Measurements of cross sections e^+e^- annihilation into hidden charm states

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Outline

- General introduction on hidden charm states and on BESIII apparatus
- Representing main results of BESIII recent works
  - **arXiv:2404.06718**

    Measurement of the Born cross section for $e^+ e^- \longrightarrow \eta h_c$ at center-of-mass energies between 4.1 and 4.6 GeV
  - **PhysRevD.109.112019**

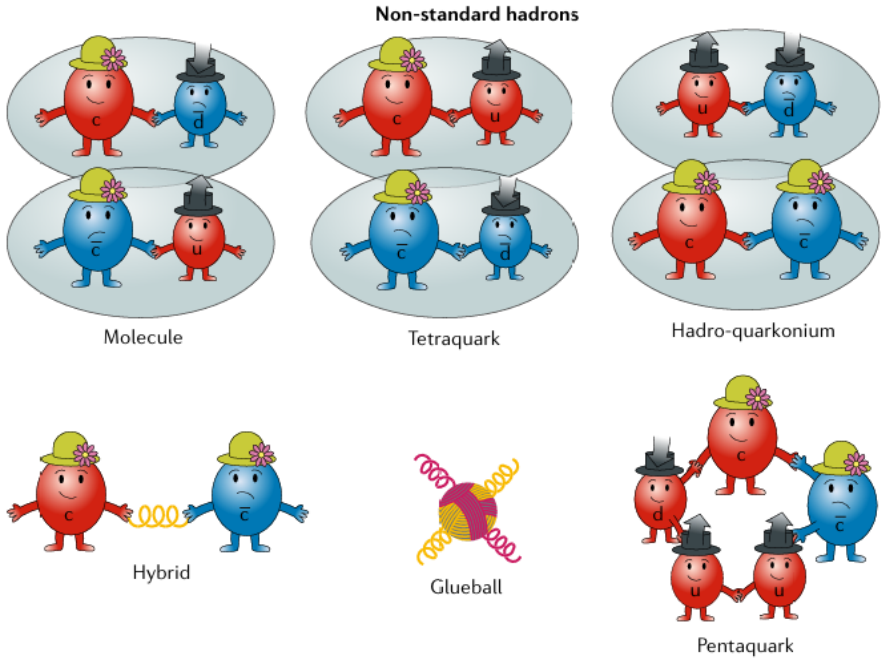
    Search for $e^+ e^- \longrightarrow K^+ K^- \psi(3770)$ at center-of-mass energies from 4.84 to 4.95 GeV
  - **PhysRevD.109.112004**

    Cross section measurement of $e^+ e^- \longrightarrow \eta\psi(2S)$ and search for $e^+ e^- \longrightarrow \eta\tilde{X}(3872)$
  - **PhysRevD 110 1, 012006 &PhysRevD.110.L031103 &PhysRevL 132, 161901 (2024)**

    X(3872) production > 4.6 GeV and Study of $e^+ e^- \longrightarrow \omega\chi_{c1,2}$
- Summary and outlook

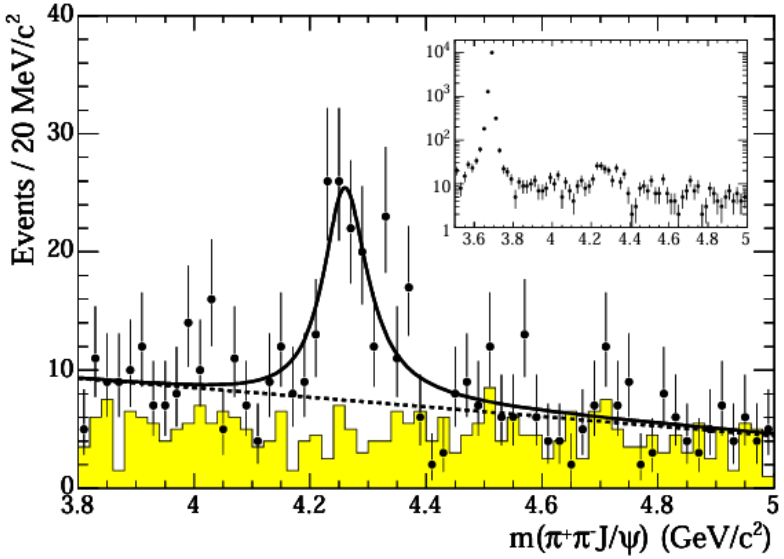
Introduction

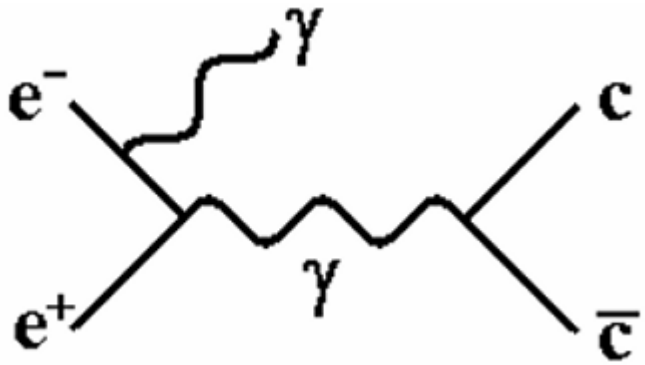
- In the past decade, many charmonium(-like) states were observed experimentally.
- Y(4260): it discovered in ISR process ($e^+e^- \longrightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$) at BaBar, confirmed by CLEO and Belle, its mass is greater than 4 GeV above $D\bar{D}$ threshold and has not observed in open charm pair cross section.



Nature Rev.Phys. 1 (2019) 8, 480-494

PRL 95 (2005) , 142001

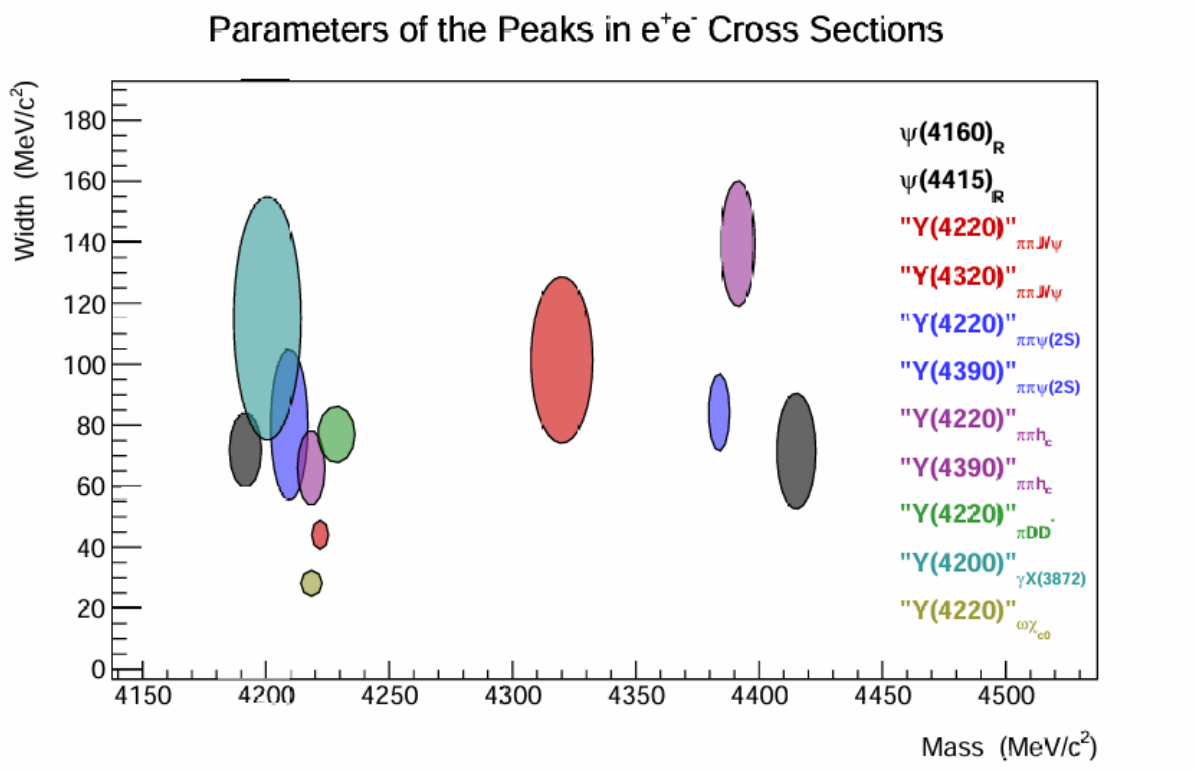




Introduction

- Vector charmonium(-like) states ($Y/\psi, J^{PC} = 1^{--}$) showing strong coupling to hidden-charm final states, such as J/ψ, $\psi(2S)$, $\psi(3770)$, etc.

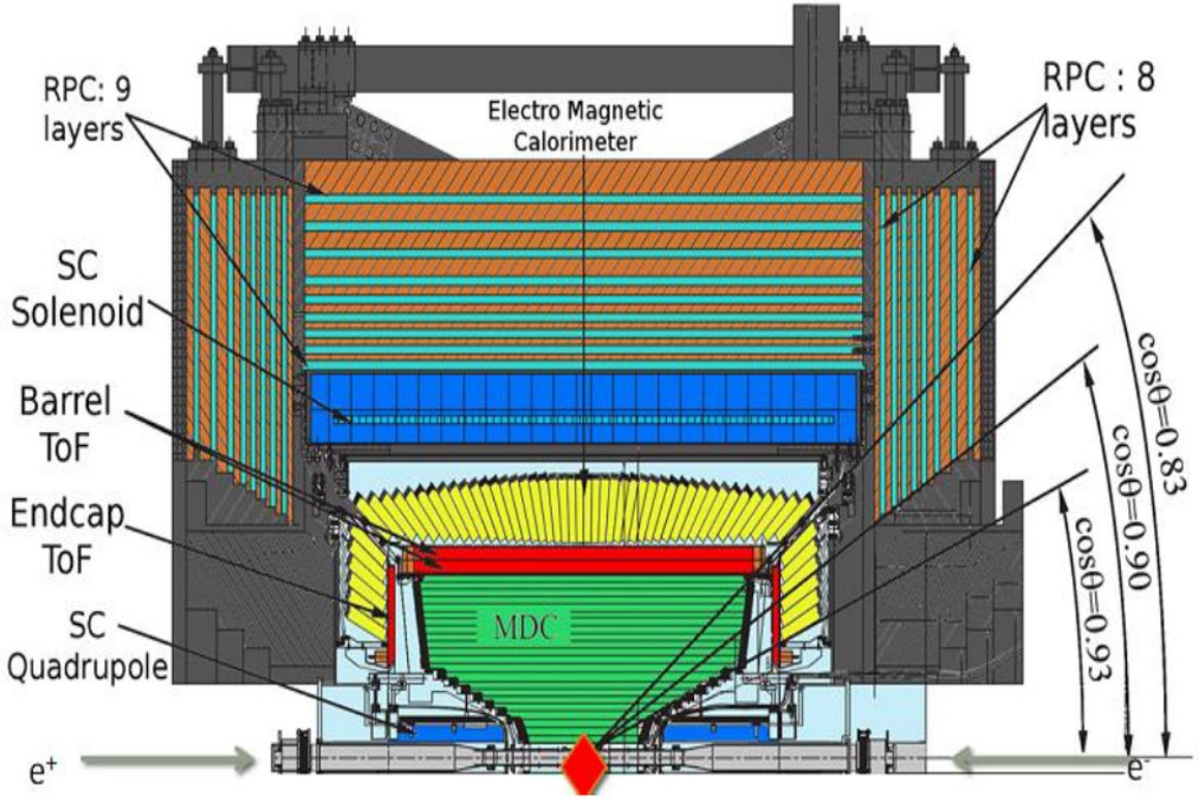
- Precise measurements of production cross sections and resonance parameters needed
  - to clarify nature of these states.
  - to distinguish among different theoretical models.

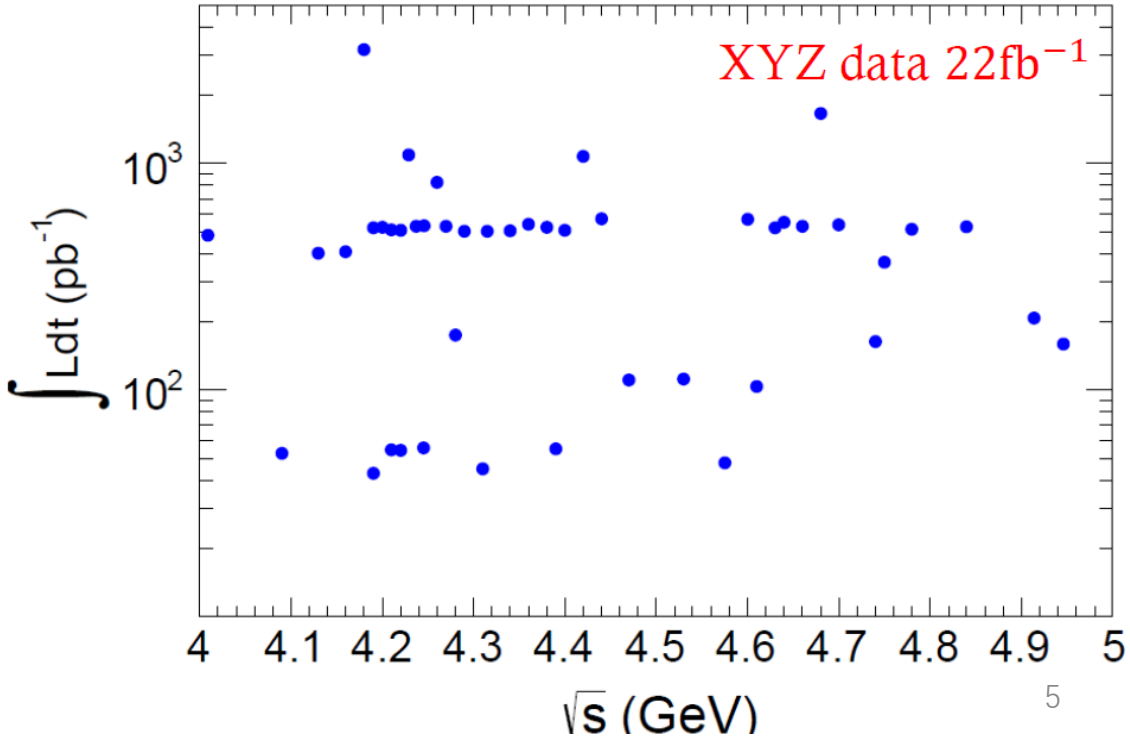


Chin.Phys.C 44 (2020) 4, 040001

More studies are still needed!

BEPCII and BESIII

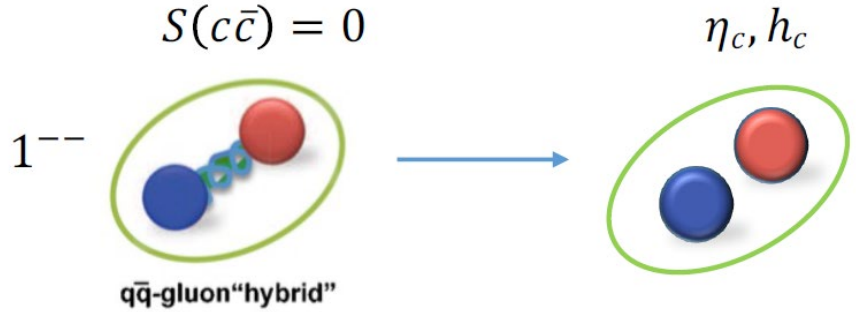


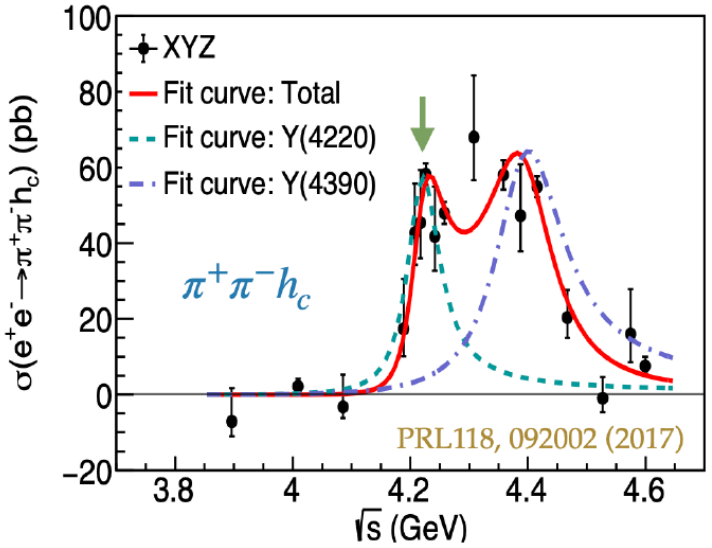


- A peak luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$
- $\tau - c$ region $\sqrt{s} = 2.0 - 4.95$ GeV
- MDC, EMC, TOF, MUC

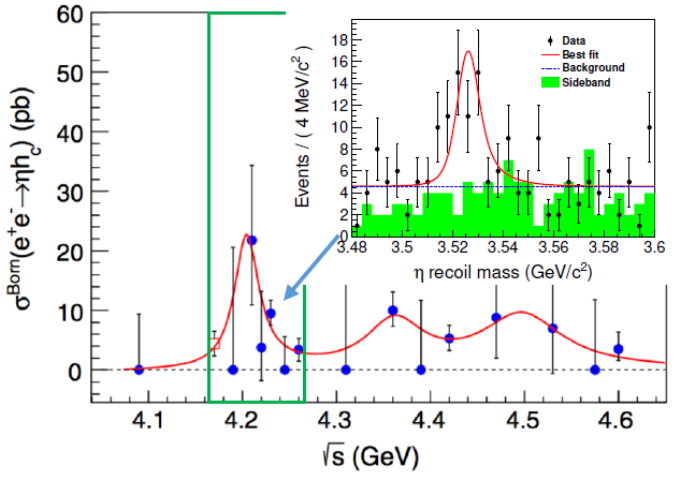
Study of $e^+ e^- \longrightarrow \eta h_c$

- Two new vector resonances were observed in $e^+ e^- \longrightarrow \pi\pi h_c$.
- The $e^+ e^- \longrightarrow \eta h_c$ is observed at the BESIII based on the data taken before 2016.
- The previous observations show a hint of new resonance around 4.2 GeV but we can't draw a clear conclusion because of the limited statistics.
- The strong coupling to h_c indicate this structure likely to be a hybrid.





PRD96, 012001 (2017)



Study of $e^+ e^- \longrightarrow \eta h_c$

Event topology:

$e^+e^- \rightarrow \eta h_c; h_c \rightarrow \gamma \eta_c; \eta_c \rightarrow$Xi;

Data sets:

- 4130 ~ 4600 MeV
- Total integrated Lum. ~15.3 fb^{-1}

MC sets:

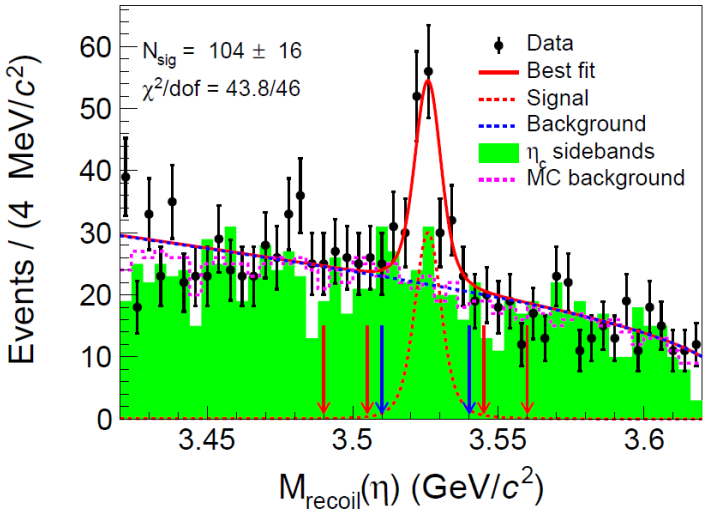
$e^+e^- \rightarrow \eta h_c$; *PHSP*

$h_c \rightarrow \gamma \eta_c; 1 + cos^2\theta$

$\eta_c \rightarrow$Xi; DIY (Body3, mH2…)

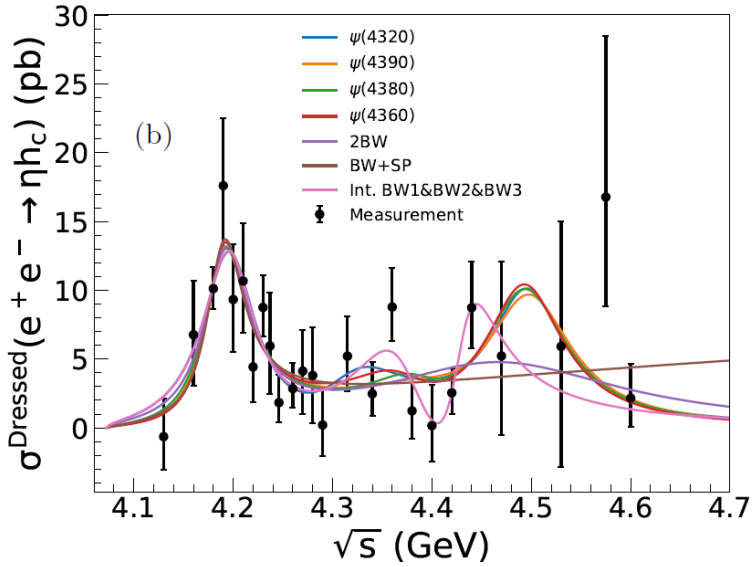
Decay mode	BR
$\eta_c \rightarrow p\bar{p}$	~0.13%
$\eta_c \rightarrow \pi^+\pi^- p\bar{p}$	~0.45%
$\eta_c \rightarrow 2(\pi^+\pi^-)$	~1.20%
$\eta_c \rightarrow 2(K^+K^-)$	~0.15%
$\eta_c \rightarrow \pi^+\pi^- K^+K^-$	~1.50%
$\eta_c \rightarrow 3(\pi^+\pi^-)$	~2.00%
$\eta_c \rightarrow K^+K^- 2(\pi^+\pi^-)$	~1.00%
$\eta_c \rightarrow K^+K^-\pi^0$	~1.20%
$\eta_c \rightarrow p\bar{p}\pi^0$	~0.18%
$\eta_c \rightarrow K_SK\pi$	~1.80%
$\eta_c \rightarrow K_SK3\pi$	~2.40%
$\eta_c \rightarrow \pi^+\pi^-\eta$	~1.60%
$\eta_c \rightarrow K^+K^-\eta$	~0.57%
$\eta_c \rightarrow 2(\pi^+\pi^-)\,\eta$	~2.70%
$\eta_c \rightarrow \pi^+\pi^-\pi^0\pi^0$	~2.40%
$\eta_c \rightarrow 2(\pi^+\pi^-)\,\pi^0\pi^0$	~11.0%

Sum of 16 channels



Unbinned maximum likelihood fit is performed to 16 data sets simultaneously.

Study of $e^+ e^- \longrightarrow \eta h_c$

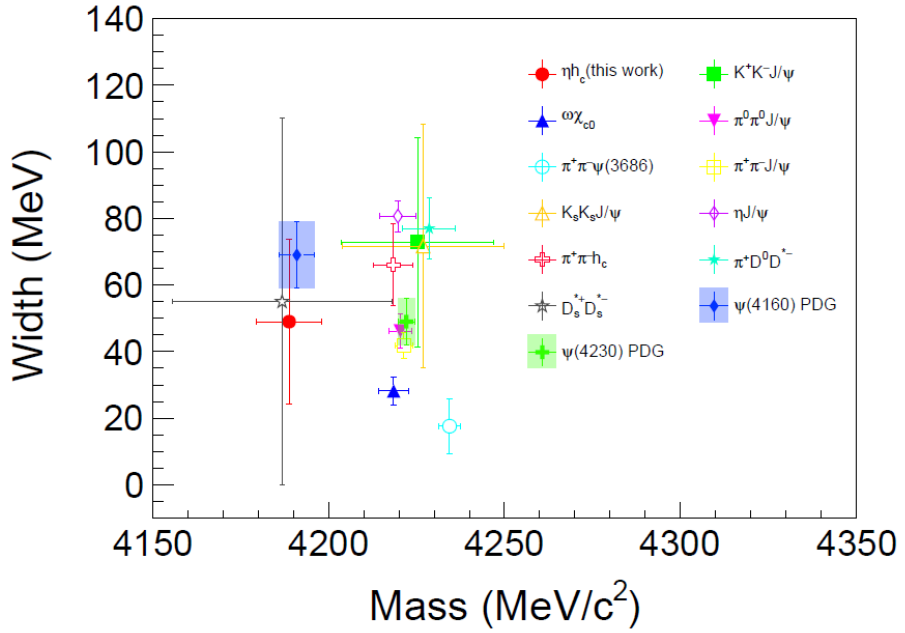


$$\sigma(s) = |BW1(s) + BW2(s)e^{i\phi 2}|^2 + |BW3(s)e^{i\phi 3}|^2$$

$$\text{Here: } BW(s) = \frac{\sqrt{12\pi\Gamma_{ee}\Gamma_{tot}Br(Y\to\eta h_c)}}{s-M^2+iM\Gamma_{tot}}\sqrt{\frac{PS(\sqrt{s})}{PS(M)}}$$

Parameters	Fitted result
M_1 (MeV)	4188.82 ± 4.73
$\Gamma_{tot}^{Y_1}$ (MeV)	49.05 ± 15.52
$\Gamma_{ee}^{Y_1}Br$ (eV)	0.80 ± 0.19
M_2 (MeV)	4368.00($fixed$)
$\Gamma_{tot}^{Y_2}$ (MeV)	96.00($fixed$)
$\Gamma_{ee}^{Y_2}Br$ (eV)	0.34 ± 0.29
ϕ_2 (rad)	3.13 ± 6.27
M_3 (MeV)	4492.15 ± 30.79
$\Gamma_{tot}^{Y_3}$ (MeV)	96.31 ± 60.58
$\Gamma_{ee}^{Y_3}Br$ (eV)	1.38 ± 0.78

- Parameters of BW2 are fixed to Y(4360) due to the low statistics.
- A resonant structure near 4.200 GeV is observed (7σ).

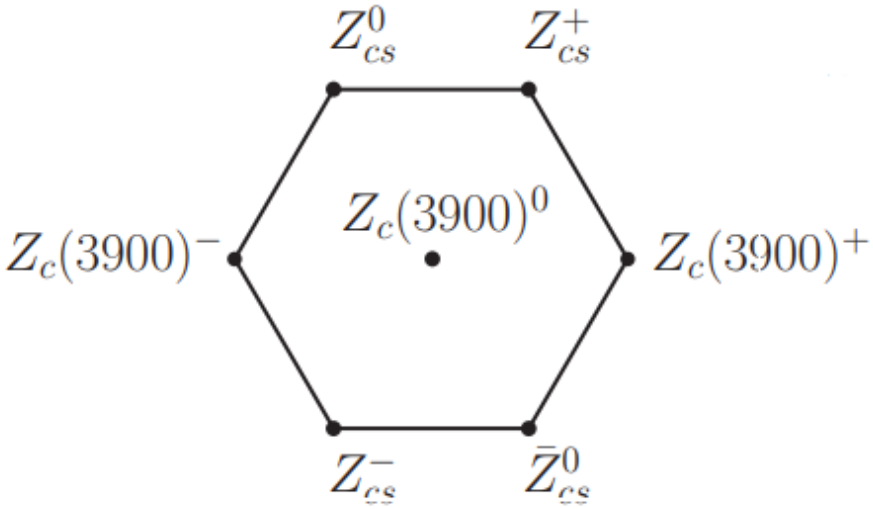


Search for $e^+ e^- \longrightarrow K^+K^-\psi(3770)$

$e^+e^- \longrightarrow K^+K^-J/\psi$
PRL 131, 211902 (2023)

$e^+e^- \longrightarrow K^+K^-\psi(2S)$
arXiv: 2407.20009

$e^+ e^- \longrightarrow K^+K^-\psi(3770)$
New data at BESIII



- Search for strange four-quark states $Z_{cs}(3985)$ by $e^+ e^- \longrightarrow K^+K^-\psi(3770)$.
- According to the quark potential model, the masses of the 5S and 6S vector charmonium states are around 4.6 GeV and 5.2 GeV, respectively. In the mass region of 4.7 GeV to 4.95 GeV, there should be only one vector charmonium 4^3D_1 state with mass about 4.8 GeV.

Search for $e^+ e^- \longrightarrow K^+K^-\psi(3770)$

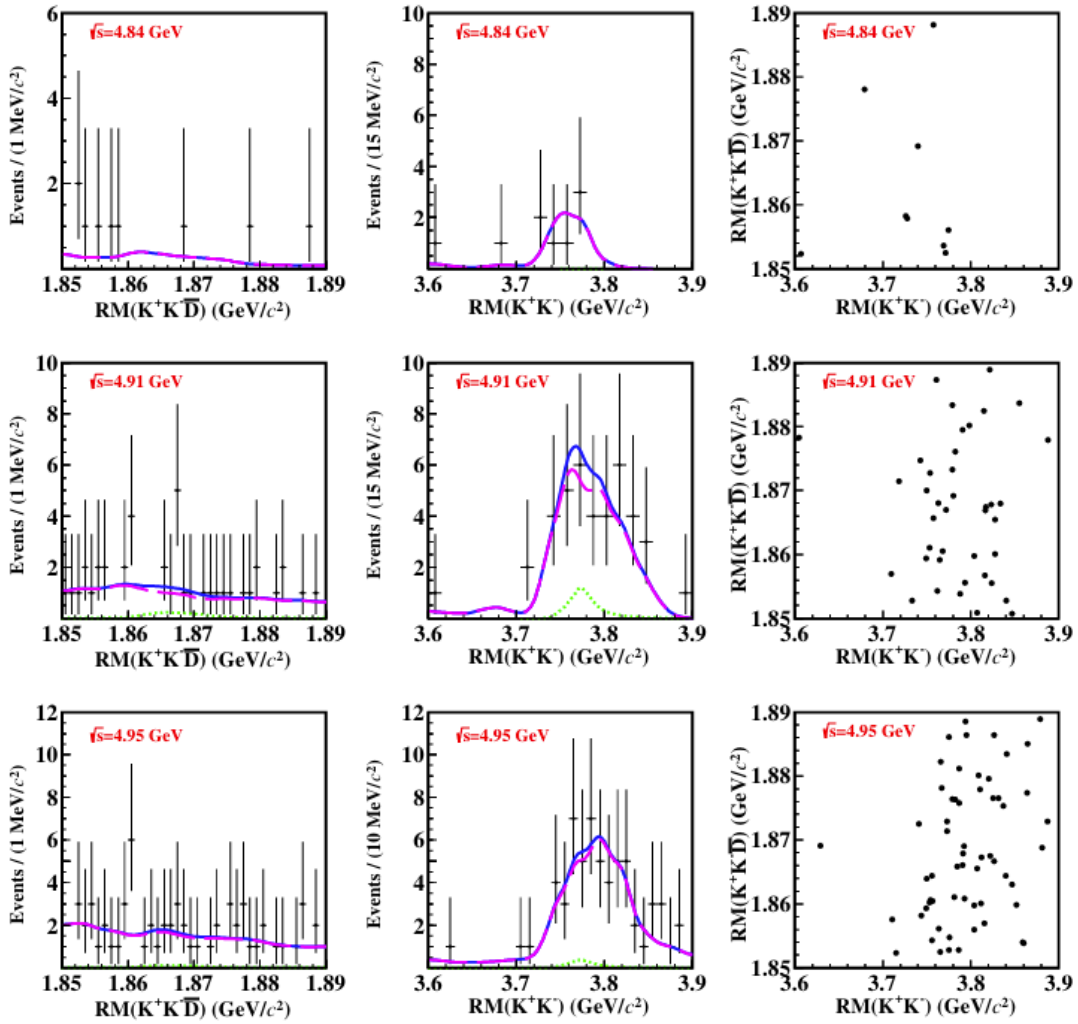
Data: 2021 $\sqrt{s} = 4.78 - 4.95\text{GeV} \sim 900\ pb^{-1}$

$\psi(3770) \rightarrow D\bar{D}$

- Charge conjugation is implied
- Using D^+ and D^0 decay modes

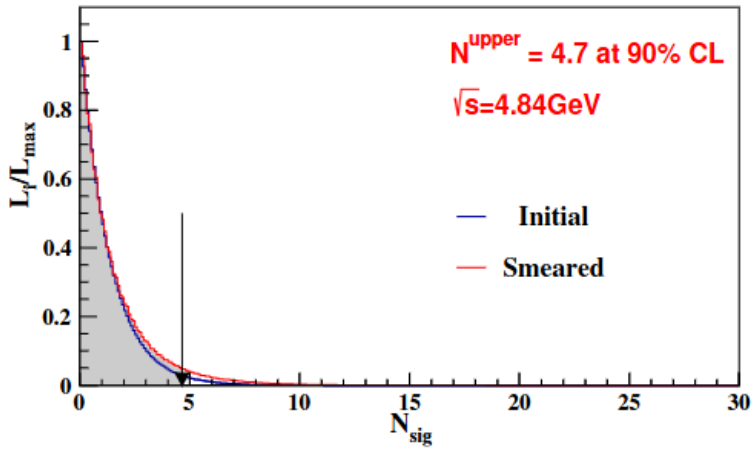
$$D^0 \rightarrow K^-\pi^+$$
$$D^0 \rightarrow K^-\pi^+\pi^0$$
$$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$$
$$D^+ \rightarrow K^-\pi^+\pi^+$$
$$D^+ \rightarrow K_S^0\pi^+$$
$$D^+ \rightarrow K_S^0\pi^+\pi^0$$
$$D^+ \rightarrow K^-\pi^+\pi^+\pi^0$$
$$D^+ \rightarrow K_S^0\pi^+\pi^+\pi^-$$
$$D^+ \rightarrow K^-K^+\pi^+$$

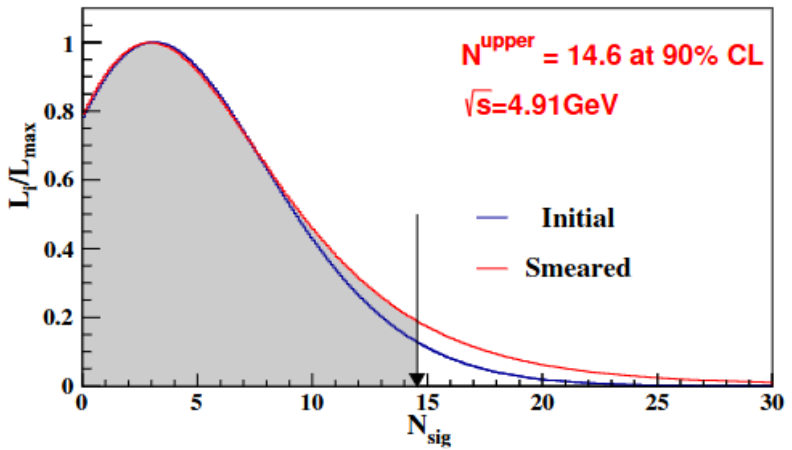
$\sim 28.6\%$

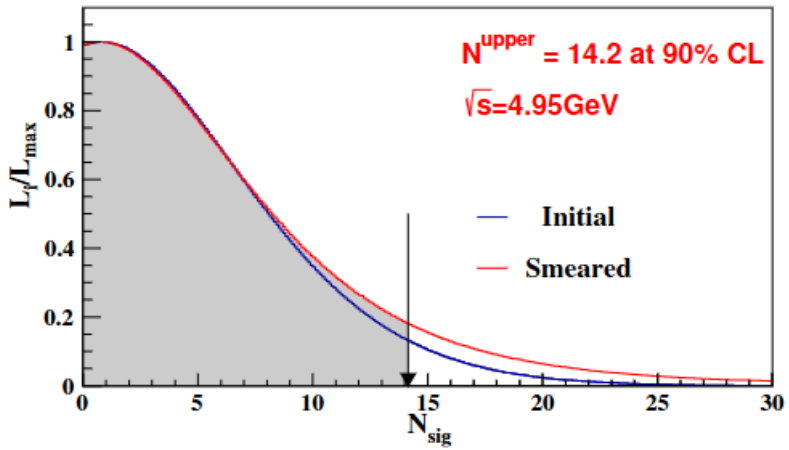


Search for $e^+ e^- \longrightarrow K^+K^-\psi(3770)$

No evidence for this decay, we set an upper limit of this decay at 90% confidence level.







$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}(\rm pb^{-1})$	$N_{\rm sig}$	$N^{\rm upper}$	$\epsilon_{\rm sig}(\%)$	$(1+\delta(s))$	$\frac{1}{\lvert 1-\Pi\rvert^2}$	σ^B(pb)
4.84	525.16±2.78	$0.00^{+0.56}_{-0.54}$	<4.7	0.487±0.015	0.727	1.056	<1.2
4.91	207.82±1.10	$3.0^{+4.2}_{-5.2}$	<14.6	1.473±0.027	0.757	1.056	<3.0
4.95	159.28±0.84	$0.8^{+6.1}_{-5.0}$	<14.2	1.736±0.028	0.772	1.056	<3.1

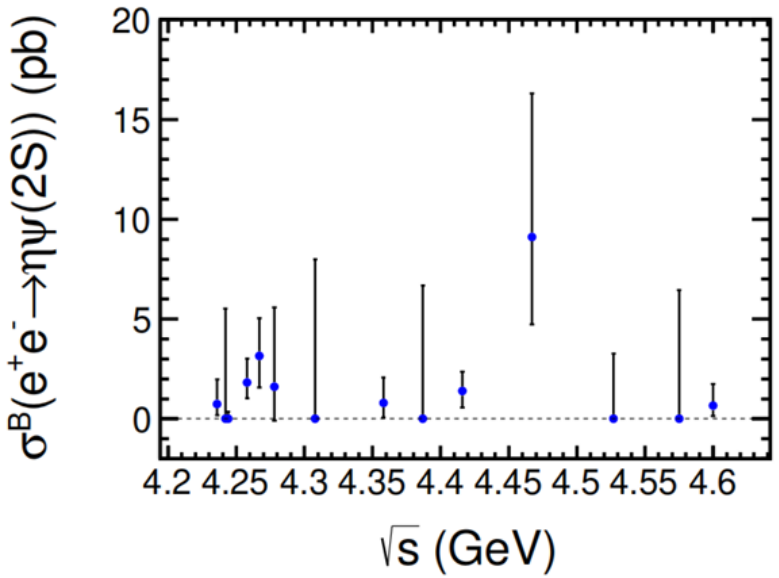
- Obviously smaller than the cross sections of $e^+e^- \to \pi^+\pi^- D^+D^-$

Study of $e^+ e^- \longrightarrow \eta\psi(2S)$

- Since the BESIII experiment observed the Y(4230) in the $e^+e^- \longrightarrow \eta J/\psi$ and $\eta' J/\psi$ processes, it follows that the process $e^+e^- \longrightarrow \eta\psi(2S)$ can be an important way to search for Y states.

- Using a total of 5.25 $fb^{-1}$of e^+e^- collision data with c.m. energies from 4.236 to 4.600 GeV, BESIII reported the first observation of the process $e^+e^- \longrightarrow \eta\psi(2S)$ with a statistical significance of 4.9 standard deviations

J. High Energ. Phys. 2021, 177 (2021)

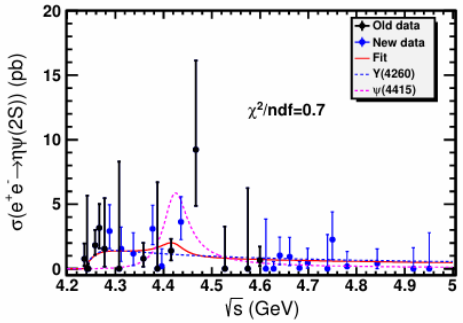


Study of $e^+ e^- \longrightarrow \eta\psi(2S)$

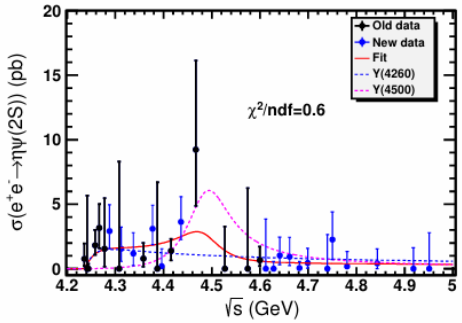
Data: 4.288 to 4.951 GeV ~ 8.7 fb^{-1}

Decay mode	generator model
$e^+e^- \to \eta\psi(2S)$	HELAMP 1 0 0 0 1 0
$e^+e^- \to \eta\tilde{X}(3872)$	PHSP
$\eta \to \gamma\gamma$	PHSP
$\psi(2S) \to \pi^+\pi^- J/\psi$	JPIPI
$\tilde{X}(3872) \to \pi^+\pi^- J/\psi$	PHSP
$J/\psi \to e^+e^-$ $J/\psi \to \mu^+\mu^-$	VLL

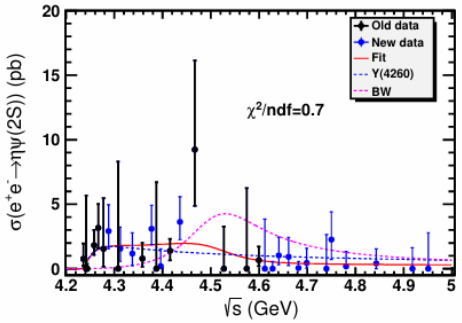
Mode 1



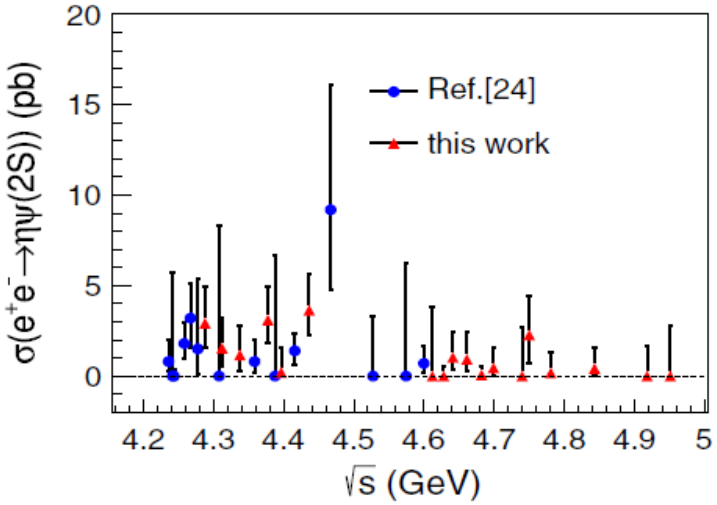
Mode 2



Mode 3



[24] J. High Energy Phys. 10 (2021) 177



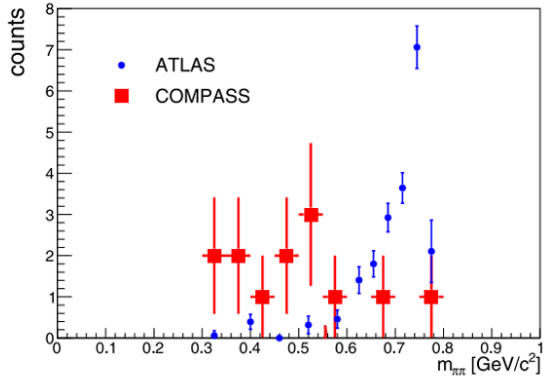
MODE	BW1	BW2	M_1	Γ_{tot1}	$\Gamma_{e^+e^-1}\mathcal{B}$	M_2	Γ_{tot2}	$\Gamma_{e^+e^-2}\mathcal{B}$	ϕ
Mode 1	$Y(4260)$	$\psi(4415)$	fixed	fixed	$(25.2 \pm 6.3) \times 10^{-3}$	fixed	fixed	18.58 ± 0.05	1.9 ± 0.2
Mode2	$Y(4260)$	$Y(4500)$	fixed	fixed	$(26.6 \pm 7.6) \times 10^{-3}$	fixed	fixed	0.35 ± 0.11	-4.1 ± 0.1
Mode 3	$Y(4260)$	R	fixed	fixed	$(30.4 \pm 9.2) \times 10^{-3}$	4.502 ± 0.051	0.200 ± 0.078	0.42 ± 0.10	4.0 ± 0.2
Mode 4	$R1$	$R2$	unstable	unstable	unstable	unstable	unstable	unstable	unstable

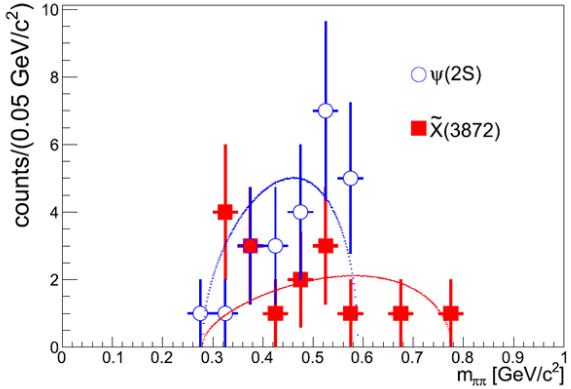
- Due to the limited statistics, it is difficult to draw a clear conclusion whether the vector charmoniumlike states exist in the cross section distribution or not.

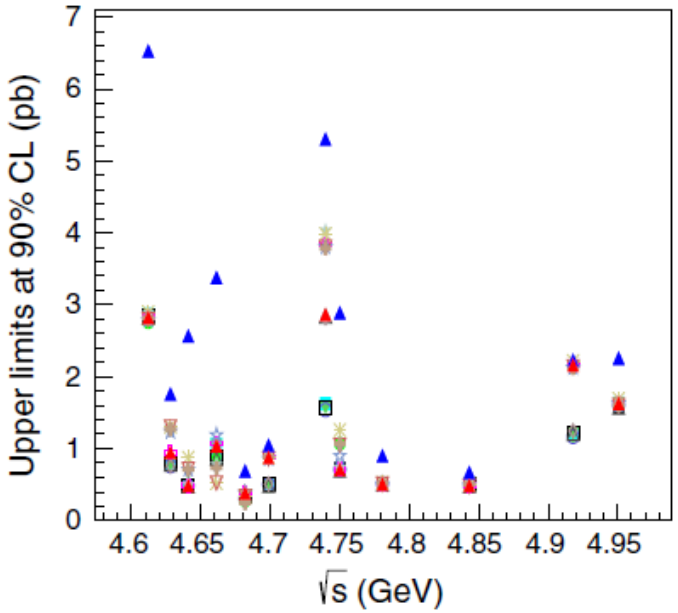
Search for $e^+ e^- \longrightarrow \eta\tilde{X}(3872)$

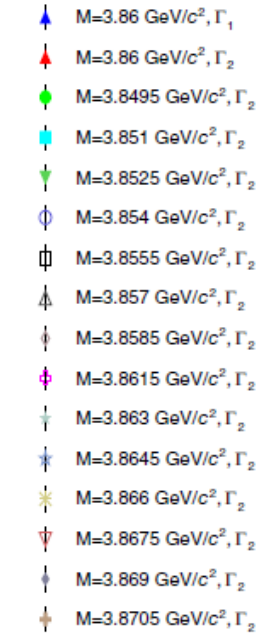
- $\tilde{X}(3872)$ state reported by the COMPASS experiment ($J^{PC} = 1^{+-}$ and Mass= 3860 MeV/c^2)

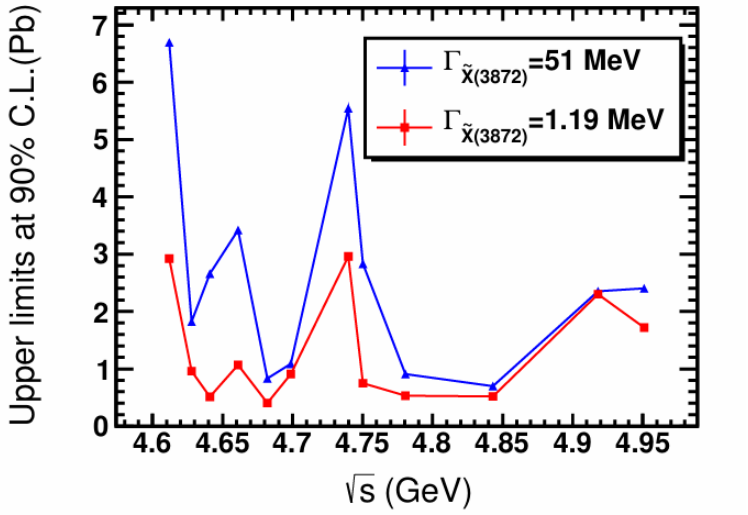
Phy. Lett. B 783, 334 (2018).









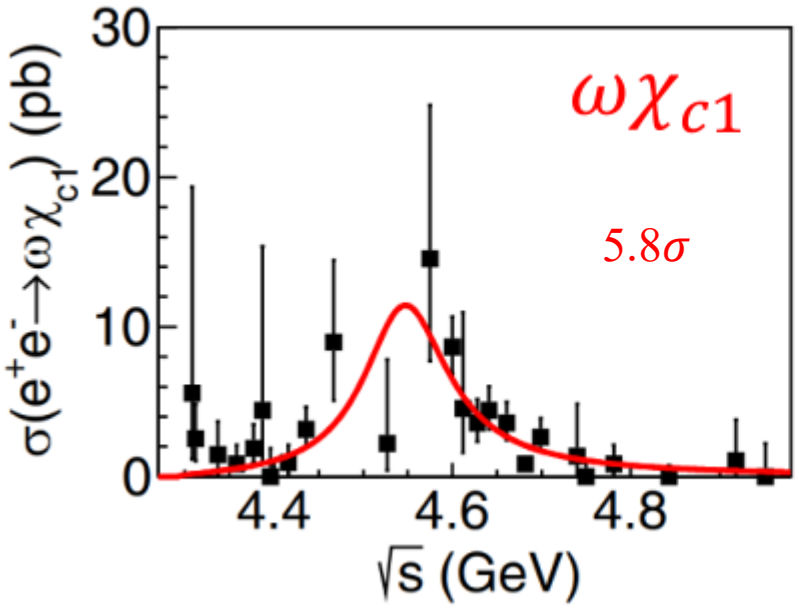


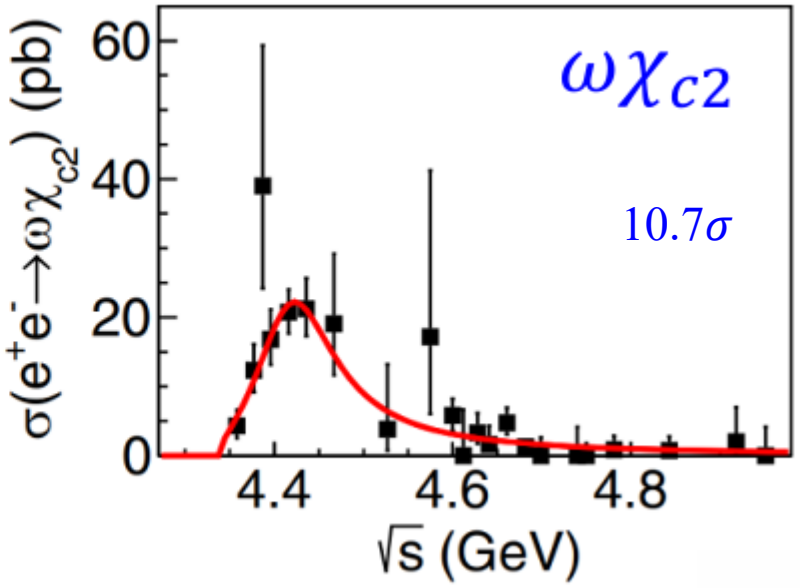
- Mass : 3860 MeV/c^2 (COMPASS result)
- Width : 51 MeV or 1.19 MeV

The upper limit from COMPASS result

The same as the width of X(3872)

Study of $e^+ e^- \longrightarrow \omega \chi_{c1,2}$





$\sqrt{s} = 4.308\sim4.951$ GeV,
$11\ \mathrm{fb}^{-1}$, > 20 energy points

Two structures are observed

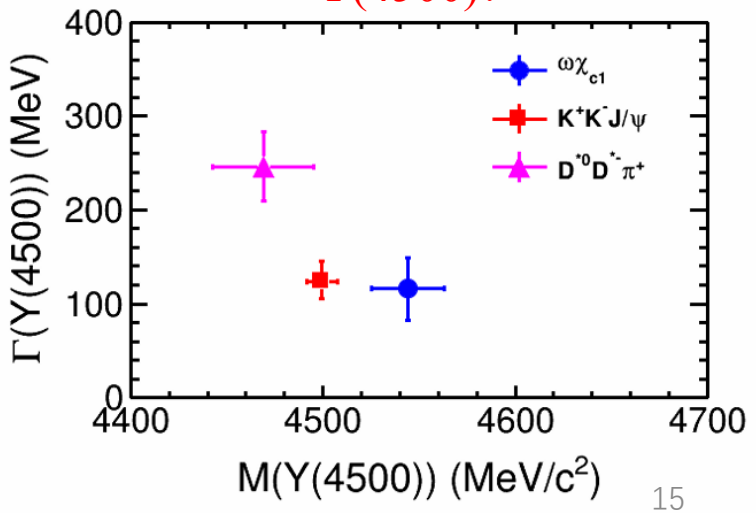
$M_1 =$
$(4544.2 \pm 18.7 \pm 1.7)\ \mathrm{MeV}/c^2$
$\Gamma_1 =$
$(116.1 \pm 33.5 \pm 1.7)\ \mathrm{MeV}$

A new particle?

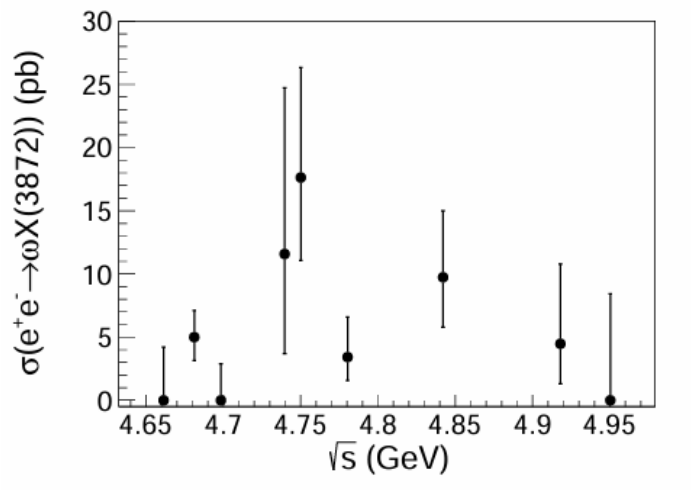
$M_2 =$
$(4413.6 \pm 9.0 \pm 0.8)\ \mathrm{MeV}/c^2$
$\Gamma_2 =$
$(110.5 \pm 15.0 \pm 2.9)\ \mathrm{MeV}$

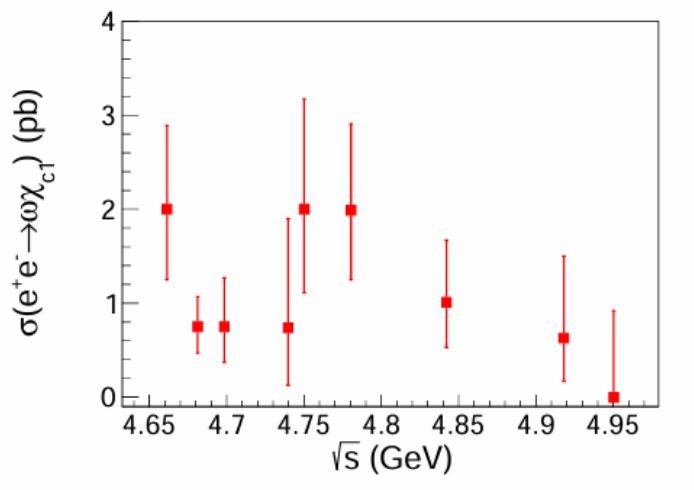
Consistent with $\psi(4415)$

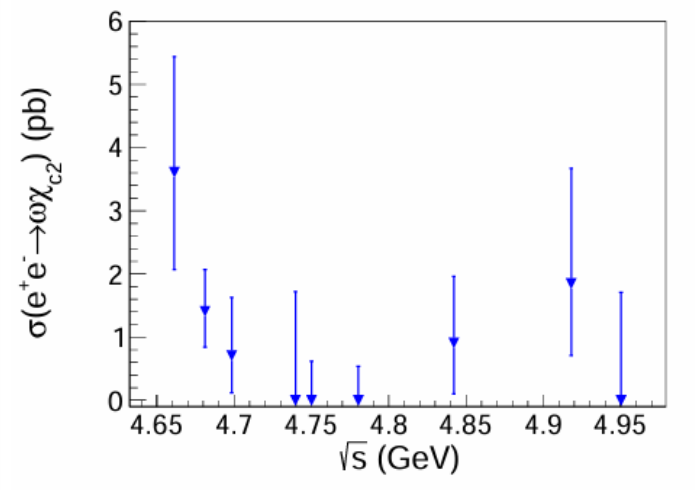
Y(4500)?



X(3872) production > 4.6 GeV







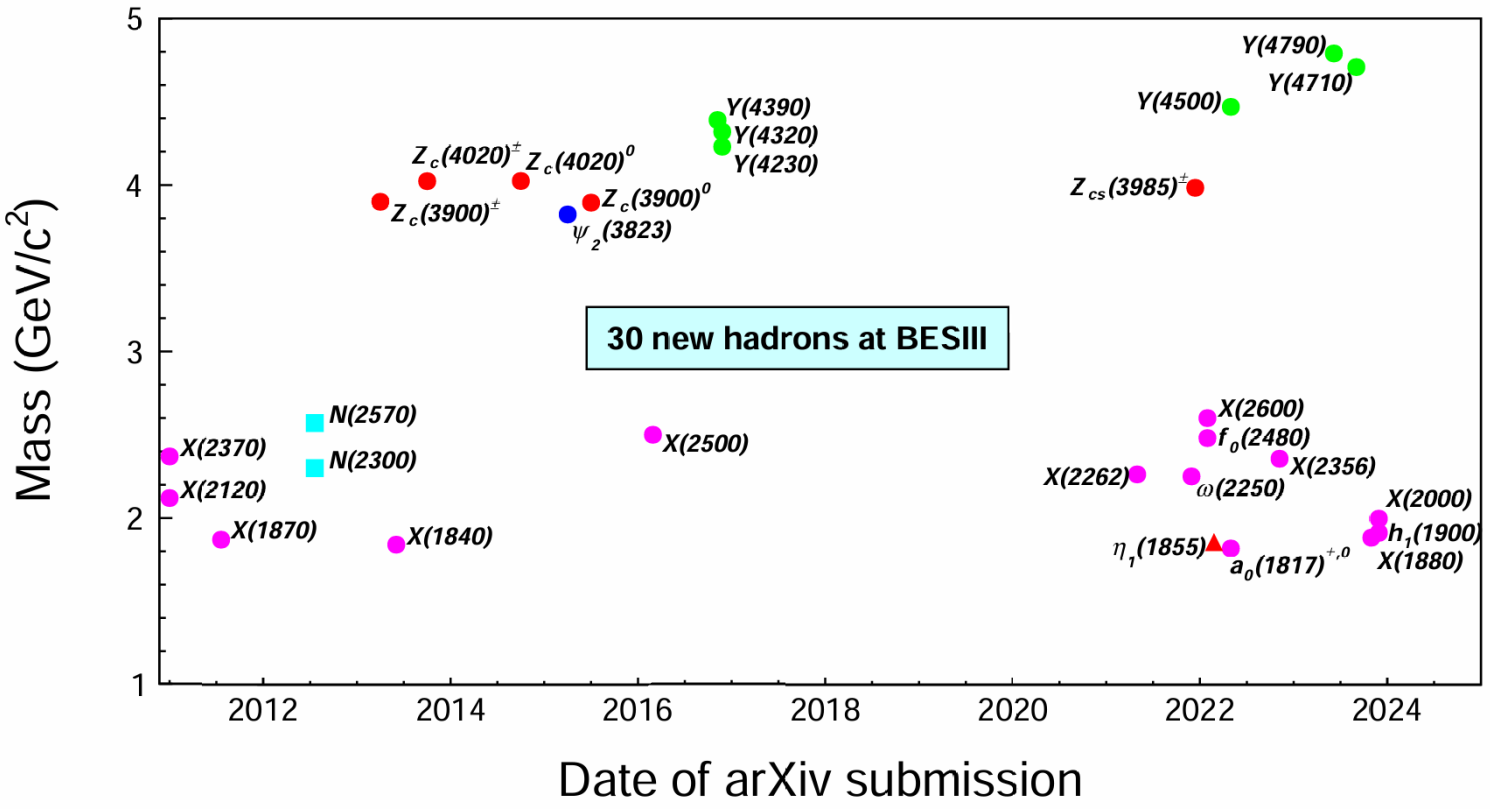
$$R_{\gamma J/\psi/\pi^+\pi^- J/\psi} \equiv \frac{\mathcal{B}(X(3872) \to \gamma J/\psi)}{\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}$$

Experiment	$R_{\gamma J/\psi/\pi\pi J/\psi}$
$e^+e^- \to \gamma X(3872)$ BESIII	0.79 ± 0.28
$B^\pm \to K^\pm X(3872)$ Belle	0.21 ± 0.06
$e^+e^- \to \omega X(3872)$ This work	0.38 ± 0.20 (< 0.83)
Average	0.25 ± 0.06

- ${}^{\sigma_{\omega X(3872)}}/_{\sigma_{\omega\chi_{c1}}} = 5.2 \pm 1.0 \pm 1.9$
- ${}^{\sigma_{\omega X(3872)}}/_{\sigma_{\omega\chi_{c2}}} = 5.5 \pm 1.1 \pm 2.4$
- ${}^{\sigma_{\phi X(3872)}}/_{\sigma_{\phi\chi_{c1}}} < 9$ @ 90% CL
- Help constrain the possible $\chi_{c1}(2P)$ component in the $X(3872)$ wave function.

${}^{\sigma_{\gamma X(3872)}}/_{\sigma_{\omega X(3872)}} < 0.23$ @ 90% CL

New hadrons discovered at BESIII



- 12 charmonium(-like) states
- 6 vector charmonium(-like) states

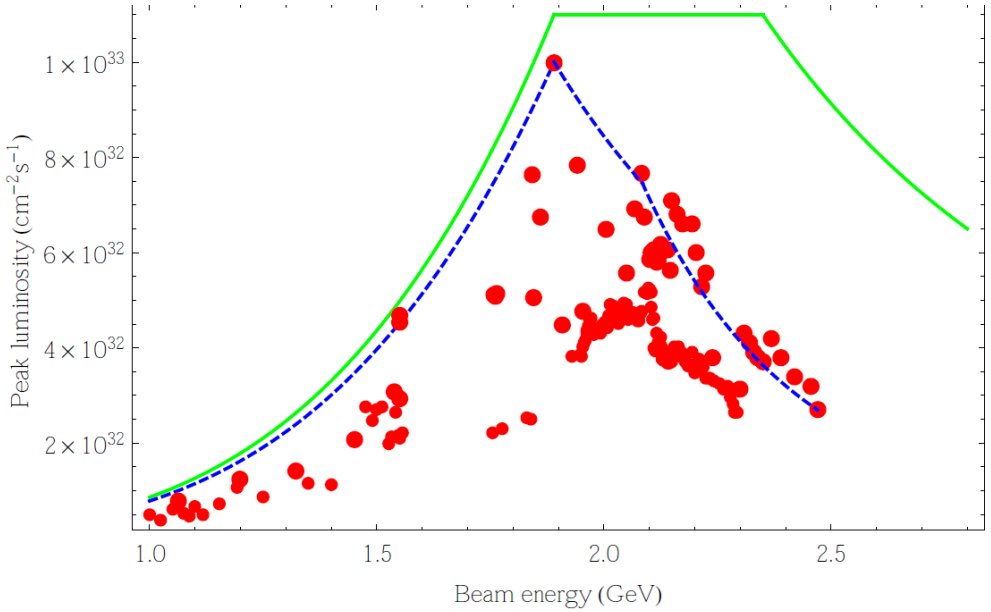
Z.Q. Liu & R. Mitchell, Science Bulletin 68 (2023) 2148–2150

Summary

- We reported cross-section measurement results including hidden charm final states at BESIII
- BESIII have a excellent performance about the charmonium(-like) states studies
- Upcoming upgrades on BEPCII and BESIII
  - Higher precision for measurements
  - Luminosity * 3 @ 2.35 GeV
  - Highest Beam Energy: 2.47 GeV -> 2.8 GeV
  - Commissioning of BEPCII-U on 2025.01.01

From Y. Zhang@Lanzhou

BEPCII-U vs BEPCII



Thank you