New data on the XYZ states from BESIII

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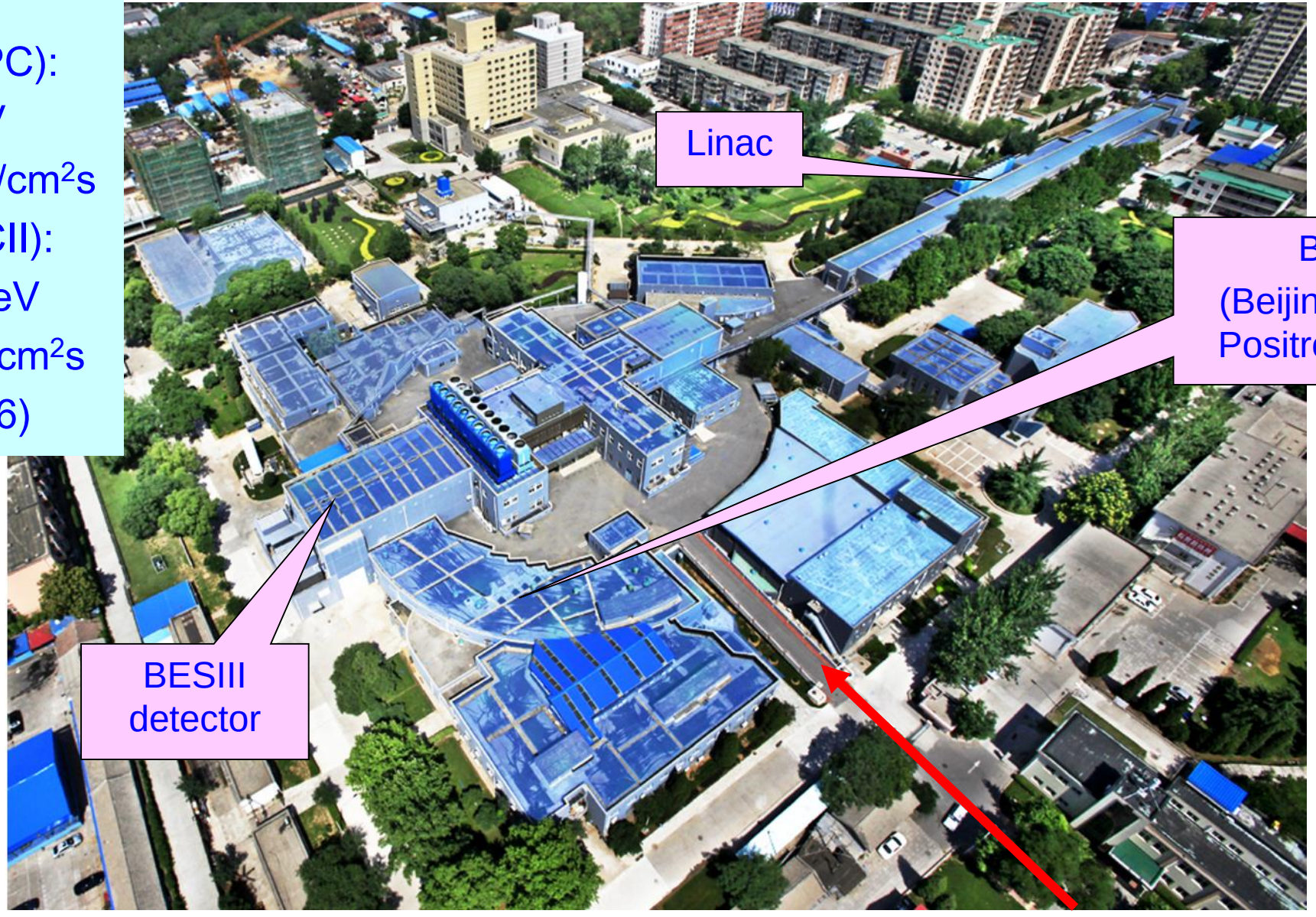
（for the BESIII Collaboration）

Frontier of QCD: Opportunities and Challenges

Peking University, Nov. 9 - 10, 2019

Beijing Electron Positron Collider (BEPC)

- founded: 1984
- 1989-2005 (BEPC):
  Ecm = 2-5 GeV
  L_{peak}=1.0x10^{31} /cm^2s
- 2008-now (BEPCII):
  Ecm = 2-4.9 GeV
  L_{peak}=1.0x10^{33}/cm^2s
  (Apr. 5, 2016)



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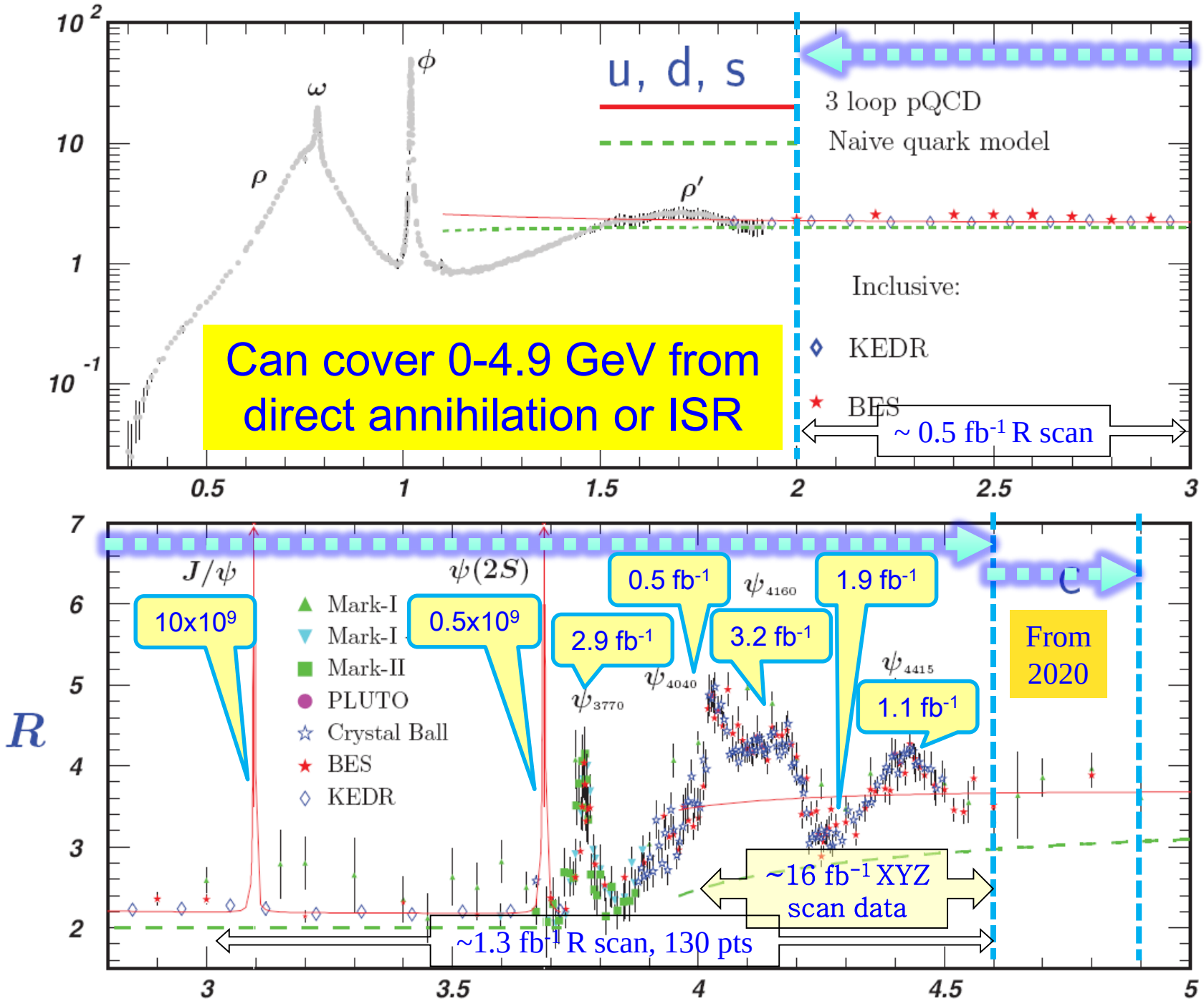


Study of QCD & EW interactions:

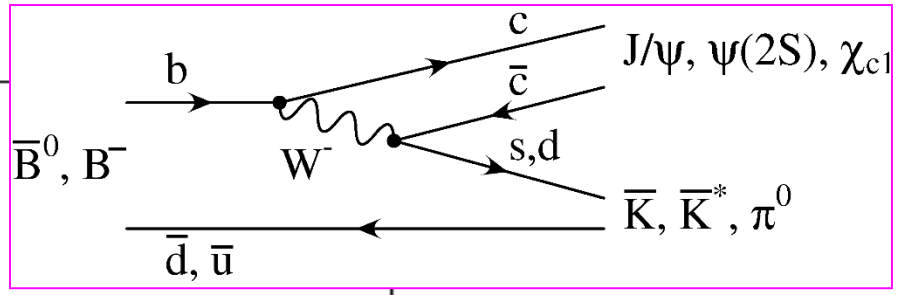
- Light Hadron Spectroscopy
- Charmonium & XYZ states
- Charm physics
- R & QCD
- Baryon properties
- τ physics
- New physics

Selected topics

- X(3872) BRs
- Y → $\bar{D}D_1$, $\bar{D}D_2$
- $Z_c(3900)$ & $Z_c(4020) \rightarrow \rho\eta_c$

X(3872): observed 16 years ago, it is still very mysterious

PRL91 262001 (2003)
140/fb data

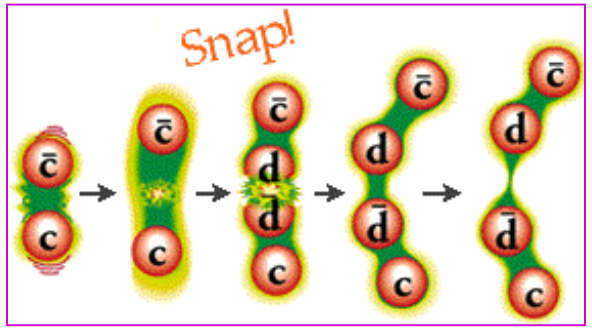


$$M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}, \Gamma < 2.7 \text{ MeV}$$

$$\frac{B(B^{\pm} \to XK^{\pm} \to \pi^+\pi^- J/\psi K^{\pm})}{B(B^{\pm} \to \psi' K^{\pm} \to \pi^+\pi^- J/\psi K^{\pm})} = (6.3 \pm 1.2 \pm 0.7)\%$$

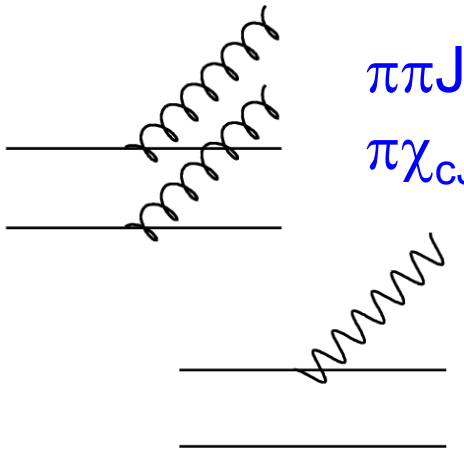
X(3872) decays

- Open charm



$\bar{D}^0 D^{*0}$? Threshold?
$\bar{D}^0 D^0 \pi^0$
$\bar{D}^0 D^0 \gamma$
$D^+ D^- \gamma$

- Transitions
  - Hadronic transitions
  - Radiative transitions



$\pi\pi J/\psi$, $\pi\pi\pi J/\psi$,
$\pi\chi_{cJ}$, $\pi\pi\chi_{cJ}$, $\pi\pi\eta_c$, …

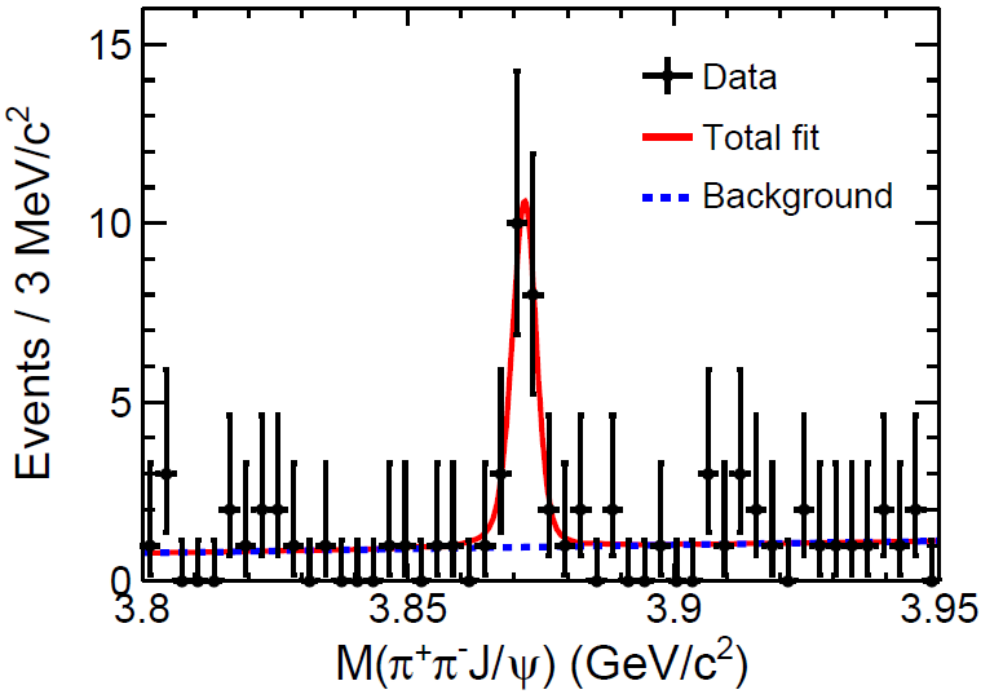
$\gamma J/\psi$, $\gamma\psi(2S)$

- Hadronic decays
- Radiative decays

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

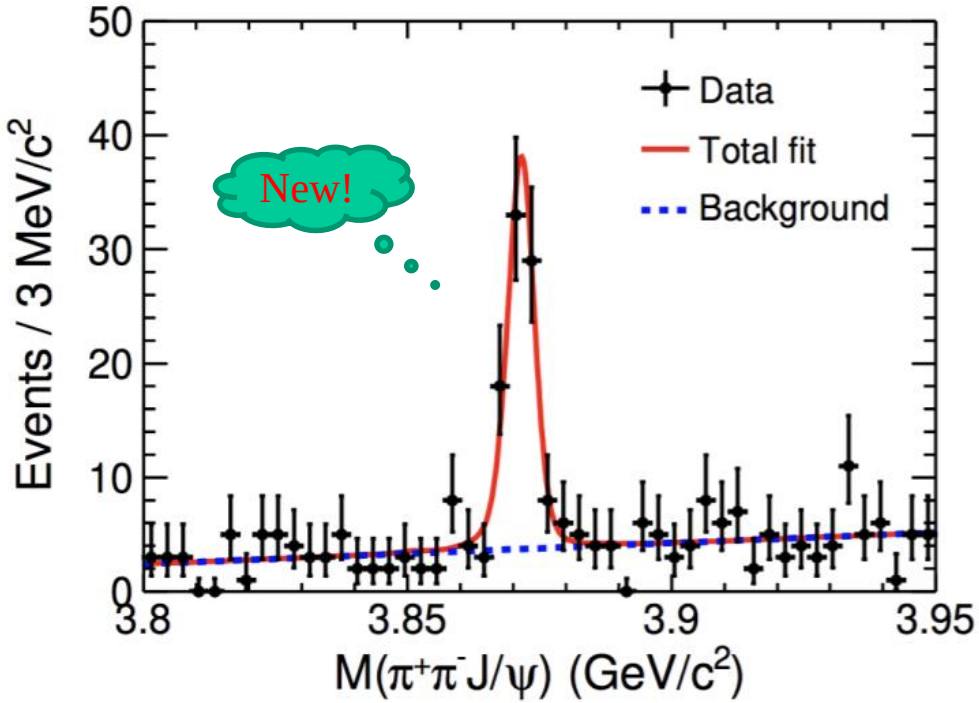
$X(3872) \to \pi^+\pi^- J/\psi$

arXiv: 1310.4101, PRL 112, 092001



4.0 fb^{-1}, 20±5 evts

arXiv: 1903.04695, PRL122, 232002



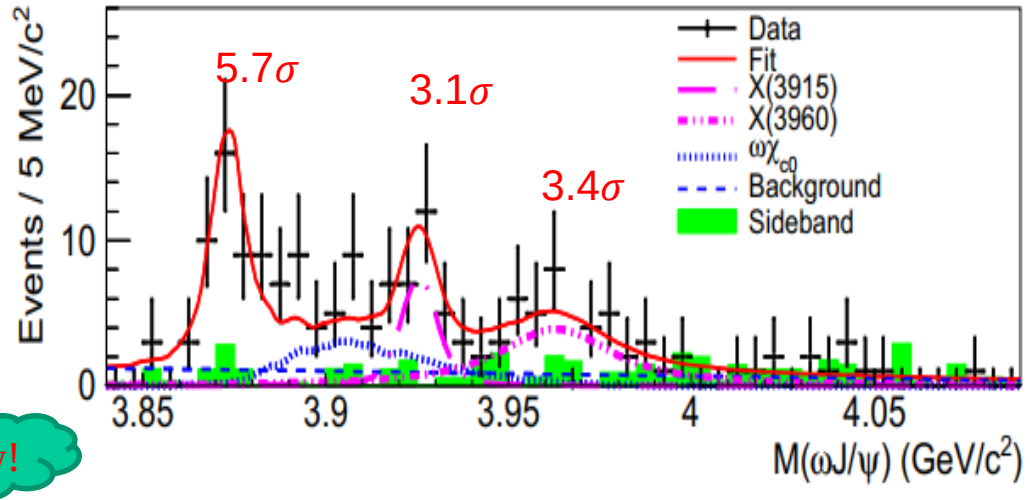
11.6 fb^{-1}, 79±9 evts

$\sigma(e^+e^- \to \gamma X(3872), X \to \pi^+\pi^- J/\psi)$=(0.29±0.11) pb @ 4.226 GeV

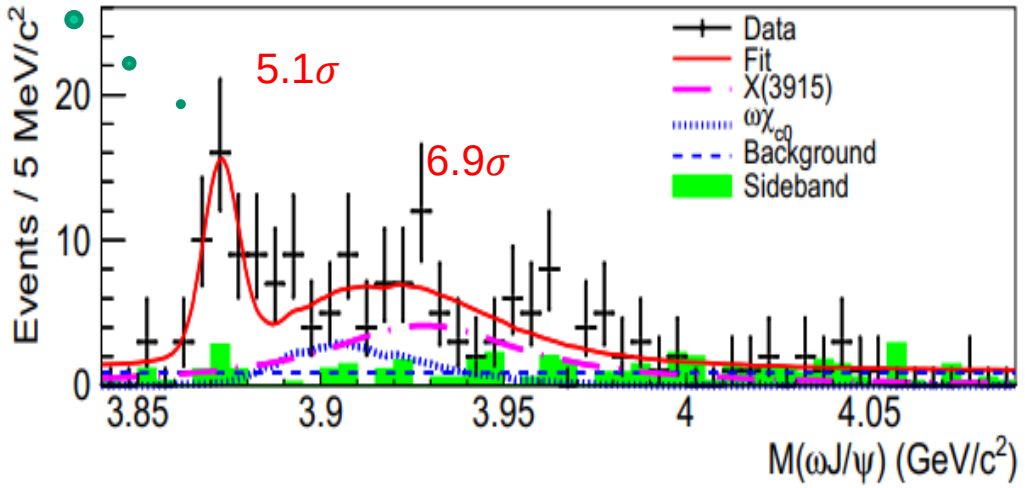
Observation of $X(3872) \to \omega J/\psi$

arXiv: 1903.04695,
PRL122, 232002

- Signal process: $e^+e^- \to \gamma X \to \gamma\omega J/\psi$, with $\omega \to \pi^+\pi^-\pi^0$, $J/\psi \to l^+l^-$



New!



There were only evidence at Belle (4.3σ) and BaBar (4σ) experiments!

- Signal PDF:
  - ✓ 3 resonances: (X(3872), X(3915) and X(3960))

$$N_{sig}(X(3872)) = 45 \pm 9 \pm 3$$

  - ✓ Two resonances: (X(3872), X(3915))

$$N_{sig}(X(3872)) = 40 \pm 8 \pm 2$$

	Mass	Width
$X(3872)$	3873.3 ± 1.1 (3872.8 ± 1.2)	1.2 (1.2)
$X(3915)$	3926.4 ± 2.2 (3932.6 ± 8.7)	3.8 ± 7.5 (59.7 ± 15.5)
$X(3960)$	3963.7 ± 5.5	33.3 ± 34.2

Hard to distinguish the two hypotheses since only 2.5σ difference.

Measurements of $e^+e^- \to \gamma X(3872)$, $X \to \gamma J/\psi, \gamma\psi(3686)$

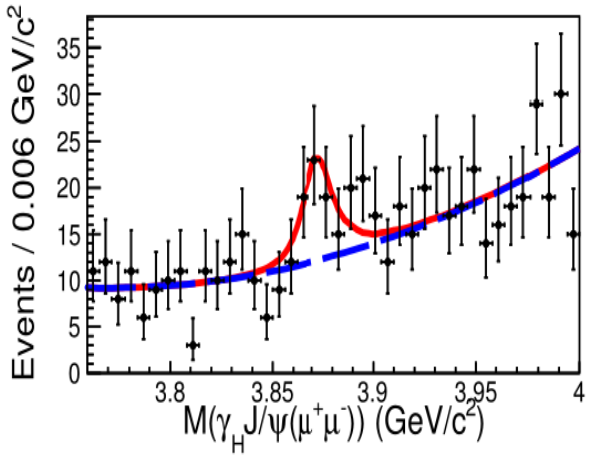
New!

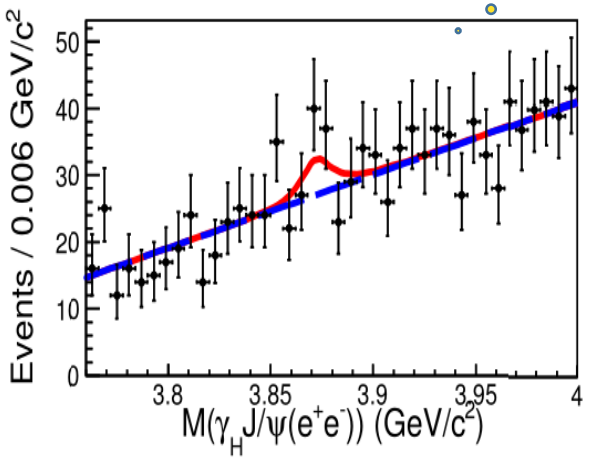
preliminary

$X(3872) \to \gamma J/\psi$

$J/\psi \to \mu\mu/ee$

Belle (4.9σ); BaBar (3.6σ); LHCb (>5σ)





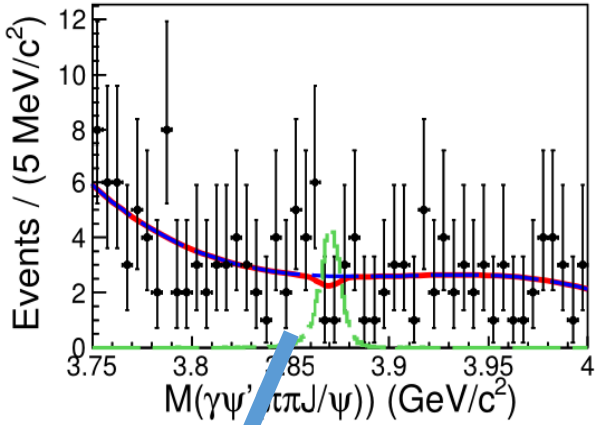
➢ Simultaneous fit; significance $> 3.5\sigma$

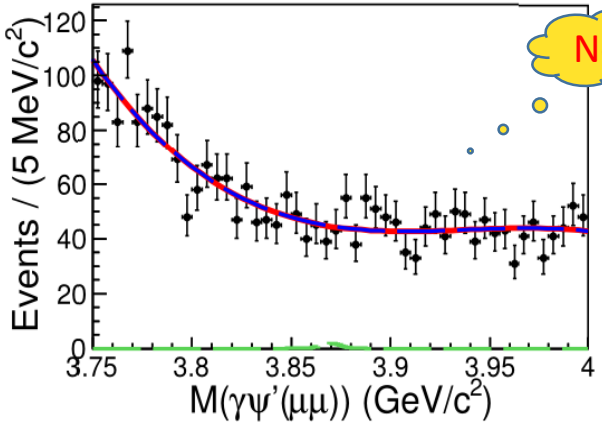
$X(3872) \to \gamma\psi(3686)$

$\psi(3686) \to \pi^+\pi^- J/\psi$

$\psi(3686) \to \mu\mu$

Belle (0.4σ); BaBar (3.5σ); LHCb (4.4σ)





New!

$\frac{B[X(3872)\to\gamma\psi(3686)]}{B[X(3872)\to\gamma J/\psi]} < 0.59$ at 90% C.L.

➢ Simultaneous fit; NO evident signal!

Expectation strength

It is still not clear if X(3872)→γψ(2S) exists or not!

Measurements of $e^+e^- \to \gamma X(3872)$, $X \to D^0\bar{D}^{*0}$, γD^+D^-

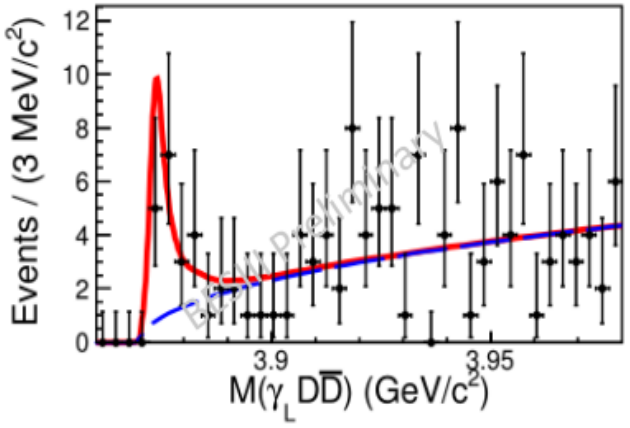
preliminary

New!

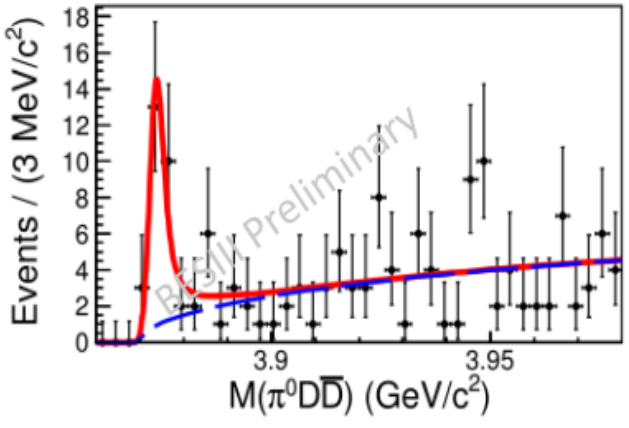
$X(3872) \to D^0\bar{D}^{*0} + c.c.$

$D^{*0} \to \gamma D^0, \pi^0 D^0$

$D^0 \to K\pi, K\pi\pi, K\pi\pi\pi$



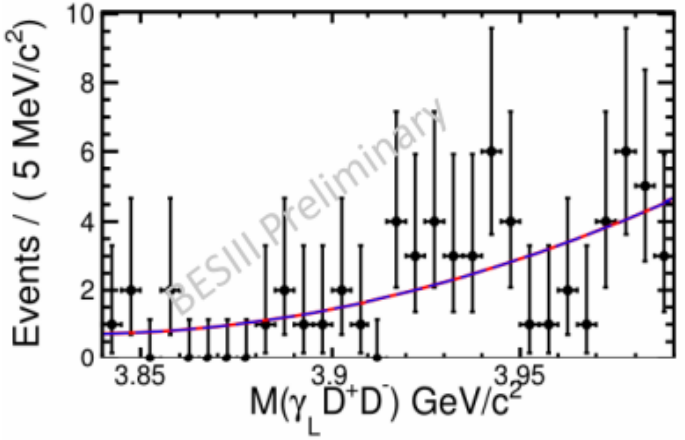
$N_{DD^*} = (25.5 \pm 4.4)$



$N_{DD^*} = (32.5 \pm 5.5)$

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

$D^{\pm} \to K\pi\pi, K\pi\pi\pi$



$N_{\gamma D^+D^-} = 0.0^{+0.5}_{-0.0}$

- Simultaneous fit on $D^{*0} \to \gamma D^0$ and $\pi^0 D^0$
- Significance $> 7.4\sigma$

No evident signal for γD^+D^-

- Relative branching ratio compared with $X(3872) \to \pi^+\pi^- J/\psi$

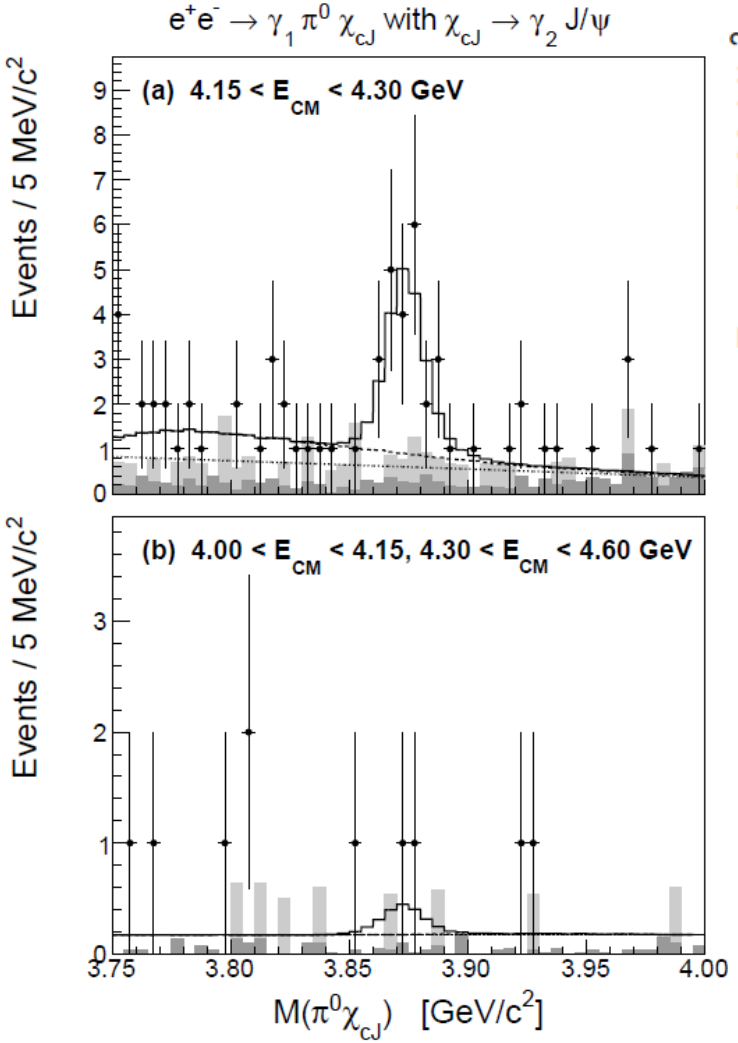
mode	$D^{*0}\bar{D}^0 + c.c.$	$\gamma J/\psi$	$\gamma\psi'$	γD^+D^-	$\omega J/\psi$	$\pi^0\chi_{c1}$
ratio	14.81 ± 3.80	0.79 ± 0.28	< 0.42	< 0.99	$1.7^{+0.4}_{-0.3} \pm 0.2$	$0.88^{+0.33}_{-0.27} \pm 0.10$

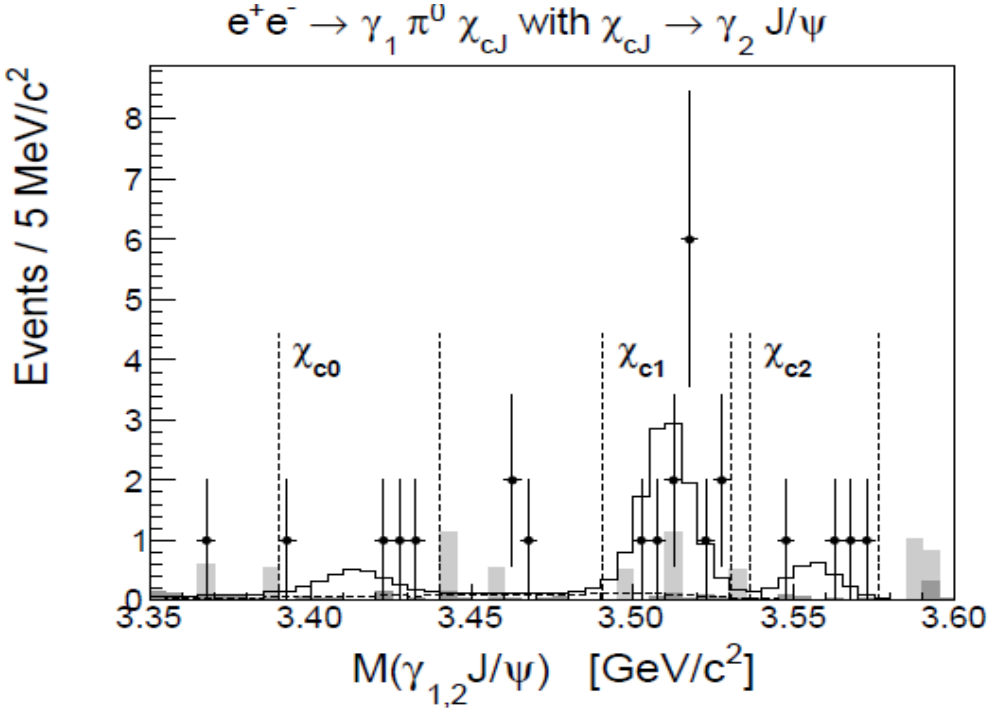
Observation of $e^+e^- \to \gamma X(3872)$, $X \to \pi^0\chi_{c1}$

arXiv: 1901.03992,
PRL 122, 202001

$e^+e^- \to \gamma X(3872)$, $X(3872) \to \pi^0\chi_{cJ}$ (with $\chi_{cJ} \to \gamma J/\psi$, $J/\psi \to l^+l^-$)

New!

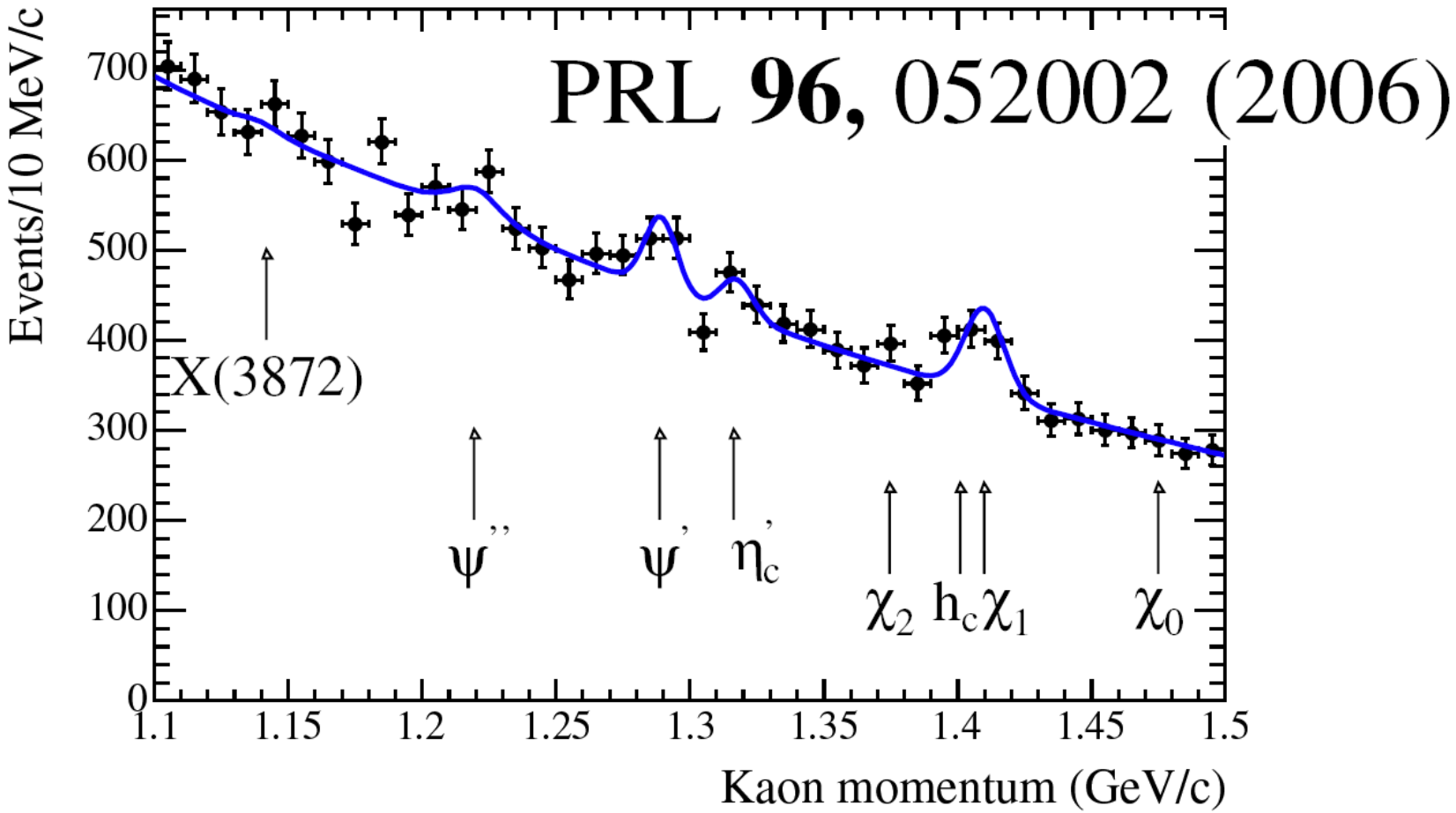




$$\frac{B(X(3872) \to \pi^0\chi_{c1})}{B(X(3872) \to \pi^+\pi^- J/\psi)} = 0.88^{+0.33}_{-0.27} \pm 0.10$$

- Clear signal of $X(3872)$ in Y(4260) region, $N_{X(3872)} = 16.9^{+5.2}_{-4.9}$
- No $X(3872)$ events outside of $Y(4260)$
- Clear cluster of $\chi_{c1}(1P)$ events in X(3872) mass window
- First observation of $X(3872) \to \pi^0\chi_{c1}(1P)$ with significance >5σ.

Production of X(3872) in B decays

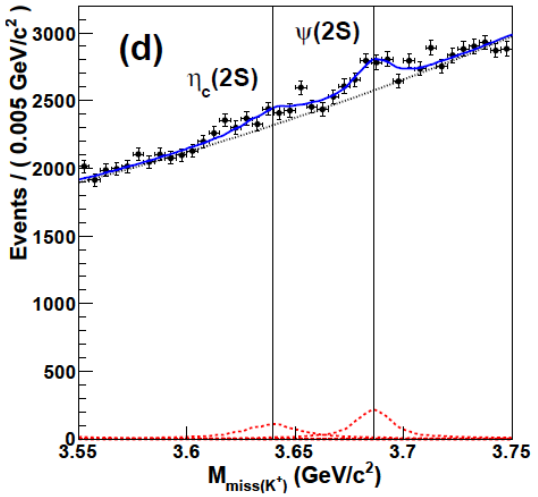


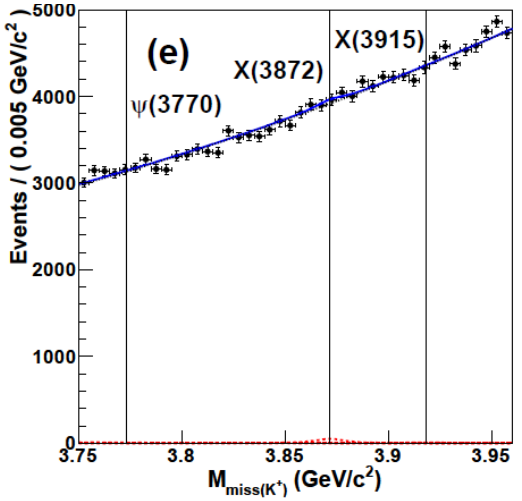
$$Bf\left(B^- \to X(3872)K^-\right) < 3.2\times10^{-4} \quad \text{at } 90\%\ \text{C. L.}$$

Production of X(3872) in B decays

arXiv:1709.06108, Phys. Rev. D 97 (2018) 012005, 711/fb

Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})
η_c	2590 ± 180	14.2	2.69 ± 0.02	$12.3 \pm 0.8 \pm 0.7$
J/ψ	1860 ± 140	13.7	2.61 ± 0.02	$9.1 \pm 0.7 \pm 0.5$
χ_{c0}	430 ± 190	2.2	2.59 ± 0.02	$2.1 \pm 0.9 \pm 0.1$ (< 3.4)
χ_{c1}	1230 ± 180	6.8	2.58 ± 0.02	$6.0 \pm 0.9 \pm 0.5$
$\eta_c(2S)$	1050 ± 240	4.1	2.66 ± 0.02	$4.9 \pm 1.1 \pm 0.3$
$\psi(2S)$	1410 ± 210	6.6	2.68 ± 0.02	$6.6 \pm 1.0 \pm 0.4$
$\psi(3770)$	-40 ± 310	-	2.66 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.4)
$X(3872)$	260 ± 230	1.1	2.69 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.7)
$X(3915)$	80 ± 350	0.3	2.69 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.9)





$$Bf\left(B^- \rightarrow X(3872)K^-\right) < 2.7 \times 10^{-4} \text{ at } 90\% \text{ C. L.}$$

The issues with past workflow

- The best B candidate is selected before looking for Kaons : it can happen that the signal side B is the best candidate ->the event is lost
  - Spurious interplay between tag and signal sides
- The best B candidate could be the wrong one : The kaon momentum is computed with the wrong boost, the signal is severely degraded

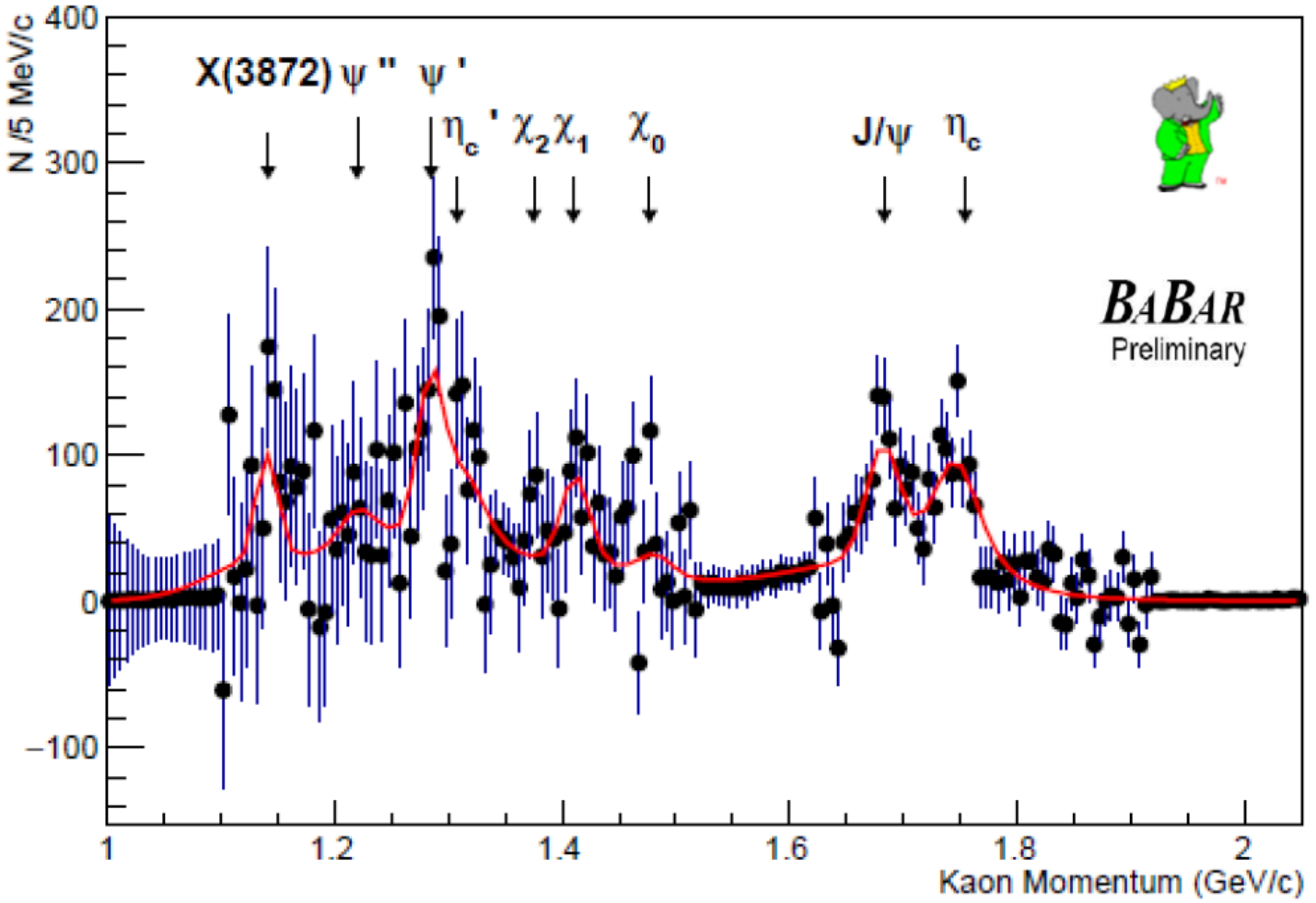
- One common solution : take all combinations: increased efficiency!!
  - For the X(3872) the efficiency gain is up to a factor 3.

New!

First evidence of the $B^+ \rightarrow X(3872) K^+$ transition

NN tuned for large mass region

N χ_1 = 1035 ± 193
N ψ'= 1278 ± 285
N X(3872)= 992 ± 285



Branching fraction results

Particle	Yield	BF(10^{-4})	
J/ψ	1463±133	10.1±0.29 (Ref from [12])	Recent BELLE-1 measurements Phys.Rev.D97(2018)012005
η_c	1334±129	9.6±1.2(stat)±0.4(sys)±0.3(ref)	8.9±0.6±0.5
			12.0±0.8±0.7
χ_{c0}	287±181	2.0±1.3(sat)±0.3 (sys)	2.0±0.9±0.1
χ_{c1}	1035±193	4.0±0.8(stat)±0.6(sys)	5.8±0.9±0.5
χ_{c2}	200±164	<2.0	
$\eta_c(2S)$	527±271	3.4±1.7(stat)±0.5(sys)	4.8±1.1±0.3
ψ'	1278±285	4.6±1(stat)±0.7(sys)	6.4±1.0±0.4
$\psi(3770)$	497±308	3.2±2.0(stat)±0.5(syst)	<2.3
$X(3872)$	992±285	2.1±0.6(stat)±0.3(syst)	1.2±1.1±0.1 <2.6

Consistent with PDG 2016 (ie our previous results!)

New!

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Global fit to X(3872) decays

Chunhua Li and CZY, arXiv:1907.09149, PRD 100, 094003 (2019)

Index (i)	Parameters	Values	Experiments
	$X(3872) \to \pi^+\pi^- J/\psi$	($\times 10^{-6}$)	
1	$B^+ \to X(3872)K^+$	$8.61 \pm 0.82 \pm 0.52$	Belle [14]
2		$8.4 \pm 1.5 \pm 0.7$	BaBar [15]
3	$B^0 \to X(3872)K^0$	$4.3 \pm 1.2 \pm 0.4$	Belle [14]
4		$3.5 \pm 1.9 \pm 0.4$	BaBar [15]
	$X(3872) \to \gamma J/\psi$	($\times 10^{-6}$)	
5	$B^+ \to X(3872)K^+$	$1.78^{+0.48}_{-0.44} \pm 0.12$	Belle [22]
6		$2.8 \pm 0.8 \pm 0.1$	BaBar [23]
7	$B^0 \to X(3872)K^0$	$1.24^{+0.76}_{-0.61} \pm 0.11$	Belle [22]
8		$2.6 \pm 1.8 \pm 0.2$	BaBar [23]
	$X(3872) \to \gamma\psi(3686)$	($\times 10^{-6}$)	
9	$B^+ \to X(3872)K^+$	$0.83^{+1.98}_{-1.83} \pm 0.44$	Belle [22]
10		$9.5 \pm 2.7 \pm 0.6$	BaBar [23]
11	$B^0 \to X(3872)K^0$	$1.12^{+3.57}_{-2.90} \pm 0.57$	Belle [22]
12		$11.4 \pm 5.5 \pm 1.0$	BaBar [23]
	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	($\times 10^{-4}$)	
13	$B^+ \to X(3872)K^+$	$0.77 \pm 0.16 \pm 0.10$	Belle [16]
14		$1.67 \pm 0.36 \pm 0.47$	BaBar [17]
15	$B^0 \to X(3872)K^0$	$0.97 \pm 0.46 \pm 0.13$	Belle [16]
16		$2.22 \pm 1.05 \pm 0.42$	BaBar [17]
	$X(3872) \to \omega J/\psi$	($\times 10^{-6}$)	
17	$B^+ \to X(3872)K^+$	$6 \pm 2 \pm 1$	BaBar [18]
18	$B^0 \to X(3872)K^0$	$6 \pm 3 \pm 1$	BaBar [18]
	Ratios		
19	$\frac{\mathcal{B}(X(3872)\to\gamma J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.79 ± 0.28	BESIII [19]
20	$\frac{\mathcal{B}(X(3872)\to D^{*0}D^0+c.c.)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	14.81 ± 3.80	BESIII [19]
21	$\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$1.6^{+0.4}_{-0.3} \pm 0.2$	BESIII [20]
22	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$0.88^{+0.33}_{-0.27} \pm 0.10$	BESIII [21]
23	$\frac{\mathcal{B}(X(3872)\to\gamma\psi(3686))}{\mathcal{B}(X(3872)\to\gamma J/\psi)}$	$2.46 \pm 0.64 \pm 0.29$	LHCb [24]
	$B^+ \to X(3872)K^+$	($\times 10^{-4}$)	
24		$2.1 \pm 0.6 \pm 0.3$	BaBar [27]
25		$1.2 \pm 1.1 \pm 0.1$	Belle [26]

$$\chi^2(x) = \sum_{i=1}^{25} \frac{(x_i - x)^2}{\sigma_i^2}$$

Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \to$ unknown	$(31.9^{+18.1}_{-31.5})\%$

Parameter index	1	2	3	4	5	6	7	8
1	1	0.87	0.84	0.75	0.64	0.79	-0.95	-0.87
2		1	0.79	0.71	0.56	0.74	-0.90	-0.77
3			1	0.78	0.54	0.73	-0.88	-0.78
4				1	0.49	0.65	-0.79	-0.69
5					1	0.51	-0.61	-0.56
6						1	-0.82	-0.72
7							1	0.84

New!

X(3872) decay BRs

Chunhua Li and CZY, arXiv:1907.09149
PRD 100, 094003 (2019)

A global fit to BaBar/Belle/LHCb/BESIII data (χ^2/ndf=25/17):

- $B(X(3872) \to \pi^+\pi^- J/\psi) = (4.1^{+1.9}_{-1.1})\%$
- $B(X(3872) \to \omega J/\psi) = (4.4^{+2.3}_{-1.3})\%$
- $B(X(3872) \to \gamma J/\psi) = (1.1^{+0.6}_{-0.3})\%$
- $B(X(3872) \to D^{*0}\overline{D}^0 + c.c.) = (52^{+25}_{-14})\%$
- $B(X(3872) \to \pi^0\chi_{c1}) = (3.6^{+2.2}_{-1.6})\%$
- $\underline{B(X(3872) \to \text{unknown}) = (32^{+18}_{-32})\%}$

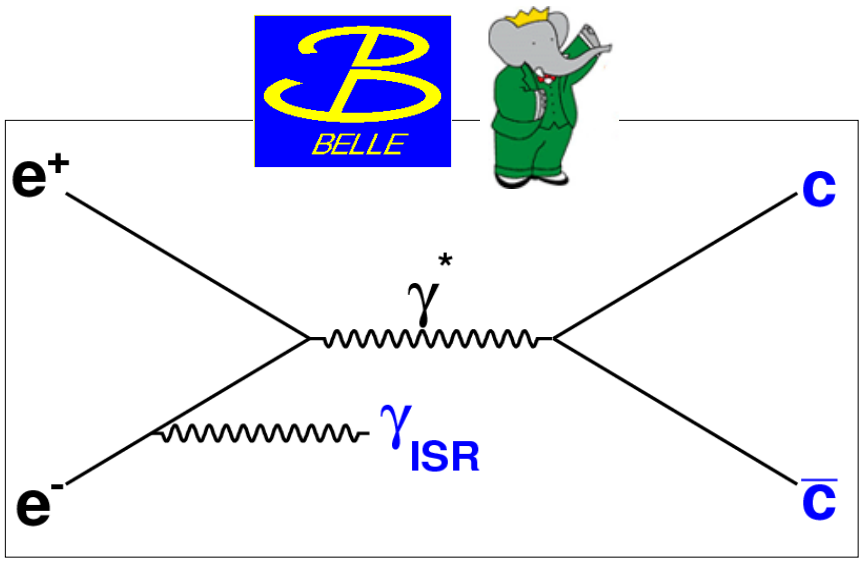
$\sigma(e^+e^- \to \gamma X(3872), X \to \pi^+\pi^- J/\psi)$=(0.29±0.11) pb @ 4.226 GeV

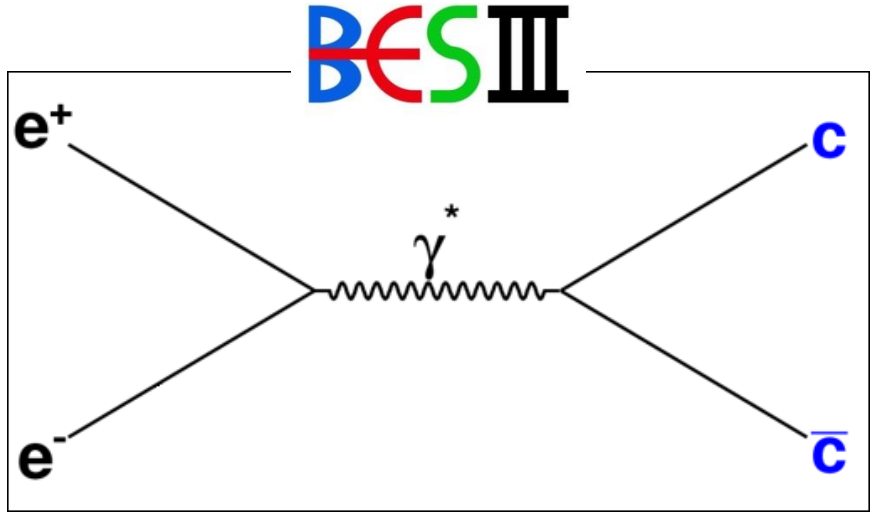
$\sigma(e^+e^- \to \gamma X(3872)) = (5.5^{+2.8}_{-3.6})$ pb @ 4.226 GeV

$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ = (85.1±5.1) pb @ 4.226 GeV

BESIII

The Y states

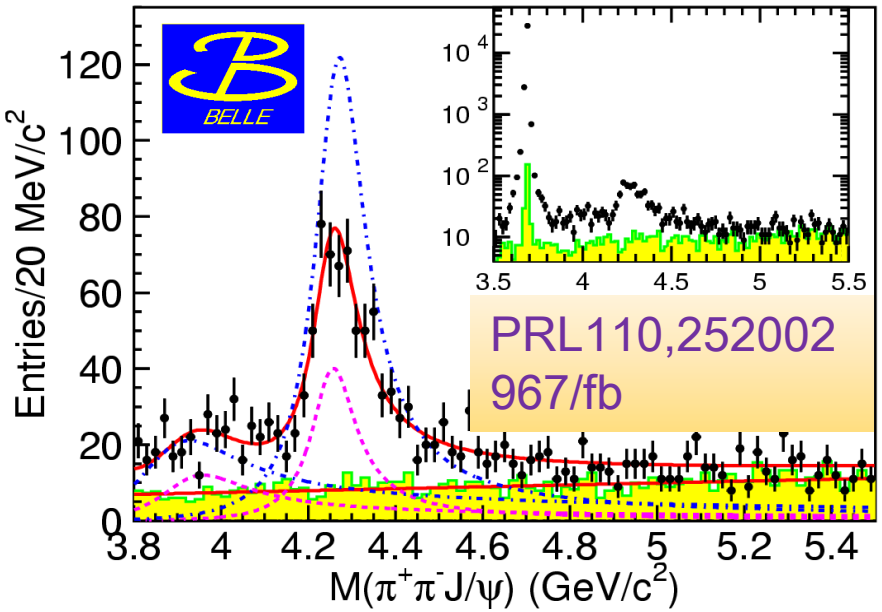




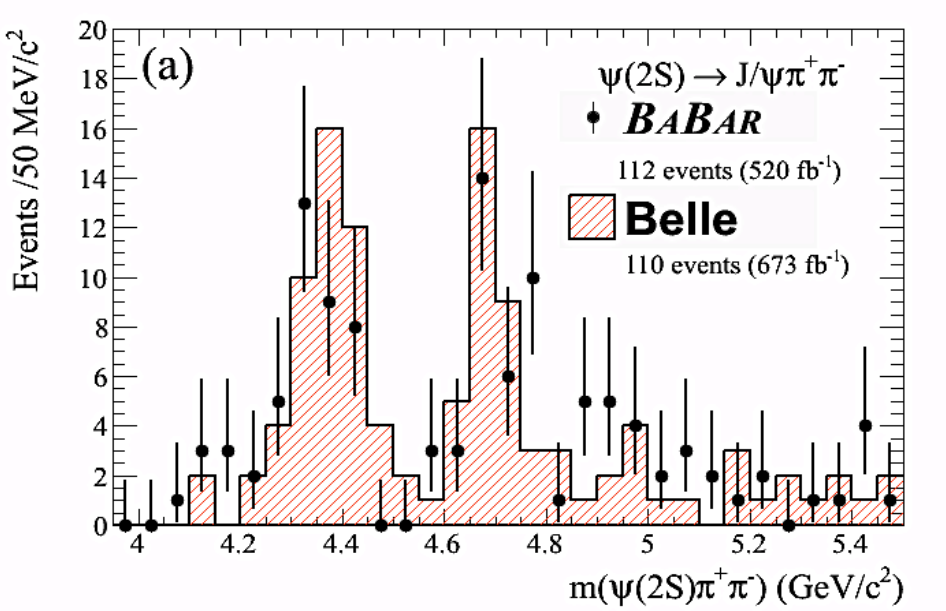
The Y states

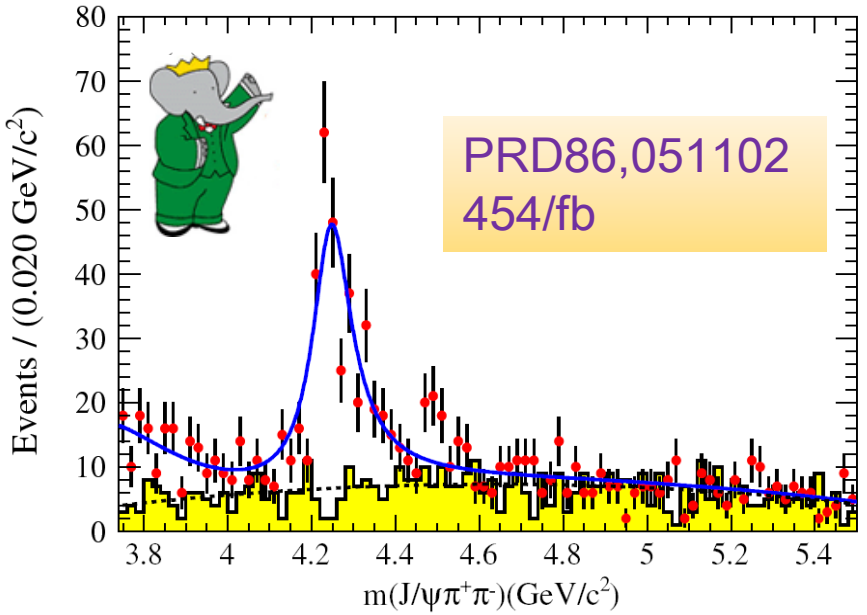
Belle: PRL99,142002, 670/fb
BaBar: PRD89, 111103, 520/fb

Y(4008)
Y(4260)
Y(4360)
Y(4630)
Y(4660)

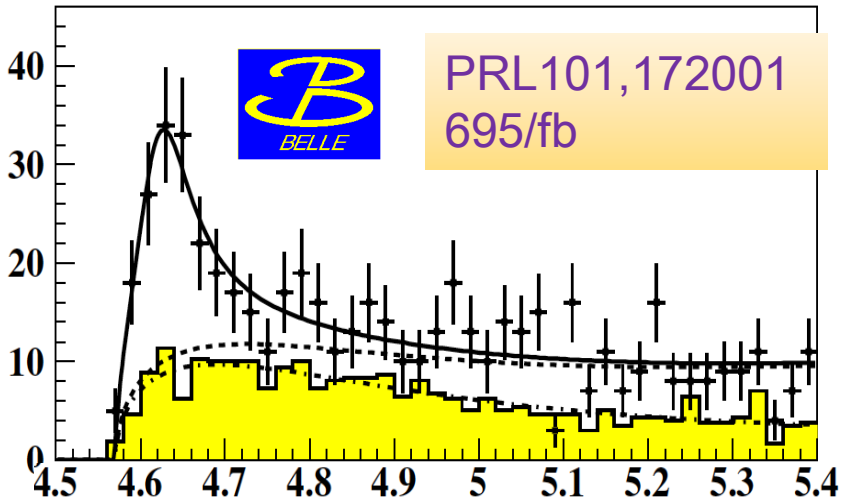


PRL110,252002
967/fb





PRD86,051102
454/fb

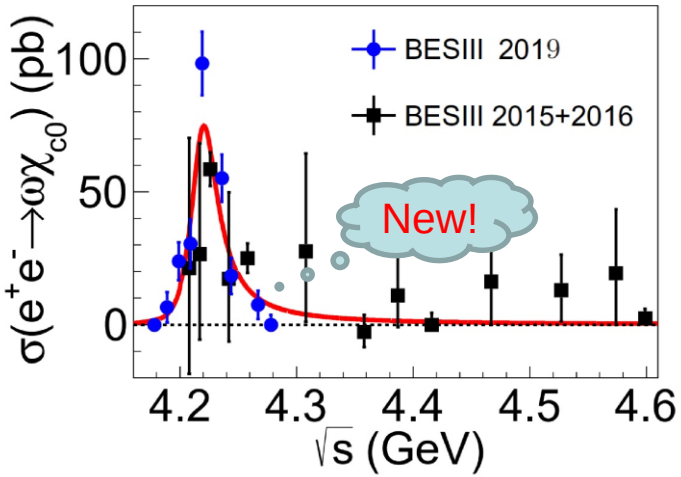


PRL101,172001
695/fb

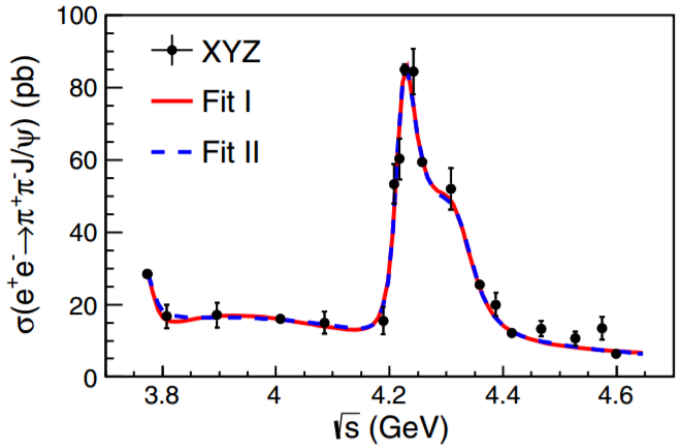
$M(\Lambda_c^+\Lambda_c^-)$

Y(4260)➔Y(4220): more modes

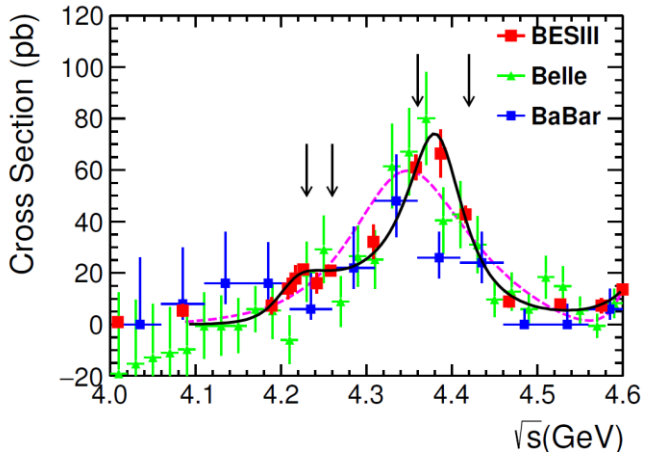
PRD99, 091103 (2019)



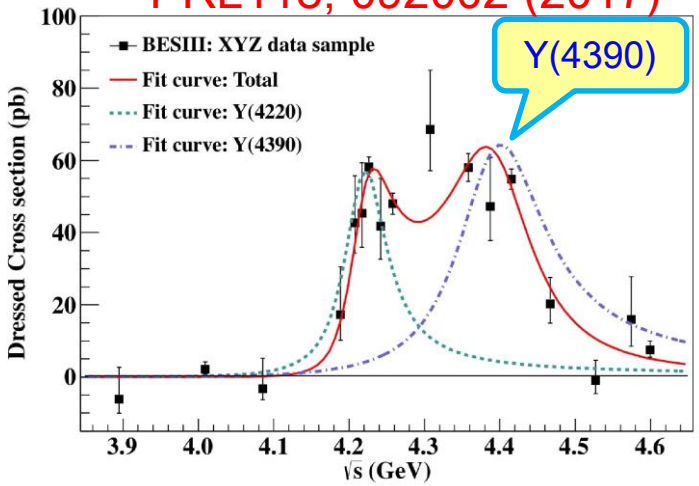
PRL118, 092001 (2017)



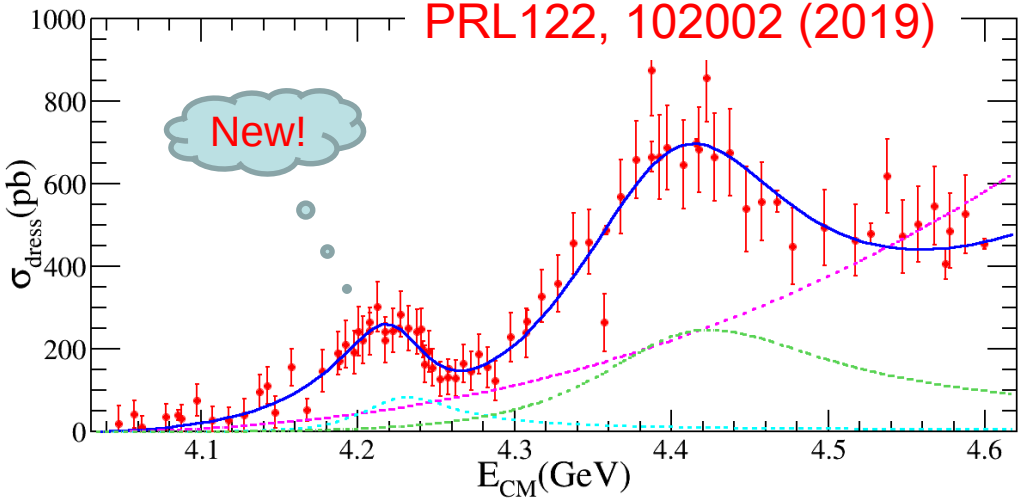
PRD96, 032004 (2017)



PRL118, 092002 (2017)



PRL122, 102002 (2019)



Y(4220) appears in $\omega\chi_{c0}$, $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^- h_c$, $D^0 D^{*-}\pi^+$

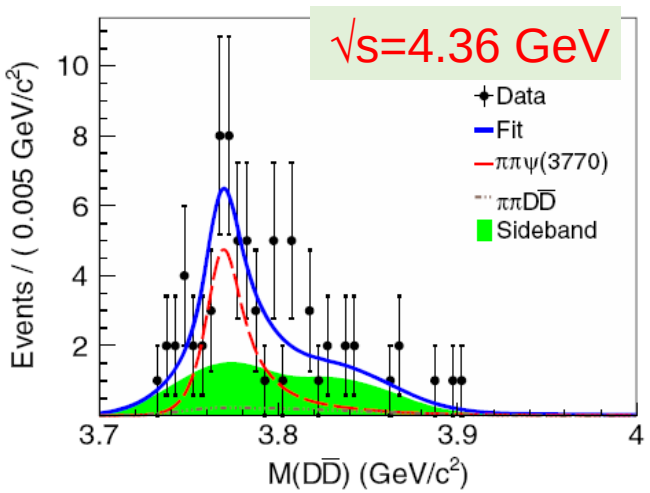
Mass~4220 MeV, width~ 60 MeV!

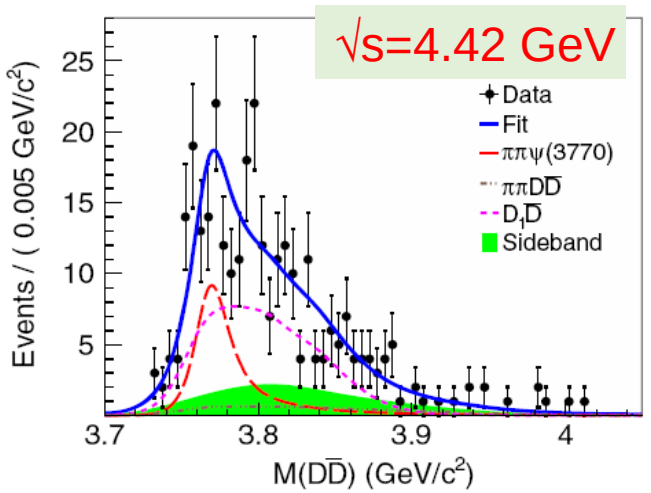
$e^+e^- \to \pi^+\pi^- D^0\bar{D}^0$ and $\pi^+\pi^- D^+D^-$

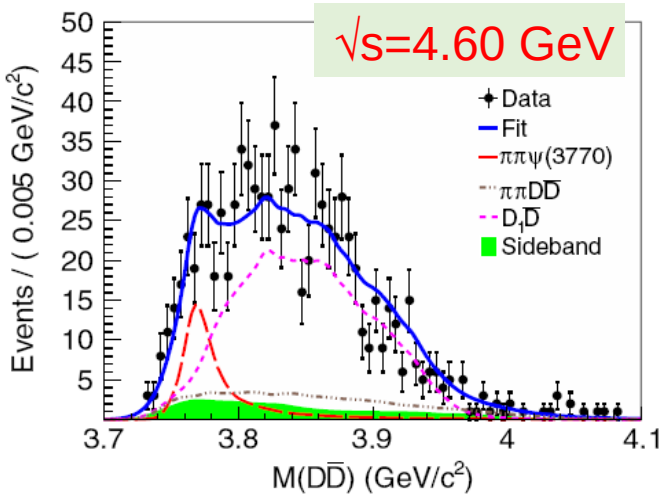
PRD100, 032005 (2019)

- Double tag analysis
- $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^+\pi^-\pi^0$
- $D^+ \to K^-\pi^+\pi^+, K^-\pi^+\pi^+\pi^0, K^0_S\pi^+, K^0_S\pi^+\pi^0$, and $K^0_S\pi^+\pi^+\pi^-$

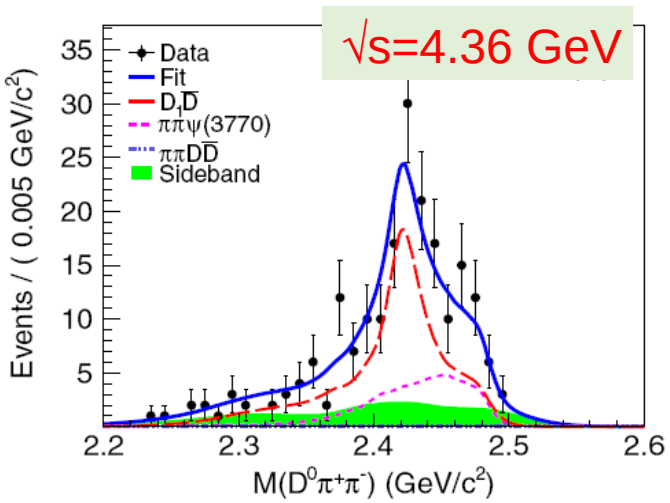
$e^+e^- \to \pi^+\pi^-\psi''$

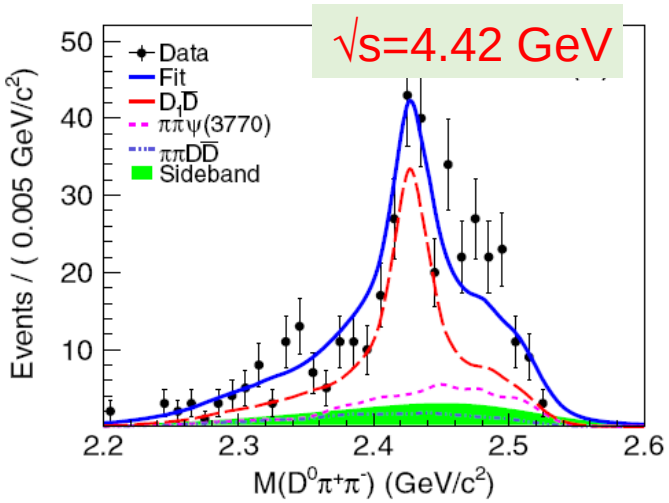


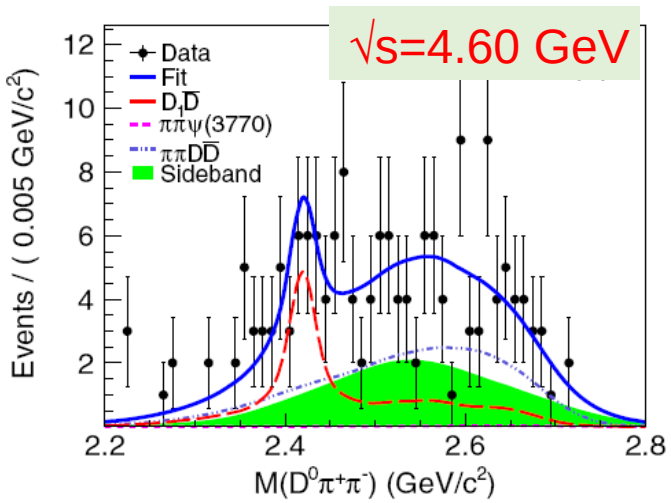




$e^+e^- \to D_1(2420)\bar{D}$



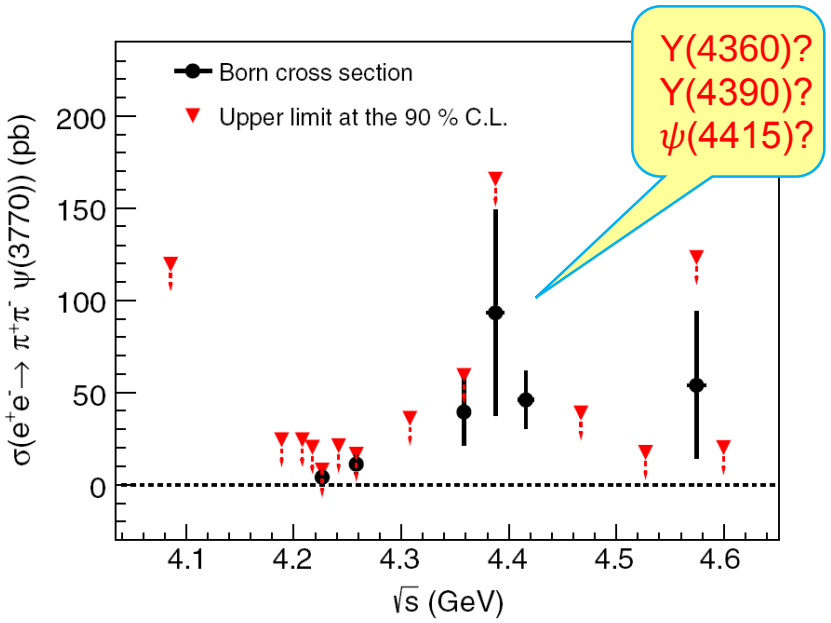




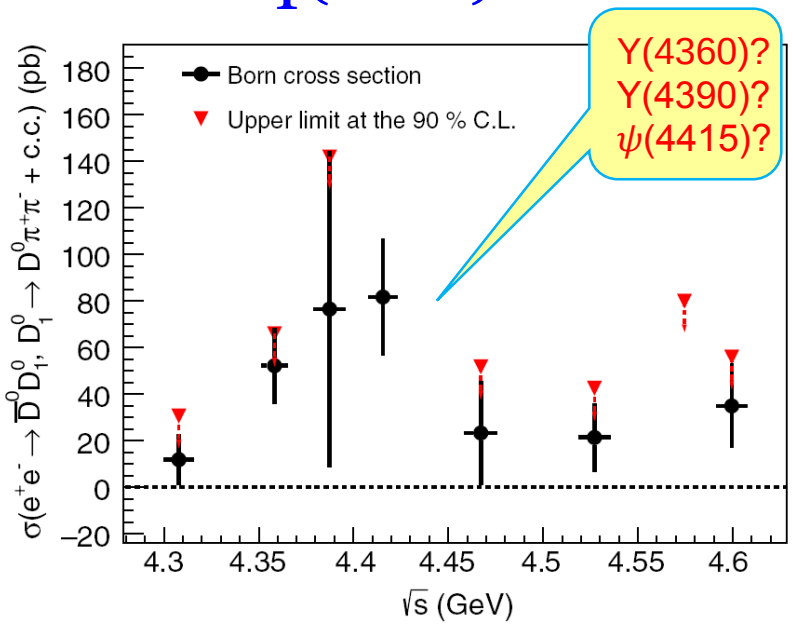
Cross sections of $e^+e^- \to \pi^+\pi^- D\bar{D}$

PRD100, 032005 (2019)

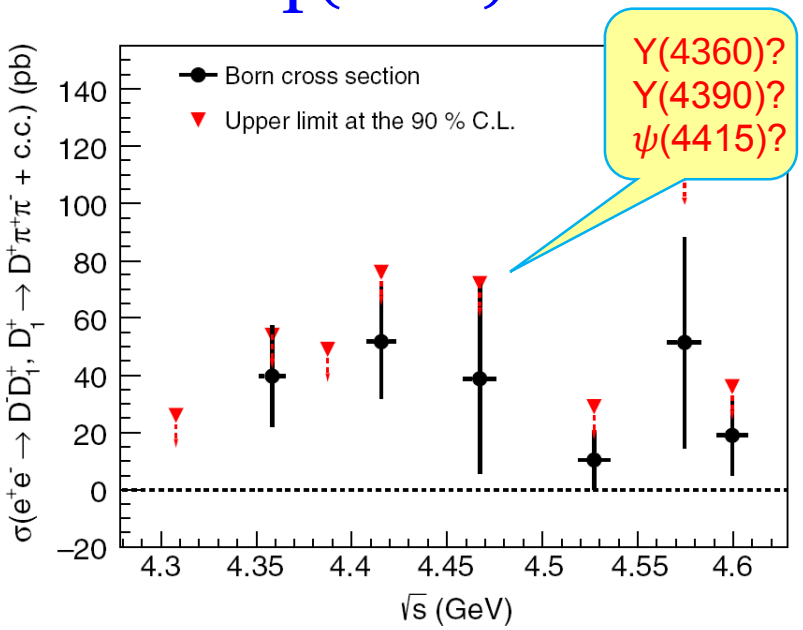
$e^+e^- \to \pi^+\pi^-\psi''$



$e^+e^- \to D_1^0(2420)\bar{D}^0 + \mathrm{c.c.}$



$e^+e^- \to D_1^+(2420)D^- + \mathrm{c.c.}$



- Two decay modes (D^+D^- and $D^0\bar{D}^0$) are used to reconstruct ψ''
- Three decay channels ($D^0\pi^+\pi^-$, $D^{*+}\pi^-$, and $D^+\pi^+\pi^-$) are used to search for $D_1(2420)$
- Clear structure at ~4.4 GeV in the line-shapes of $e^+e^- \to \pi^+\pi^-\psi''$ and $e^+e^- \to D_1(2420)\bar{D}$
- No abnormal threshold effect seen

$e^+e^- \to \pi^+\pi^- D^+D^-$

arXiv:1909.12478

- Single tag analysis $D^+ \to K^-\pi^+\pi^+$

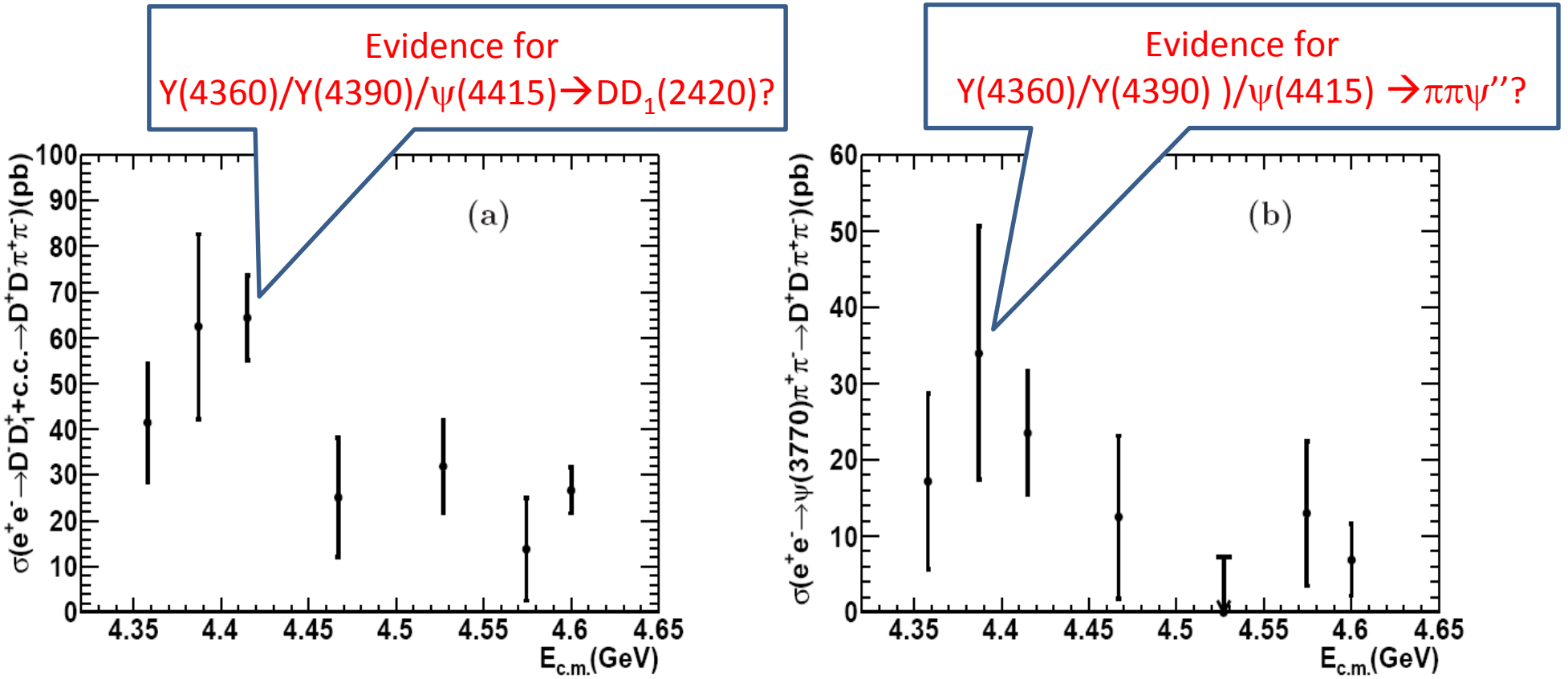
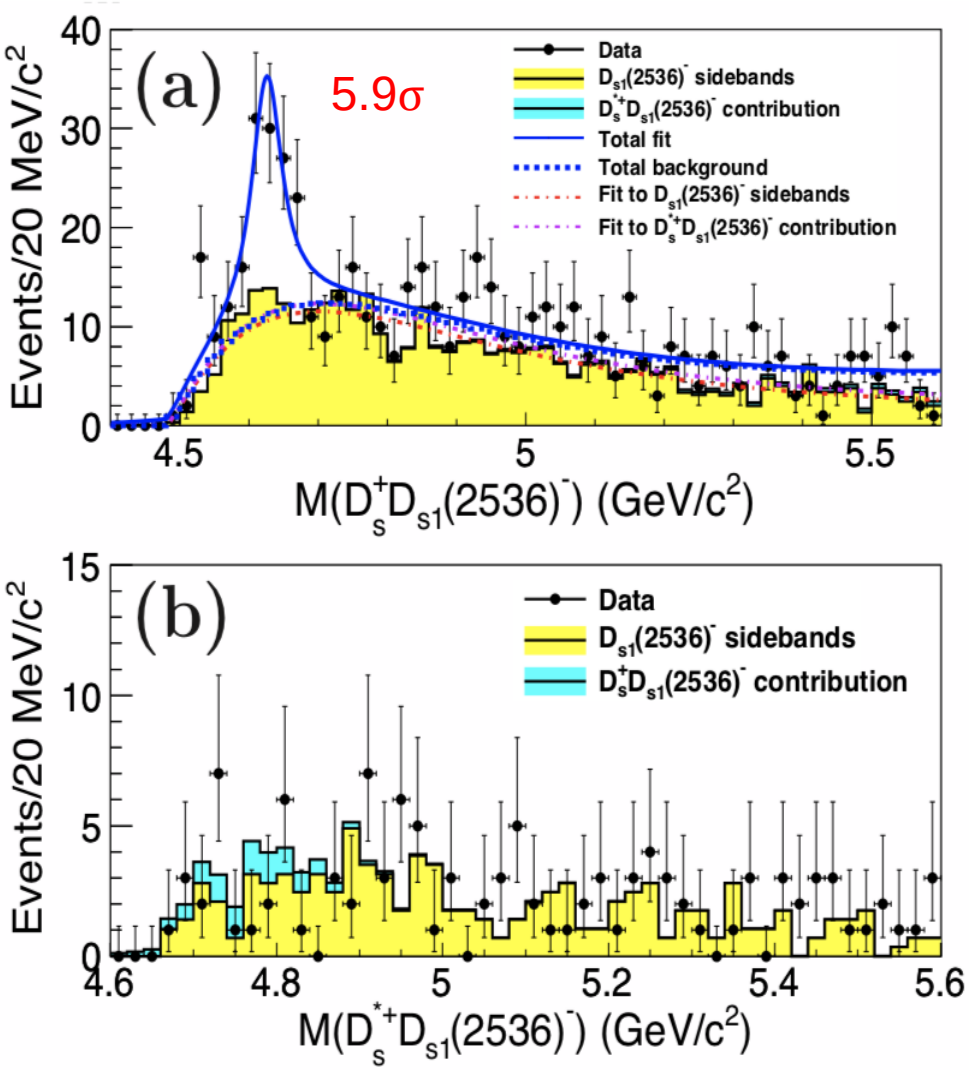


FIG. 4. The measured Born cross sections of the signal processes (a) $e^+e^- \to D_1(2420)^+D^- + c.c. \to D^+D^-\pi^+\pi^-$ and (b) $e^+e^- \to \psi(3770)\pi^+\pi^- \to D^+D^-\pi^+\pi^-$. The short horizontal line is the upper limit of cross section.

arXiv:1911.00671

Observation of $e^+e^- \to D_s^+ D_{s1}(2536)^- + c.c.$

New!



An unbinned simultaneous likelihood fit to the $M(D_s^+ D_{s1}(2536)^-)$ distribution for selected $D_{s1}(2536)^-$ candidates, normalized $D_{s1}(2536)^-$ mass sidebands, and $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background contribution.

Four components in the fit:

- signal: BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s1}(2536)^-$ mass sidebands: threshold function
- $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background: threshold function
- non-resonant: two-body phase space

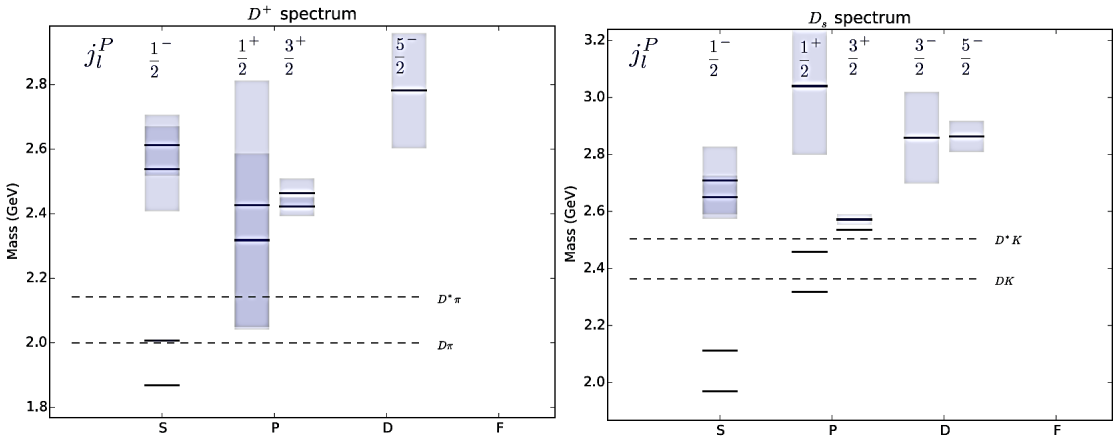
$M=(4625.9^{+6.2}_{-6.0}(\text{stat.}) \pm 0.4(\text{syst.})\ \text{MeV}/c^2$
$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat.}) \pm 4.0(\text{syst.})\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-) =$ $(14.3^{+2.8}_{-2.6}(\text{stat.}) \pm 1.5(\text{syst.})\ \text{eV}$

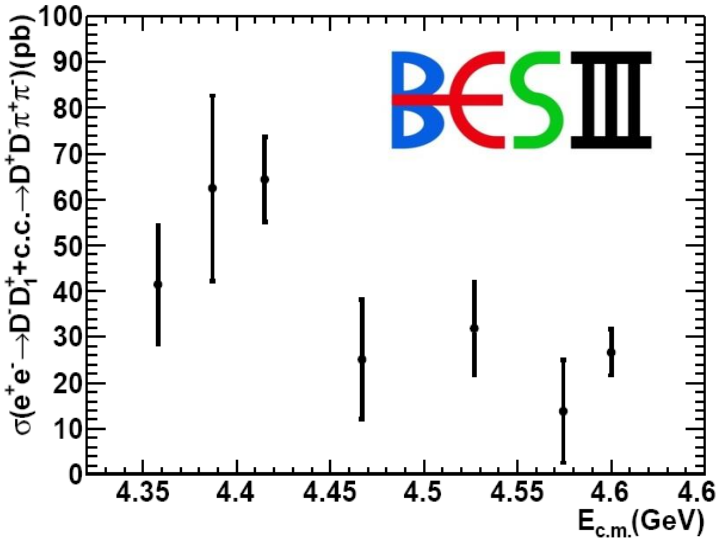
Possible background from $e^+e^- \to D_s^{*+}(\to D_s^+\gamma) D_{s1}(2536)^-$, where the photon from the D_s^{*+} remains undetected is studied in data, no obvious structure is observed in $e^+e^- \to D_s^{*+}(\to D_s^+\gamma) D_{s1}(2536)^-$.

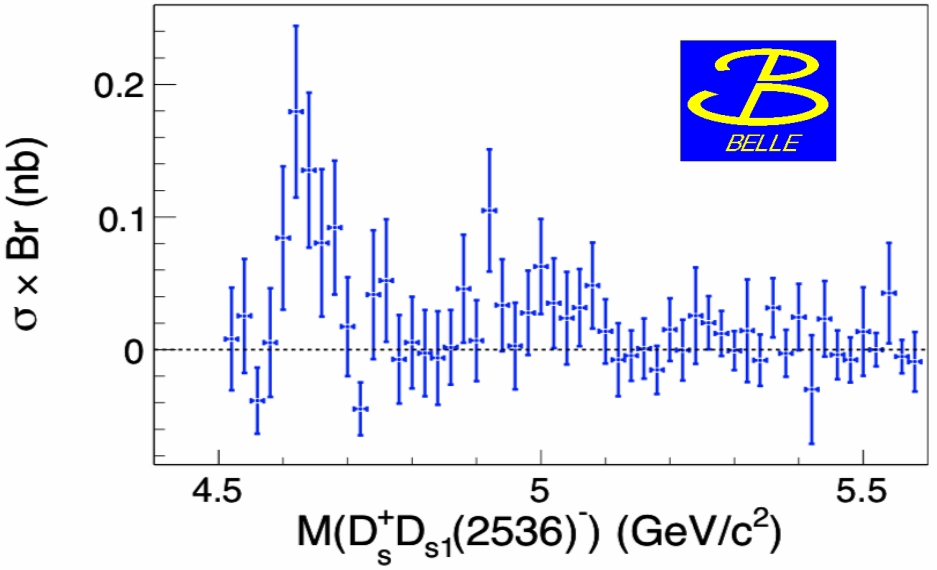
Comparison between $D_1(2420)\bar{D}$ and $D_{s1}(2536)^+D_s^-$

D_1 and D_{s1} are $j_l^P = 3/2^+$ heavy-light states;

Y(4360)/Y(4390)/ψ(4415) & Y(4630)/Y(4660) are just above DD_1 and D_sD_{s1} thresholds, respectively.



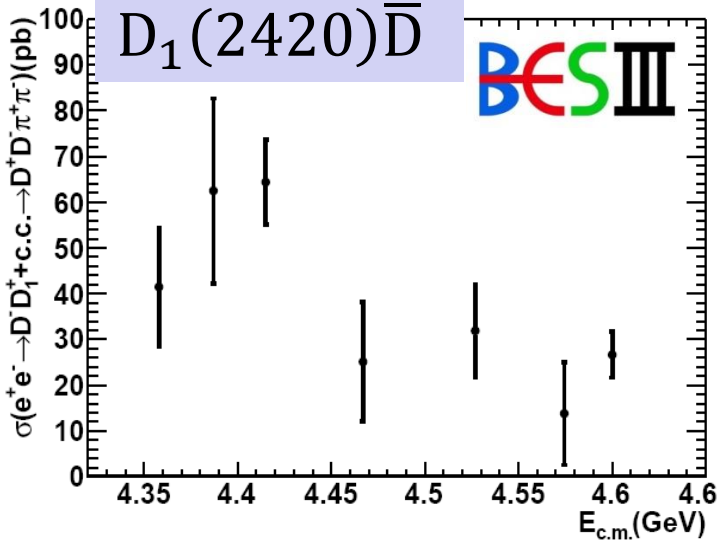




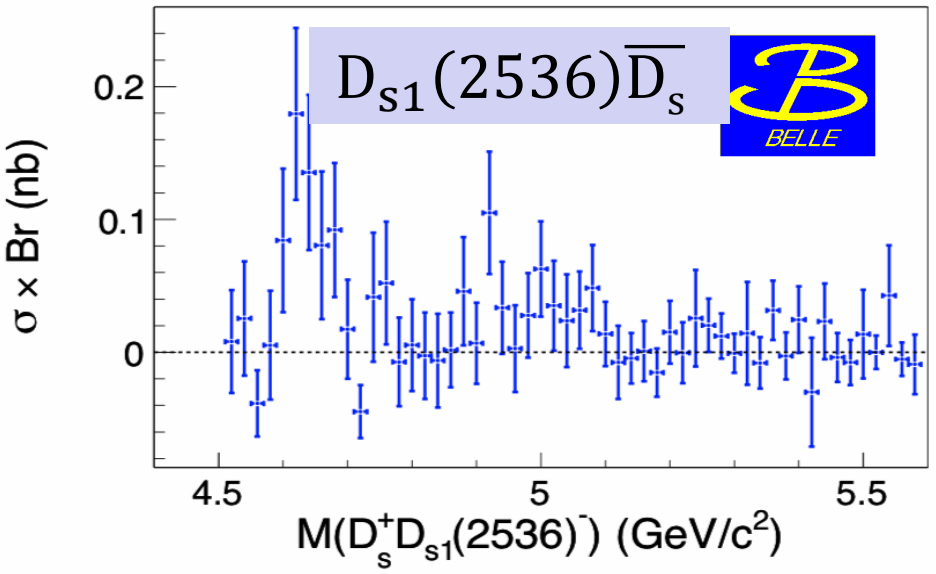
Do Y(4360)/Y(4390)/ψ(4415) & Y(4630)/Y(4660) have similar structure?

Other $j_l^P = 3/2^+$ states: $D_2(2460)\bar{D}$ and $D_{s2}(2573)^+D_s^-$

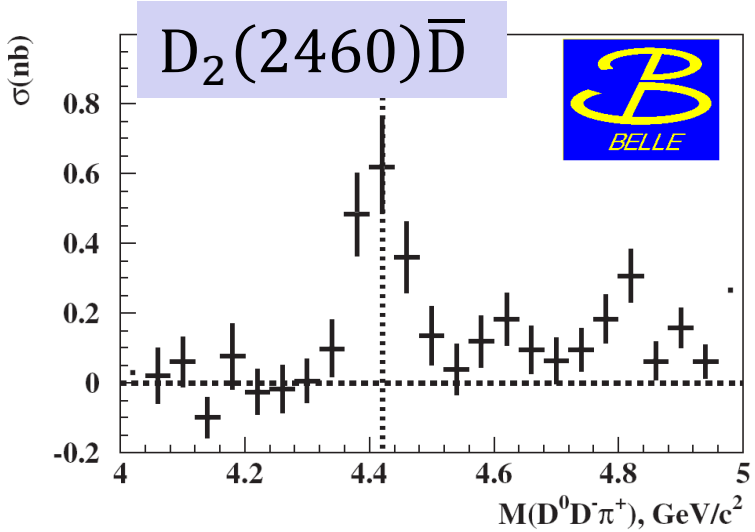
$D_1(2420)\bar{D}$



$D_{s1}(2536)\bar{D}_s$



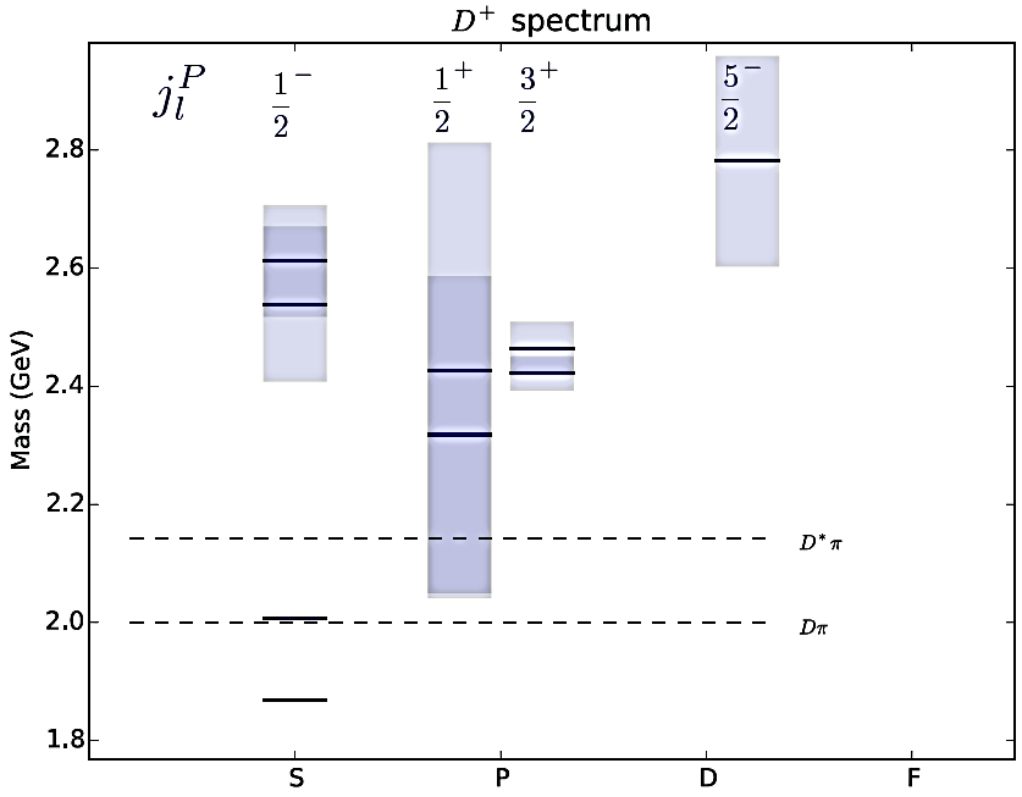
$D_2(2460)\bar{D}$

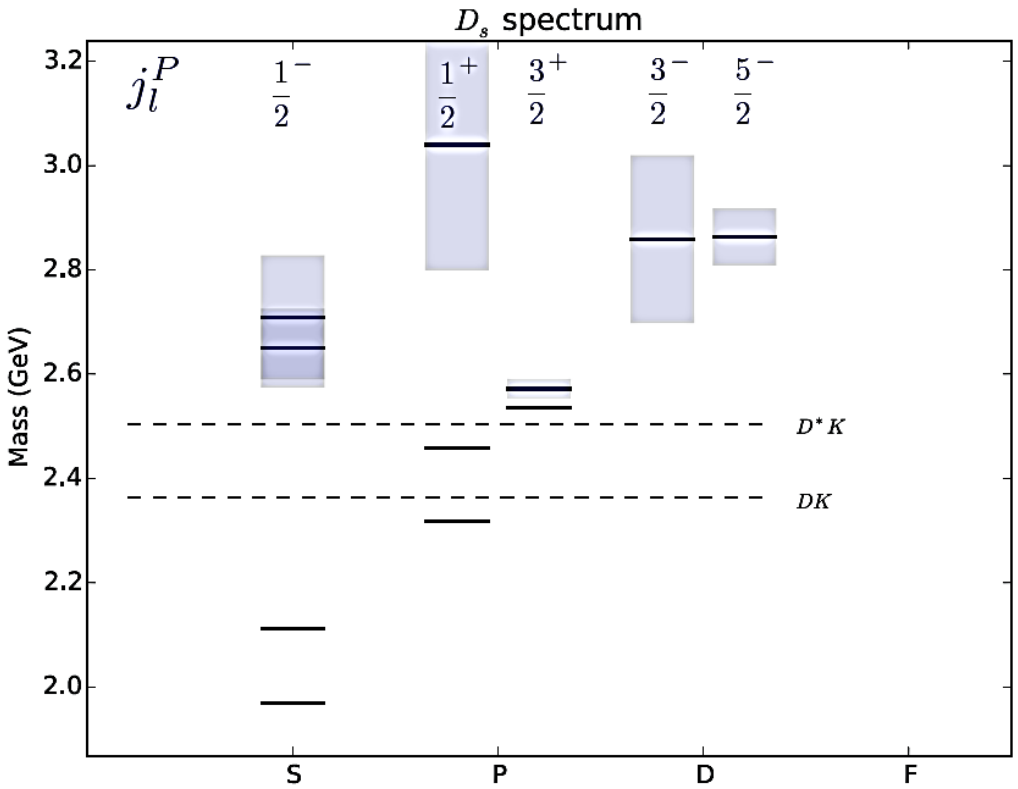


$D_{s2}(2573)\bar{D}_s$?

Do Y(4360)/Y(4390)/ψ(4415) & Y(4630)/Y(4660) have similar structure?

Are $j_l^P = 1/2^+$ heavy-light states also produced by resonances?





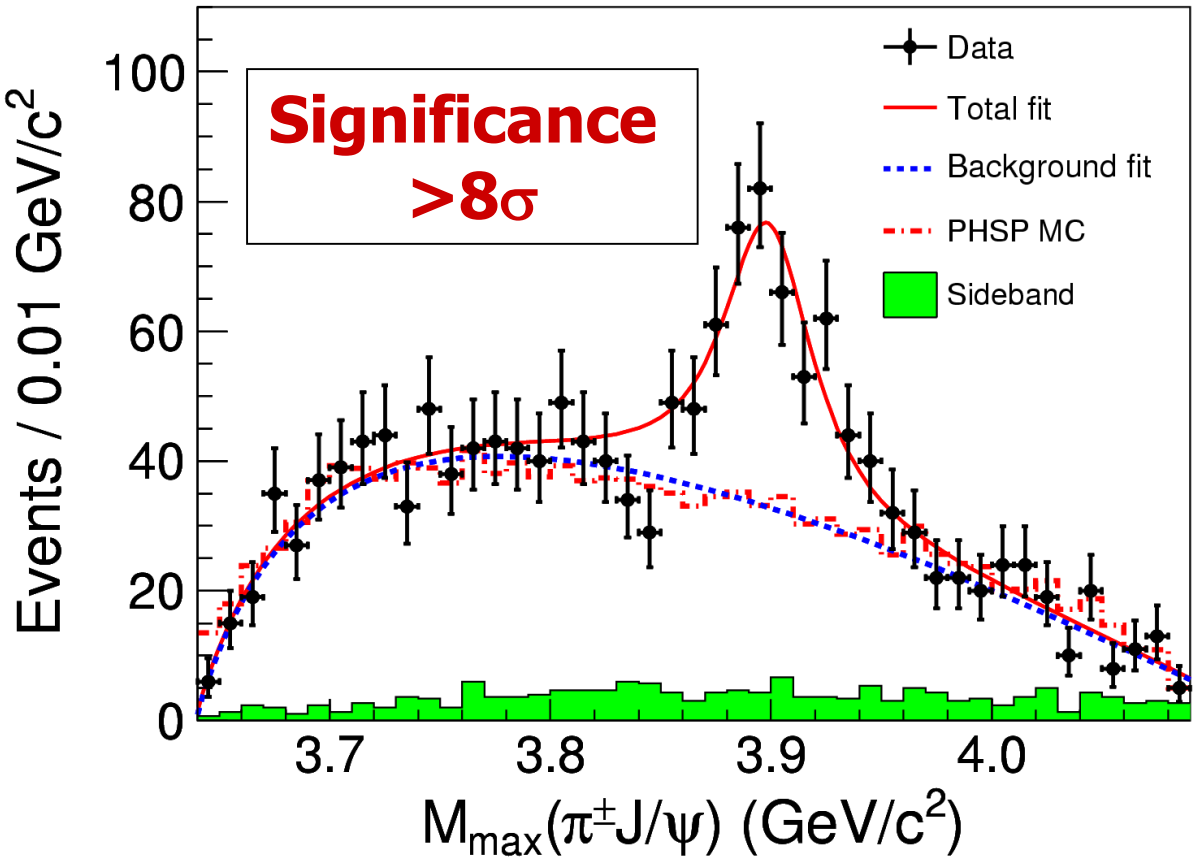
D_0 and D_1 are wide

$D_{s0}(2317)$ & $D_{s1}(2460)$ are narrow and $D_s^* D_{s0}(2317)$ & $D_s D_{s1}(2460)$ thresholds ~ 4430 MeV

BESIII has a data sample at ~ 4440 MeV!

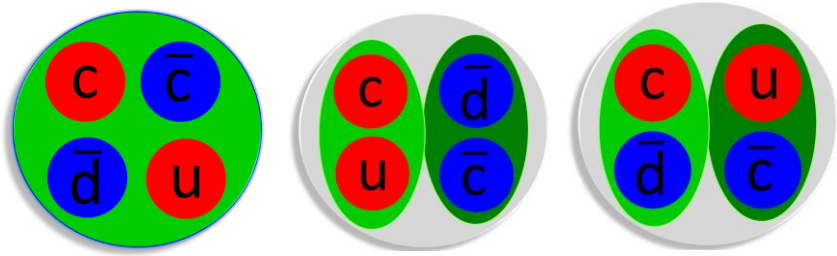
$Z_c(3900)$ & $Z_c(4020)$

Discovery of the $Z_c(3900)$



In $e^+e^- \to \pi^+\pi^- J/\psi$ events at 4.26 GeV, a particle decays into $\pi^\pm J/\psi$ is observed!

- Couples to $\bar{c}c$
- Has electric charge
- At least 4 quarks
- A tetraquark state?
  A $\bar{D}D^*$ molecule?

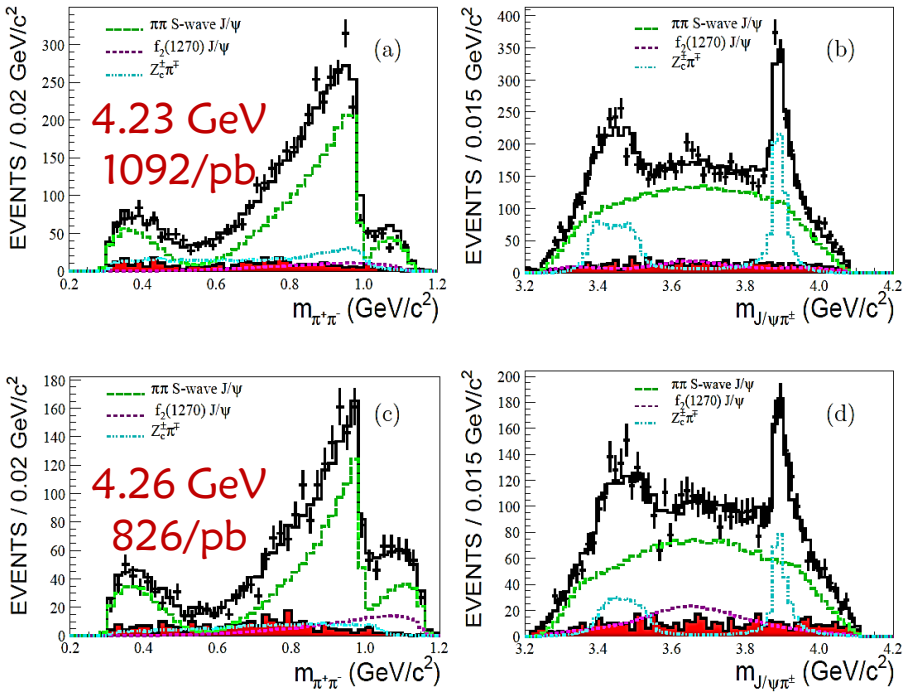


- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

PRL110, 252001 (2013)

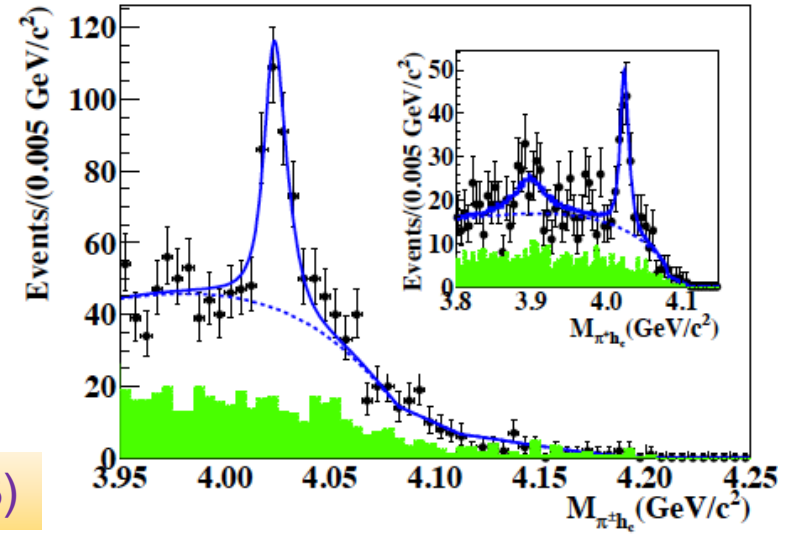
Properties of the $Z_c(3900)$ & $Z_c(4020)$

- $I^G=1^+$
- $J^{PC}=1^{+-}$
- Decay modes
  - ✓ $\pi J/\psi$
  - ✓ $\bar{D}D^*$
  - ✓ $\rho\eta_c$ (4.2σ)
  - ✓ πh_c (2.1σ)
  - ✓ Not to light hadrons



- Partner state: $Z_c(4020)$
  - ✓ $I^G=1^+$; $J^{PC}=?^{?-}$
  - ✓ Couples to πh_c and $\bar{D}^*D^*$
  - ✓ Couples possibly to $\pi\psi'$
  - ✓ M=4022.9±2.8 MeV
  - ✓ Γ=7.9±3.7 MeV

PRL 111, 242001 (2013)



PRL 119, 072001 (2017)

PWA of $e^+e^-\to\pi^+\pi^-J/\psi$

- Asymmetric line shape
- JP=1+ preferred over 0-, 1-, 2-, 2+ by at least 7σ.
- Significant $f_0(980)$ contribution
- $\pi\pi$ D-wave fraction increases as E_{cm} increases

Evidence for $Z_c \to \rho\eta_c$

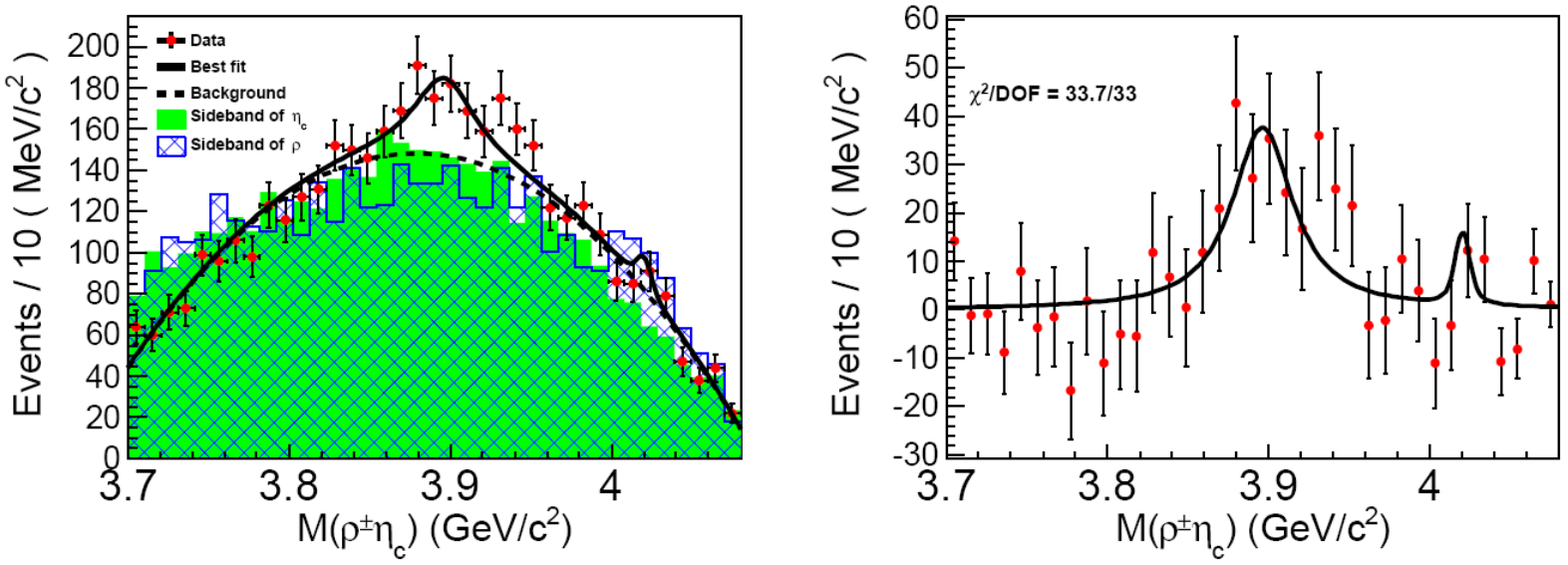
New

arXiv:1906.00831

- $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$
- $\eta_c \to$ 9 hadronic decays

Decay mode	BR
$\eta_c \to p\bar{p}$	~0.13%
$\eta_c \to 2(K^+K^-)$	~0.15%
$\eta_c \to \pi^+\pi^-K^+K^-$	~1.50%
$\eta_c \to K^+K^-\pi^0$	~1.20%
$\eta_c \to p\bar{p}\pi^0$	~0.18%
$\eta_c \to K_SK\pi$	~1.80%
$\eta_c \to \pi^+\pi^-\eta$	~1.60%
$\eta_c \to K^+K^-\eta$	~0.57%
$\eta_c \to \pi^+\pi^-\pi^0\pi^0$	~2.40%

- Strong evidence of $e^+e^- \to \pi Z_c$, $Z_c \to \rho\eta_c$ at $\sqrt{s} = 4.23$, statistical significance is 4.2σ. (3.9σ including systematics)
- $e^+e^- \to \pi Z_c'$, $Z_c' \to \rho\eta_c$ not seen.



$e^+e^- \to \pi Z_c$, $Z_c \to \rho\eta_c$ @ 4.23 GeV

Evidence for $Z_c \to \rho\eta_c$

New

arXiv:1906.00831

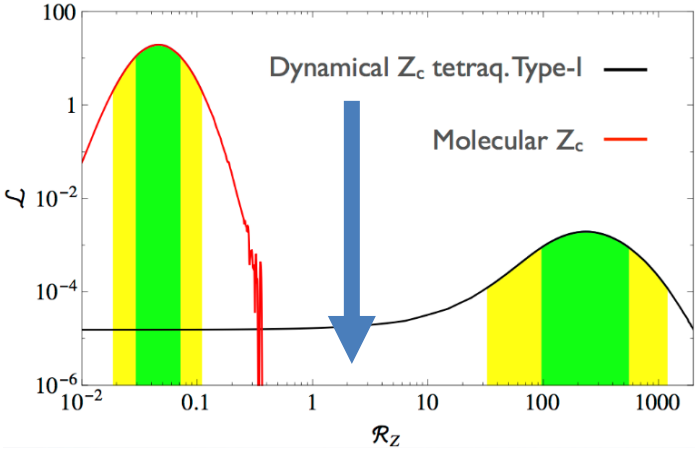
- **Measure Born cross section at 4.23 GeV:**

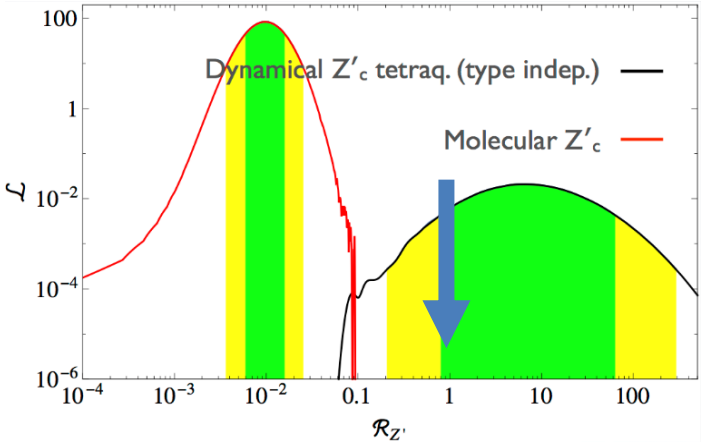
$\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46\ ^{+12}_{-11} \pm 10\ )$ **pb**

$\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c) = (48 \pm 11 \pm 11\ )$ **pb**

Ratio	Measurement	Tetraquark	Molecule
$R_{Z_c(3900)}$	2.3 ± 0.8 [29]	230^{+330}_{-140} [12] $0.27^{+0.40}_{-0.17}$ [12] 0.66 [13] 0.56 ± 0.24 [14] 0.95 ± 0.40 [15] 1.08 ± 0.88 [16] 1.28 ± 0.37 [17] 1.86 ± 0.41 [17]	$0.046^{+0.025}_{-0.017}$ [12] 1.78 ± 0.41 [17] 6.84×10^{-3} [18] 0.12 [19]
$R_{Z_c(4020)}$	< 1.2 [4]	$6.6^{+56.8}_{-5.8}$ [12]	$0.010^{+0.006}_{-0.004}$ [12]

A.Esposito, A.L.Guerrieri, A.Pilloni, Phys. Lett. B 746, 194 (2015)





$$R_z = \frac{B(Z_c \to \rho\eta_c)}{B(Z_c \to \pi J/\psi)}$$

$$R_{z'} = \frac{B(Z'_c \to \rho\eta_c)}{B(Z'_c \to \pi h_c)}$$

[12] A. Esposito, A. L. Guerrieri and A. Pilloni, Phys. Lett. B **746**, 194 (2015).
[13] L. Maiani, V. Riquer, R. Faccini, F. Piccinini, A. Pilloni and A. D. Polosa, Phys. Rev. D **87**, 111102 (2013).
[14] S. S. Agaev, K. Azizi and H. Sundu, Phys. Rev. D **93**, 074002 (2016).
[15] J. M. Dias, F. S. Navarra, M. Nielsen and C. M. Zanetti, Phys. Rev. D **88**, 016004 (2013).
[16] Z. G. Wang and J. X. Zhang, Eur. Phys. J. C **78**, 14 (2018).
[17] F. Goerke, T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij and P. Santorelli, Phys. Rev. D **94**, 094017 (2016).
[18] S. Patel, M. Shah, K. Thakkar and P. C. Vinodkumar, PoS Hadron **2013**, 189 (2013).
[19] H. W. Ke, Z. T. Wei and X. Q. Li, Eur. Phys. J. C **73**, 2561 (2013).

Z_c states have both tetraquark and molecule components?

Refined calculations needed!

Summary

- BESIII achieved a lot in the experimental study of the XYZ states.
- X(3872) BRs are determined, still ~30% decays unknown.
- Y→ $j_l^P=1/2^-$ + $j_l^P=3/2^+$ heavy-light mesons may help reveal the nature of Y(4360)/Y(4390)/ψ(4415) & Y(4630)/Y(4660) states.
- Z_c states are still very puzzling.
- More analyses with BESIII data are on going, lots of fun ahead, and also lots of *Opportunities and Challenges* for QCD!

Thanks a lot!

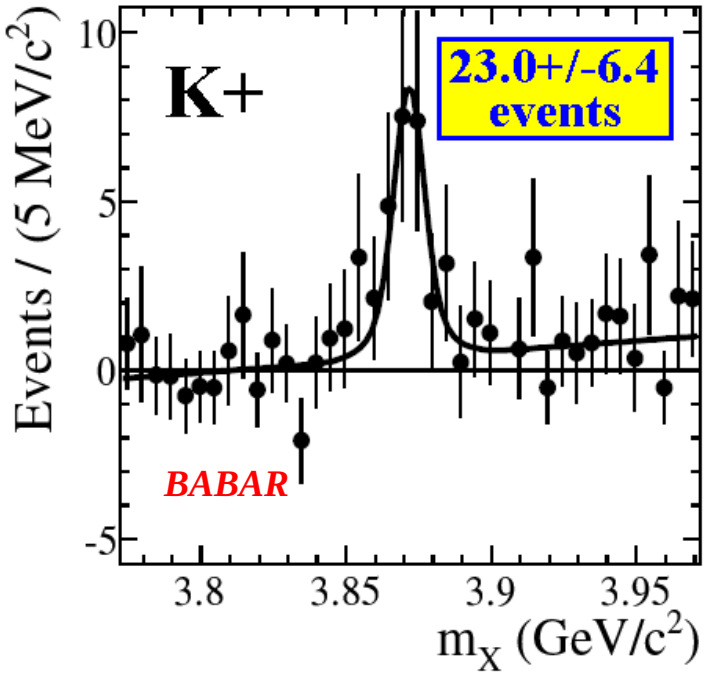
Thank you!

谢谢！

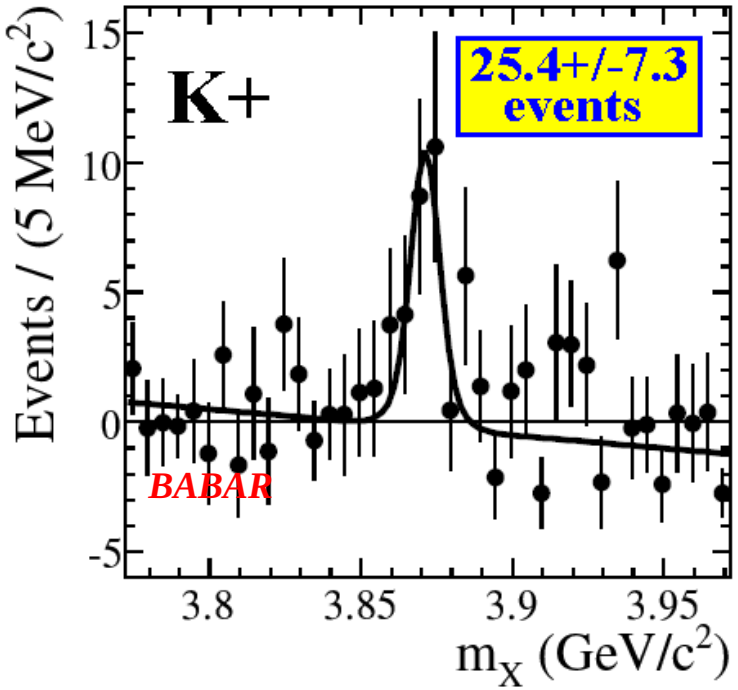
B→KX(3872), X→γJ/ψ & γψ′ from BaBar

PRL 102, 132001 (2009), 424/fb

$X(3872) \to J/\psi\,\gamma$ 3.6σ



$X(3872) \to \psi(2S)\,\gamma$ 3.5σ



$Bf(B^+ \to X_{3872} K^+) \times (X_{3872} \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$

$Bf(B^+ \to X_{3872} K^+) \times (X_{3872} \to \psi'\gamma) = (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$

$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 3.4 \pm 1.4$$

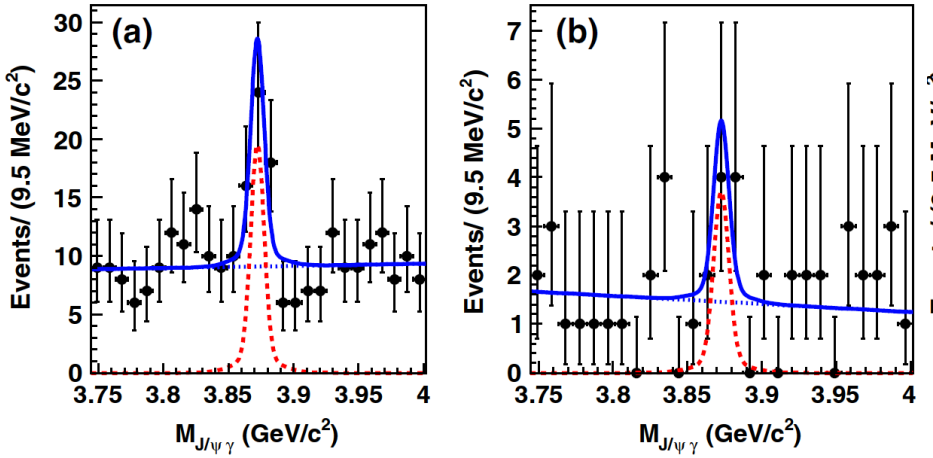
$B(X_{3872} \to \gamma\psi') > B(X_{3872} \to \gamma J/\psi)$ ←bad for molecules

Swanson PLB 598, 197 (2004)

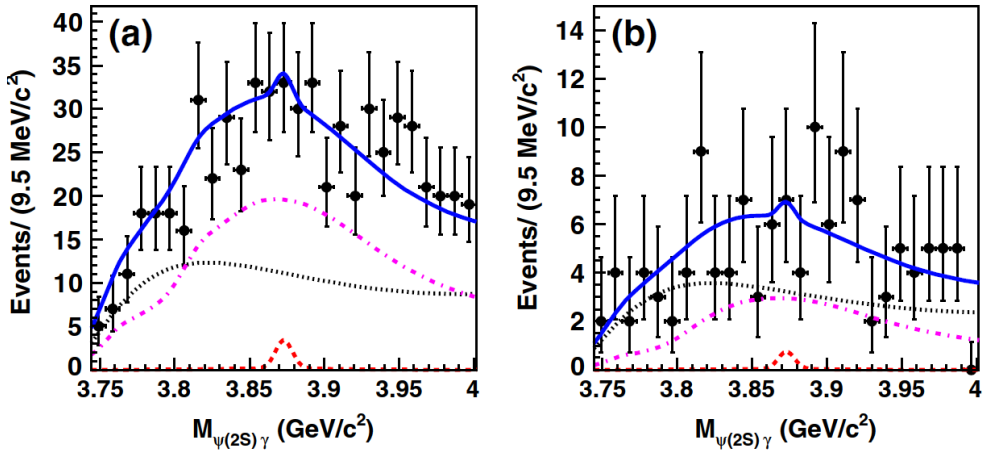
B→KX(3872), X→γJ/ψ & γψ′ from Belle

PRL 107, 091803 (2011), 711/fb

X(3872)→ J/ψ γ



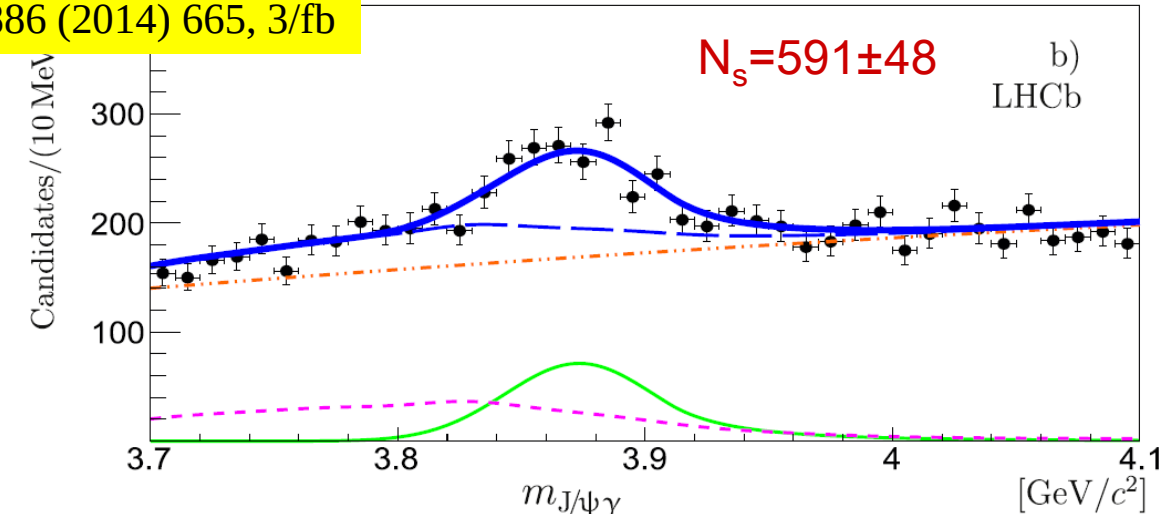
X(3872)→ ψ(2S) γ



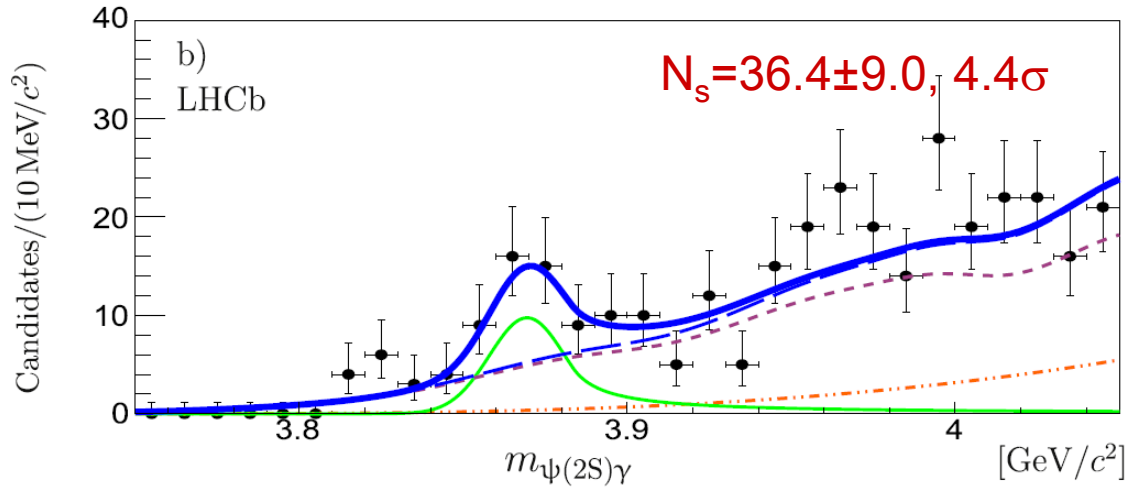
Decay	ϵ (%)	Yield (Y)	Branching fraction	$\mathcal{S}(\sigma)$
$B \to X(3872)(\to J/\psi\gamma)K$			$\mathcal{B}$ ($\times 10^{-6}$)	
K^+	18.3	$30.0^{+8.2}_{-7.4}$	$1.78^{+0.48}_{-0.44} \pm 0.12$	4.9
K^0	14.5	$5.7^{+3.5}_{-2.8}$	$1.24^{+0.76}_{-0.61} \pm 0.11$ (< 2.4)	2.4
$B \to X(3872)(\to \psi'\gamma)K$			$\mathcal{B}$ ($\times 10^{-6}$)	
K^+	14.7	$5.0^{+11.9}_{-11.0}$	$0.83^{+1.98}_{-1.83} \pm 0.44$ (< 3.45)	0.4
K^0	10.8	$1.5^{+4.8}_{-3.9}$	$1.12^{+3.57}_{-2.90} \pm 0.57$ (< 6.62)	0.3

B→KX(3872), X→γJ/ψ & γψ′ from LHCb

NPB 886 (2014) 665, 3/fb



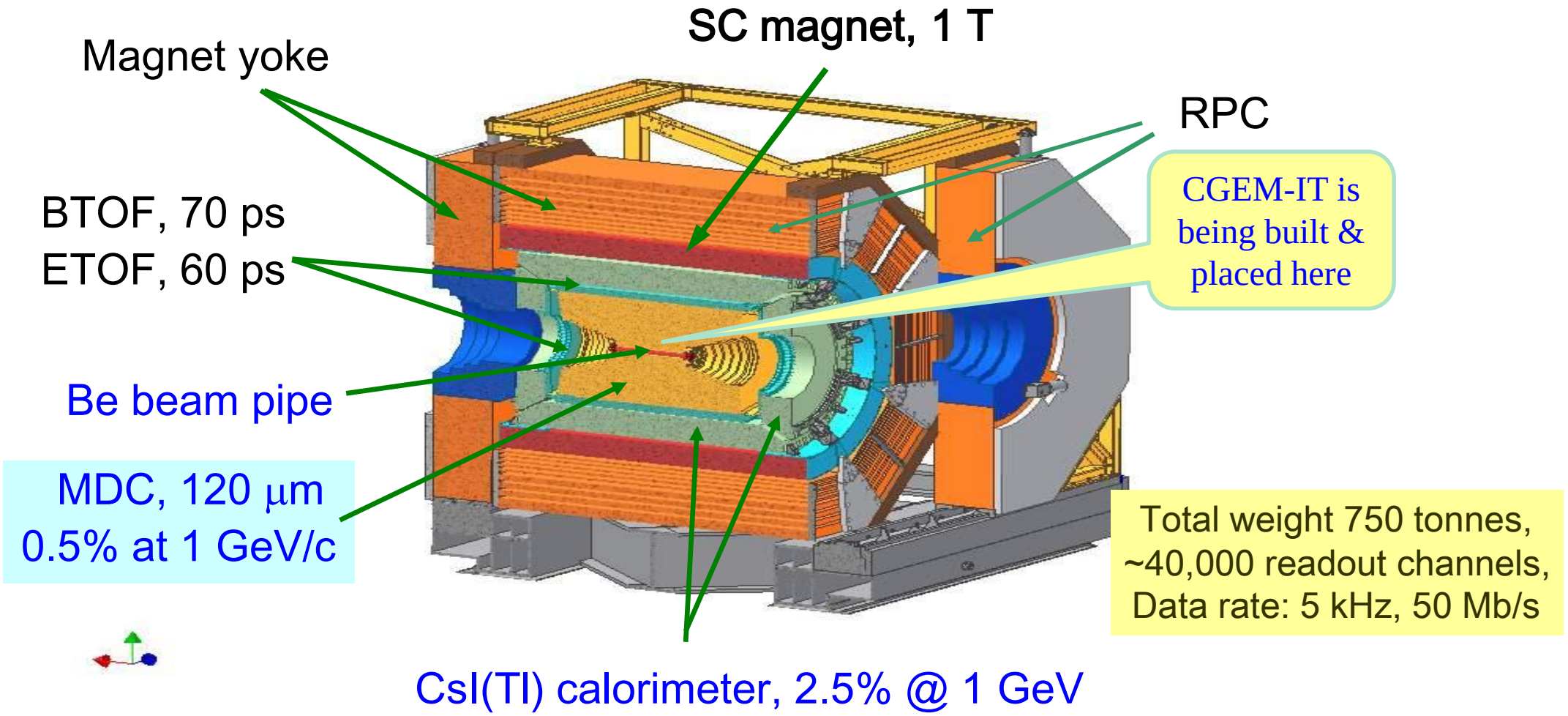
X(3872)→ J/ψ γ



X(3872)→ ψ(2S) γ

$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

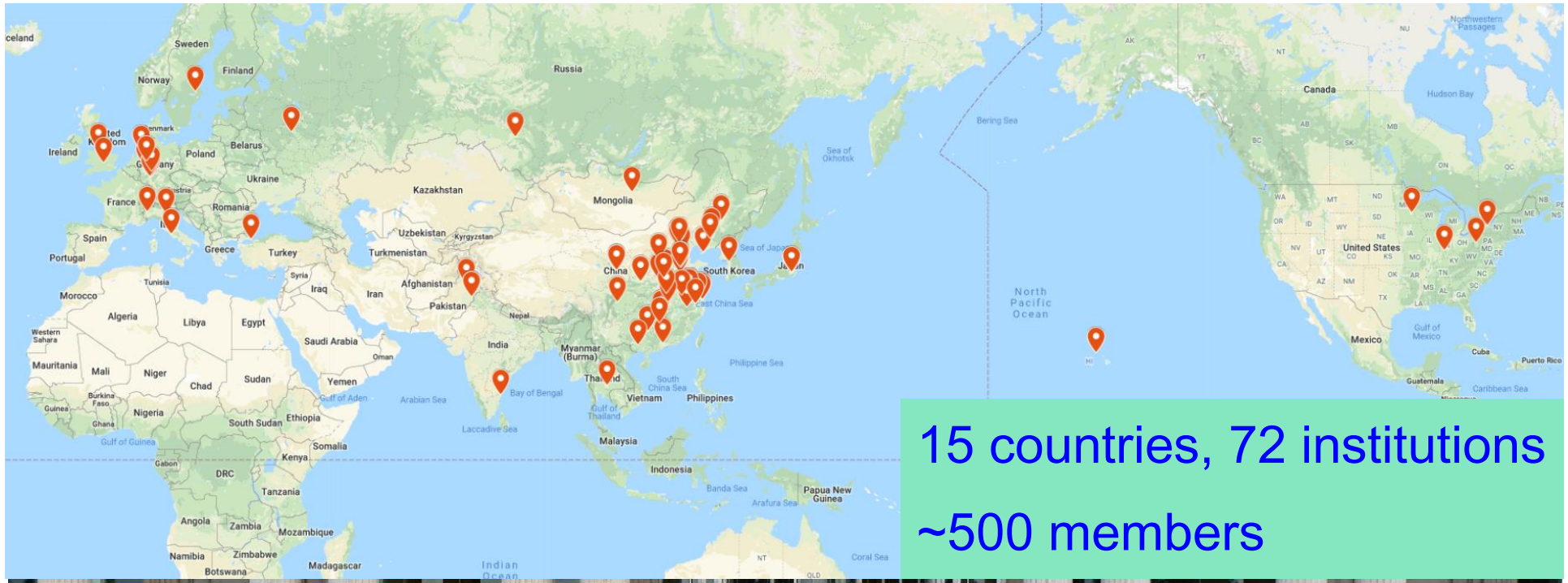
BESIII detector



Has been in full operation since 2008,

all subdetectors are in very good status!

BESIII Collaboration



15 countries, 72 institutions

~500 members