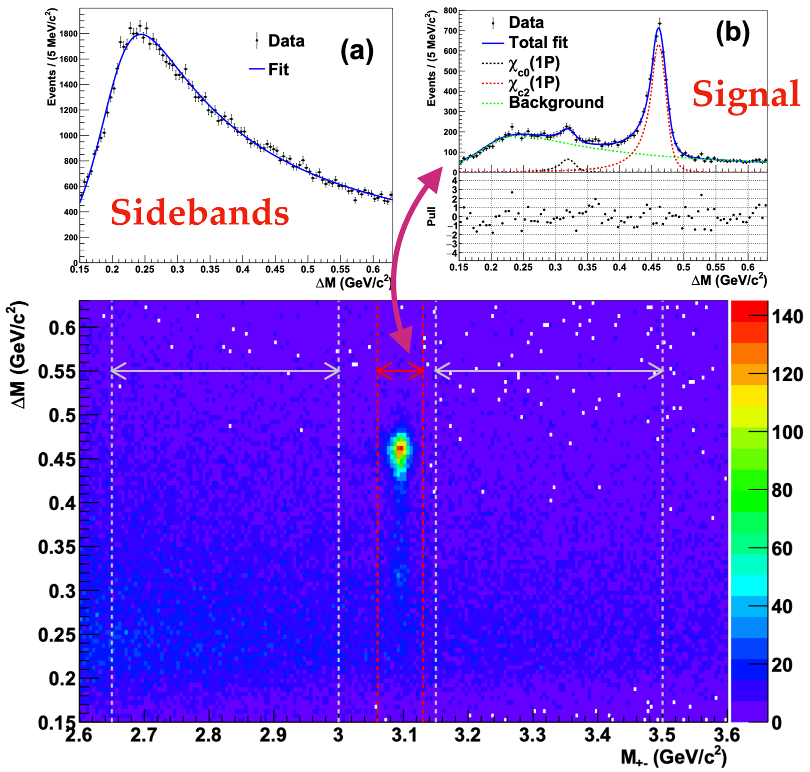
Detection efficiency

Integrated luminosity

- **Signal extraction strategy (highlights)**
  - a clear separated cluster from p_T^*-balance requirements:

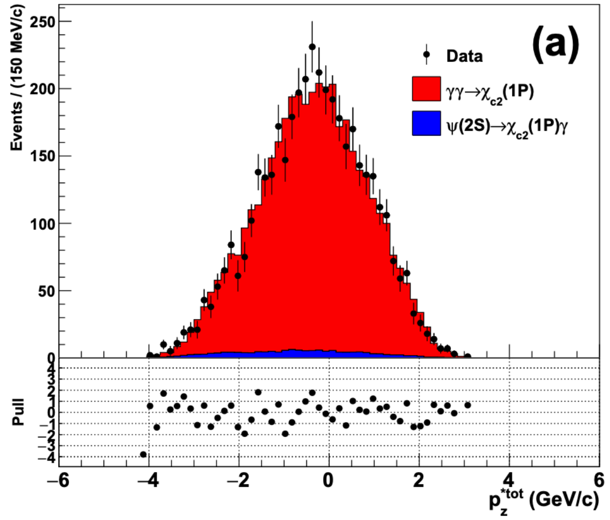


  - background component is removed using side bands (asymmetric)



  - better fit method w.r.t. previous method (improved detection efficiency)

  - peaking background from ISR $\psi(2S)$ production is also treated (MC Based)



2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

Results:

Mass of R

Spin QN

Number of two photo proceed events

$$\Gamma^{R}_{\gamma\gamma}\mathcal{B}(R \to \text{final state}) = \frac{m_R^2 N_R}{4\pi^2(2J+1)(\int \mathcal{L}dt)\eta L_{\gamma\gamma}(m_R)}$$

Resonance R = $\chi_{c2}(1P)$

Luminosity function

Detection efficiency

Integrated luminosity

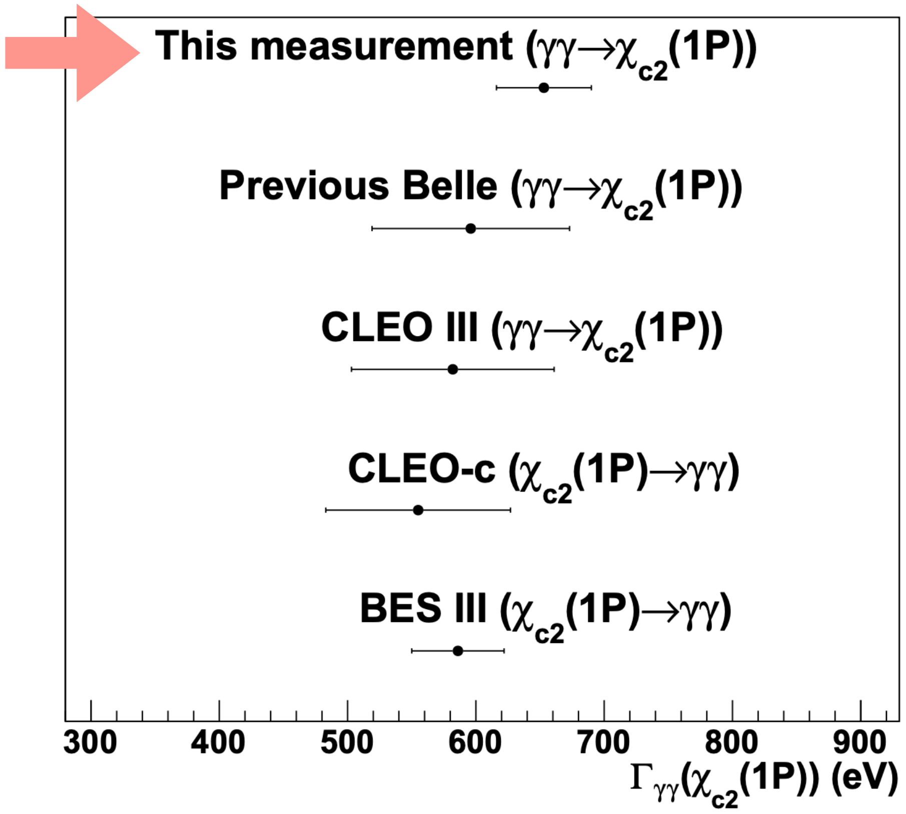
= 14.8 ± 0.3 (stat.) ± 0.7 (syst.) eV

- Number of signal: 4960.3 ± 97.9
- $m_R = 3.556$ GeV/c^2 **PDG**
- $\int \mathscr{L}dt = 971$ fb^{-1}
- $\eta = 7.36\%$
- $L_{\gamma\gamma}(m_R) = 7.70 \times 10^{-4}$ GeV^{-1}
- $\mathscr{B}(\chi_{c2}(1P) \to J/\psi\gamma) = 19.0 \pm 0.5\ \%$ **PDG**
- $\mathscr{B}(J/\psi \to l^+l^-) = 11.93 \pm 0.5\ \%$ **PDG**

Most precise measurement **= 653 ± 13 (stat.) ± 31 (syst.) ± 17 (B.R.) eV**

— compatible precision with BES III

— consistent with previous Belle results



Model predictions

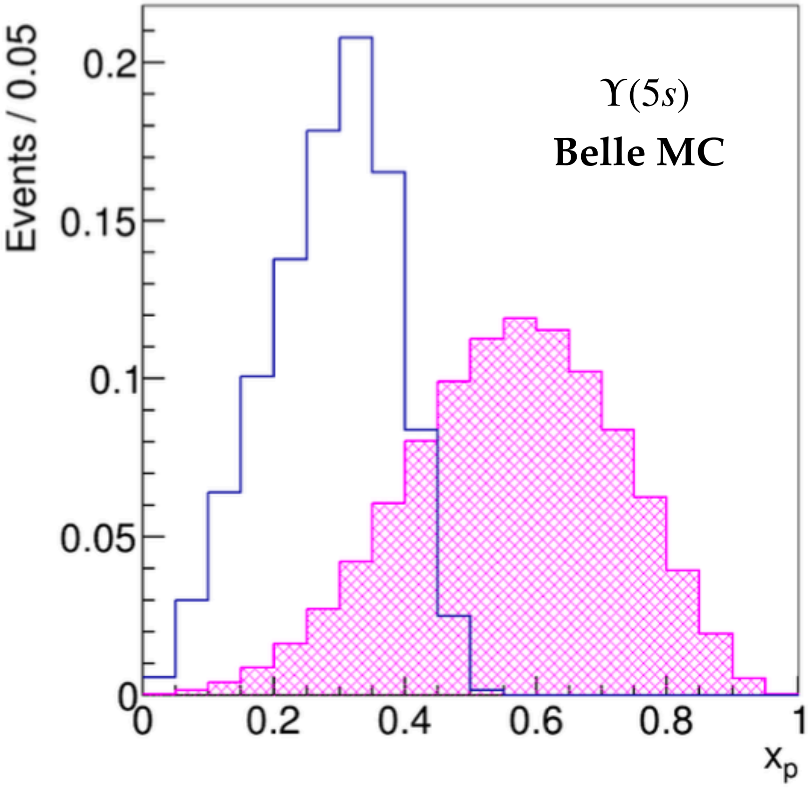
Reference	Model	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ (keV)
Barbieri [9]	Nonrelativistic approximation	0.93
Münz [10]	Bethe-Salpeter equation with relativistic corrections	0.44 ± 0.14
Godfrey [11]	Relativistic quark model	0.46
Gupta [12]	Relativistic quark model	0.57
Ebert [13]	Relativistic quark model	0.50
Bodwin [14]	Rigorous QCD prediction	0.81 ± 0.29
Huang [15]	Rigorous QCD prediction	0.49 ± 0.15
Schuler [16]	Nonrelativistic QCD factorization framework	0.28
Crater [17]	Two-body Dirac equations of constraint dynamics	0.743
Lansberg [18]	Effective Lagrangian	0.70
Hwang [19]	Light-Front Quantization	$0.346^{+0.009}_{-0.011}$

3 Scan of $e^+e^- \to B_s^0\bar{B}_s^0X$ cross section measurement

[JHEP 08 2023, 131 (2023)]

Inclusive approach

- Open bottom threshold cross section
  - $\sigma(e^+e^- \to B_s^0\bar{B}_s^0X)$ in 10.63 to 11.02 GeV range
    - $= \sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})$ upto $B_s^0\bar{B}_s^0\pi^0\pi^0$ threshold 11.004 GeV
  - $\sigma(e^+e^- \to B\bar{B}X)$ in 10.63 to 11.02 GeV range
- D^0 (Ds) mesons as proxy for a B^0 (B^0s)
  - reconstructed through $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$ in bins of x_p
  - their momentum to identify the quark-level process
  - cross section from solving equations below



Normalized $x_p = p/\sqrt{(E_{cms}/2)^2 - m^2}$

$$\begin{aligned}\sigma(e^+e^- \to b\bar{b} \to D_s^\pm\, X) = {} & 2\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0\, X)\mathcal{B}(B_s^0 \to D_s^\pm\, X) \\ & + 2\,\sigma(e^+e^- \to B\bar{B}\, X)\mathcal{B}(B \to D_s^\pm\, X),\end{aligned}$$

$$\begin{aligned}\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0\, X) = {} & 2\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0\, X)\mathcal{B}(B_s^0 \to D^0/\bar{D}^0\, X) \\ & + 2\,\sigma(e^+e^- \to B\bar{B}\, X)\mathcal{B}(B \to D^0/\bar{D}^0\, X).\end{aligned}$$

$e^+e^- \to b\bar{b} \to D_{(s)} + X$

$e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c} \to D_{(s)} + X$

- e.g. $\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)$ is calculated from subtraction of $\sigma(e^+e^- \to D_s^\pm X)$ - continuum

Data Sample and other details

- Energy scan data + 121 fb^{-1} $\Upsilon(5s)$ + 571 fb^{-1} $\Upsilon(4s)$ + 74 fb^{-1} below $B\bar{B}$ threshold (10.52 GeV)
- 23 data points across energy range
- Analysis method is same as used in CLEO analysis Phys. Rev. Lett. 95 (2005) 261801

3 Scan of $e^+e^- \to B_s^0\bar{B}_s^0X$ cross section

[JHEP 08 2023, 131 (2023)]

Results

Production fraction of $B_s^0\bar{B}_s^0X$: f_s

$$f_s = (22.0^{+2.0}_{-2.1})\%$$

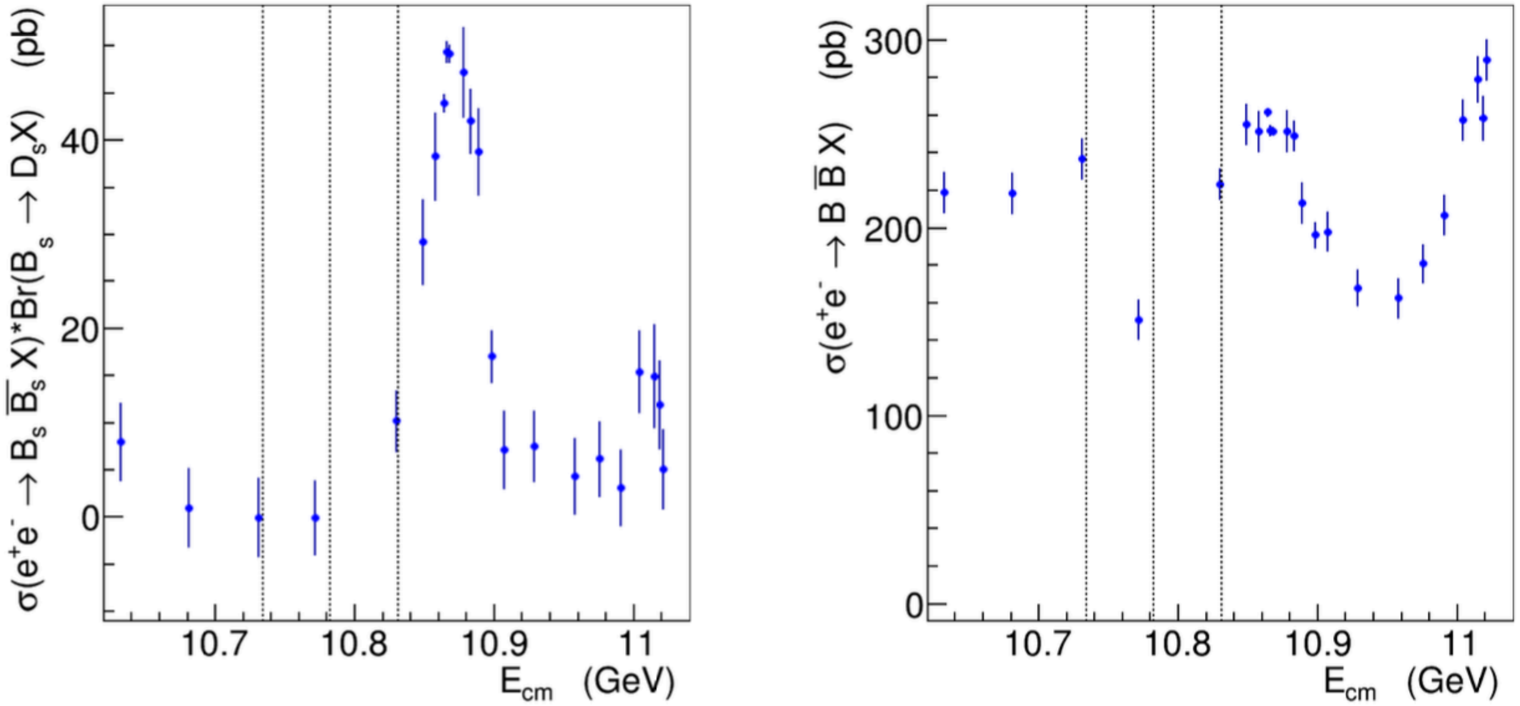
w/ constraint $f_s + f_{B\bar{B}X} + f_{\cancel{B}} = 1$

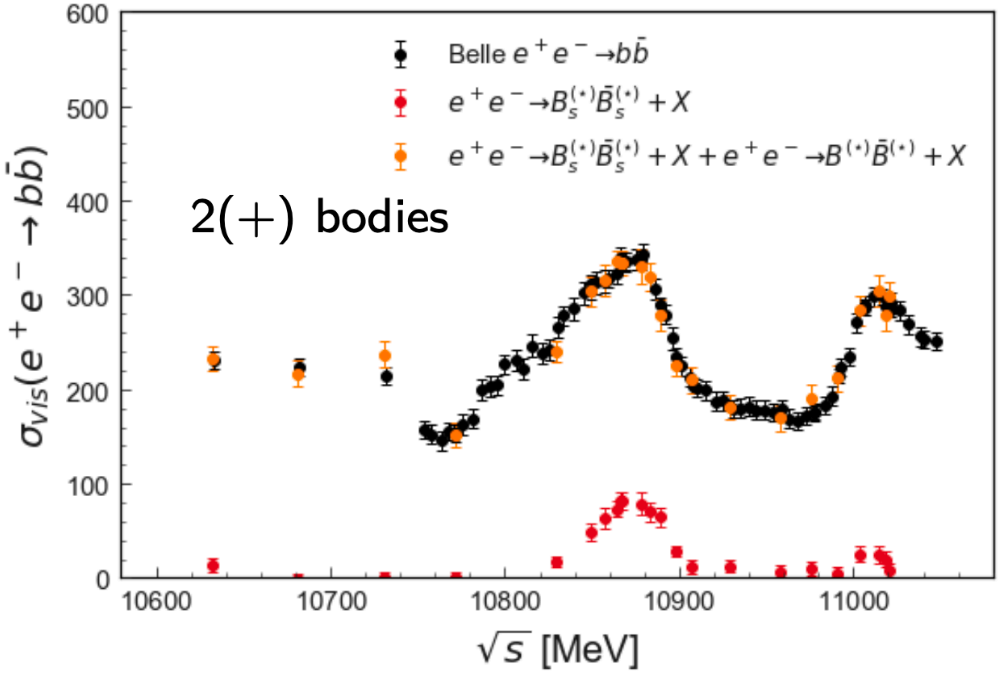
- supersedes previous Belle measurements

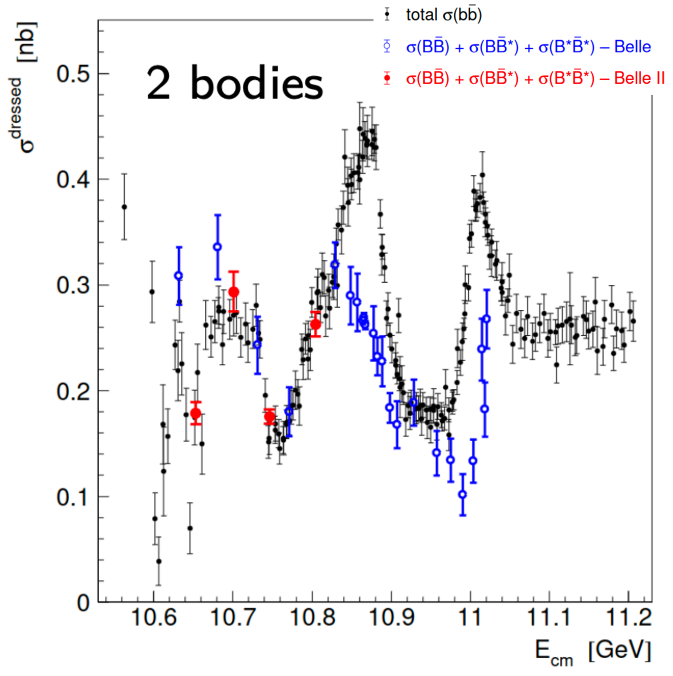
$$f_s = 28.5 \pm 4.99\,\%$$

Energy dependence of cross section

- measured with high precision
- provides good grounds for Belle II







See more in talk by Alexander E. Bondar
Energy scan results from Belle II

Summary

1. **Double charmonium state:** No significant signal of the double charmonium state is found for $\eta_c J/\psi$ (for exclusive reconstruction) and the recoil mass of γ_{ISR} (for inclusive reconstruction). The cross sections for $e^+e^- \to \eta_c J/\psi$ near the threshold are significantly larger (w/ 3.3σ). **Expected to be revisited Belle II** [JHEP 08 2023, 121 (2023)]
2. **Two-photon decay width:** Most precise measurement for two-photon decay width of $\chi_{c2}(1P)$ is obtained with improved techniques and full dataset of Belle. [JHEP 01 2023, 160 (2023)] and has a compatible precision with that from previous BES III results [Phys. Rev. D 96 (2017) 092007].
3. **The $e^+e^- \to B_s^0\bar{B}_s^0X$ cross section:** energy dependent cross sections measured with relatively high precision and shows a clear peak near the $\Upsilon(5S)$ energy and a hint of a peak near the $\Upsilon(6S)$. It can be used by the **Belle II experiment** for exploratory studies of various energy regions of interest. [JHEP 08 2023, 131 (2023)]

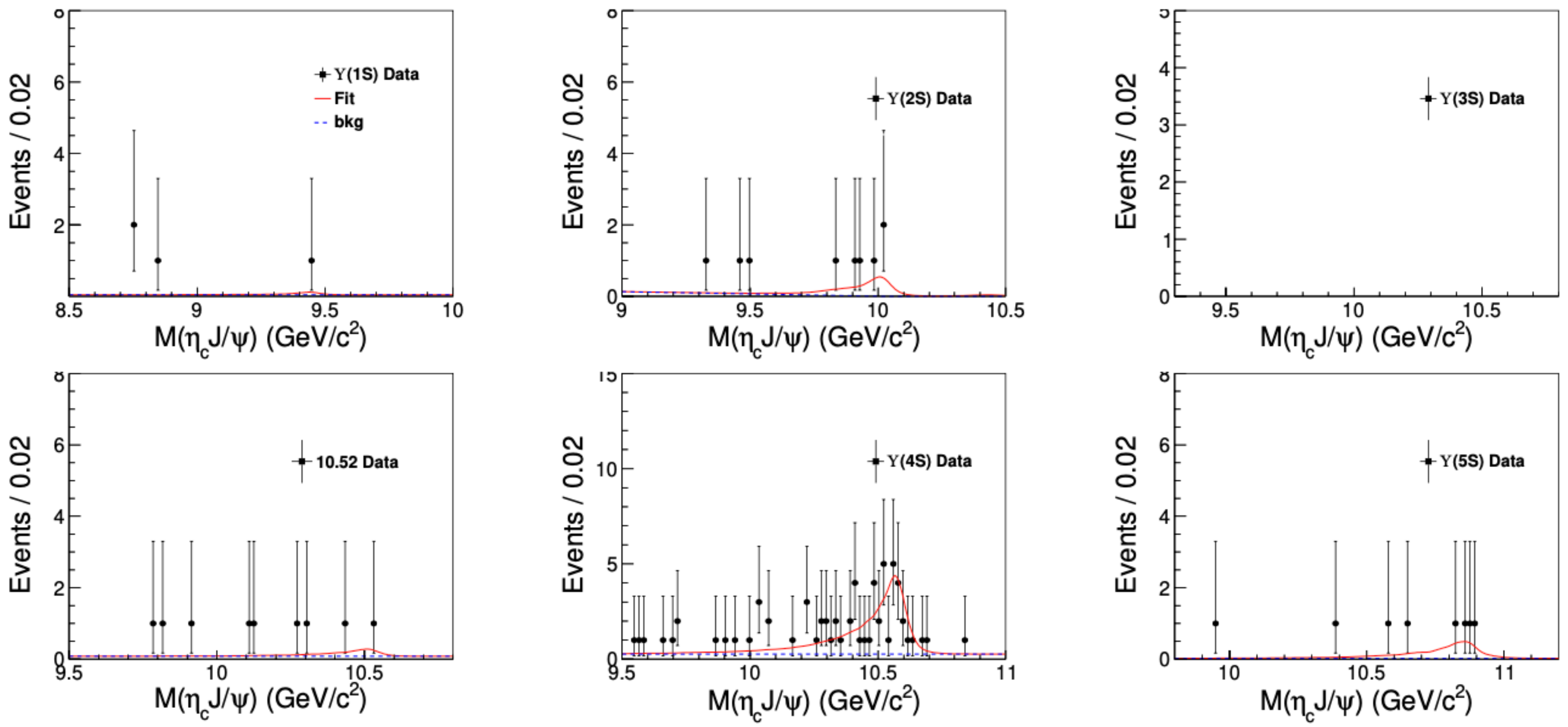
Thanks

Backup

Double charmonium at $\Upsilon(4S)$ and $\Upsilon(5S)$

- **Exclusive Reconstruction** of $\eta_c J/\psi$
  - Invariant mass of $M(\eta_c J/\psi)$
    - Event/track selections + recoil mass squared of $\eta_c J/\psi = |p_{e^-e^+} - p_{\eta_c J/\psi}|^2/c^2$ in [-0.05, 0.08] GeV²/c⁴
  - Background mainly from combinatorial of η_c and J/ψ reconstruction and no peaking expected
  - Unbanned extended maximum likelihood fits are performed (except $\Upsilon(3S)$)
  - Signal component are described using shapes derived from MC study and smoothed using kernel estimation
  - Background: first order polynomial

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	10.52 GeV	$\Upsilon(4S)$	$\Upsilon(5S)$
$\mathcal{L}$ [fb^{-1}]	5.7	24.9	2.9	89.4	711.0	121.4
N^{exc}	$0.7^{+1.5}_{-0.9}$	$6.2^{+3.1}_{-2.3}$	< 1.9	$2.6^{+3.5}_{-2.5}$	$45.0^{+8.9}_{-8.2}$	$6.5^{+3.4}_{-2.7}$
ϵ^{exc}	8.3%	6.9%	5.7%	5.6%	5.6%	5.4%
σ^{exc} [fb]	$57^{+122}_{-73} \pm 6$	$140^{+70}_{-52} \pm 14$	< 442	$20^{+27}_{-19} \pm 6$	$44^{+9}_{-8} \pm 5$	$39^{+20}_{-14} \pm 7$
N^{inc}	23.7 ± 12.3	62.0 ± 17.9	8.5 ± 5.2	94.7 ± 23.8	1116.2 ± 62.9	91.1 ± 21.5
ϵ^{inc}	38.6%	29.6%	26.4%	26.1%	25.4%	24.7%
σ^{inc} [fb]	$89.1 \pm 46.2 \pm 20.5$	$70.1 \pm 20.2 \pm 8.9$	$91.8 \pm 56.2 \pm 52.3$	$33.8 \pm 8.5 \pm 2.8$	$52.1 \pm 2.9 \pm 5.0$	$25.4 \pm 6.0 \pm 2.8$
σ^{comb} [fb]	$78.3^{+47.5}_{-43.0}$	80.2 ± 20.4	$87.0^{+71.0}_{-59.0}$	32.5 ± 8.5	50.2 ± 5.0	27.5 ± 6.1



M’ is used to improve the resolution on recoil mass, background is third order polynomial (inclusive)

Searching double-charmonium state with $\eta_c J/\psi$

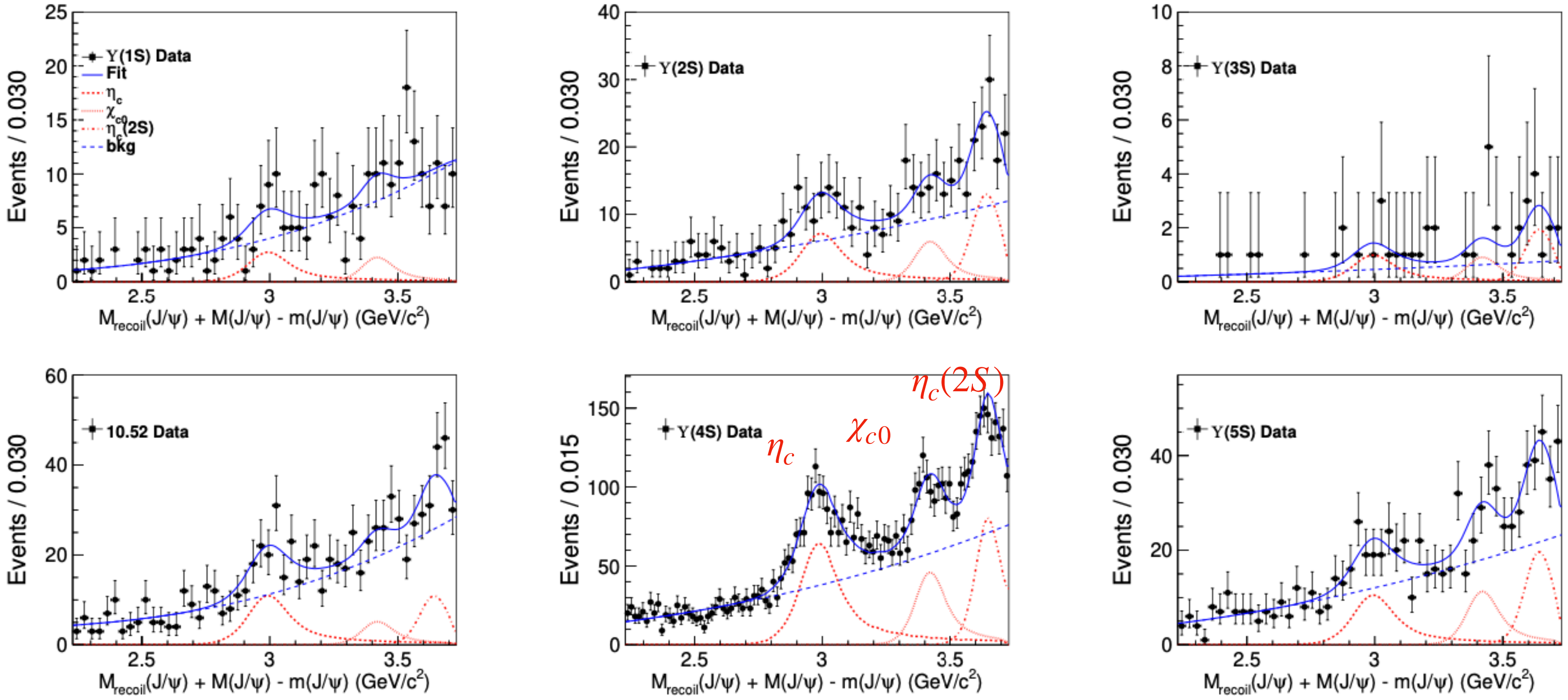
[JHEP 08 2023, 121 (2023)]

Double charmonium at $\Upsilon(4S)$ and $\Upsilon(5S)$

- **Inclusive reconstruction** of J/ψ recoil-mass
  - $M'_{recoil}(J/\psi) = M_{recoil}(J/\psi) + M(J/\psi) - m(J/\psi)$
    - To improve the resolution of recoil mass
    - $M_{recoil}(J/\psi) = \sqrt{|p_{e^+e^-} - p_{J/\psi}|^2}/c$
  - Clear peaks for η_c, χ_{c0} and $\eta_c(2S)$ are visible and in agreement with previous Belle results
  - Unbinned extended maximum likelihood fits
  - Signal component are described using shapes derived from MC study and smoothed using kernel estimation
  - Background: third order polynomial

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	10.52 GeV	$\Upsilon(4S)$	$\Upsilon(5S)$
$\mathcal{L}$ [fb^{-1}]	5.7	24.9	2.9	89.4	711.0	121.4
N^{exc}	$0.7^{+1.5}_{-0.9}$	$6.2^{+3.1}_{-2.3}$	< 1.9	$2.6^{+3.5}_{-2.5}$	$45.0^{+8.9}_{-8.2}$	$6.5^{+3.4}_{-2.7}$
ϵ^{exc}	8.3%	6.9%	5.7%	5.6%	5.6%	5.4%
σ^{exc} [fb]	$57^{+122}_{-73} \pm 6$	$140^{+70}_{-52} \pm 14$	< 442	$20^{+27}_{-19} \pm 6$	$44^{+9}_{-8} \pm 5$	$39^{+20}_{-14} \pm 7$
N^{inc}	23.7 ± 12.3	62.0 ± 17.9	8.5 ± 5.2	94.7 ± 23.8	1116.2 ± 62.9	91.1 ± 21.5
ϵ^{inc}	38.6%	29.6%	26.4%	26.1%	25.4%	24.7%
σ^{inc} [fb]	$89.1 \pm 46.2 \pm 20.5$	$70.1 \pm 20.2 \pm 8.9$	$91.8 \pm 56.2 \pm 52.3$	$33.8 \pm 8.5 \pm 2.8$	$52.1 \pm 2.9 \pm 5.0$	$25.4 \pm 6.0 \pm 2.8$
σ^{comb} [fb]	$78.3^{+47.5}_{-43.0}$	80.2 ± 20.4	$87.0^{+71.0}_{-59.0}$	32.5 ± 8.5	50.2 ± 5.0	27.5 ± 6.1

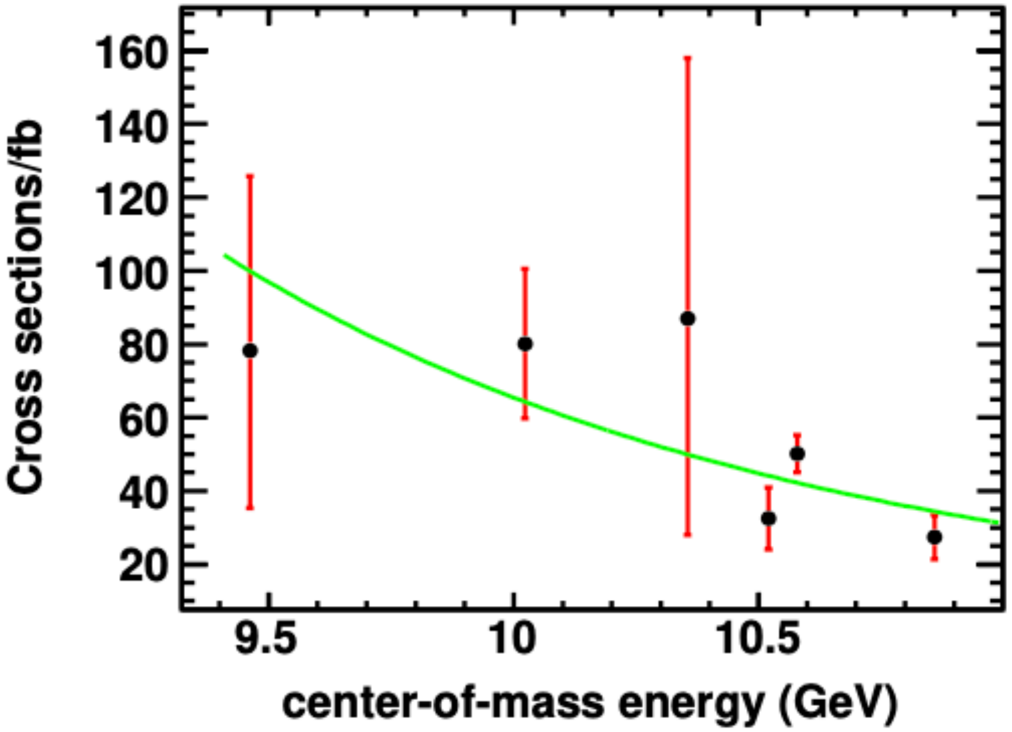
Inclusive



Double charmonium at $\Upsilon(4S)$ and $\Upsilon(5S)$: Cross section

- Combined from both methods (detailed table in the backup)
  - Extract cross section-dependent likelihood distribution from both methods
  - Cross section dependent joint probability density function (PDF) is obtained
- fit with $\propto 1/s^n$ + extrapolate for the threshold region to check continuum contribution
  - from $e^+e^- \to \gamma^* \to \eta_c J\psi$ OR $e^+e^- \to \Upsilon(nS) \to \gamma^* \to \eta_c J\psi$)

$$\sigma = A\frac{\sqrt{2\mu\Delta M}}{\left(\frac{s}{s_0}\right)^n},$$



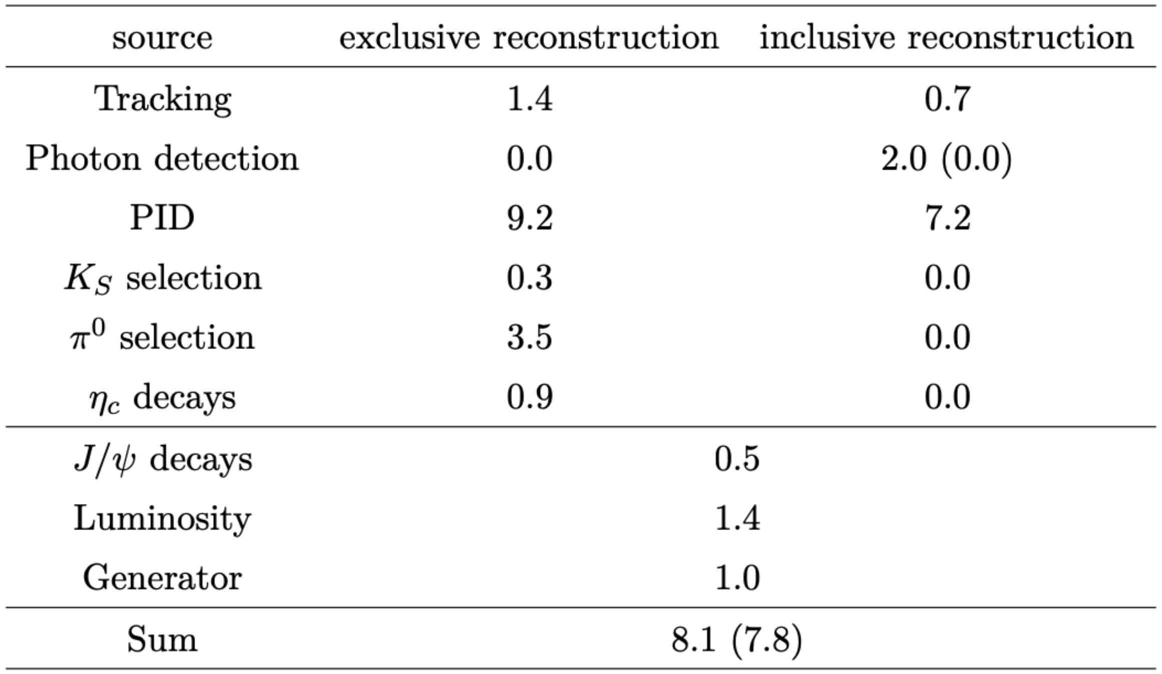
M' is used to improve the resolution on recoil mass, background is third order polynomial (inclusive)

1 Searching double-charmonium state with $\eta_c J/\psi$

[JHEP 08 2023, 121 (2023)]

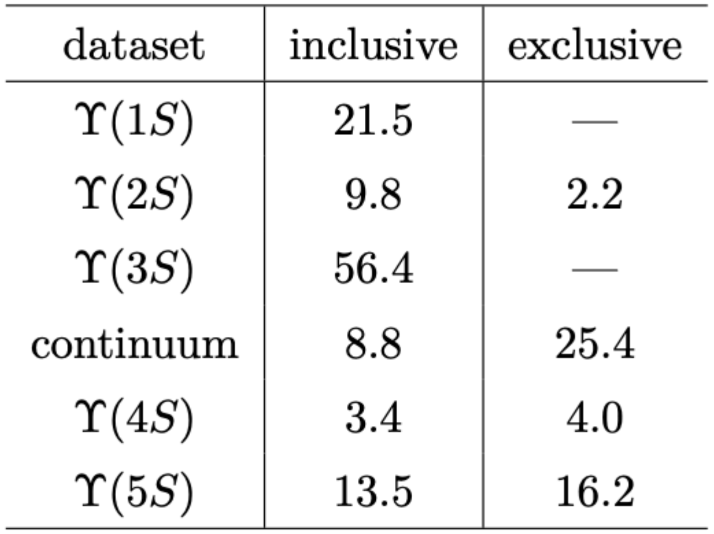
Belle (this talk)

- **Systematics (except fitting below)**



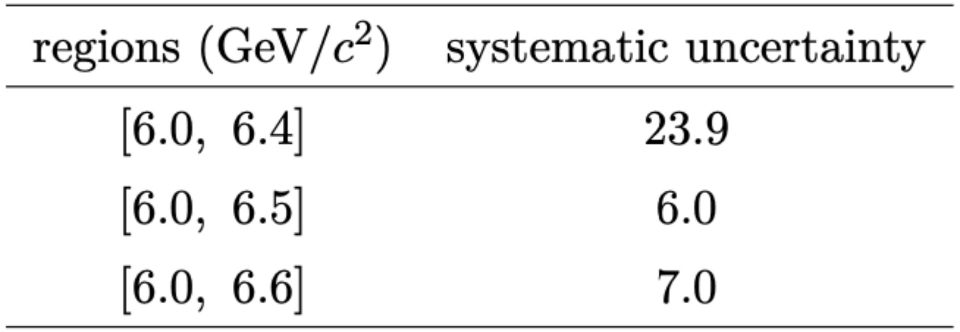
source	exclusive reconstruction	inclusive reconstruction
Tracking	1.4	0.7
Photon detection	0.0	2.0 (0.0)
PID	9.2	7.2
K_S selection	0.3	0.0
π^0 selection	3.5	0.0
η_c decays	0.9	0.0
J/ψ decays	0.5	
Luminosity	1.4	
Generator	1.0	
Sum	8.1 (7.8)	

- **Fitting Systematics: cross sections for different datasets**



dataset	inclusive	exclusive
$\Upsilon(1S)$	21.5	—
$\Upsilon(2S)$	9.8	2.2
$\Upsilon(3S)$	56.4	—
continuum	8.8	25.4
$\Upsilon(4S)$	3.4	4.0
$\Upsilon(5S)$	13.5	16.2

- **Fitting Systematics: cross sections for different mass**



regions (GeV/c^2)	systematic uncertainty
[6.0, 6.4]	23.9
[6.0, 6.5]	6.0
[6.0, 6.6]	7.0

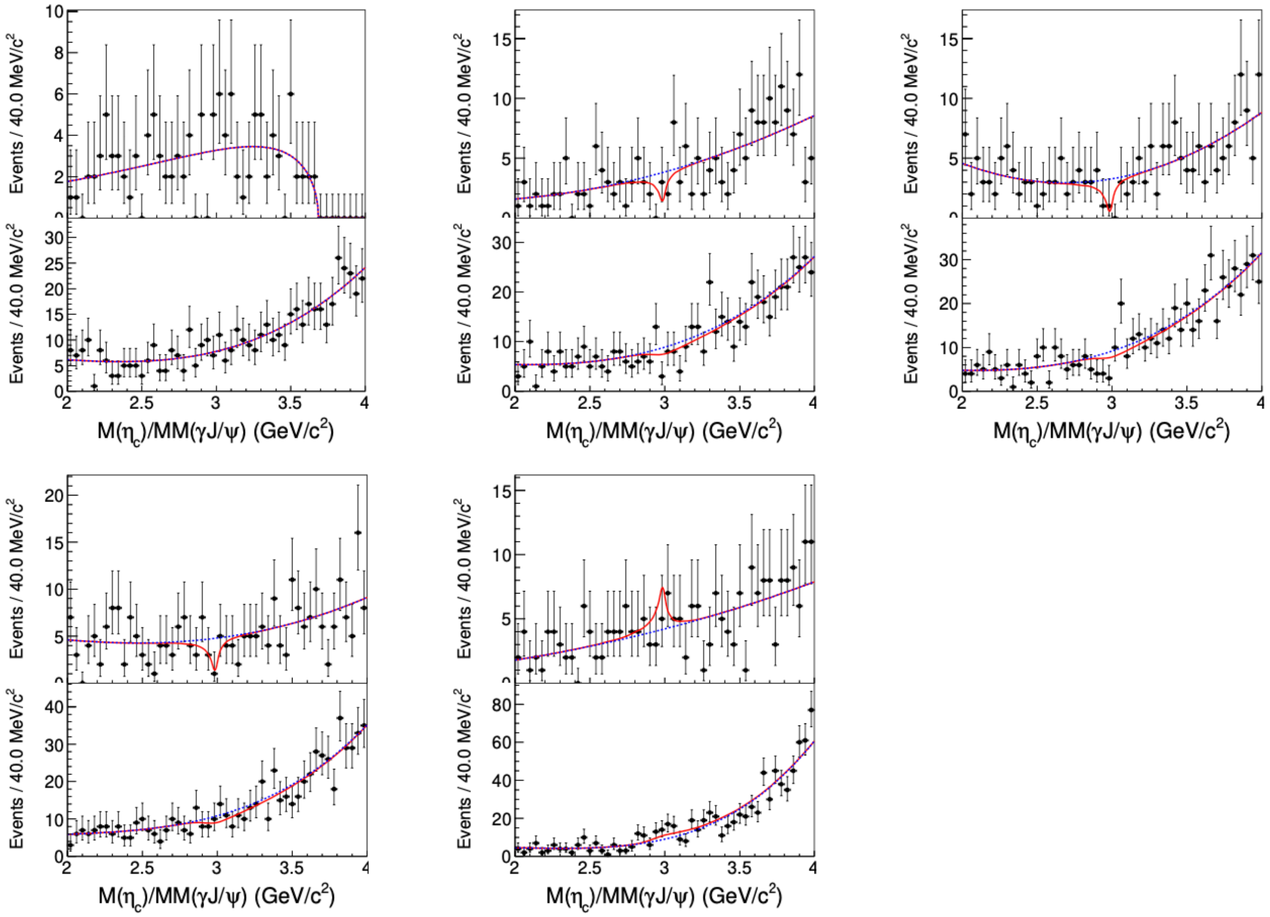
1 Searching double-charmonium state with $\eta_c J/\psi$

[JHEP 08 2023, 121 (2023)]

Belle (this talk)

- **Exclusive/Inclusive Reconstruction** Cross section

A.1 Step size 400 MeV/c



- **Exclusive Reconstruction** of $\eta_c J/\psi$
  - Possible background from $\Upsilon(4S) \to B\bar{B}$ is removed with demanding the ratio of the second to the zeroth order Fox-Wolfram moments[4] is required to be > 0.13

- **Inclusive + Exclusive simultaneous fits**
  - A simultaneous unbinned maximum likelihood fit for the $\eta_c J/\psi$ invariant mass and γ_{ISR} recoil mass is performed.
  - The signal-yield fractions from the two reconstruction methods are fixed to the corresponding branching fractions and reconstruction efficiencies
  - The background shapes are parameterized with the ARGUS function, whose parameters are obtained from the fit to the η_c and J/ψ sideband events
  - Singal are described w/ Breit-Wigner function with free mass and width convolved with the Gaussian functions from the resolution study

2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

- **Systematic Uncertainties**

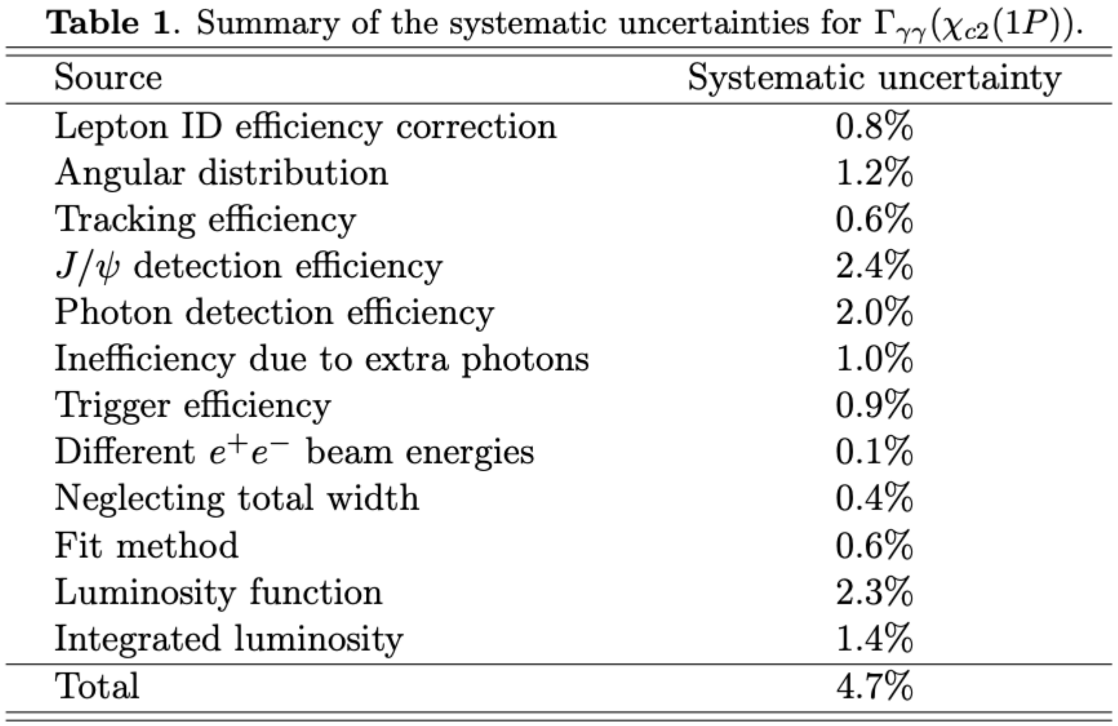


Table 1. Summary of the systematic uncertainties for $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$.

Source	Systematic uncertainty
Lepton ID efficiency correction	0.8%
Angular distribution	1.2%
Tracking efficiency	0.6%
J/ψ detection efficiency	2.4%
Photon detection efficiency	2.0%
Inefficiency due to extra photons	1.0%
Trigger efficiency	0.9%
Different e^+e^- beam energies	0.1%
Neglecting total width	0.4%
Fit method	0.6%
Luminosity function	2.3%
Integrated luminosity	1.4%
Total	4.7%

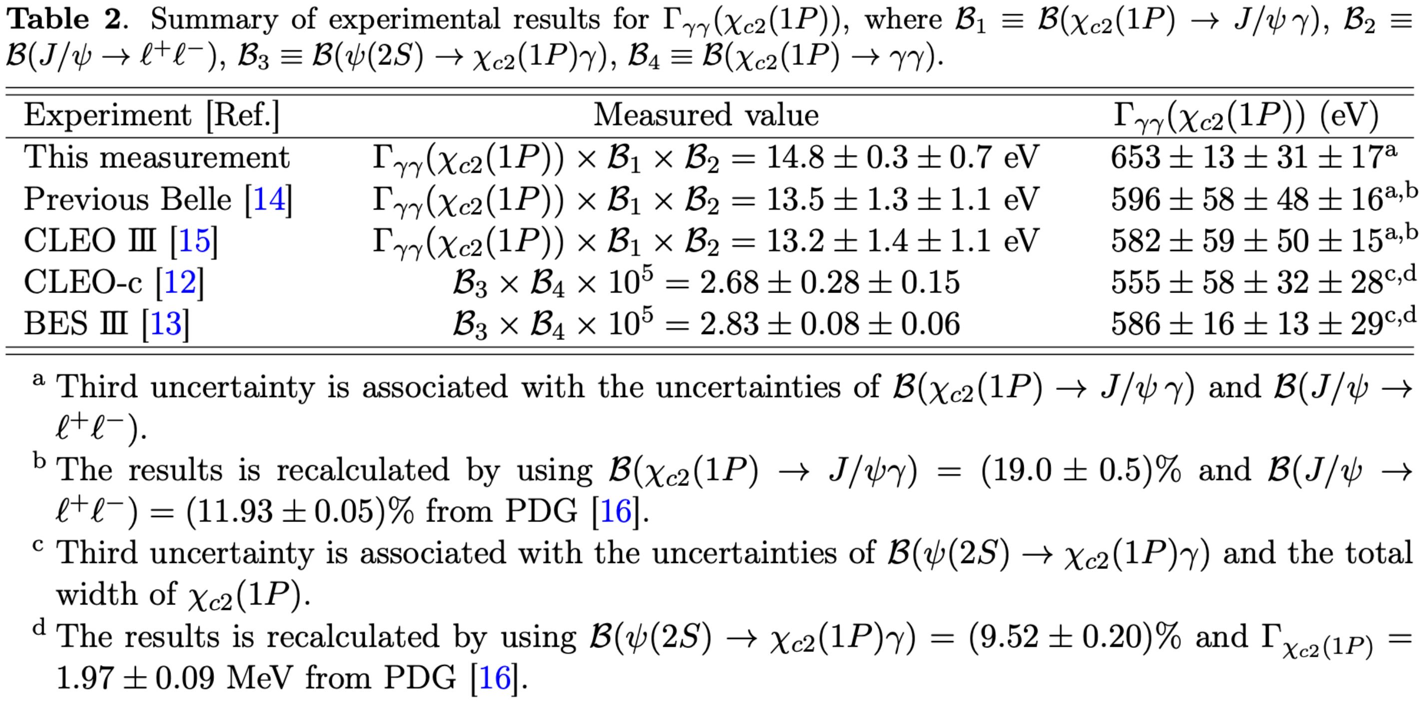


Table 2. Summary of experimental results for $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$, where $\mathcal{B}_1 \equiv \mathcal{B}(\chi_{c2}(1P) \to J/\psi\,\gamma)$, $\mathcal{B}_2 \equiv \mathcal{B}(J/\psi \to \ell^+\ell^-)$, $\mathcal{B}_3 \equiv \mathcal{B}(\psi(2S) \to \chi_{c2}(1P)\gamma)$, $\mathcal{B}_4 \equiv \mathcal{B}(\chi_{c2}(1P) \to \gamma\gamma)$.

Experiment [Ref.]	Measured value	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ (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	$653 \pm 13 \pm 31 \pm 17^{a}$
Previous 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	$596 \pm 58 \pm 48 \pm 16^{a,b}$
CLEO III [15]	$\Gamma_{\gamma\gamma}(\chi_{c2}(1P)) \times \mathcal{B}_1 \times \mathcal{B}_2 = 13.2 \pm 1.4 \pm 1.1$ eV	$582 \pm 59 \pm 50 \pm 15^{a,b}$
CLEO-c [12]	$\mathcal{B}_3 \times \mathcal{B}_4 \times 10^5 = 2.68 \pm 0.28 \pm 0.15$	$555 \pm 58 \pm 32 \pm 28^{c,d}$
BES III [13]	$\mathcal{B}_3 \times \mathcal{B}_4 \times 10^5 = 2.83 \pm 0.08 \pm 0.06$	$586 \pm 16 \pm 13 \pm 29^{c,d}$

[a] Third uncertainty is associated with the uncertainties of $\mathcal{B}(\chi_{c2}(1P) \to J/\psi\,\gamma)$ and $\mathcal{B}(J/\psi \to \ell^+\ell^-)$.

[b] The results is recalculated by using $\mathcal{B}(\chi_{c2}(1P) \to J/\psi\gamma) = (19.0 \pm 0.5)\%$ and $\mathcal{B}(J/\psi \to \ell^+\ell^-) = (11.93 \pm 0.05)\%$ from PDG [16].

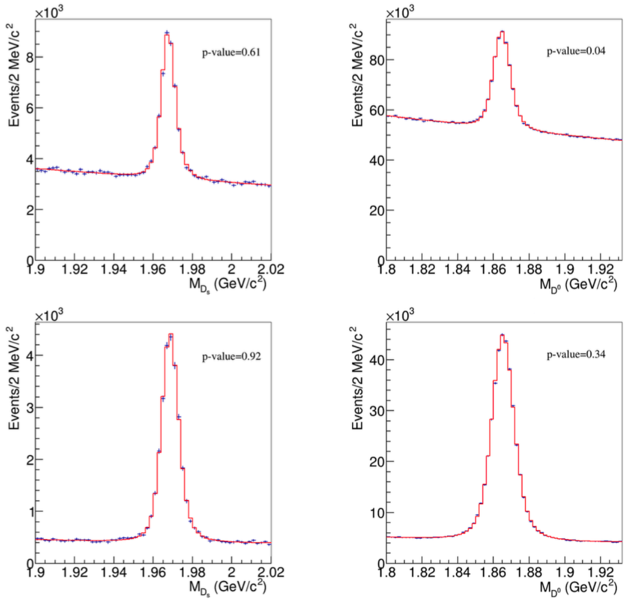
[c] Third uncertainty is associated with the uncertainties of $\mathcal{B}(\psi(2S) \to \chi_{c2}(1P)\gamma)$ and the total width of $\chi_{c2}(1P)$.

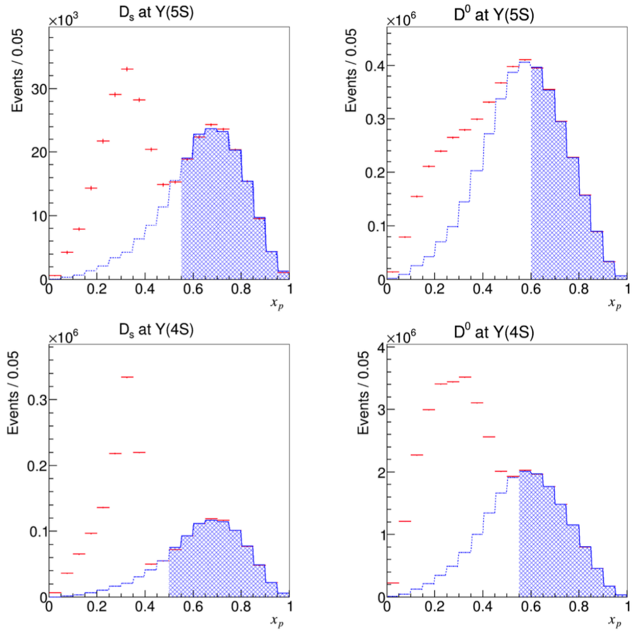
[d] The results is recalculated by using $\mathcal{B}(\psi(2S) \to \chi_{c2}(1P)\gamma) = (9.52 \pm 0.20)\%$ and $\Gamma_{\chi_{c2}(1P)} = 1.97 \pm 0.09$ MeV from PDG [16].

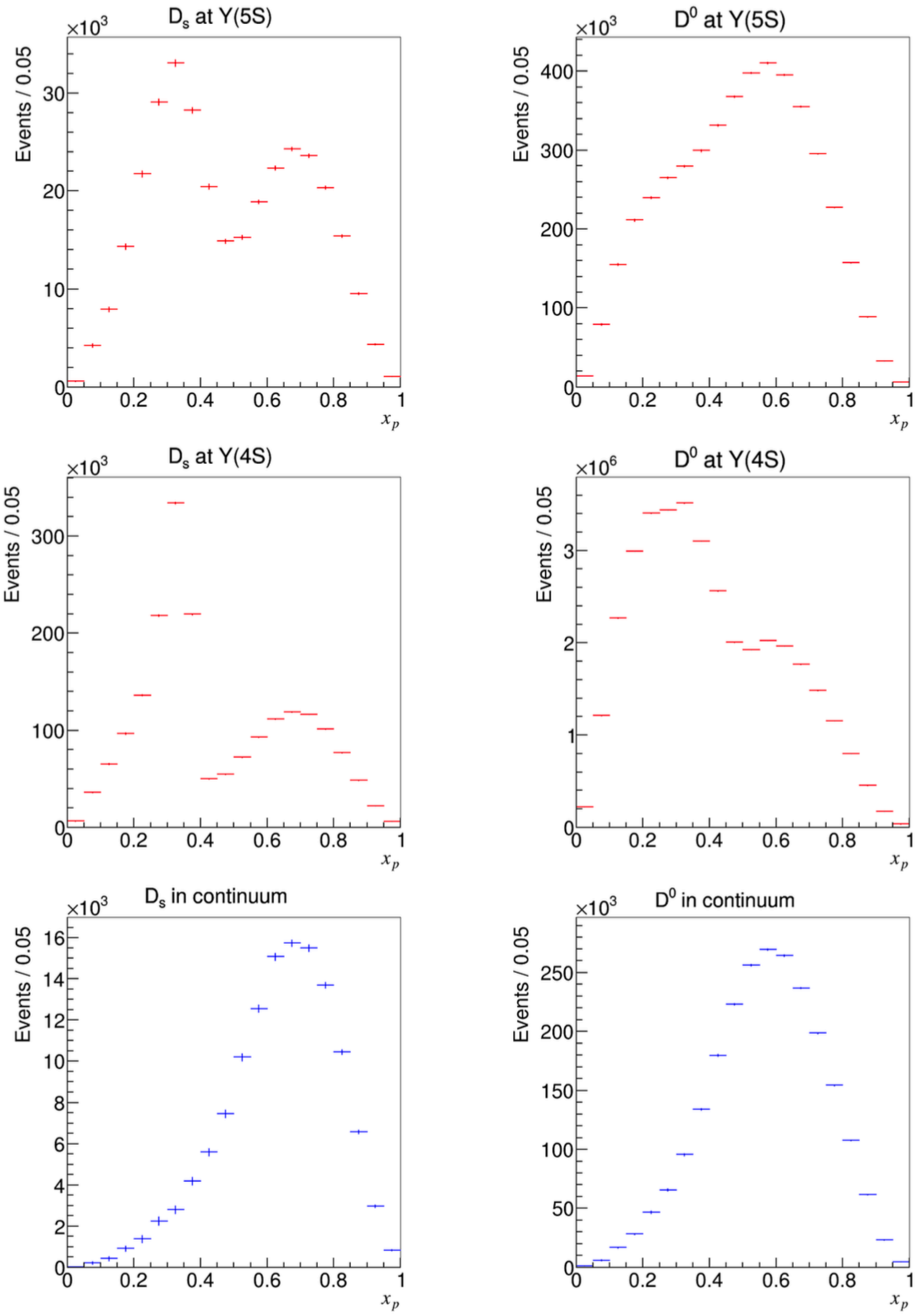
2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

- The signals are described by a sum of four Gaussians with parameters determined from the MC simulation.
- The background is described by a second-order polynomial.

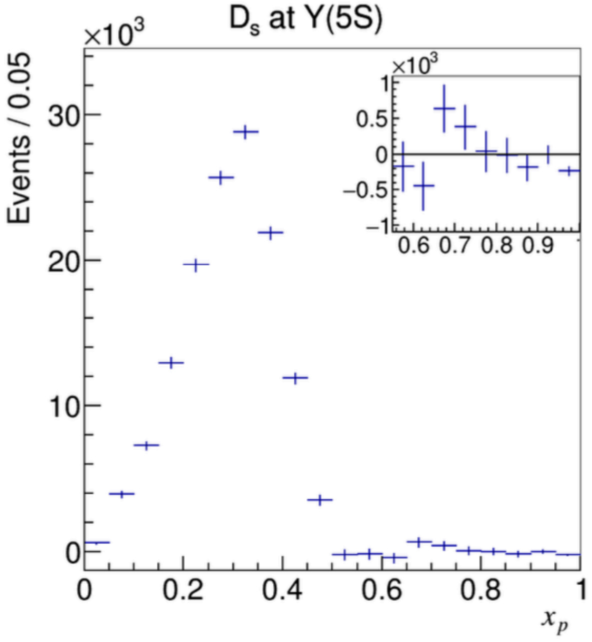


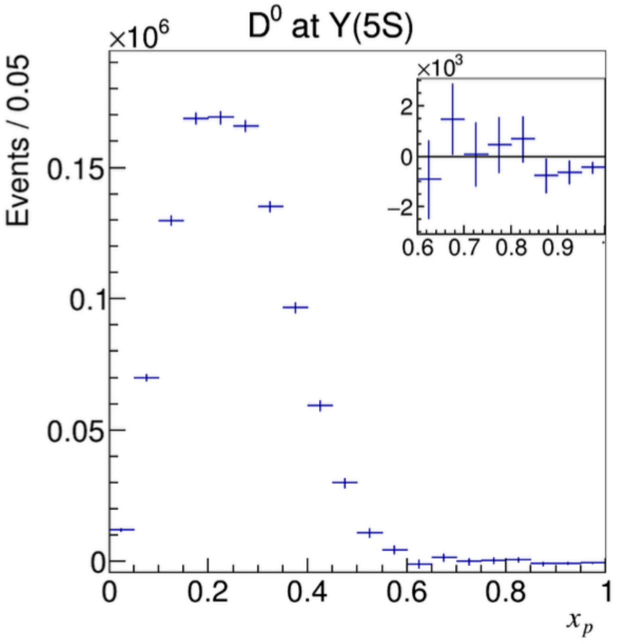


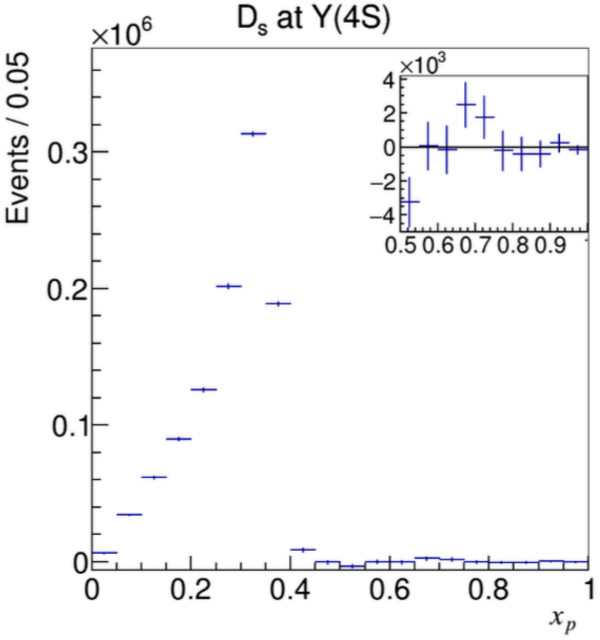


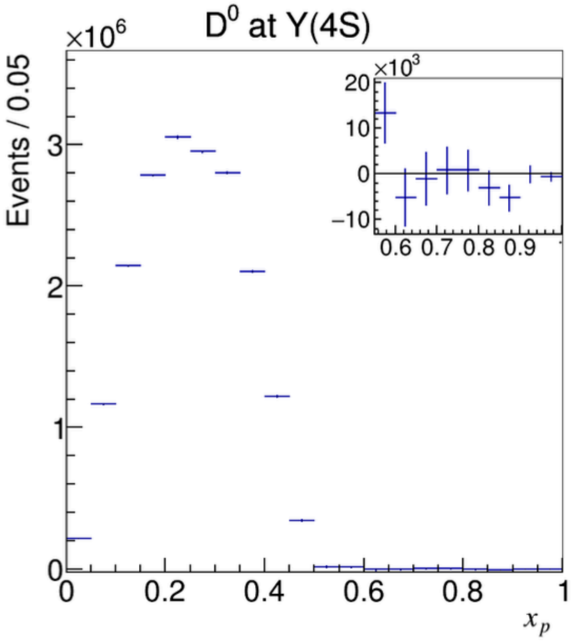
3 Scan of $e^+e^- \to B_s^0\bar{B}_s^0X$ cross section

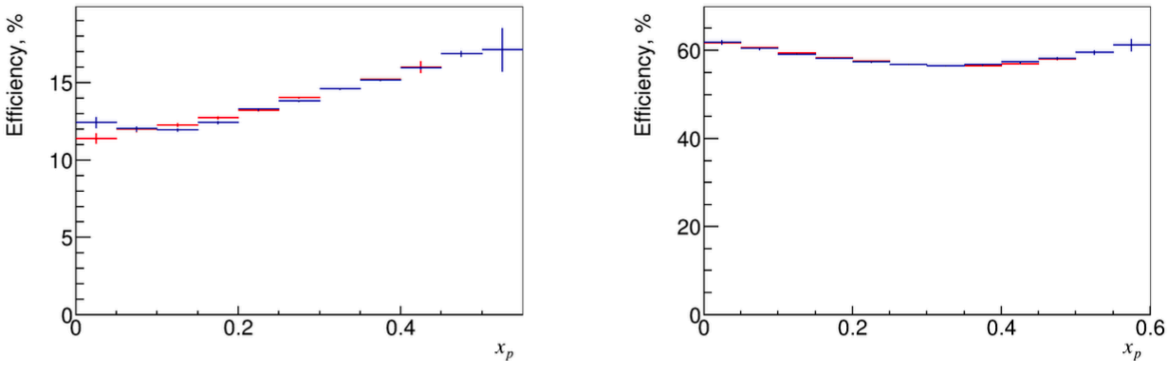
[JHEP 08 2023, 131 (2023)]









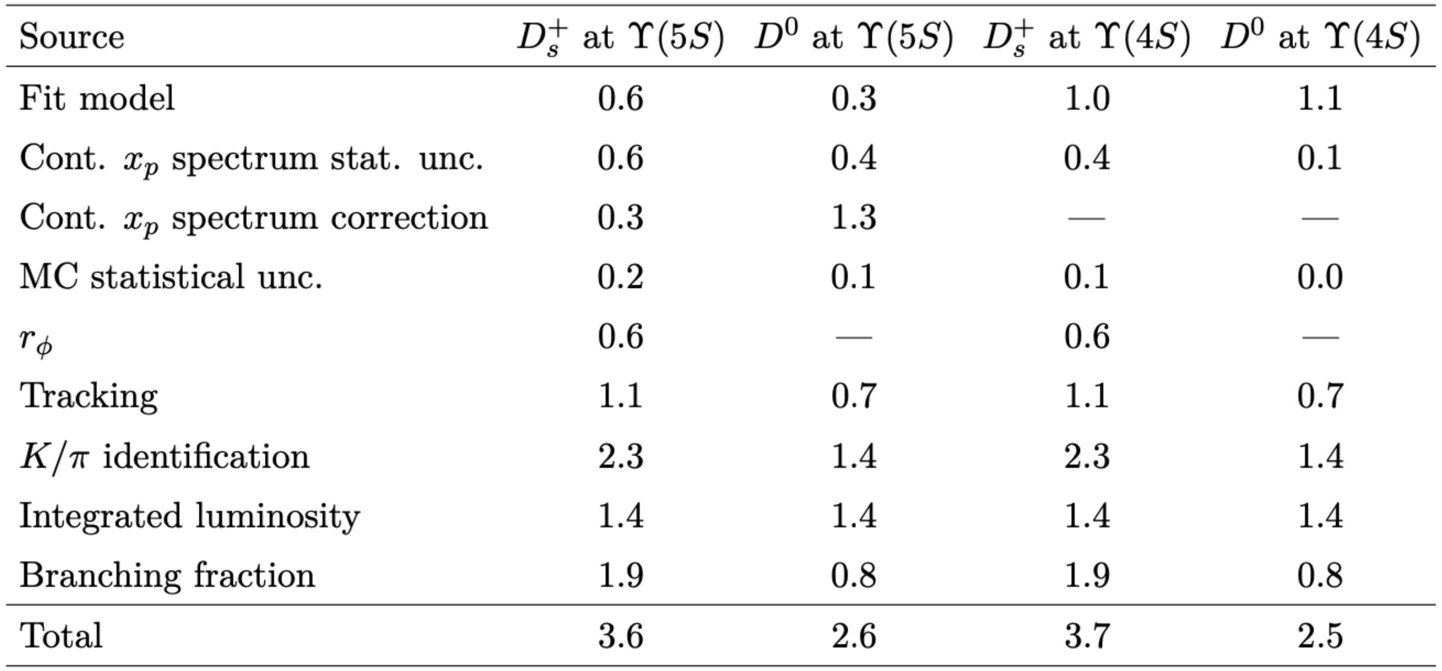


3 Scan of $e^+e^- \to B_s^0\bar{B}_s^0X$ cross section

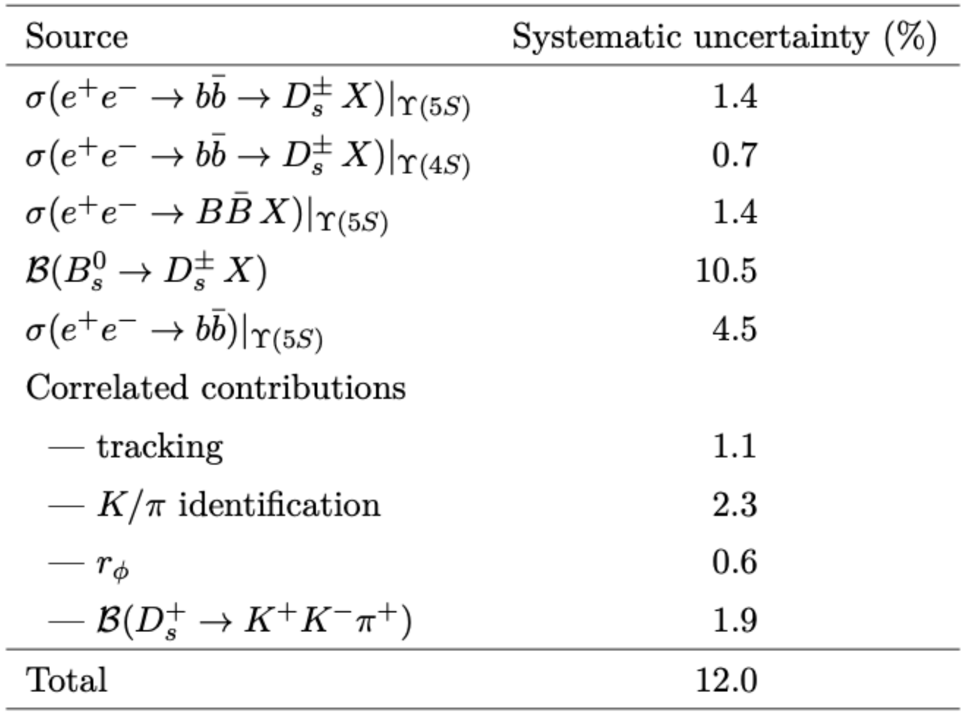
[JHEP 08 2023, 131 (2023)]

- Cross section results $\sigma(e^+e^- \to b\bar{b} \to DX)$

Systematic uncertainty sources



Source	D_s^+ at $\Upsilon(5S)$	D^0 at $\Upsilon(5S)$	D_s^+ at $\Upsilon(4S)$	D^0 at $\Upsilon(4S)$
Fit model	0.6	0.3	1.0	1.1
Cont. x_p spectrum stat. unc.	0.6	0.4	0.4	0.1
Cont. x_p spectrum correction	0.3	1.3	—	—
MC statistical unc.	0.2	0.1	0.1	0.0
r_ϕ	0.6	—	0.6	—
Tracking	1.1	0.7	1.1	0.7
K/π identification	2.3	1.4	2.3	1.4
Integrated luminosity	1.4	1.4	1.4	1.4
Branching fraction	1.9	0.8	1.9	0.8
Total	3.6	2.6	3.7	2.5



Source	Systematic uncertainty (%)
$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)\|_{\Upsilon(5S)}$	1.4
$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)\|_{\Upsilon(4S)}$	0.7
$\sigma(e^+e^- \to B\bar{B}X)\|_{\Upsilon(5S)}$	1.4
$\mathcal{B}(B_s^0 \to D_s^\pm X)$	10.5
$\sigma(e^+e^- \to b\bar{b})\|_{\Upsilon(5S)}$	4.5
Correlated contributions	
— tracking	1.1
— K/π identification	2.3
— r_ϕ	0.6
— $\mathcal{B}(D_s^+ \to K^+K^-\pi^+)$	1.9
Total	12.0

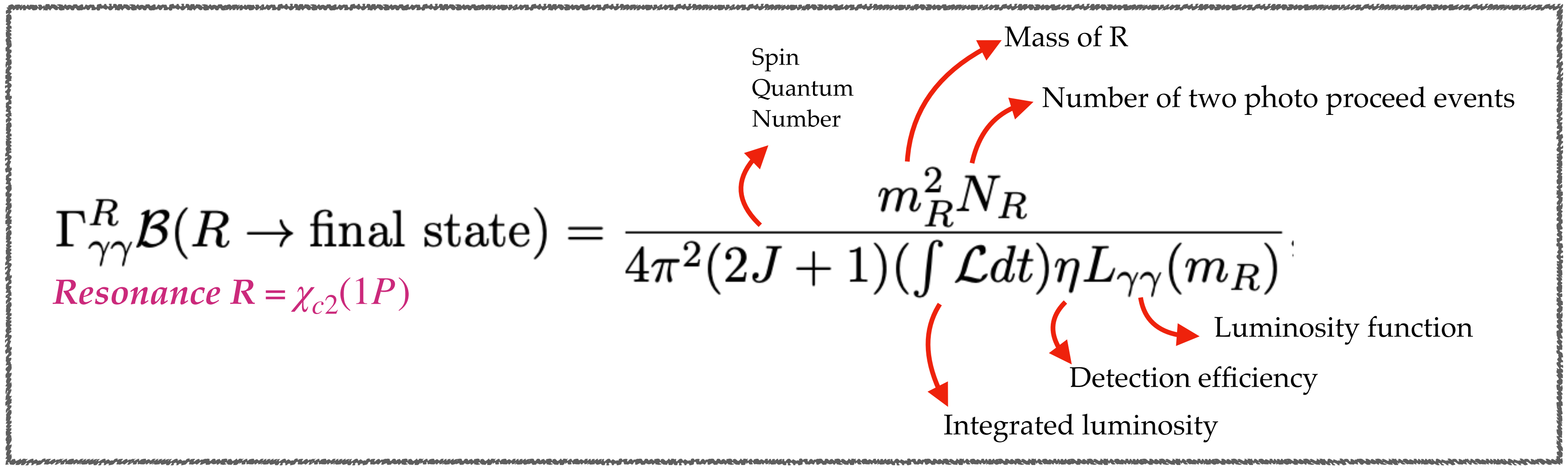
Table 4. Systematic uncertainty in f_s.

2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

Analysis Method

- Approach #2: Study of $\gamma\gamma \to \chi_{c2}(1P)$ collisions
  - $\gamma\gamma \to \chi_{c2}(1P) \to J/\psi(\to l^+l^-)\gamma$; ***zero-tag mode***
  - Event selections: similar to previous Belle measurement and decay width as;

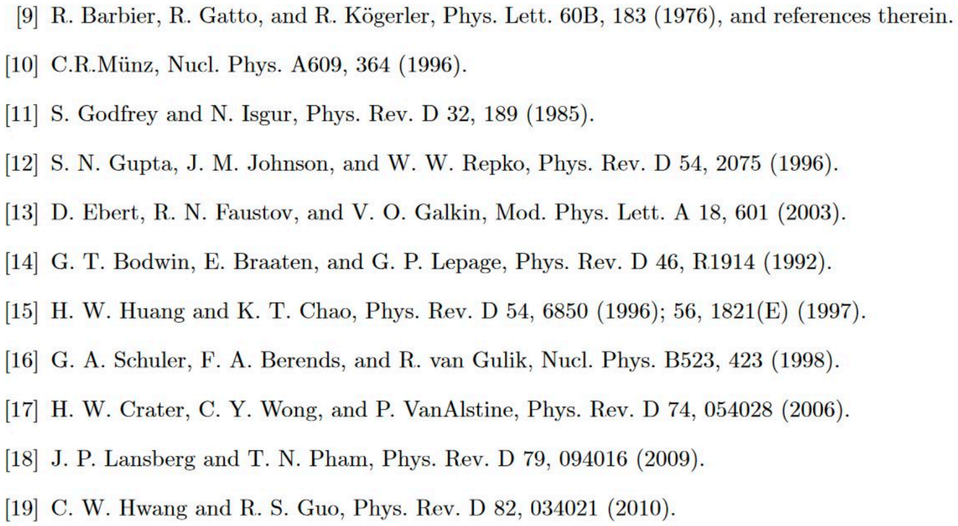


$$\Gamma^R_{\gamma\gamma}\mathcal{B}(R \to \text{final state}) = \frac{m_R^2 N_R}{4\pi^2(2J+1)(\int \mathcal{L}dt)\eta L_{\gamma\gamma}(m_R)}$$

Resonance R = $\chi_{c2}(1P)$

- **Signal extraction analysis strategy**
  - p_T^* -balance requirements: a clear, separated cluster for $\chi_{c2}(1P)$
  - background component is removed using side bands (asymmetric)
    - better fit method w.r.t. previous method (improved detection efficiency)
  - peaking background from ISR $\psi(2S)$ production is also treated (MC Based)

- **Theory models**



[9] R. Barbier, R. Gatto, and R. Kögerler, Phys. Lett. 60B, 183 (1976), and references therein.
[10] C.R.Münz, Nucl. Phys. A609, 364 (1996).
[11] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
[12] S. N. Gupta, J. M. Johnson, and W. W. Repko, Phys. Rev. D 54, 2075 (1996).
[13] D. Ebert, R. N. Faustov, and V. O. Galkin, Mod. Phys. Lett. A 18, 601 (2003).
[14] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D 46, R1914 (1992).
[15] H. W. Huang and K. T. Chao, Phys. Rev. D 54, 6850 (1996); 56, 1821(E) (1997).
[16] G. A. Schuler, F. A. Berends, and R. van Gulik, Nucl. Phys. B523, 423 (1998).
[17] H. W. Crater, C. Y. Wong, and P. VanAlstine, Phys. Rev. D 74, 054028 (2006).
[18] J. P. Lansberg and T. N. Pham, Phys. Rev. D 79, 094016 (2009).
[19] C. W. Hwang and R. S. Guo, Phys. Rev. D 82, 034021 (2010).

3 Scan of $e^+e^- \to B_s^0\bar{B}_s^0 X$ cross section measurement

[JHEP 08 2023, 131 (2023)]

Results

- Cross section (in pb) results $\sigma(e^+e^- \to b\bar{b} \to DX)$

	$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)$	$\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X)$
$\Upsilon(5S)$	$151.8 \pm 1.0 \pm 5.5$	$379.7 \pm 1.6 \pm 10.0$
$\Upsilon(4S)$	$248.6 \pm 0.6 \pm 9.2$	$1468.5 \pm 0.9 \pm 36.6$

- Branching fraction $\mathcal{B}(B \to D/\bar{D}X)$

$$\mathcal{B}(B \to D^0/\bar{D}^0 X) = (66.63 \pm 0.04 \pm 1.77)\%,$$
$$\mathcal{B}(B \to D_s^\pm X) = (11.28 \pm 0.03 \pm 0.43)\%.$$

  - lower uncertainty then world average:
  - 3σ tension for D_s

- Production fraction of $B_s^0\bar{B}_s^0 X$: f_s

$$f_s = (23.0 \pm 0.2 \pm 2.8)\%.$$

OR $f_s = (22.0^{+2.0}_{-2.1})\%$ w/ constraint $f_s + f_{B\bar{B}X} + f_{\not{B}} = 1$

  - supersedes previous Belle measurements

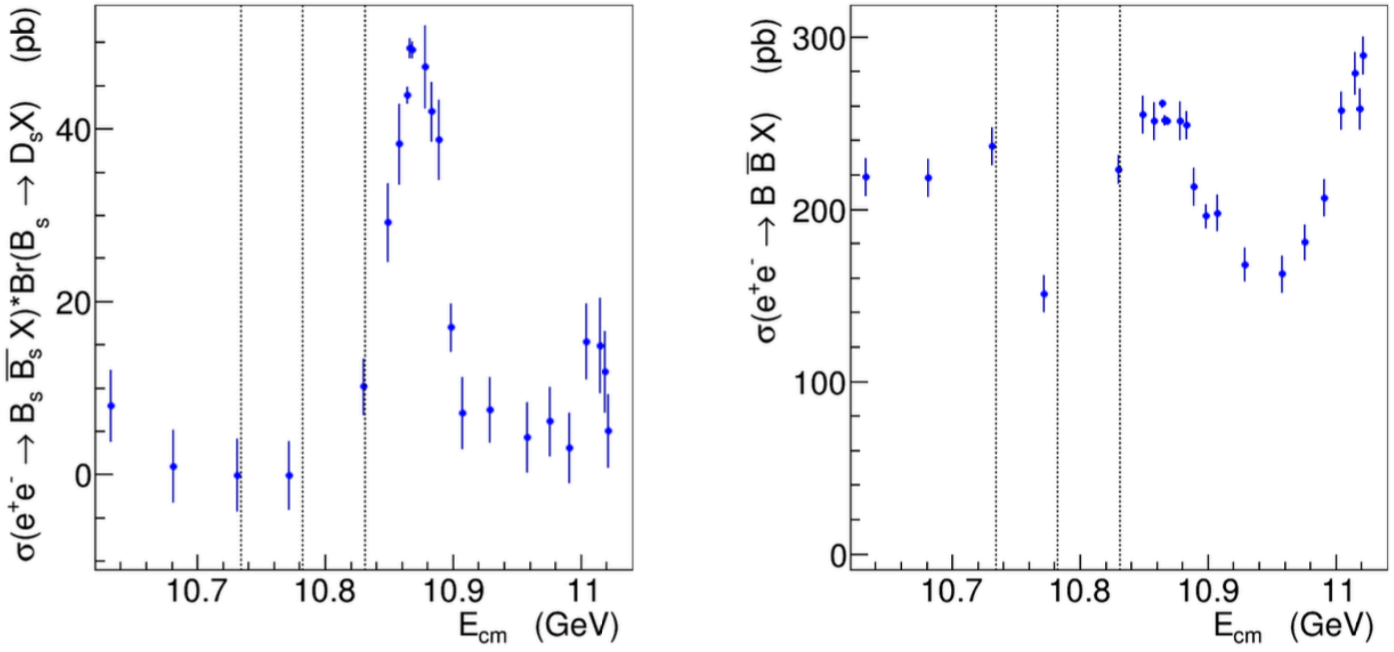
- Ratio $\mathcal{B}(B \to D^0/\bar{D}^0 X)/\mathcal{B}(B_s^0 \to D_s^\pm X)$

$$\frac{\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)}{\mathcal{B}(B_s^0 \to D_s^\pm X)} = 0.416 \pm 0.018 \pm 0.092$$

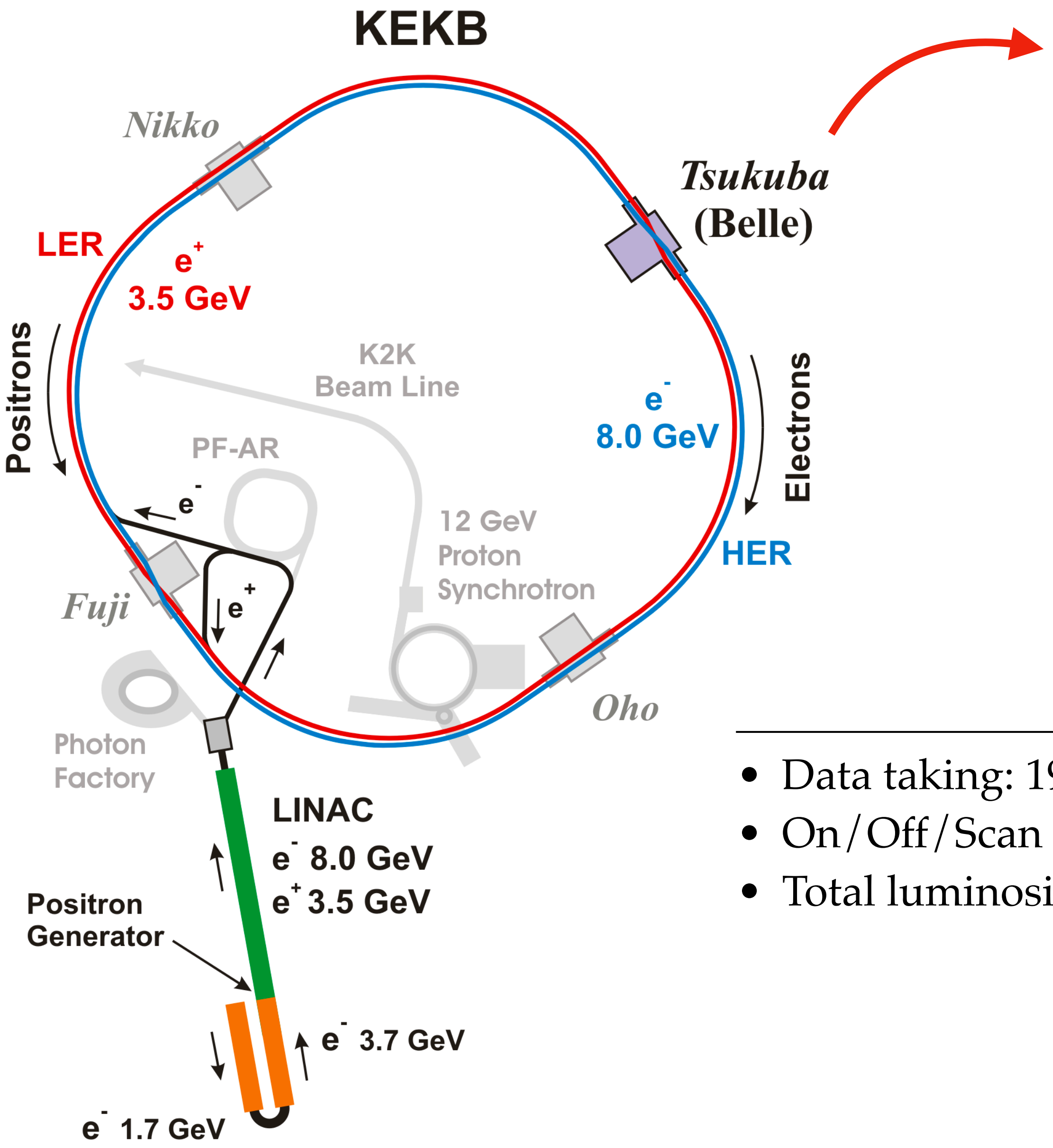
Energy Dependence of cross section

$$\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X) \cdot \mathcal{B}(B_s^0 \to D_s^\pm X)$$
$$\sigma(e^+e^- \to B\bar{B} X)$$

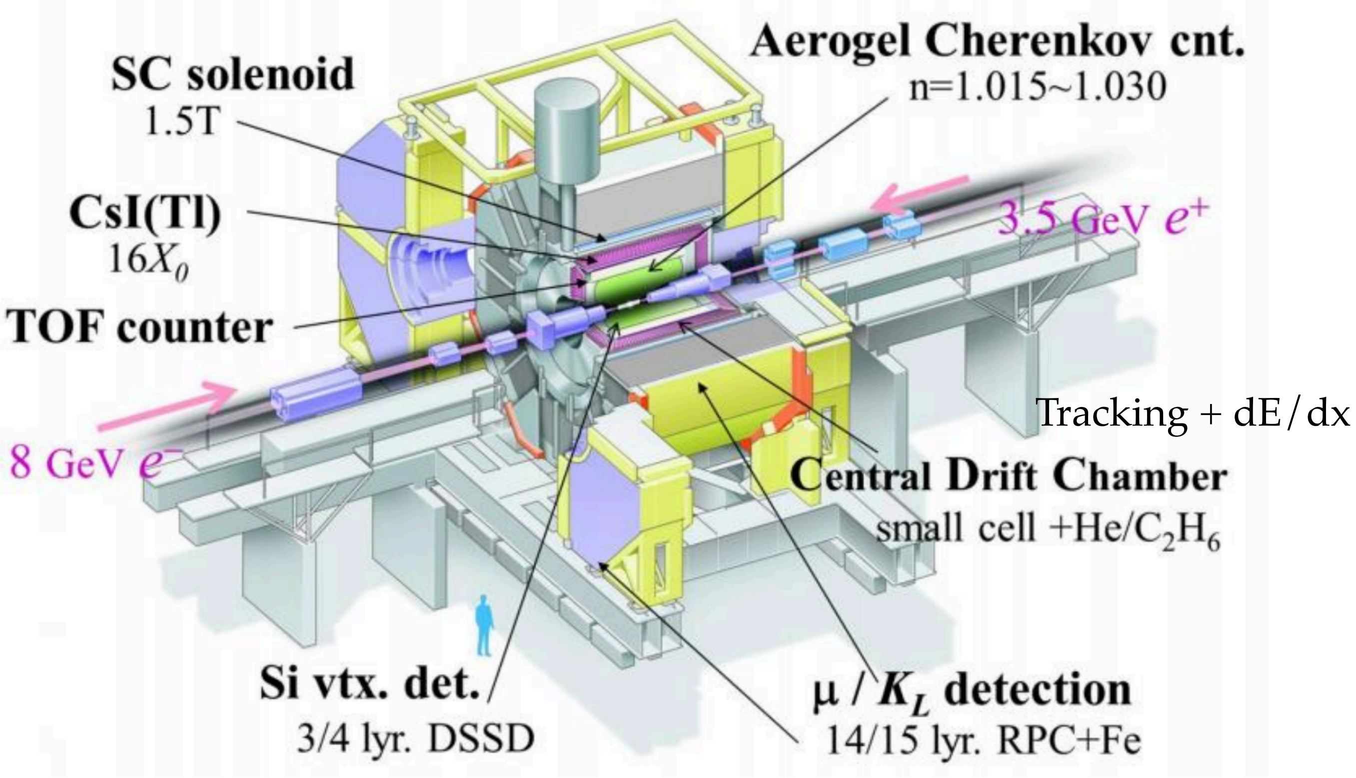
- now with high precision
- provides good grounds for Belle II



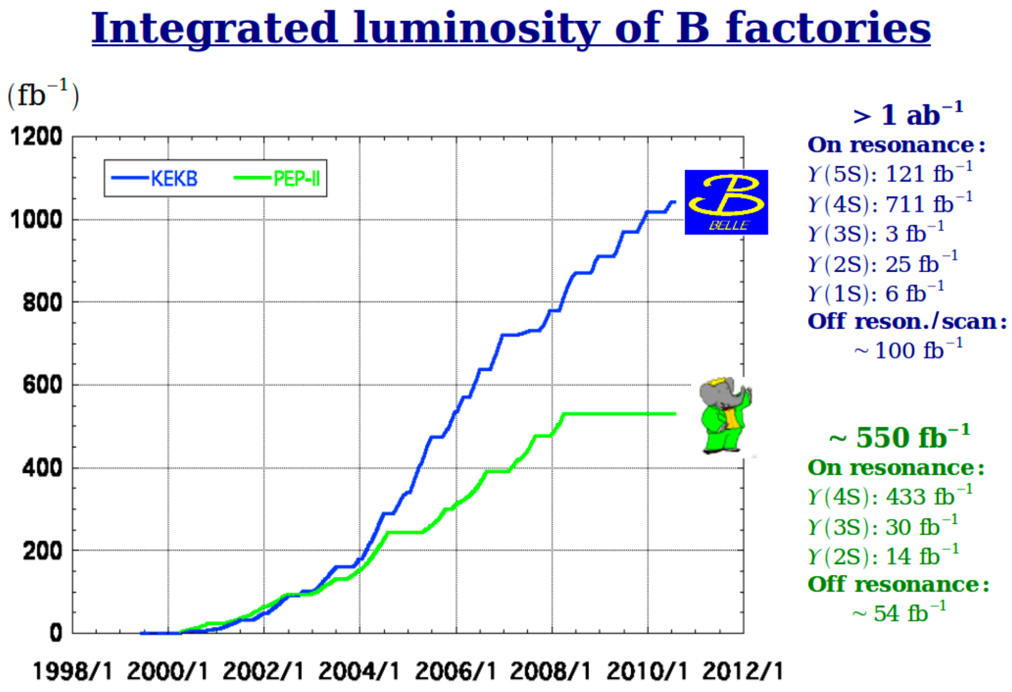
Belle Detector



Belle e^- : 8 GeV, e^+ : 3.5 GeV



- Data taking: 1999 – 2010
- On/Off/Scan $\Upsilon(nS)$ peaks
- Total luminosity: 1 ab^{-1}



2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]

Goal

- Two-photon decay width provides important information on spectroscopy, exotic states as well as testing QCD models
- **Resonance production** $\gamma\gamma \to R$ (e.g. $R = \chi_{c2}(1P)$)
  - R comes with many fundamental constraints (e.g. quantum numbers)
  - Decay width is fundamental and direct observable for probing internal structure of meson ($q\bar{q}$)
  - $\chi_{c2}(1P)$ (p-wave charmonium) is even special for probing QCD vs pQCD scenario
    - Theory models predict $\chi_{c2}(1P)$ mass in wide range 280-930 eV
    - Previous attempts by Belle (2002), CLEO (2006, 2008) and BESIII (2017)

Method

The overall signal detection efficiency in this analysis is estimated to be 7.36% using the signal MC.

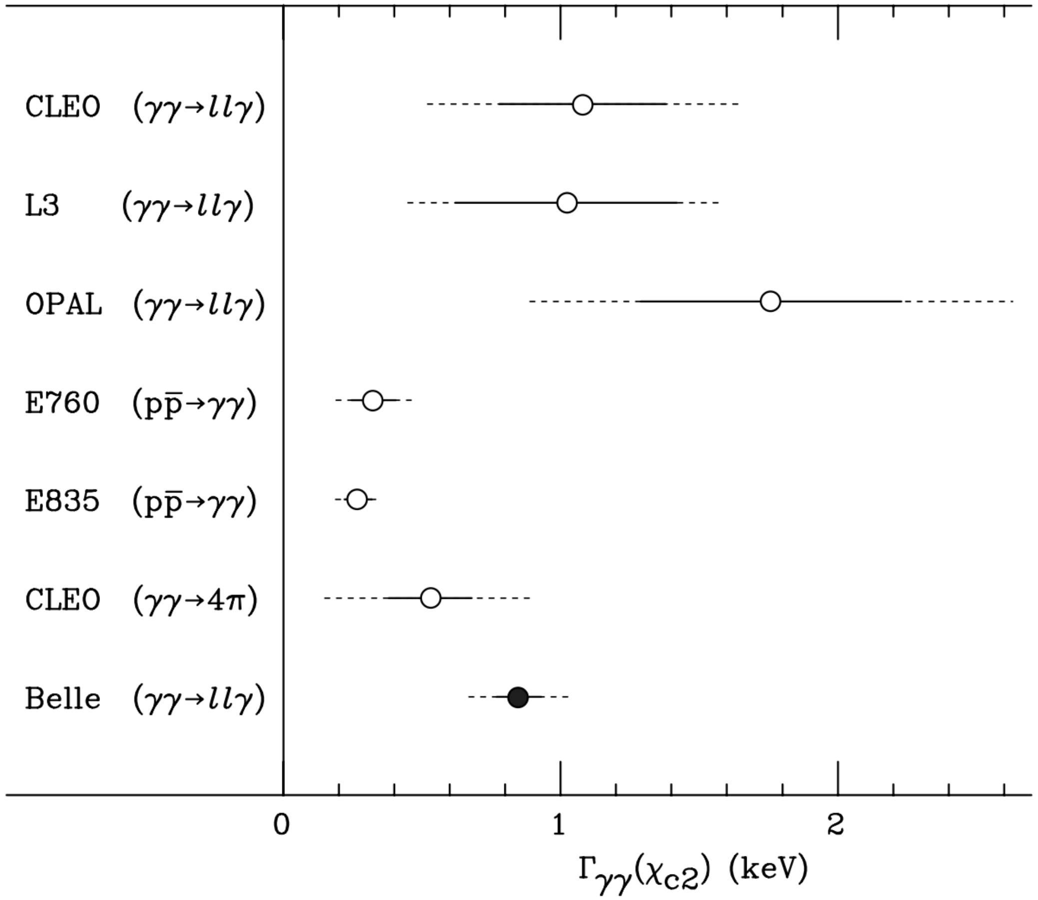
---

*Recalculated $\mathscr{B}(\chi_{c2}(1P) \to J/\psi\gamma)$ for = (19.0 ± 0.5)% and $\mathscr{B}(J/\psi \to l^+l^-)$ = 11.93 ± 0.05 MeV from PDG

**Recalculated $\mathscr{B}(\psi(2S) \to \chi_{c2}(1P)\gamma)$ for = (9.52 ± 0.20)% and $\Gamma_{\gamma\gamma}(\chi_{c2}(1P))$ = 1.97 ± 0.09 MeV from PDG

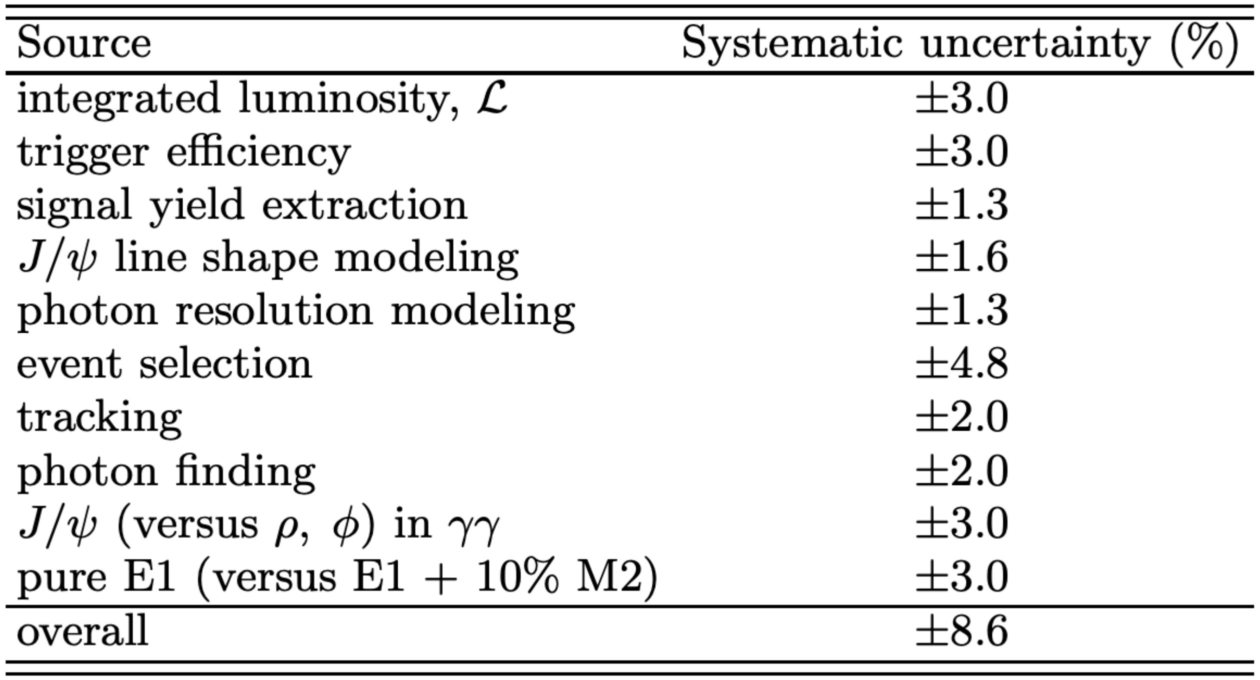
2 Two-photon decay width of $\chi_{c2}(1P)$

[JHEP 01 2023, 160 (2023)]



CLEO 2006: Systematics

TABLE IV: Sources of systematic uncertainties.



Source	Systematic uncertainty (%)
integrated luminosity, $\mathcal{L}$	±3.0
trigger efficiency	±3.0
signal yield extraction	±1.3
J/ψ line shape modeling	±1.6
photon resolution modeling	±1.3
event selection	±4.8
tracking	±2.0
photon finding	±2.0
J/ψ (versus ρ, ϕ) in $\gamma\gamma$	±3.0
pure E1 (versus E1 + 10% M2)	±3.0
overall	±8.6