# Study of charmonia production in $e^+e^-$ annihilation at center-of-mass energies above 3.81 GeV

Olga Bakina
Joint Institute for Nuclear Research, Dubna
on behalf of the BESIII Collaboration

The 21st Lomonosov Conference on Elementary Particle Physics
Moscow, Russia, August, 24-30, 2023

# The BESIII experiment

**$e^+e^-$ collisions** in the τ-charm energy region, $L_{peak} = 1\times10^{33}\,cm^{-2}\,s^{-1}$

Data taking from 2009: the largest data sets at the **J/ψ**, **ψ(3686)**, and **ψ(3770)** peaks; scan data at **$\sqrt{s}$ = 2.00 – 4.95 GeV**

**Superconducting Solenoidal Magnet: 0.9/1.0 T**

**MDC**

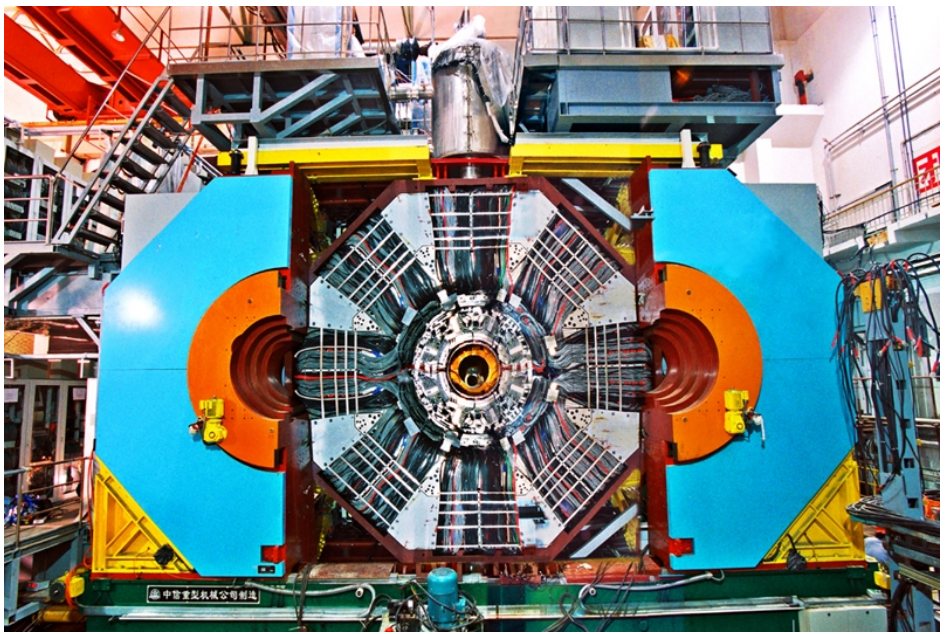
dE/dx: 6%

$\sigma_p/p$: 0.5% at 1 GeV/c

**TOF**

$\sigma_T$: 68 ps

110 ps (60 ps)



**EMC**

ΔE/E: 2.5% (5%) at 1 GeV

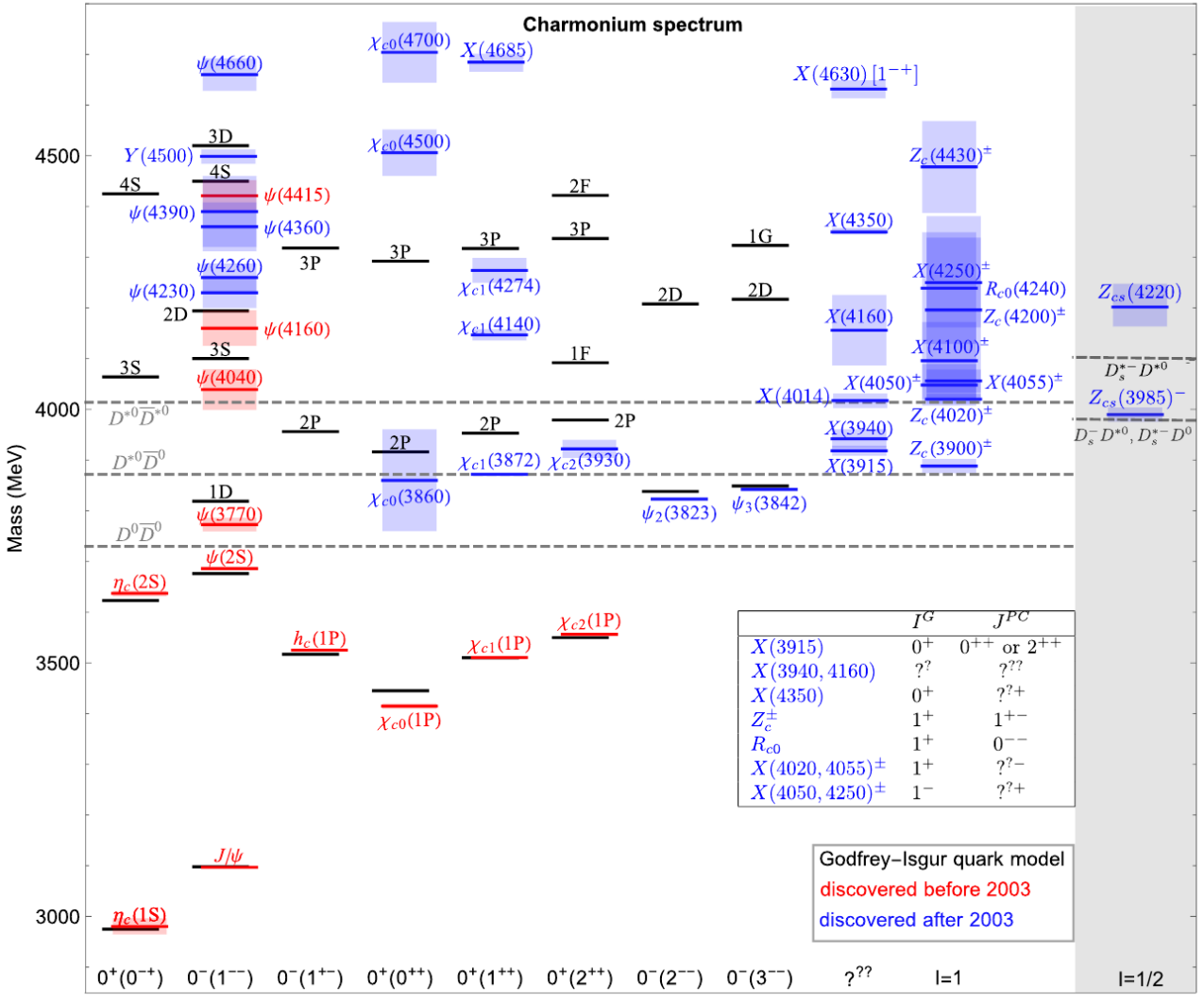
$\sigma_z$: 0.6 cm/$\sqrt{E}$

**MUC**

$\sigma_{R\Phi}$: 2 cm

**Figure:** The BESIII detector at BEPCII.

# Charmonium(-like) states




| | $I^G$ | $J^{PC}$ |
|---|---|---|
| $X(3915)$ | $0^+$ | $0^{++}$ or $2^{++}$ |
| $X(3940, 4160)$ | $?^?$ | $?^{??}$ |
| $X(4350)$ | $0^+$ | $?^{?+}$ |
| $Z_c^{\pm}$ | $1^+$ | $1^{+-}$ |
| $R_{c0}$ | $1^+$ | $0^{--}$ |
| $X(4020, 4055)^{\pm}$ | $1^+$ | $?^{?-}$ |
| $X(4050, 4250)^{\pm}$ | $1^-$ | $?^{?+}$ |

# The first observation of three charmonium-like states in $e^+e^- \to D^{*0}D^{*-}\pi^+$

**Data:** $\mathcal{L} = 17.9$ fb$^{-1}$, $\sqrt{s} = 4.189 - 4.951$ GeV

Phys.Rev.Lett. 130 (2023) 12, 121901

**Channel:** $e^+e^- \to D^{*0}D^{*-}\pi^+ + cc.$, $D^{*0}(D^{*-}) \to D^0(D^-)\pi^0$, $D^0 \to K^-\pi^+/K^-\pi^+\pi^0/K^-\pi^+\pi^+\pi^-$, $D^- \to K^+\pi^-\pi^-$, $\pi^0 \to \gamma\gamma$

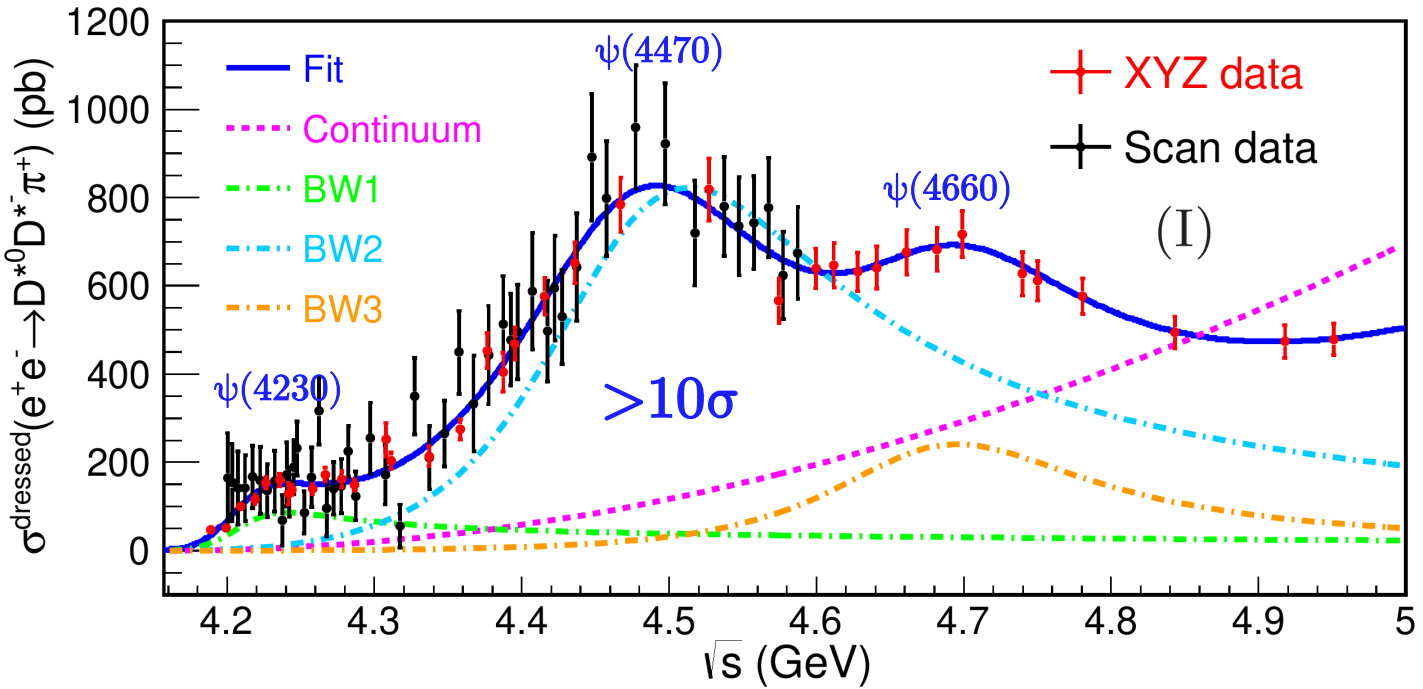



**Figure:** The fit result to the dressed cross section line shape of $e^+e^- \to D^{*0}D^{*-}\pi^+$.

# The first observation of a new X(3872) production process $e^+e^- \to \omega X(3872)$

**Data:** $\mathcal{L} = 4.7$ fb$^{-1}$, $\sqrt{s} = 4.661 - 4.951$ GeV

Phys.Rev.Lett. 130 (2023) 15, 151904

**Channel:** $e^+e^- \to \omega X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ ($l = e, \mu$), $\omega \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$

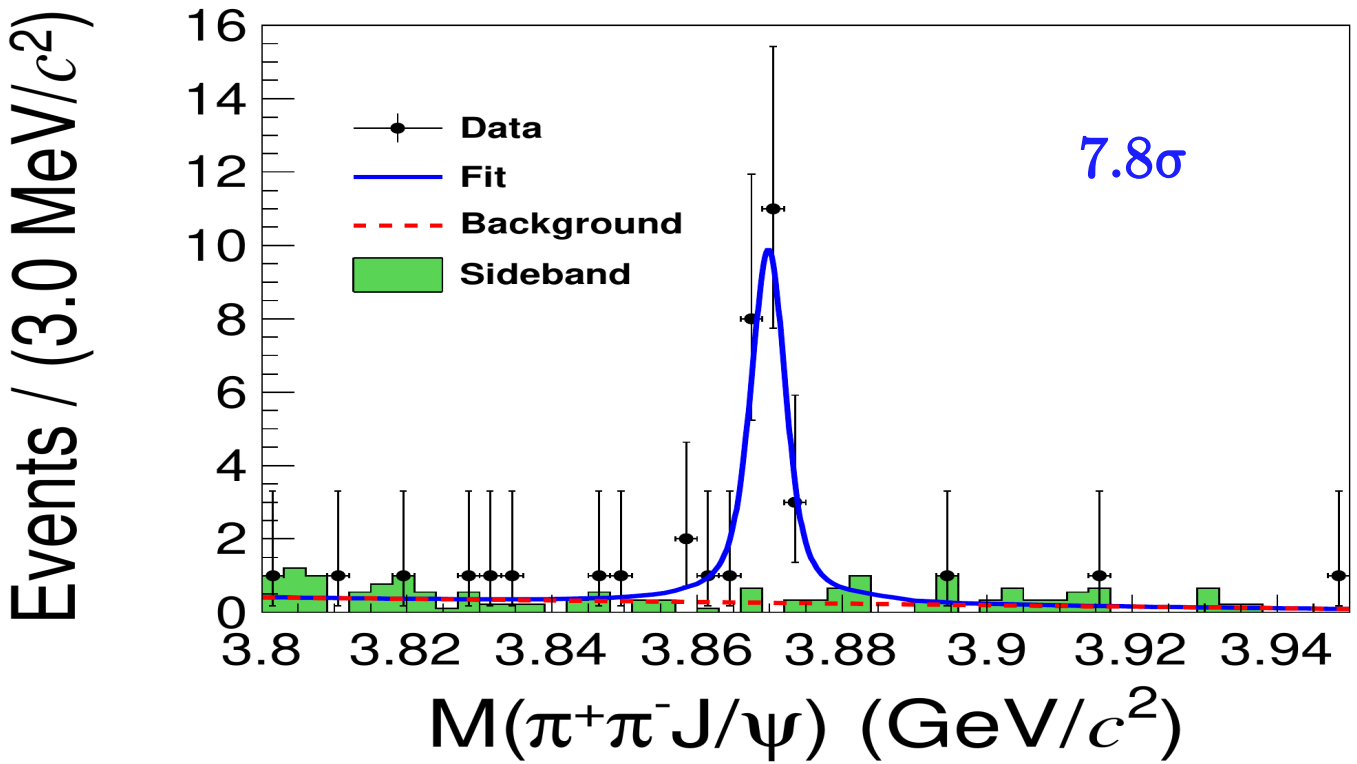



**Figure:** Fit to the M ($\pi^+\pi^- J/\psi$) distribution. The filled histogram represents events from the $\omega$ and $J/\psi$ two-dimensional sidebands.

# Observation of charmonium-like states in the process $e^+e^- \to K^0_S K^0_S J/\psi$

**Data:** $\mathcal{L} = 21.2$ fb$^{-1}$, $\sqrt{s} = 4.128 - 4.951$ GeV

Phys.Rev.D 107 (2023) 9, 092005

**Channel:** $e^+e^- \to K^0_S K^0_S J/\psi$, $J/\psi \to l^+ l^-$ ($l = e, \mu$), $K^0_S \to \pi^+\pi^-$, $K^0_S \to \pi^+\pi^-$ or $\pi^0\pi^0$

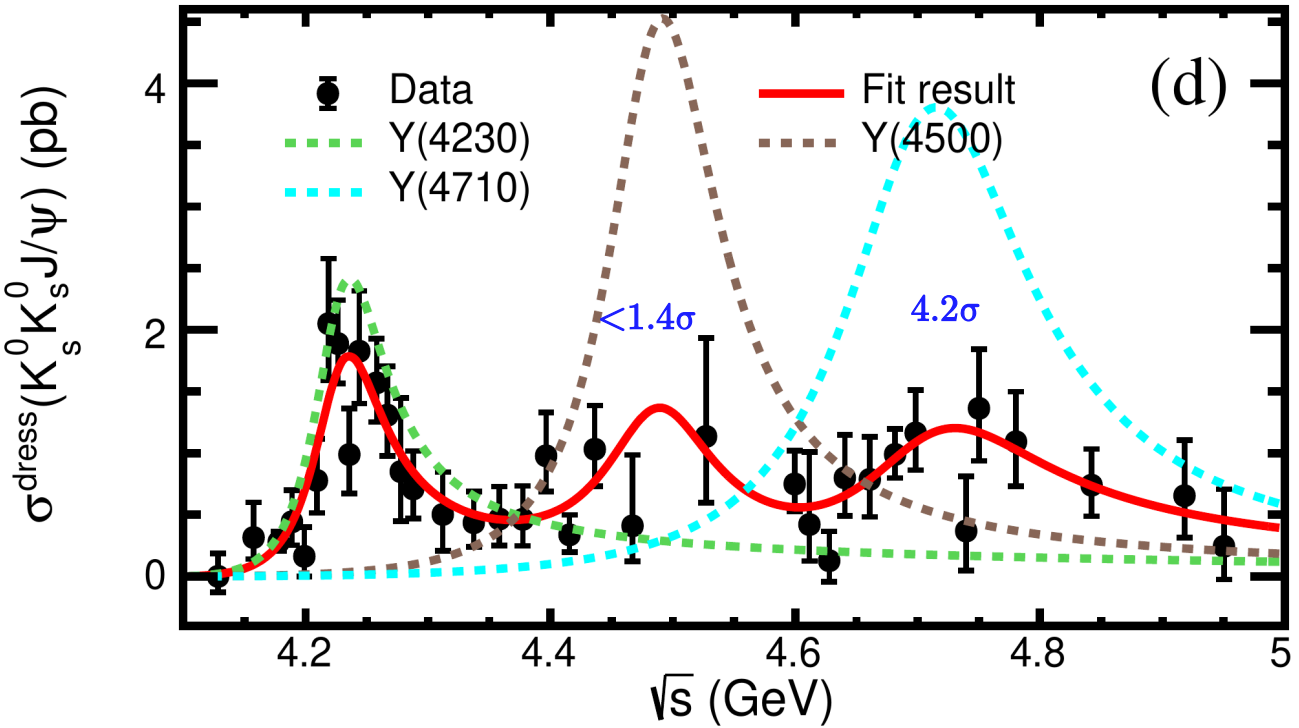



**Figure:** Maximum likelihood fit to the dressed cross sections of $e^+e^- \to K^0_S K^0_S J/\psi$. The mass and width of the Y(4500) state are fixed.

# The first observation of charmonium-like states in the process $e^+e^- \to \pi^+\pi^-\psi_2(3823)$

**Data:** $\mathcal{L} =$ 11.3 fb$^{-1}$, $\sqrt{s} = 4.23 - 4.70$ GeV

Phys.Rev.Lett. 129 (2022) 10, 102003

**Channel:** $e^+e^- \to \pi^+\pi^-\psi_2(3823)$, $\psi_2(3823) \to \gamma\chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$, $J/\psi \to l^+ l^-$ ($l = e, \mu$)

**The most precise measurement of the mass:**

- $M[\psi_2(3823)] = 3823.12 \pm 0.43_{stat} \pm 0.13_{syst}$ MeV/c$^2$

**The most stringent constraint on the width:**

- $\Gamma[\psi_2(3823)] < 2.9$ MeV at the 90% C.L.

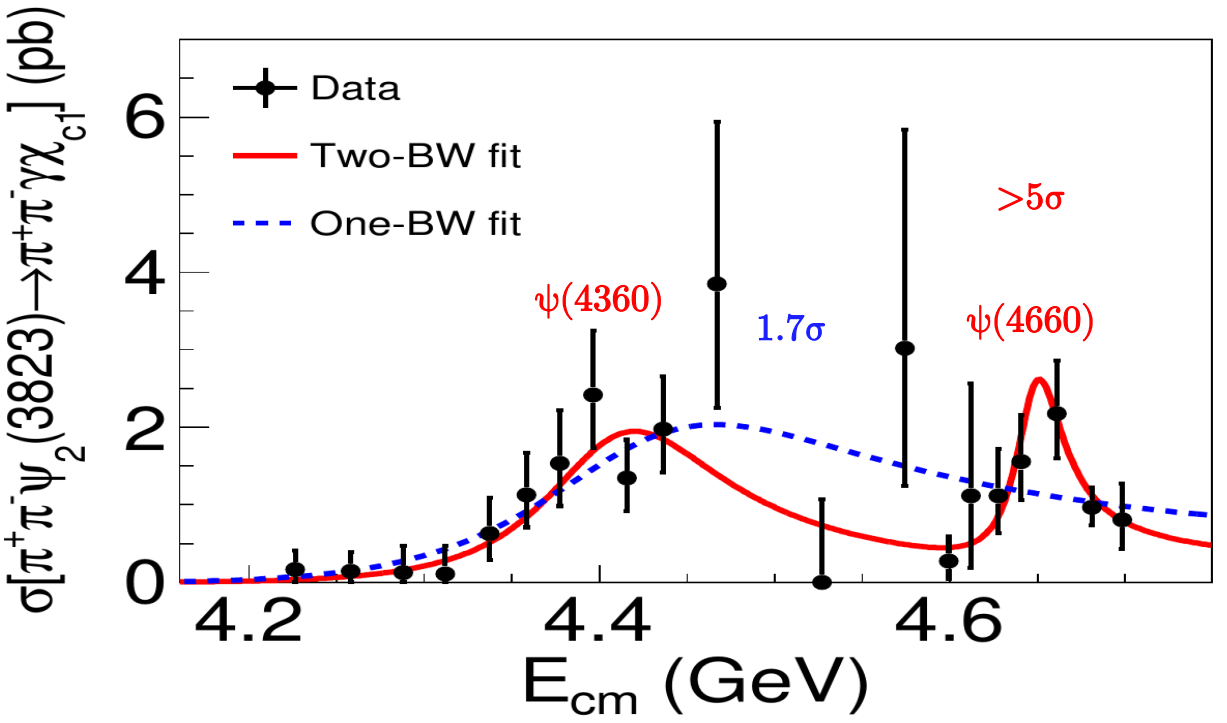



**Figure:** Result of the fit to the $\sqrt{s}$-dependent cross section $\sigma[e^+e^- \to \pi^+\pi^-\psi_2(3823)]$ times the branching ratio $B[\psi_2(3823) \to \gamma\chi_{c1}]$.

# Search for charmonium-like states in the processes $e^+e^- \to \varphi\chi_{c1,c2}$ (or $\gamma X$) $\to \gamma\varphi J/\psi$

**Data:** $\mathcal{L} = 6.4$ fb$^{-1}$, $\sqrt{s} = 4.600 - 4.951$ GeV

**JHEP 01 (2023) 132**

**Channel:** $e^+e^- \to \gamma\varphi J/\psi$, $J/\psi \to l^+ l^-$ ($l = e, \mu$), $\varphi \to K^+K^-/K^0_S K^0_L$

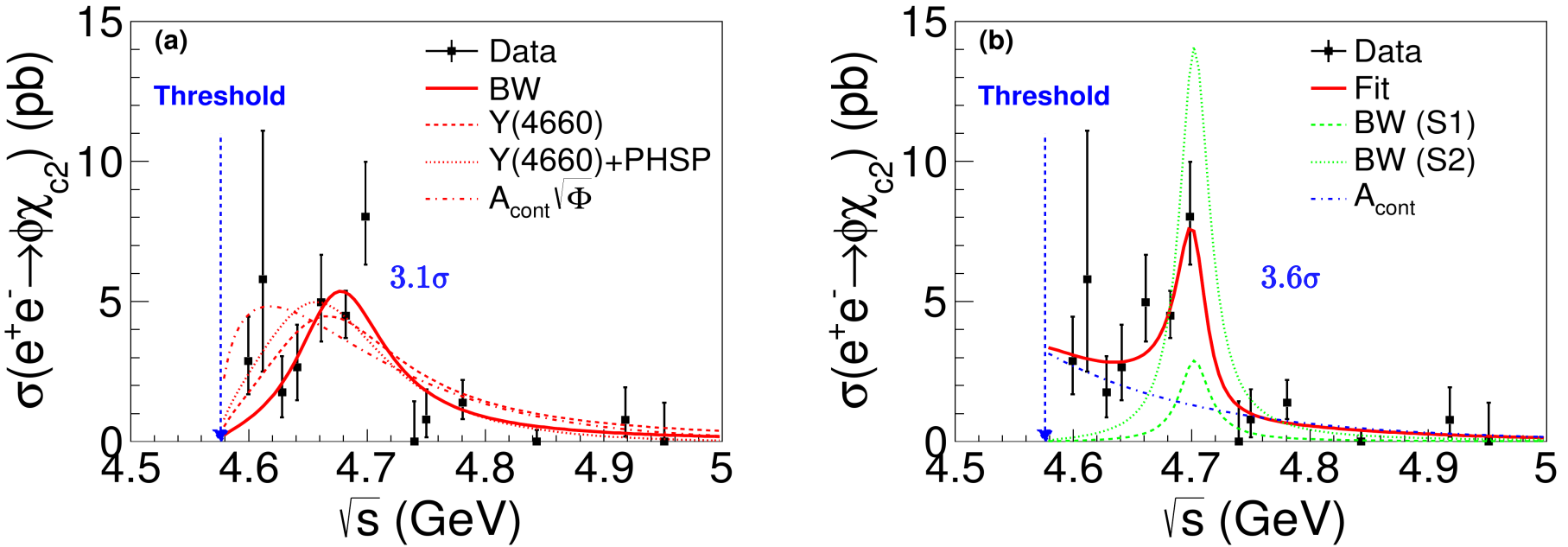



**Figure:** (a) Fit to the cross section of $e^+e^- \to \varphi\chi_{c2}$ with a single BW. (b) Fit to the cross section of $e^+e^- \to \varphi\chi_{c2}$ with the coherent sum of a BW and continuum amplitude.

# Prompt inclusive charmonium production

Goal:

- **Test the NRQCD factorization hypothesis:** the independence of Long Distance Matrix Elements (LDME) that describe the hadronization of the $c\bar{c}$ pair from the process (hadron-hadron collisions, electroproduction, or $e^+e^-$ annihilation);
- **Clarify the contribution of the color octet channel** in the range of $\sqrt{s}$ below the $J/\psi c\bar{c}$ threshold (~6 GeV): the color-octet LDMEs are non-zero if $\sigma > 10$ pb at $\sqrt{s} = 4.6 \sim 5.6$ GeV (Eur. Phys. J. C (2017) 77: 597);
- **Test if unknown channels/states exist.**

Data only available at $\sqrt{s} = 10.6$ GeV:

- **2.5 ± 0.3 pb** (BaBar)
- **1.5 ± 0.2 pb** (Belle)
- **1.9 ± 0.2 pb** (CLEO)

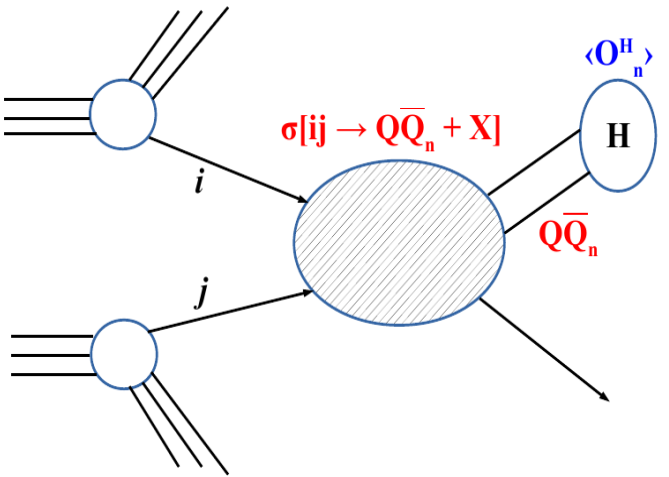



**Figure:** NRQCD factorization. The LDMEs $\langle O^H_n \rangle$ are determined from experimental data.

# Prompt inclusive J/ψ production

**Data:** $\mathcal{L} = 22$ fb$^{-1}$, $\sqrt{s} = 3.81 - 4.95$ GeV

**Channel:** $J/\psi \to \mu^+\mu^-, \psi(3686) \to J/\psi\, \pi^+\pi^-, \chi_{cJ} \to \gamma J/\psi$, $(J = 1, 2)$

- Prompt J/ψ originates from sources other than known decays or initial-state radiation (ISR).
- Major background sources:
  - inclusive J/ψ decays of ψ(3686) and $\chi_{cJ}$, $(J = 1, 2)$;
  - ISR return to the J/ψ and ψ(3686) resonances.
- The preliminary result for the prompt inclusive J/ψ production in the range 4.53 ~ 4.95 GeV is

$$\sigma = 14.0 \pm 1.7_{\text{stat}}\ \text{pb}$$

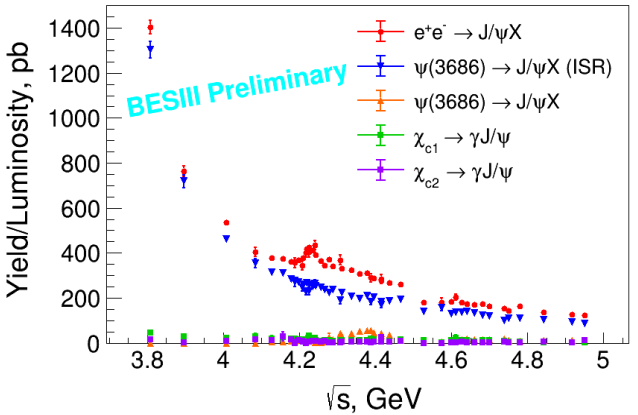



**Figure:** Yield of J/ψ from different sources normalized to corresponding luminosity.

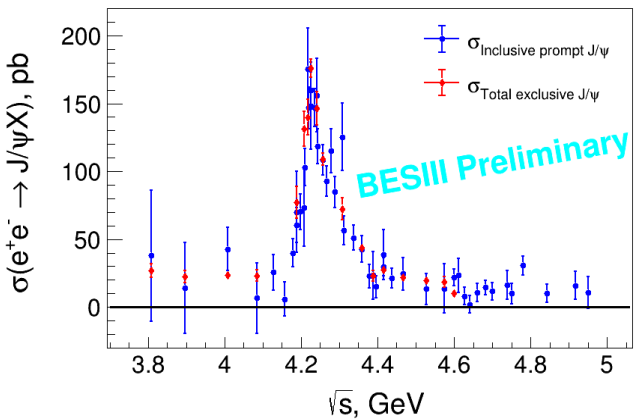



**Figure:** Prompt inclusive and total exclusive J/ψ cross sections.

# Prompt inclusive ψ(3686) production

**Data:** $\mathcal{L} = 22$ fb$^{-1}$, $\sqrt{s} = 4.01 - 4.95$ GeV

**Channel:** $\psi(3686) \to J/\psi\,\pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$

- Prompt ψ(3686) originates from sources other than the ISR return to the ψ(3686) resonance.

- The preliminary result for the prompt inclusive ψ(3686) production in the range 4.84 ~ 4.95 GeV is

$$\sigma = 16.9 \pm 2.8_{\text{stat}}\ \text{pb}$$

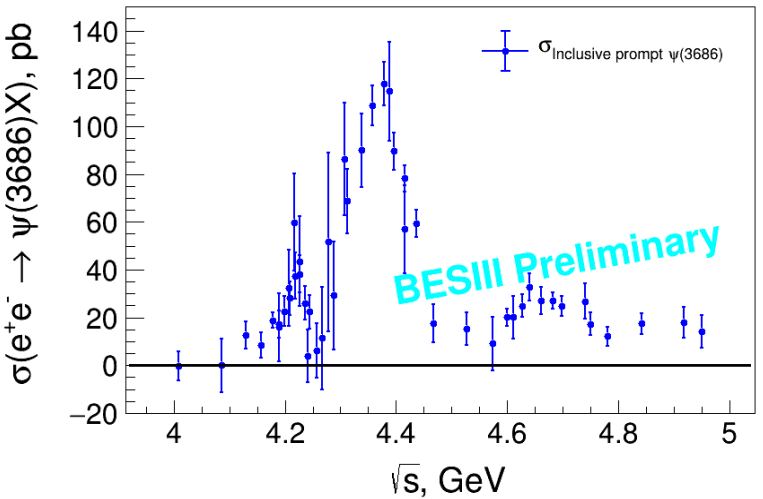



**Figure:** Prompt inclusive ψ(3686) cross-sections.

# Summary

- The charmonia production is a proven tool for verifying the basics of QCD;
- The BESIII experiment successfully applies $e^+e^-$ annihilation data sets to search for new exotic charmonium-like states and study their properties;
- The prompt inclusive production of classical charmonia allows the BESIII experiment to test various theoretical models of the strong interaction at low energies, especially, NRQCD.

Thank you for your attention!