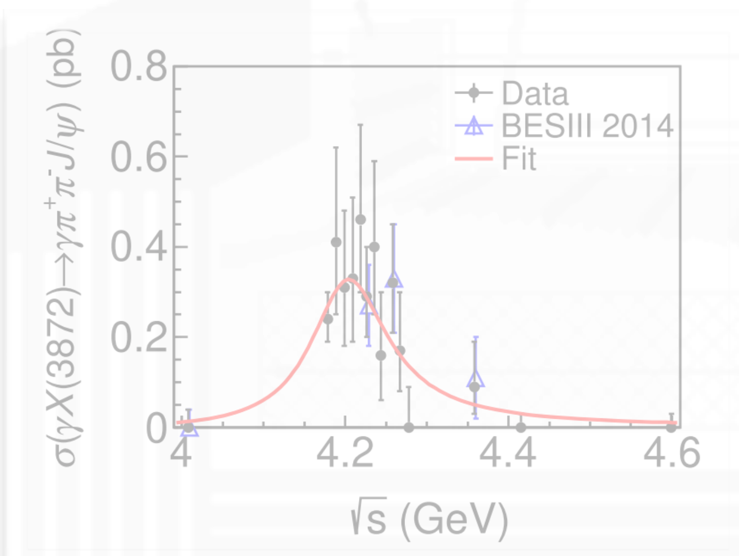
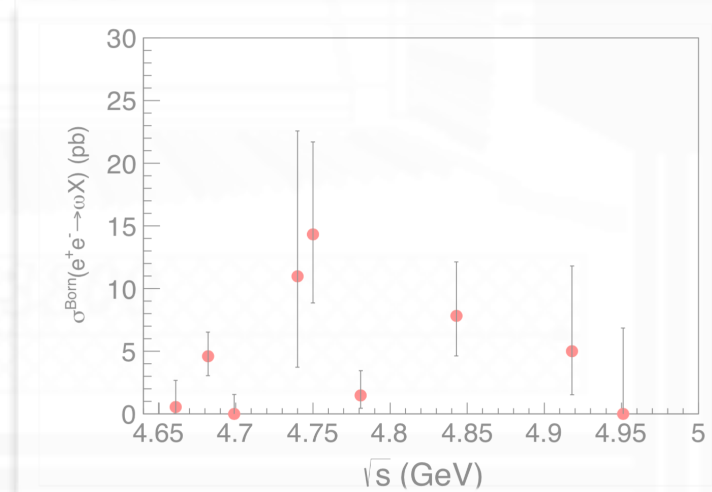
The study of X(3872) at BESIII

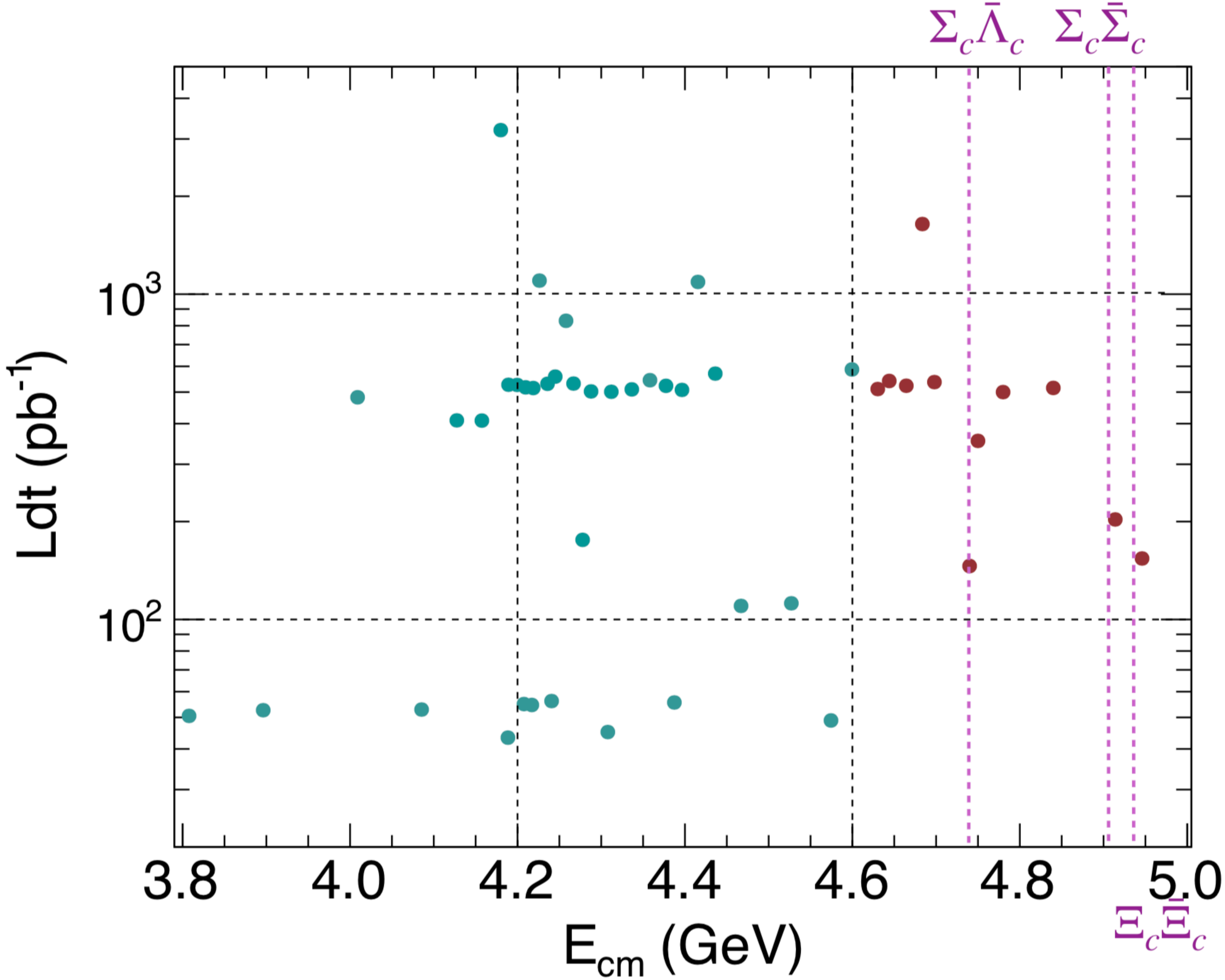
第十届手征有效场论研讨会

Chunhua Li
Nanjing Normal University
chunhua@njnu.edu.cn

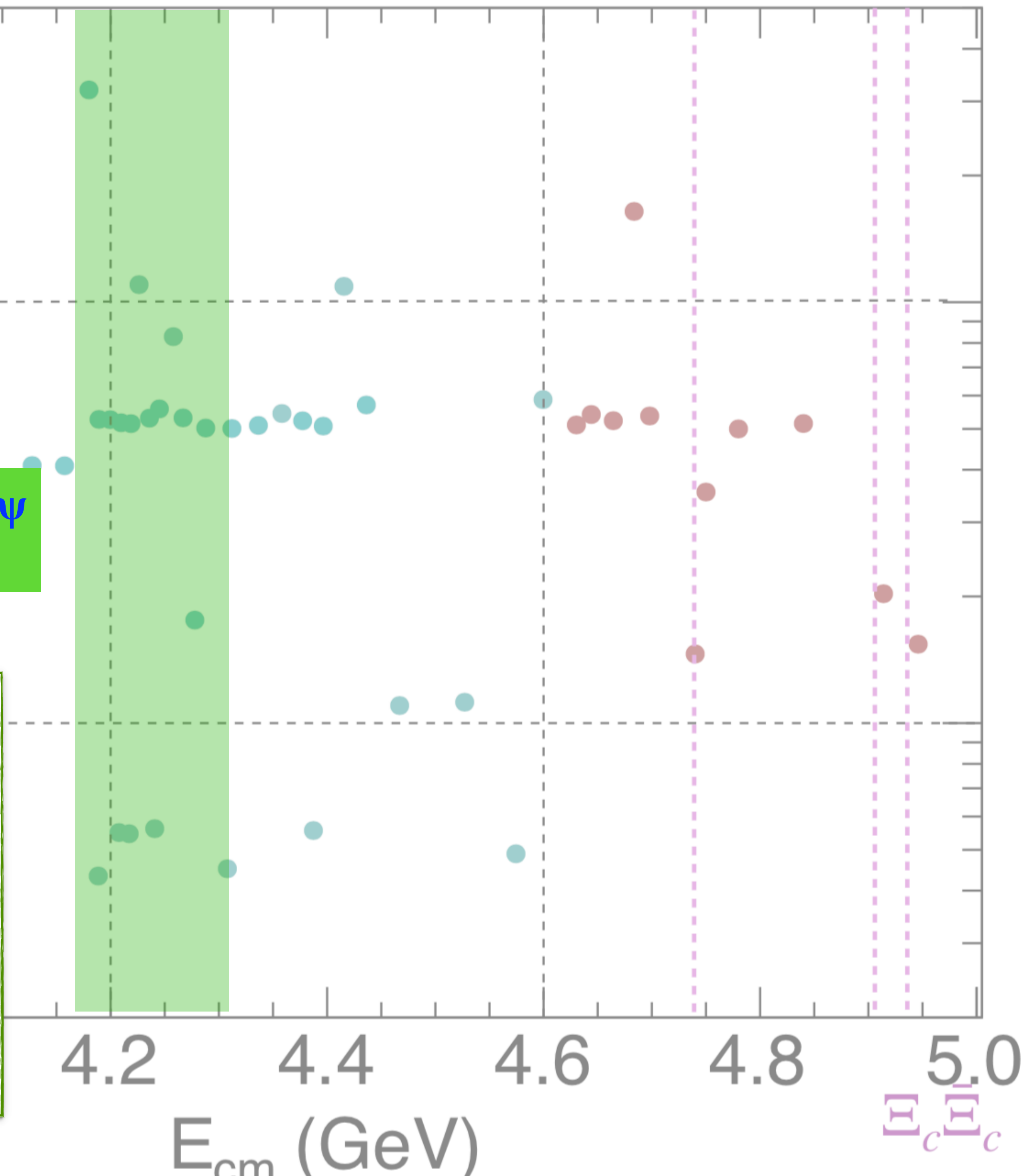


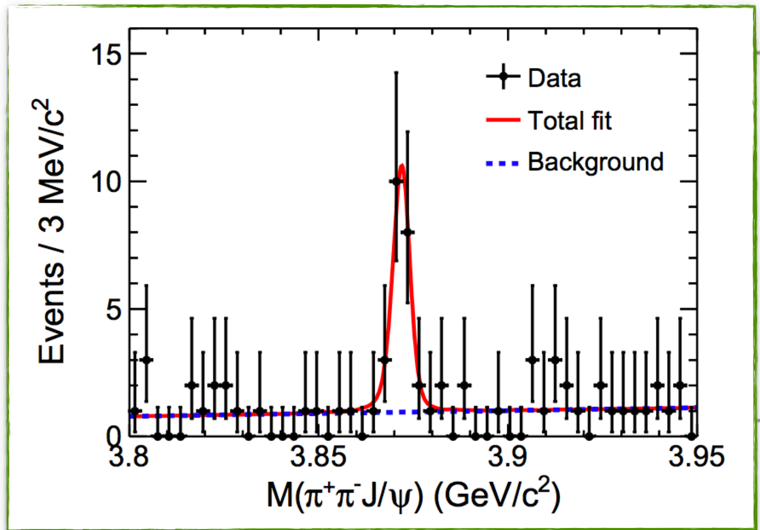


Productions of X(3872) at BESIII

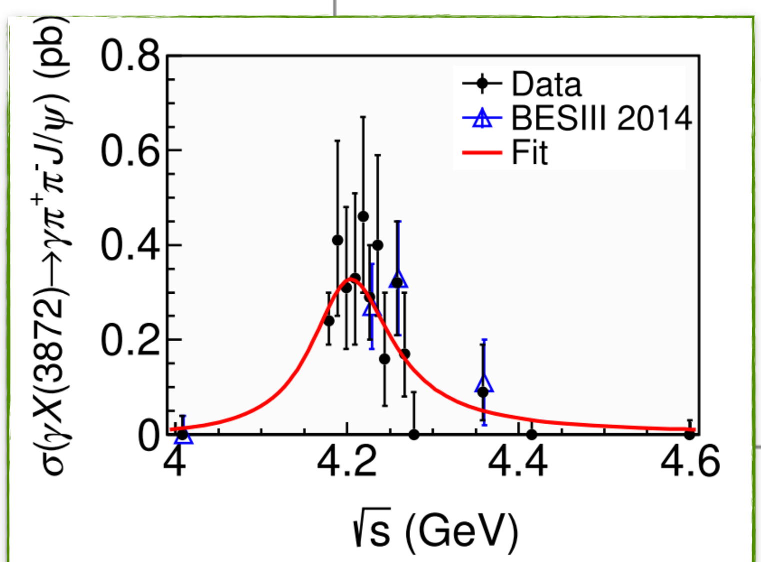


Productions of X(3872) at BESIII





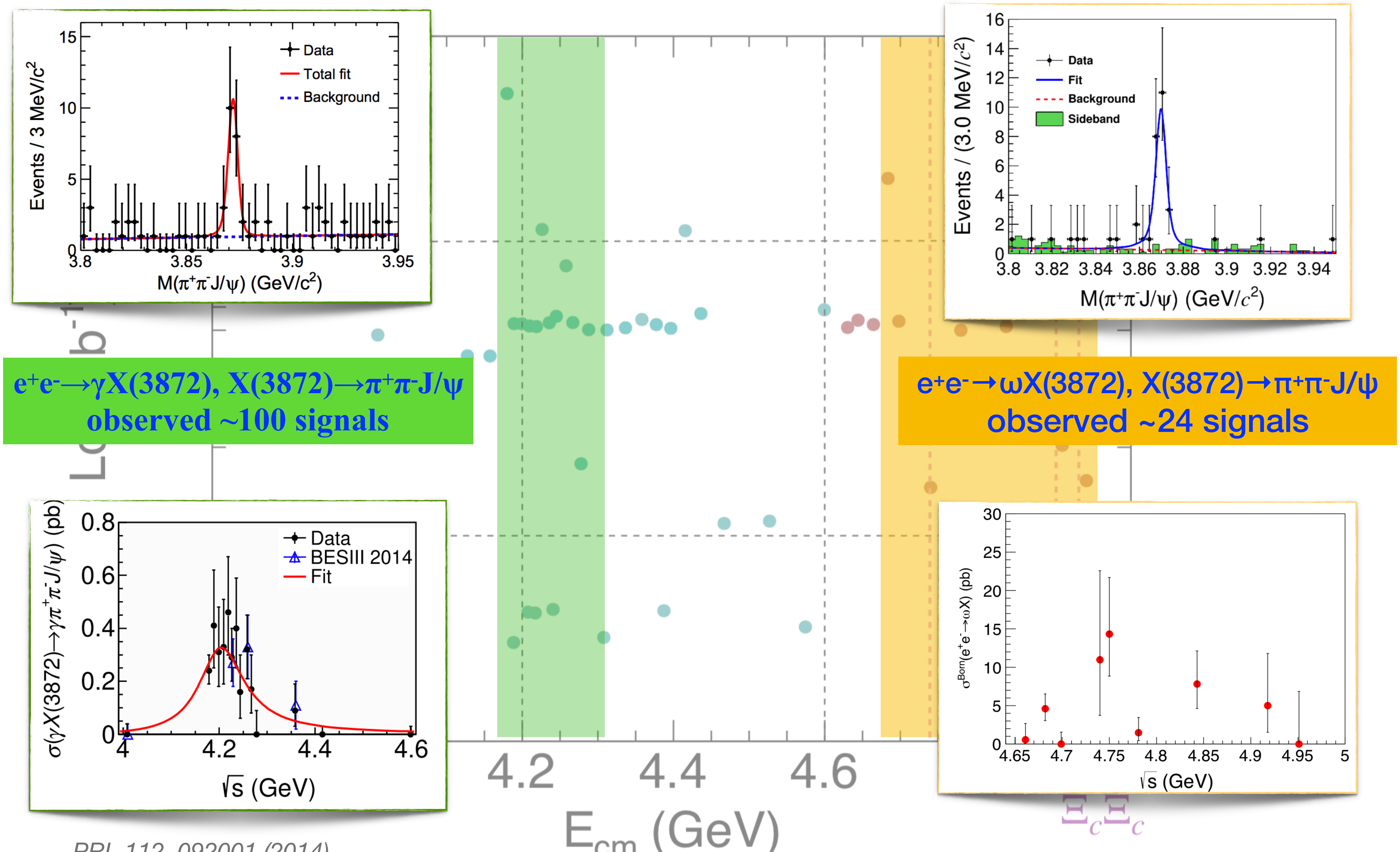
e⁺e⁻→γX(3872), X(3872)→π⁺π⁻J/ψ
observed ~100 signals



PRL 112, 092001 (2014)
PRL 122, 232002 (2019)

PRL 130, 151904 (2023)

Productions of X(3872) at BESIII



$e^+e^- \to \gamma X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$
observed ~100 signals

$e^+e^- \to \omega X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$
observed ~24 signals

PRL 112, 092001 (2014)
PRL 122, 232002 (2019)

PRL 130, 151904 (2023)

X(3872) radiative decays at BESIII

Chunhua Li & CZY, PRD 100, 094003 (2019)

E1 transitions 2P→1S, 2S,1D

Multiplets	Initial meson	Final meson	E_γ (MeV) NR	E_γ (MeV) GI	Γ_{thy} (keV) NR	Γ_{thy} (keV) GI	Γ_{expt} (keV)
1P → 1S	$\chi_2(1^3P_2)$	$J/\psi(1^3S_1)$	429.	429.	424.	313.	426. ± 51.
	$\chi_1(1^3P_1)$		390.	389.	314.	239.	291. ± 48.
	$\chi_0(1^3P_0)$		303.	303.	152.	114.	119. ± 19.
	$h_c(1^1P_1)$	$\eta_c(1^1S_0)$	50[illegible]	[illegible]	[illegible]	[illegible]	
2P → 2S	$\chi_2(2^3P_2)$	$\psi'(2^3S_1)$	276.	282.	304.	207.	
	$\chi_1(2^3P_1)$		232.	258.	183.	183.	
	$\chi_0(2^3P_0)$		162.	223.	64.	135.	
	$h_c(2^1P_1)$	$\eta_c'(2^1S_0)$	285.	[illegible]	[illegible]	[illegible]	
2P → 1S	$\chi_2(2^3P_2)$	$J/\psi(1^3S_1)$	779.	784.	81.	53.	
	$\chi_1(2^3P_1)$		741.	763.	71.	14.	
	$\chi_0(2^3P_0)$		681.	733.	56.	1.3	
	$h_c(2^1P_1)$	$\eta_c(1^1S_0)$	839.	856.	140.	85.	
2P → 1D	$\chi_2(2^3P_2)$	$\psi_3(1^3D_3)$	163.	128.	88.	29.	
		$\psi_2(1^3D_2)$	[illegible]	[illegible]	[illegible]	[illegible]	
		$\psi(1^3D_1)$	[illegible]	[illegible]	[illegible]	[illegible]	
	$\chi_1(2^3P_1)$	$\psi_2(1^3D_2)$	123.	113.	35.	18.	
		$\psi(1^3D_1)$	152.	179.	22.	21.	
	$\chi_0(2^3P_0)$	$\psi(1^3D_1)$	81.	143.	13.	51.	
	$h_c(2^1P_1)$	$\eta_{2c}(1^1D_2)$	133.	117.	60.	27.	

$\chi_{c1}(2P)\to\gamma\psi(2S)$

$\chi_{c1}(2P)\to\gamma J/\psi$

$\chi_{c1}(2P)\to\gamma\psi_2(3823)$

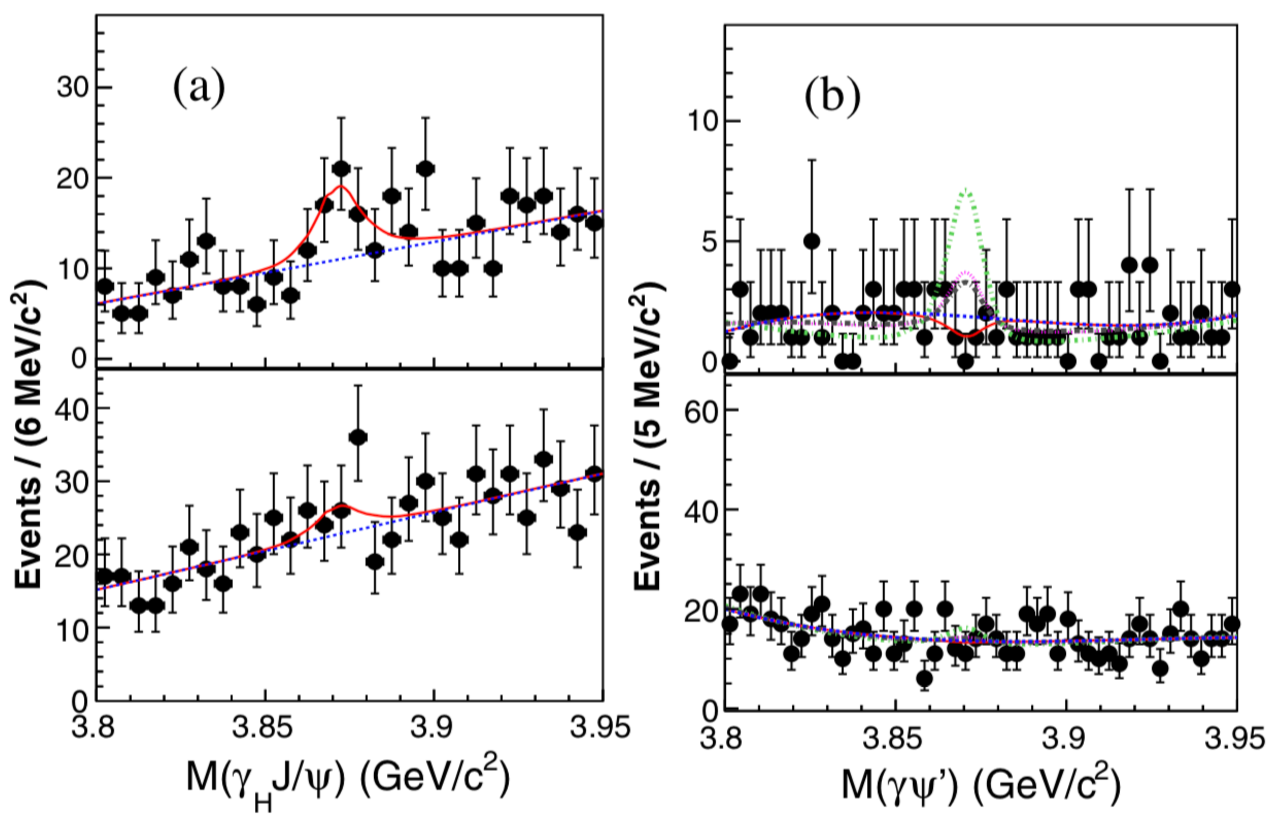
PRD 72, 054026 (2005)

X(3872) radiative decays at BESIII

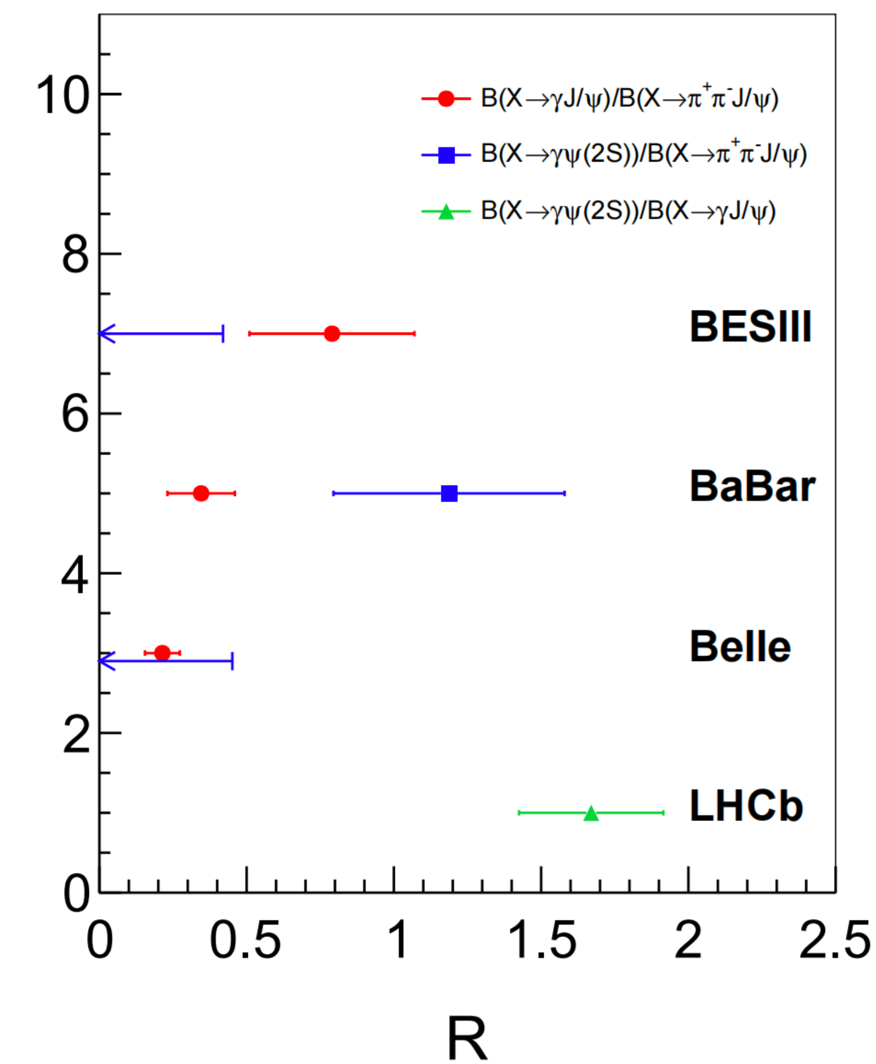
$e^+e^- \to \gamma X(3872)$

Chunhua Li & CZY, PRD 100, 094003 (2019)

$X \to \gamma J/\psi$ $X \to \gamma\psi(2S)$



PRL124, 242001 (2020)



Symmetry 2025, 17,1959

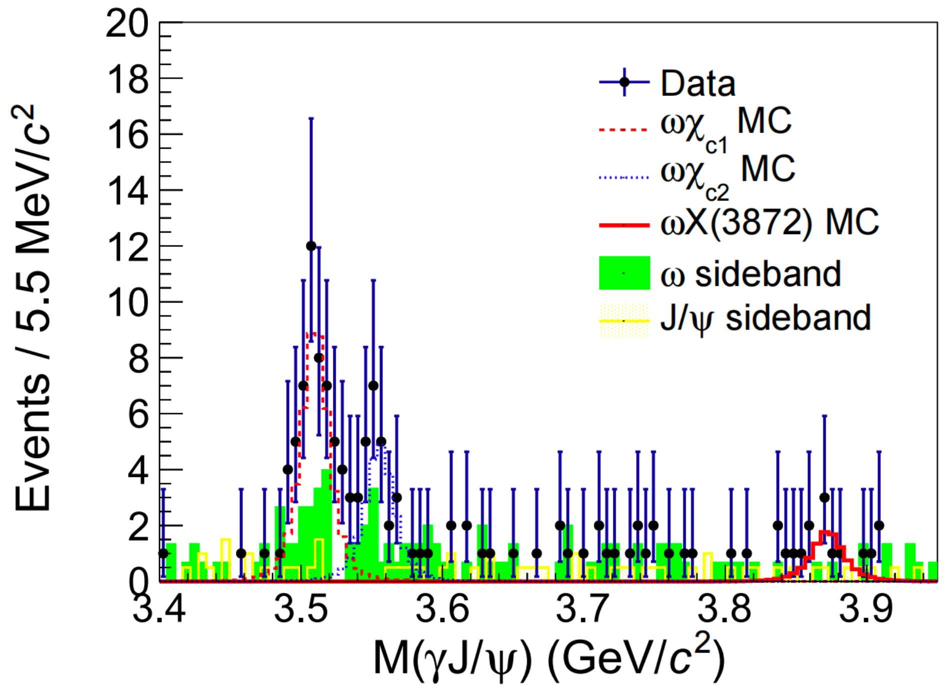
- Challenge to study $X \to \gamma J/\psi$ via $e^+e^- \to \gamma X(3872)$
  - Dominant backgrounds: $e^+e^- \to (\gamma\gamma)e^+e^-$, $(\gamma\gamma)\mu^+\mu^-$

$e^+e^- \to \omega X$, $X \to \gamma J/\psi$

PRD 110 (2024) 1,012006

- Study $X \to \gamma J/\psi$ decay via $e^+e^- \to \omega X(3872)$

hua Li & CZY, PRD 100, 094003 (2019)



	$\frac{\mathcal{B}(X(3872)\to\gamma J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	
BESIII: e+e- →ωX(3872)	$0.38 \pm 0.20_{\rm stat.} \pm 0.01_{\rm syst}$ < 0.83 (2.3σ)	This work
BESIII: e+e- →γX(3872)	0.79 ± 0.28	PRL 124, 242001 (2020)
Belle: B→KX(3872)	0.21 ± 0.06	PRD 84, 052004 (2011) PRL 107,091803
BaBar: B→KX(3872)	0.22±0.10	PRD 71, 071103 (2005) PRL 102,132001

X(3872) radiative decays at BESIII

Chunhua Li & CZY, PRD 100, 094003 (2019)

E1 transitions 2P→1S, 2S,1D

Multiplets	Initial meson	Final meson	E_γ (MeV) NR	GI	Γ_{thy} (keV) NR	GI	Γ_{expt} (keV)
1P → 1S	$\chi_2(1^3P_2)$	$J/\psi(1^3S_1)$	429.				
	$\chi_1(1^3P_1)$		390.				
	$\chi_0(1^3P_0)$		303.	303.	152.	114.	119. ± 19.
	$h_c(1^1P_1)$	$\eta_c(1^1S$					
2P → 2S	$\chi_2(2^3P_2)$	$\psi'(2^3S$					
	$\chi_1(2^3P_1)$						
	$\chi_0(2^3P_0)$						
	$h_c(2^1P_1)$	$\eta_c'(2^1S$					
2P → 1S	$\chi_2(2^3P_2)$	$J/\psi(1^3S$					
	$\chi_1(2^3P_1)$						
	$\chi_0(2^3P_0)$						
	$h_c(2^1P_1)$	$\eta_c(1^1S$					
2P → 1D	$\chi_2(2^3P_2)$	$\psi_3(1^3D_3)$	163.	128.	88.	29.	
		$\psi_2(1^3D_2)$					
		$\psi(1^3D_1)$					
	$\chi_1(2^3P_1)$	$\psi_2(1^3D_2)$	123.	113.	35.	18.	
		$\psi(1^3D_1)$	152.	179.	22.	21.	
	$\chi_0(2^3P_0)$	$\psi(1^3D_1)$	81.	143.	13.	51.	
	$h_c(2^1P_1)$	$\eta_{2c}(1^1D_2)$	133.	117.	60.	27.	

$$\mathcal{R}_{\chi_{c1}(2P)} \equiv \frac{\mathcal{B}(\chi_{c1}(2P)\to\gamma\psi(1^3D_2),\ \psi(1^3D_2)\to\gamma\chi_{c1}(1P))}{\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi)}$$

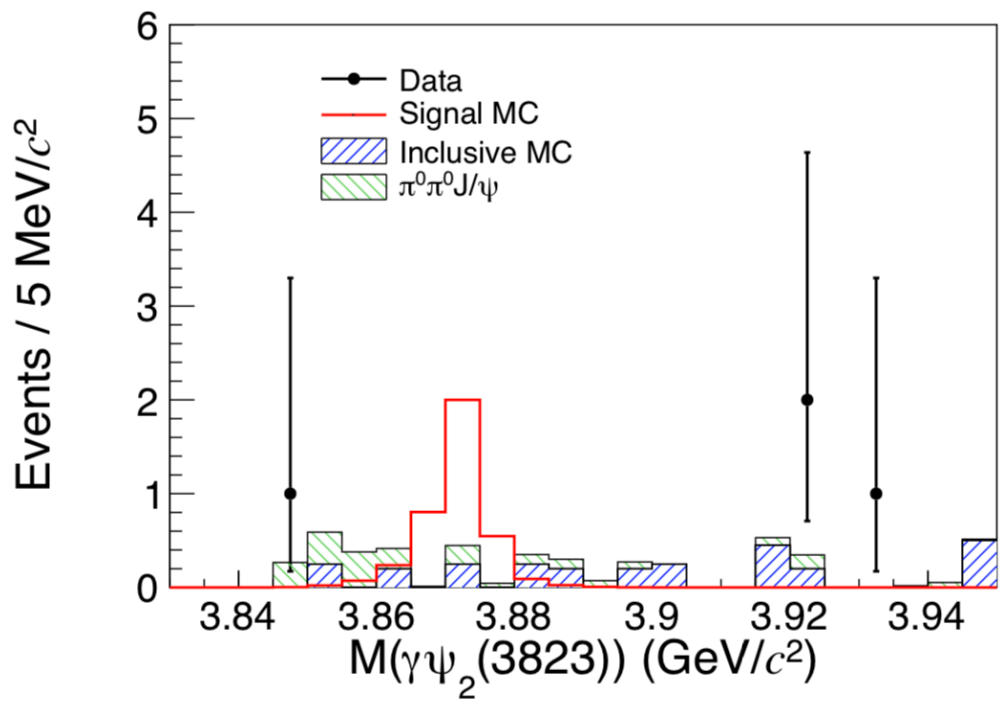
$$\Gamma_{\chi_{c1}(3872)} = 1190 \pm 210 \text{ keV [2]}$$
$$\Gamma_{\psi_2(3823)} = 520 \pm 100 \text{ keV [23]}$$
$$\mathcal{B}(\chi_{c1}(3872)\to\pi^+\pi^-J/\psi) = (3.8\pm1.2)\times10^{-2} \text{ [2]}$$

	NR [20]	GI [20]	LQCD [23]
$\Gamma_{\chi_{c1}(2P)\to\gamma\psi(1^3D_2)}$ (keV)	35	18	–
$\Gamma_{\psi(1^3D_2)\to\gamma\chi_{c1}(1P)}$ (keV)	307	268	337 ± 27
$\mathcal{R}_{\chi_{c1}(2P)}$	0.46 ± 0.19	0.21 ± 0.09	0.50 ± 0.21, 0.26 ± 0.11

$\chi_{c1}(2P)\to\gamma\ \psi_2(3823)$

PRD 72, 054026 (2005)

$e^+e^- \to \gamma X,\ X \to \gamma \psi_2(3823)$ *PRD* 110 (2024) 1, 012012



Chunhua Li & CZY, PRD 100, 094003 (2019)

$$\frac{\mathcal{B}(X(3872)\to\gamma X(3823), X(3823)\to\gamma\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} < 0.075$$

$\Gamma_{\chi_{c1}(3872)} = 1190 \pm 210$ keV [2]

$\Gamma_{\psi_2(3823)} = 520 \pm 100$ keV [23]

$\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi) = (3.8 \pm 1.2) \times 10^{-2}$ [2]

	NR [20]	GI [20]	LQCD [23]
$\Gamma_{\chi_{c1}(2P)\to\gamma\psi(1^3D_2)}$ (keV)	35	18	–
$\Gamma_{\psi(1^3D_2)\to\gamma\chi_{c1}(1P)}$ (keV)	307	268	337 ± 27
$\mathcal{R}_{\chi_{c1}(2P)}$	0.46 ± 0.19	0.21 ± 0.09	0.50 ± 0.21, 0.26 ± 0.11

- Upper limit contradicts theoretical predictions under the assumption that the X(3872) is the pure charmonium 2P state.

Coupled-channel analysis of the X(3872) line shape at BESIII

PRL 132 (2024)15, 151903

Line shape parameterization

$$\frac{d\mathrm{Br}(D^0\bar{D}^0\pi^0)}{dE} = \boldsymbol{B}\frac{1}{2\pi}\times\frac{g * k_{\mathrm{eff}}(E)}{|D(E)|^2}\times \mathrm{Br}(D^{*0}\to D^0\pi^0)$$

$$\frac{d\mathrm{Br}(\pi^+\pi^- J/\psi)}{dE} = \boldsymbol{B}\frac{1}{2\pi}\times\frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$

$$D(E) = E - E_X + \frac{1}{2}g * \left(\kappa_{\mathrm{eff}}(E) + ik_{\mathrm{eff}}(E) + \kappa^c_{\mathrm{eff}}(E) + ik^c_{\mathrm{eff}}(E)\right) + \frac{i}{2}\Gamma_0$$

$$k_{\mathrm{eff}}(E) = \sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2+\Gamma^2/4}+E-E_R}$$

$$\kappa_{\mathrm{eff}}(E) = -\sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2+\Gamma^2/4}-E+E_R}$$

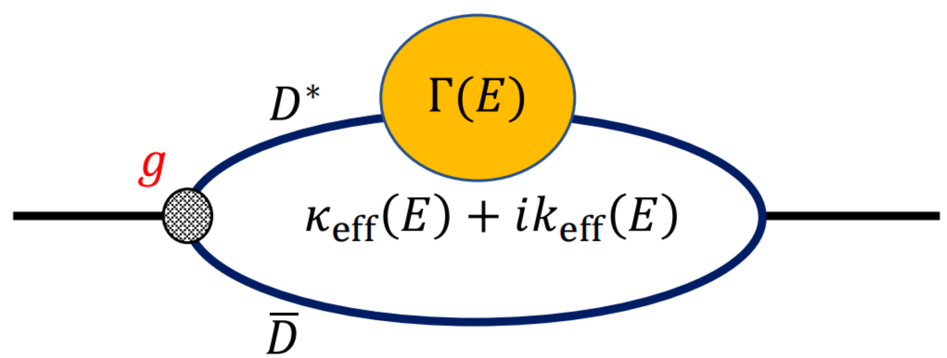
$$+\sqrt{\mu_p}\sqrt{\sqrt{(E_X-E_R)^2+\Gamma_X^2/4}-E_X+E_R}$$

$$\Gamma_0 = \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

$$E_X = M_X - (m_{D^0} + m_{\bar{D}^0} + m_{\pi^0})$$

* Due to the limited statistics, $\boldsymbol{\Gamma_{unknown}/\Gamma_{\pi^+\pi^- J/\psi}}$ is fixed [Chunhua Li, Chang-Zheng Yuan, PRD 100(2019) 094003]
* It brings us the largest uncertainty

[C. Hanhart, PRD 81, 094028]



Composite particle with one unstable constituent

Important features:

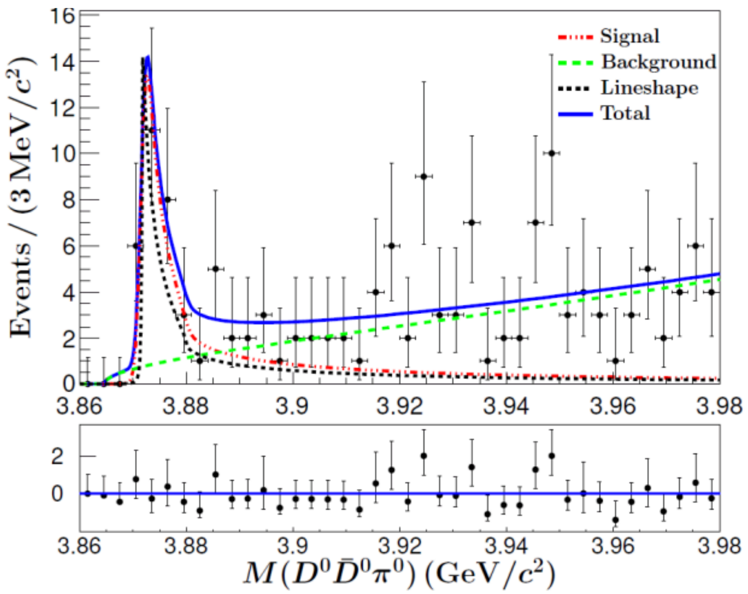
- Model independent
- With subtraction, M_X becomes physical.
- Including the width of D^*
- Including the coupled channel effect
- **Fit parameters**: g, $\Gamma_{\pi^+\pi^- J/\psi}$, M_X

Junli Ma's talk, 9th XYZ workshop

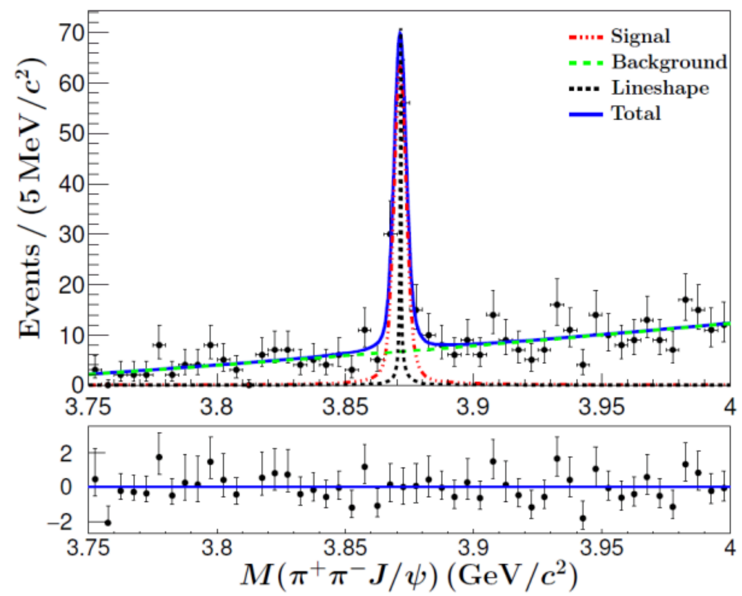
Coupled-channel analysis of the X(3872) line shape at BESIII

PRL 132 (2024)15, 151903

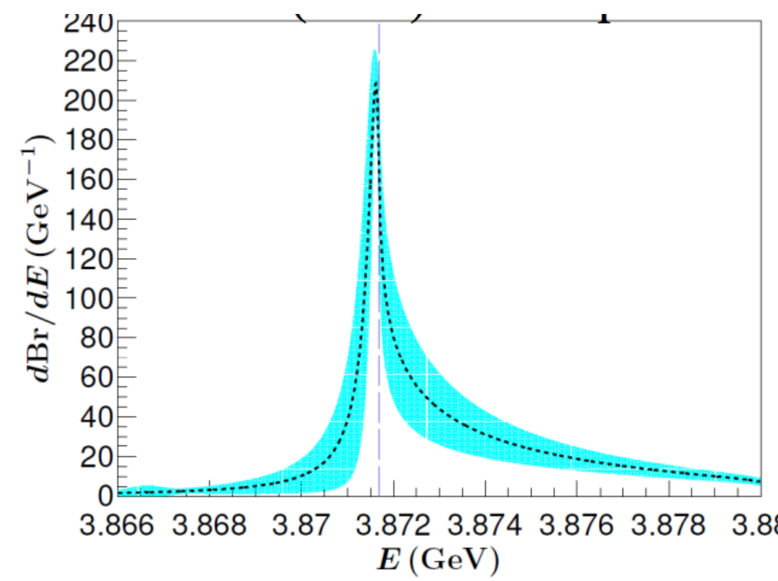
Fit results



Resolution~1 MeV



Resolution~1.9 MeV



Parameters	g	Γ_0 (MeV)	M_X (MeV)
Fit results	0.16 ± 0.10	2.67 ± 1.77	3871.63 ± 0.13
g	1.00	0.89	-0.60
Γ_0		1.00	-0.29
M_X			1.00

$\mu_{X(3872)}^{prod} = (9.8 \pm 3.9) \times 10^4$

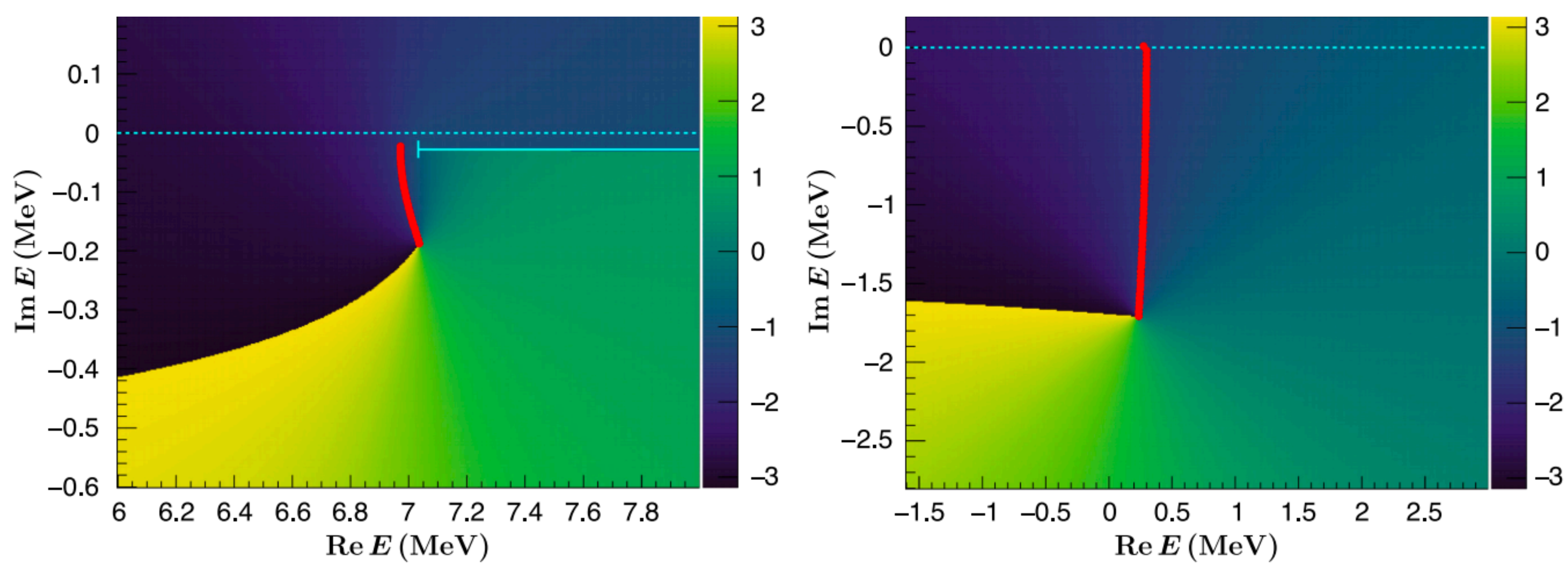
Large systematic uncertainty from $\Gamma_{unknow}/\Gamma_{\pi^+\pi^- J/\psi}$

Junli Ma's talk, 9th XYZ workshop

Coupled-channel analysis of the X(3872) line shape at BESIII

PRL 132 (2024)15, 151903

- Search for the poles of the amplitude in the complex energy plane.
- $E_{\mathrm{I}} = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV
- $E_{\mathrm{II}} = \left(0.26 \pm 5.74^{+5.14}_{-38.32}\right) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ MeV



- Effective range expansion

$$D(k) = \frac{1}{a} - ik + \frac{r_e}{2}k^2 + \mathcal{O}(k^3)$$

$$a = \left(-16.5^{+7.0+5.6}_{-27.6-27.7}\right)\ \text{fm} \qquad r_e = \left(-4.1^{+0.9+2.8}_{-3.3-4.4}\right)\ \text{fm}$$

a: scattering length

r_e: effective range

$$\boxed{\begin{aligned} a &= -\frac{2(1-Z)}{(2-Z)}\frac{1}{\gamma} + \mathcal{O}(\beta^{-1}), \\ r_e &= -\frac{Z}{1-Z}\frac{1}{\gamma} + \mathcal{O}(\beta^{-1}), \end{aligned}}$$

➜ Z=0.18, similar to deuteron (0.22)

Z: the probability of containing a compact component

$X(3872) \to \pi^+\pi^-\chi_{c1}$ *PRD(L) 109, 071101 (2024)*

Theoretical calculations on the pionic transitions between the charmonium states ^3P_J

*PRD **77**, 014013 (2008)*

$$\frac{\Gamma\,(2\,^3P_1 \to \chi_{c1}\,\pi\pi)}{\Gamma\,(2\,^3P_1 \to \chi_{c2}\,\pi\pi)} \approx 10^4$$

$$\frac{\Gamma\,(2\,^3P_1 \to \chi_{c1}\pi^0)}{\Gamma\,(2\,^3P_1 \to \chi_{c1}\pi^+\pi^-)} \approx 0.04$$

$\chi_{b1}(2P) \to \pi^+\pi^-\chi_{b1}$ =(9.2±0.6±0.9)x10^{-3}

$\chi_{b2}(2P) \to \pi^+\pi^-\chi_{b2}$ =(4.9±0.4±0.6)x10^{-3}

*PRD **84**, 011104 (2011)*

Belle:

$$\mathcal{B}(B^+ \to X(3872)K^+) \times (X(3872) \to \chi_{c1}\pi^+\pi^-) < 1.5 \times 10^{-6}$$ *PRD 93, 052016 (2016)*

$$\mathcal{B}(B^+ \to K^+X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^-J/\psi) = (8.61 \pm 0.82\ (\text{stat}) \pm 0.52\ (\text{syst})) \times 10^{-6}$$

PRD 84, 052004 (2011)

$$\frac{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^-\chi_{c1}]}{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^-J/\psi]} < 0.2$$

X(3872)→$\pi^+\pi^-\chi_{c1}$ *PRD(L) 109, 071101 (2024)*

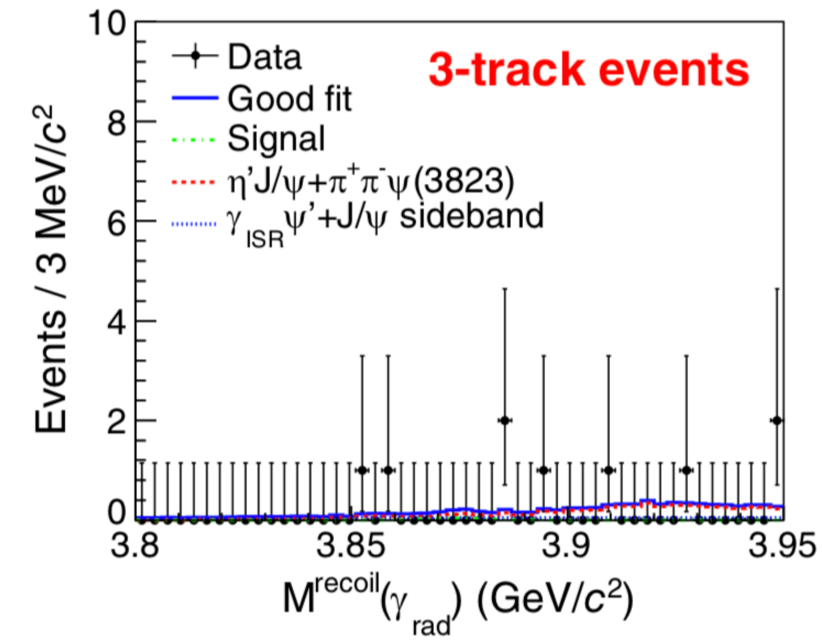
- Search for $e^+e^-\to\gamma X(3872)$, $X(3872)\to\pi^+\pi^-\chi_{c1}$.

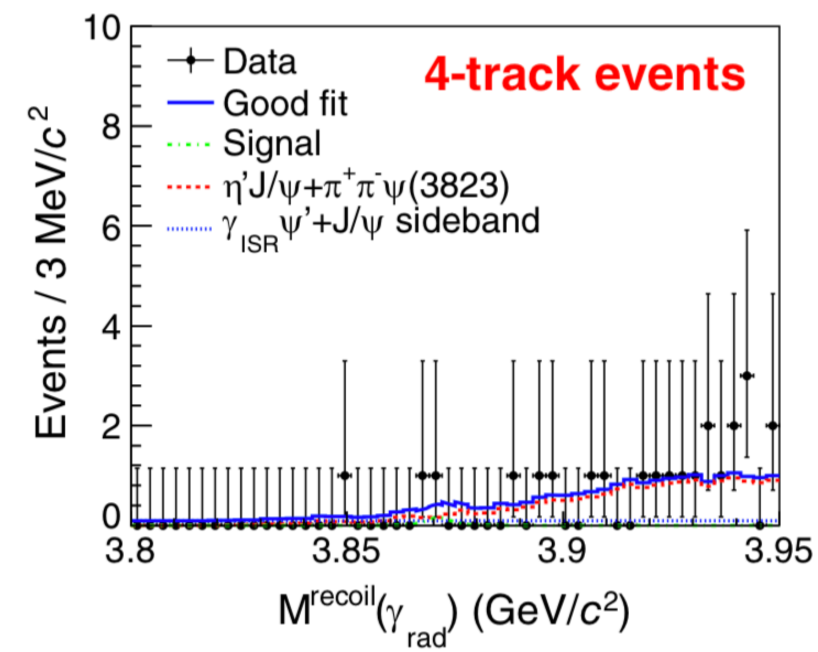
$$\frac{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^-\chi_{c1}]}{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^- J/\psi]} < 0.18$$

$$\frac{\mathcal{B}[\chi_{c1}(3872)\to\pi^0\chi_{c1}]}{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^- J/\psi]} = 0.88^{+0.33}_{-0.27} \pm 0.10$$

Exp. $$\frac{\Gamma[\chi_{c1}(3872)\to\chi_{c1}\pi^0]}{\Gamma[\chi_{c1}(3872)\to\chi_{c1}\pi^+\pi^-]} > 5$$

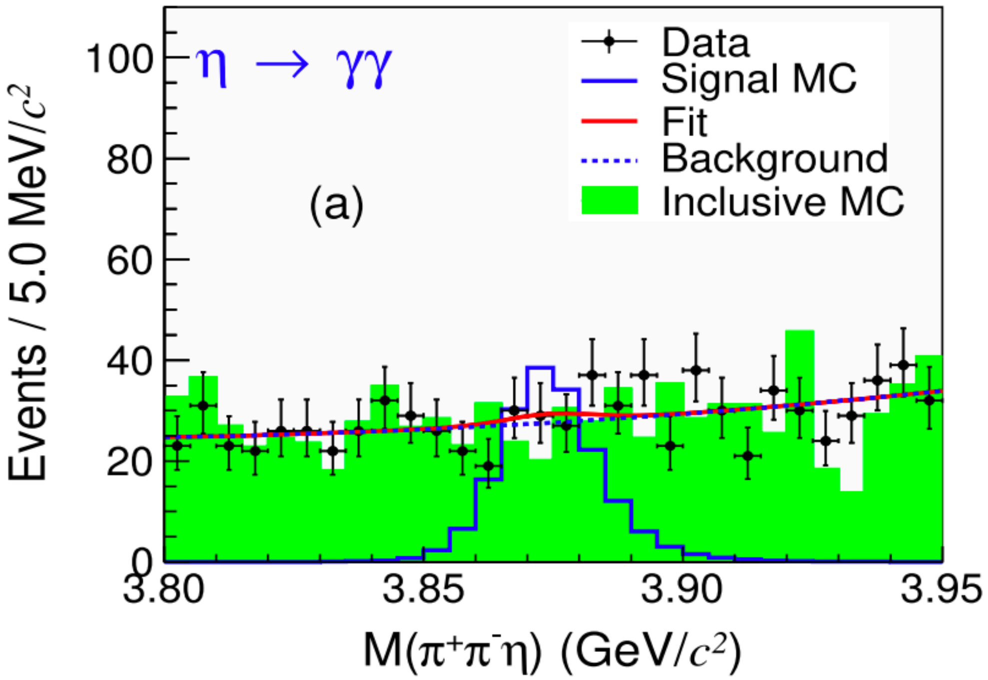
Theo. $$\frac{\Gamma(2^3P_1\to\chi_{c1}\pi^0)}{\Gamma(2^3P_1\to\chi_{c1}\pi^+\pi^-)} \approx 0.04$$

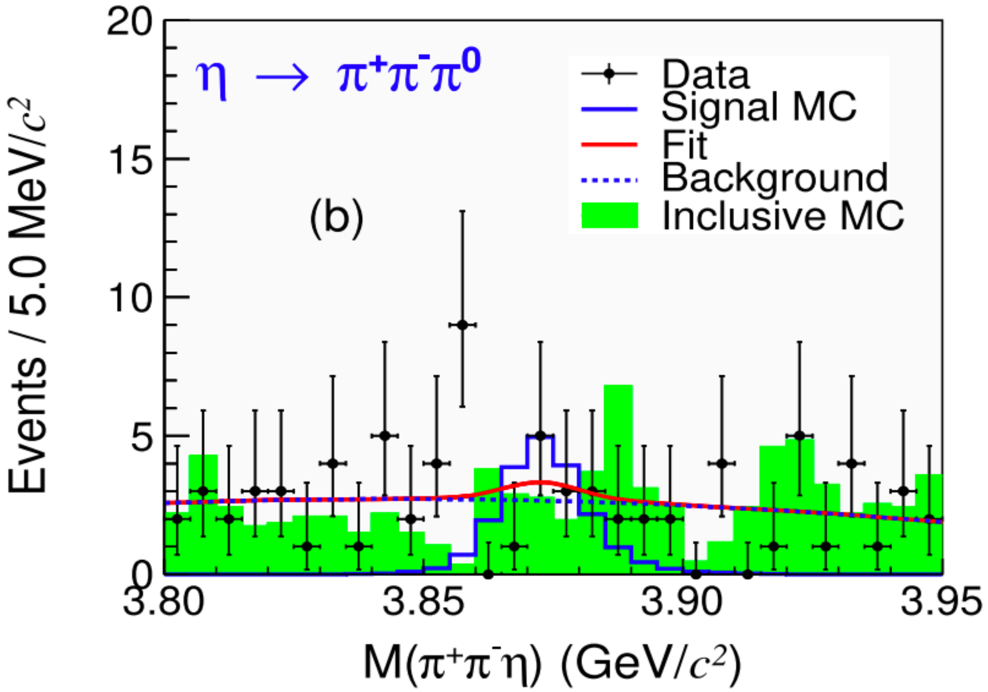


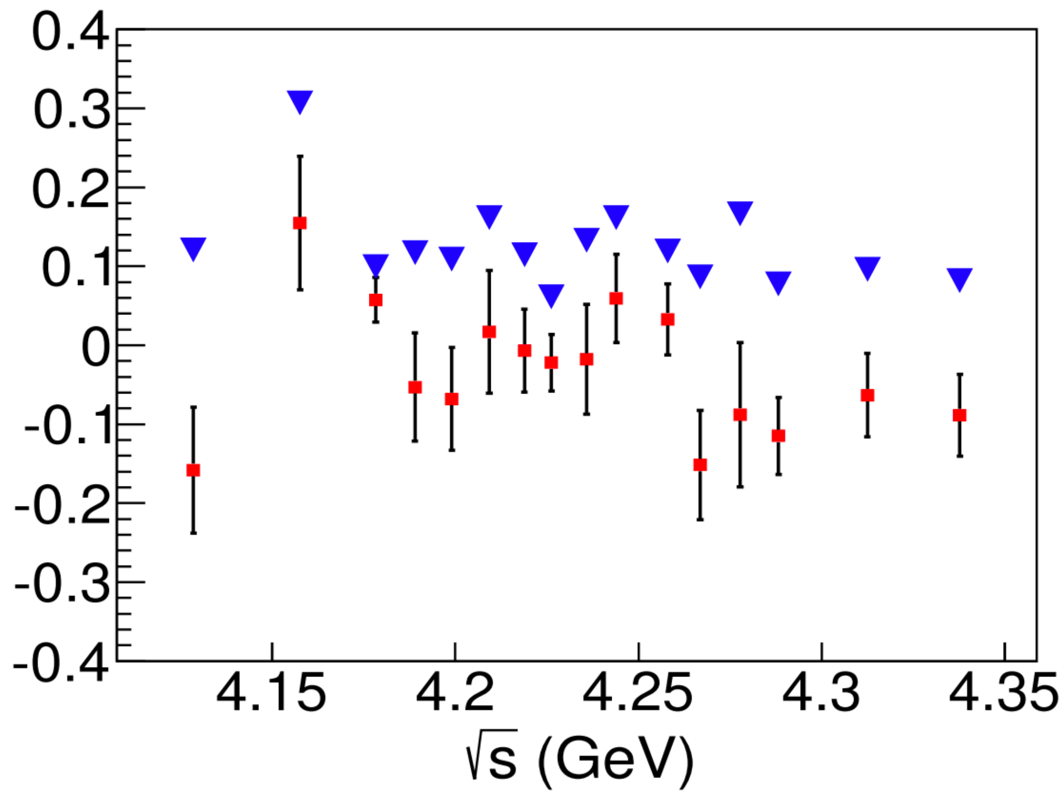


$X(3872) \to \pi^+\pi^-\eta$ *PRD(L) 109, 011102 (2024)*

Chunhua Li & CZY, PRD 100, 094003 (2019)







$$\frac{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^-\eta]}{\mathcal{B}[\chi_{c1}(3872)\to\pi^+\pi^- J/\psi]} < 0.12$$

$$\Rightarrow \mathcal{B}[\chi_{c1}(3872) \to \pi^+\pi^-\eta] < 0.6\%$$

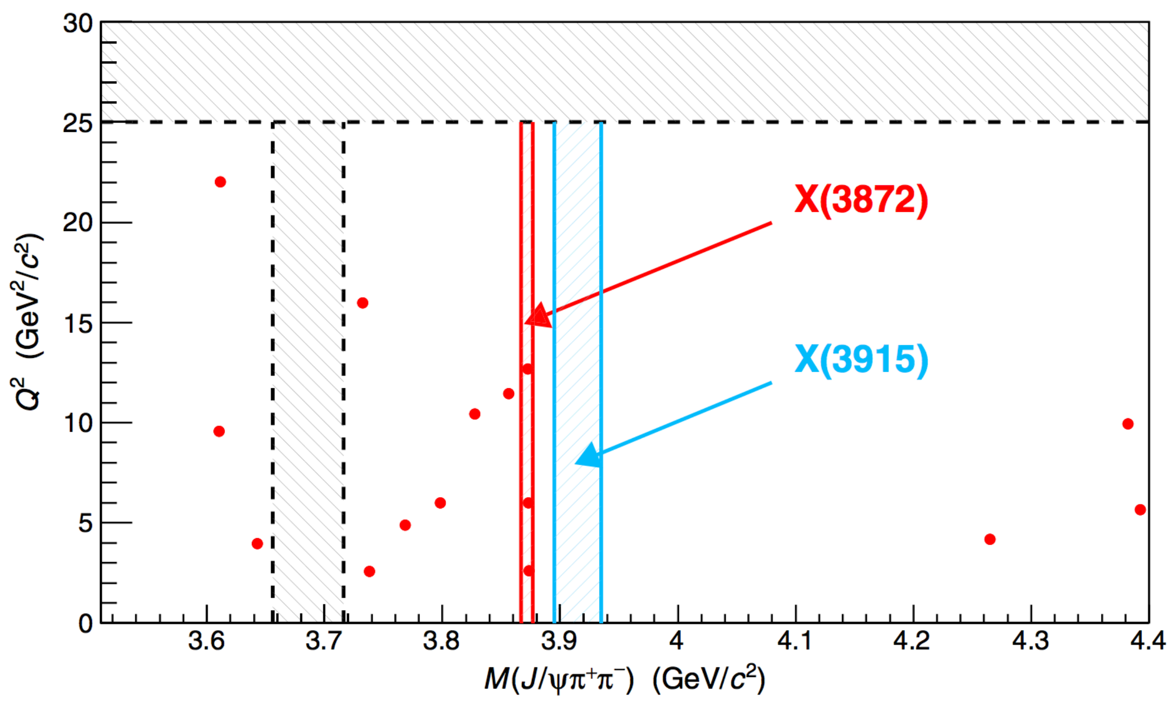
Molecule model *PRD **106**, 074015 (2022)*

B(X(3872)→light hadrons)~ (1-10)%

Search for $e^+e^- \to X(3872)$ via two-photon fusion

- Mesons with $J^{PC} = 1^{++}$ can be produced if on or both photons are highly virtual γ^*. *[NPB523, 423 (1998)]*.
- If X(3872) has a molecular component in its structure, it has a steeper Q^2 dependence than the ccbar state. [Q^2 is the invariant mass squared of the virtual photon]
- Belle reported an observation of X(3872) in two photon interaction with 3.2σ in $e^+e^- \to e^+e^- J/\psi\pi^+\pi^-$.

Belle, PRL 126, 122001 (2021)

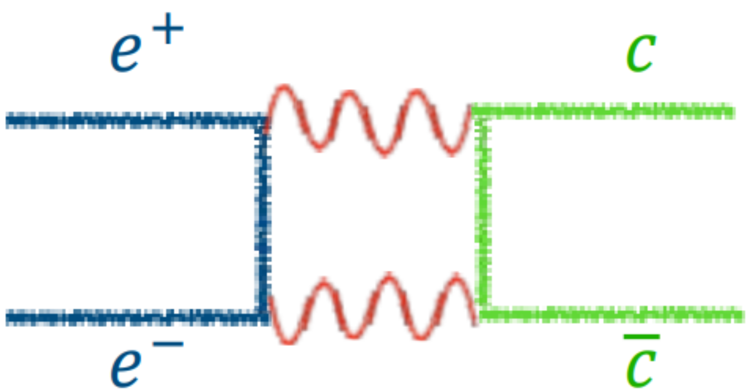


$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}(\text{stat}) \pm 0.7(\text{syst})\ \text{eV}$$

assuming the Q^2 dependence predicted by a ccbar meson model

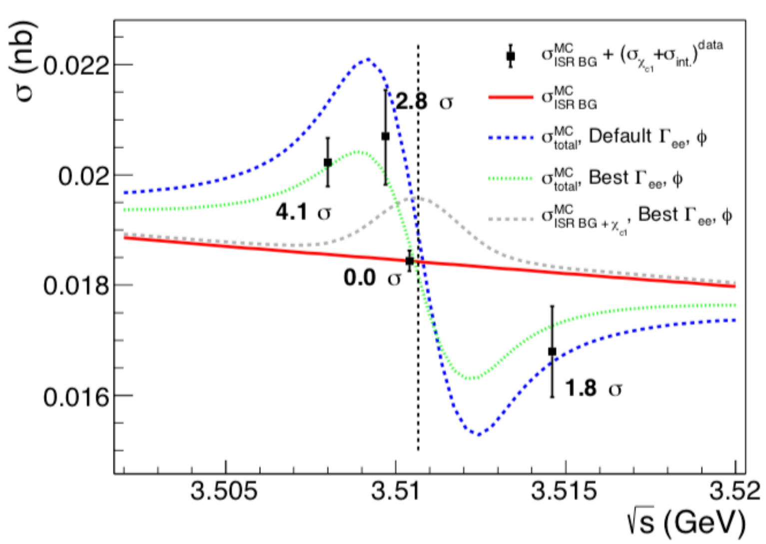
Search for $e^+e^-\to X(3872)$ via two-photon fusion

- Direct formation of C-even states with two-photon fusion process

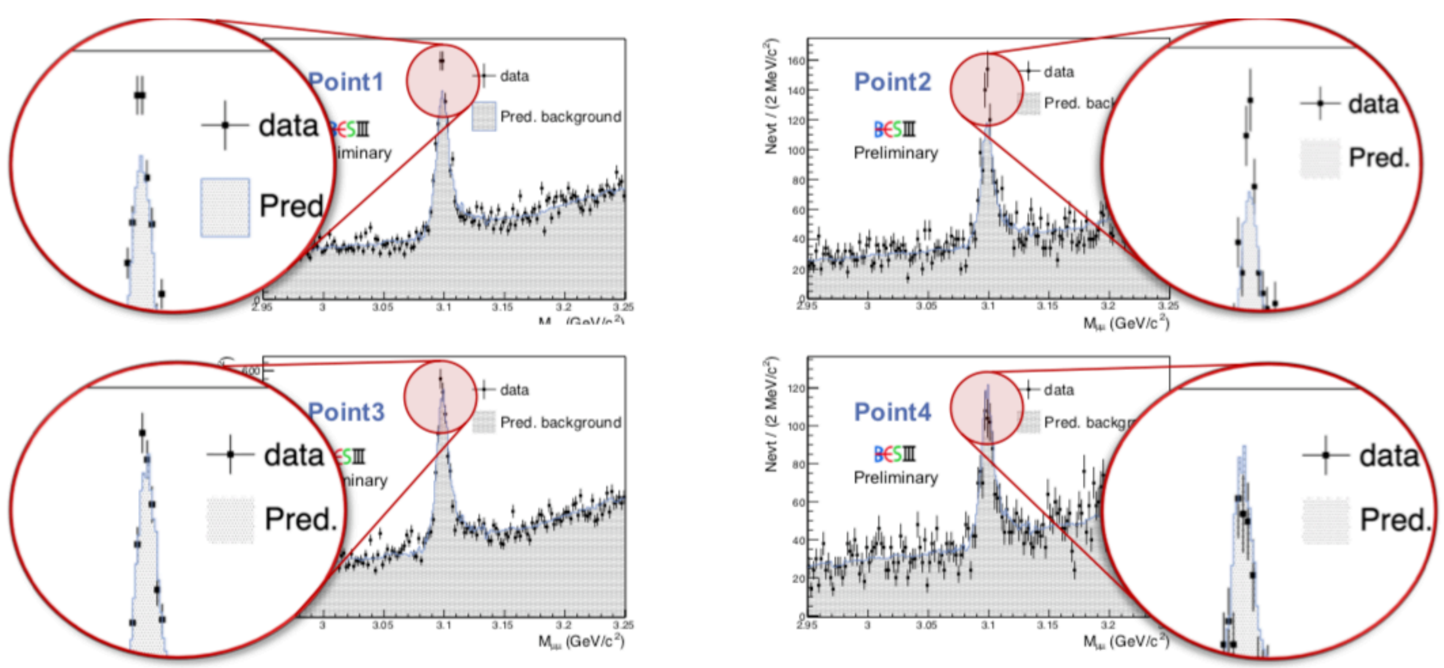


$J^{PC} = 1^{++}, 2^{++}$

- BESIII observed $e^+e^-\to\chi_{c1}(1P)$ with 5.1σ significance

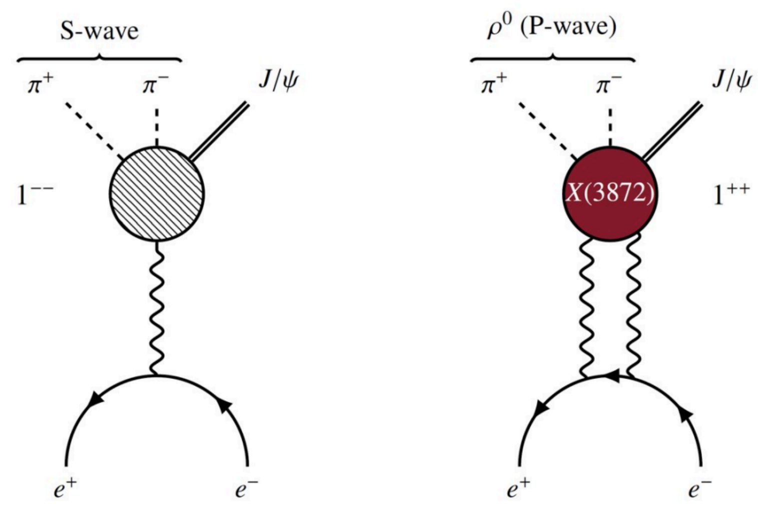


PRL 129, 122001 (2022)



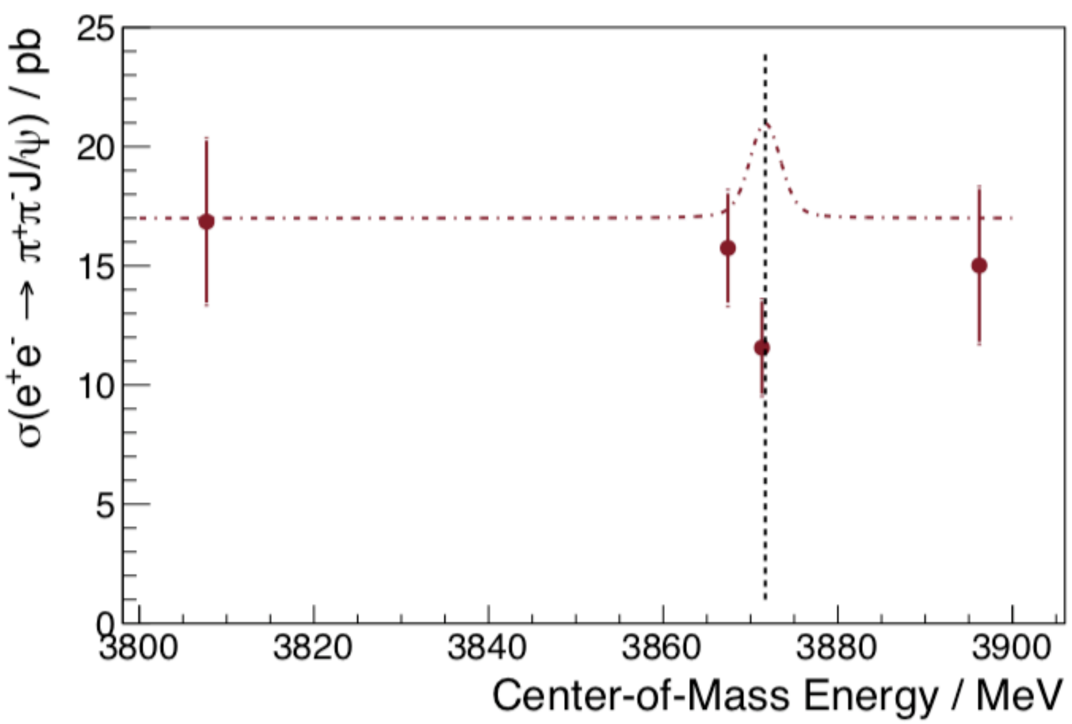
Search for e⁺e⁻→X(3872) via two-photon fusion

- Direct formation of C-even states with two-photon fusion process *PRD 107, 032007 (2023)*

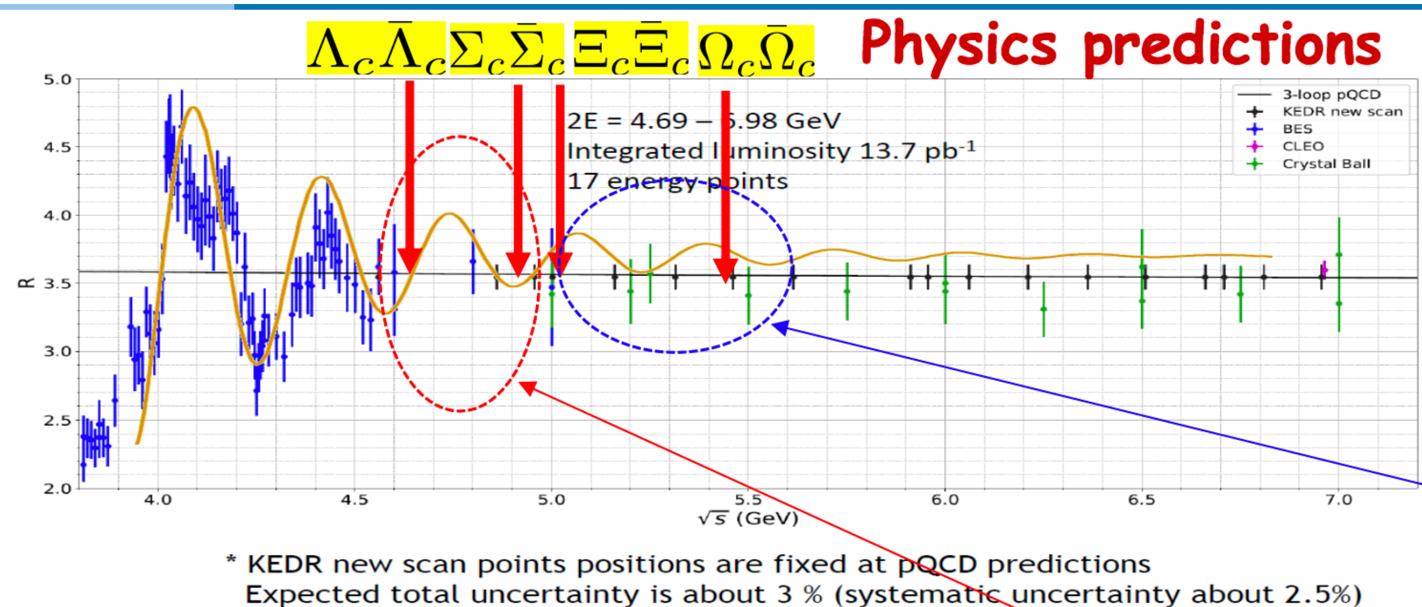


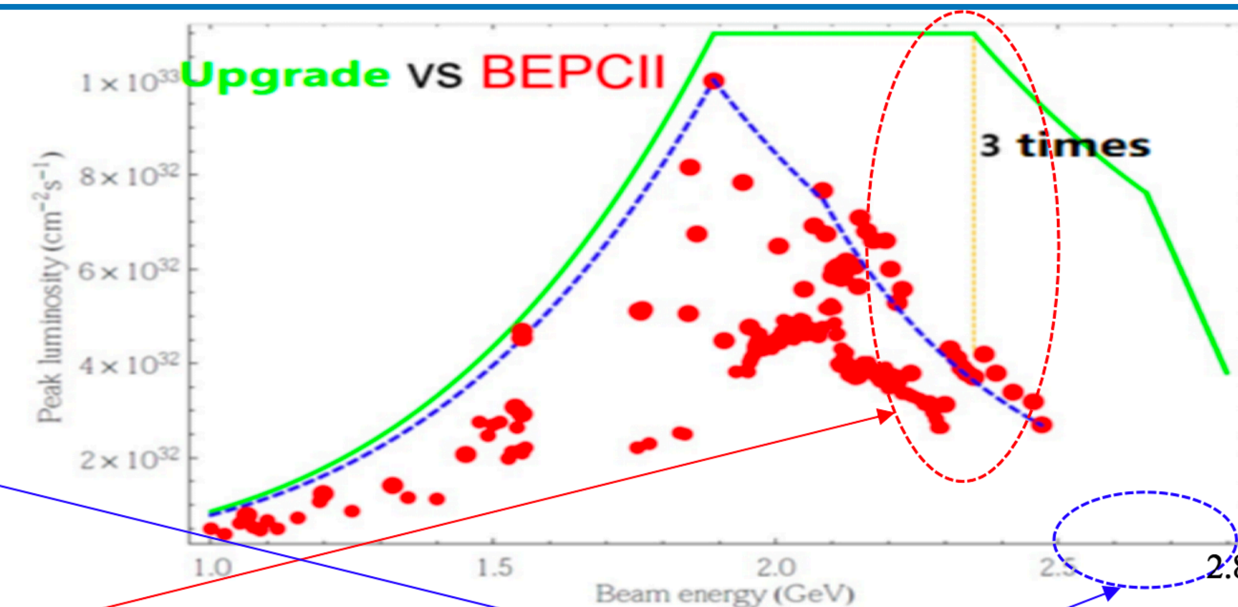
- Search for $e^+e^- \rightarrow X(3872) \rightarrow \pi^+\pi^- J/\psi$

$$\Gamma_{ee} \times \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi) < 7.5 \times 10^{-3}\,\mathrm{eV}$$



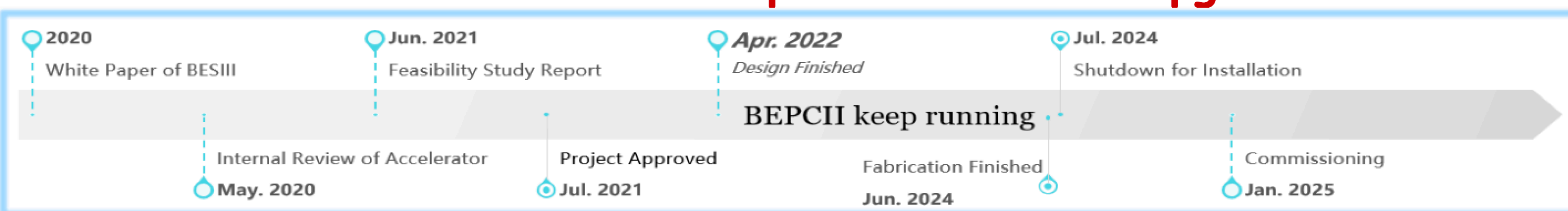
BEPCII-U Operation plan





BEPCII upgrade aims at: Increase luminosity by a factor of 3 & Increase beam energy to 2.8GeV

Timeline of BEPCII operation and its upgrade



Y. Zhang, BESIII 2024 Winter Col. Meeting

BEPCII-U Operation plan

- Jul. 2024 – Dec. 2024 Summer shutdown for installation
- Jan. 2025 – Jul. 2025 Commissioning & Data taking @1.843GeV ψ (3686)
- Aug. 2025 Summer shutdown
- Sep. 2025 – Jul. 2026 Data taking @1.843GeV & 2.35GeV (project test)
- Aug. 2026 – Sep. 2026 Summer shutdown & LINAC final upgrade
- Oct. 2026 – Sep. 2028 Data taking within beam energy 2.1-2.5GeV
- Sep. 2028 – Jul. 2030 Data taking within beam energy 2.5-2.8GeV

C.H.Yu, BESIII 2025 Summer Col. Meeting

BEPCII-U Operation plan

- Jul. 2 Summer shutdown for installation
- Jan. 2 Commissioning & Data taking @1.843GeV ψ (3686)
- Aug. 2025 Summer shutdown
- Sep. 2 g @1.843GeV & 2.35GeV (project test)
- Aug. 2026 – Sep. 2026 Summer shutdown & LINAC final upgrade
- Oct. 2
- Sep. 2

Run plan 2025–2026:

Restart in August 2025

- Reached 720 mA × 720 mA
  $\mathcal{L}_{\text{peak}} = 3.8 \times 10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$

- Beamtime allocation (not final)
  Collect more data on $\psi(2S)$
  Run at 4680 MeV — start collecting $\Lambda_c^+ \overline{\Lambda}_c^-$ sample (requested total of 9 fb^{-1})
  Scans around $X(3872)$ and χ_{c2} (about one month each)

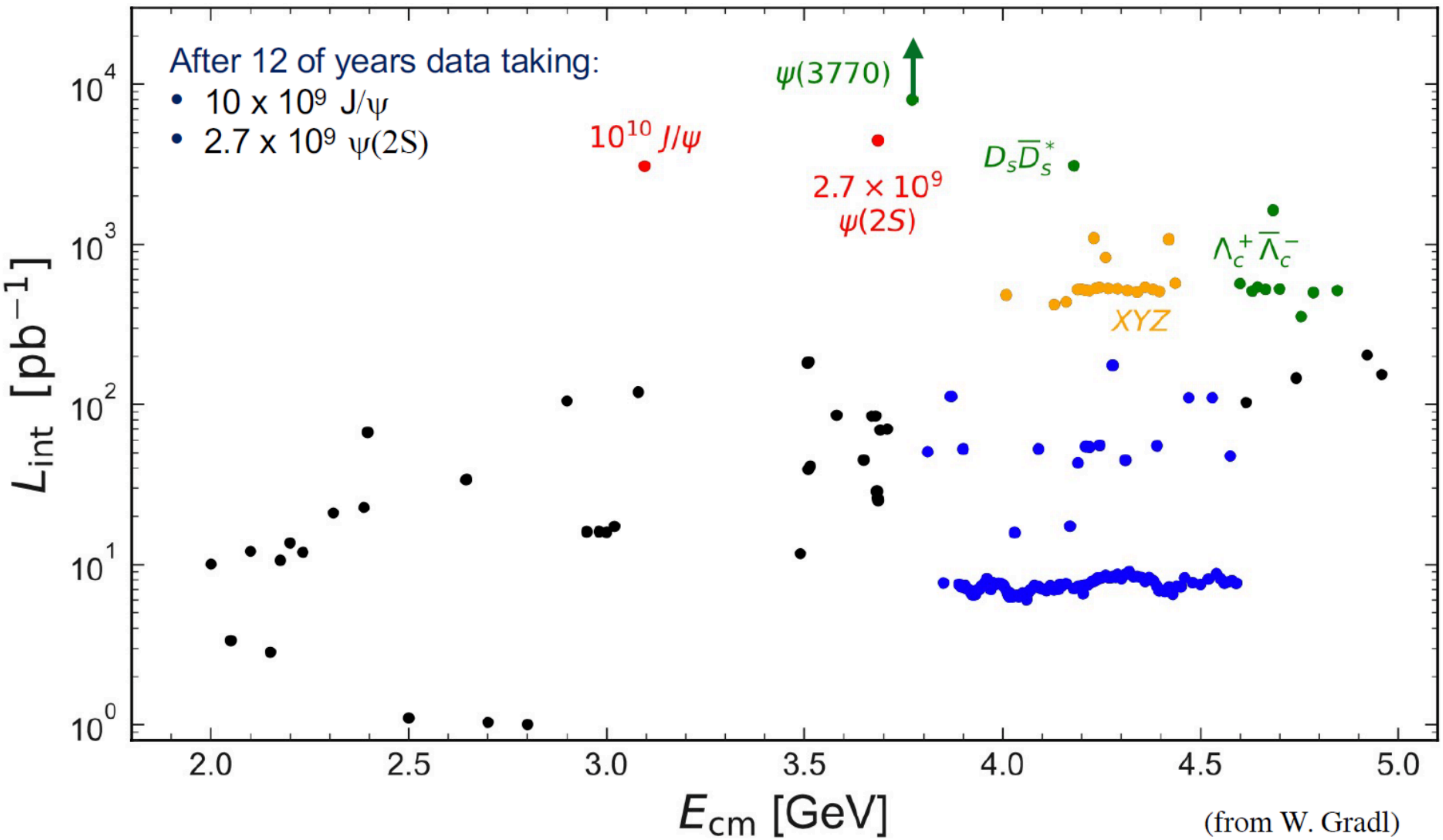
- No dedicated synchrotron runs any more:
  9–10 months of physics running for us per year!

C.H.Yu, BESIII 2025 Summer Col. Meeting

Summary

- BESIII play an important role on the study of X(3872)
  - Clean environment and good resolutions make abundant studies on X(3872), e.g. line shape, decays, and productions.
  - BEPCII-U brings us more data
- Belle II+LHC(LHCb, CMS, ATLAS) are all operating, and possible future experiments STCF
- We can look forward to richer experimental results in the future.

Data Samples at BESIII



(from W. Gradl)