The XV International Conference on Heavy Quarks and Leptons
HQL2021
September 13th - 17th, 2021 University of Warwick, Coventry, UK

XYZ states

Recent results from BESIII

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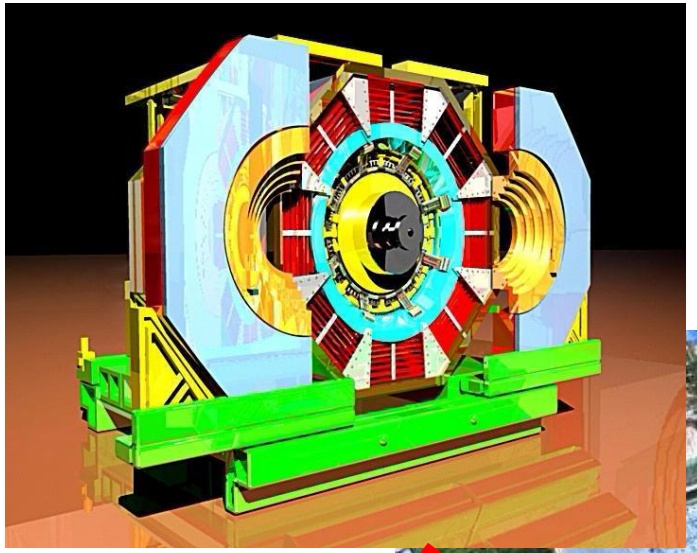
on behalf of the BESIII Collaboration

Department of Physics and INFN – Turin, Italy

The experimental scenario

BESIII @ BEPC-II

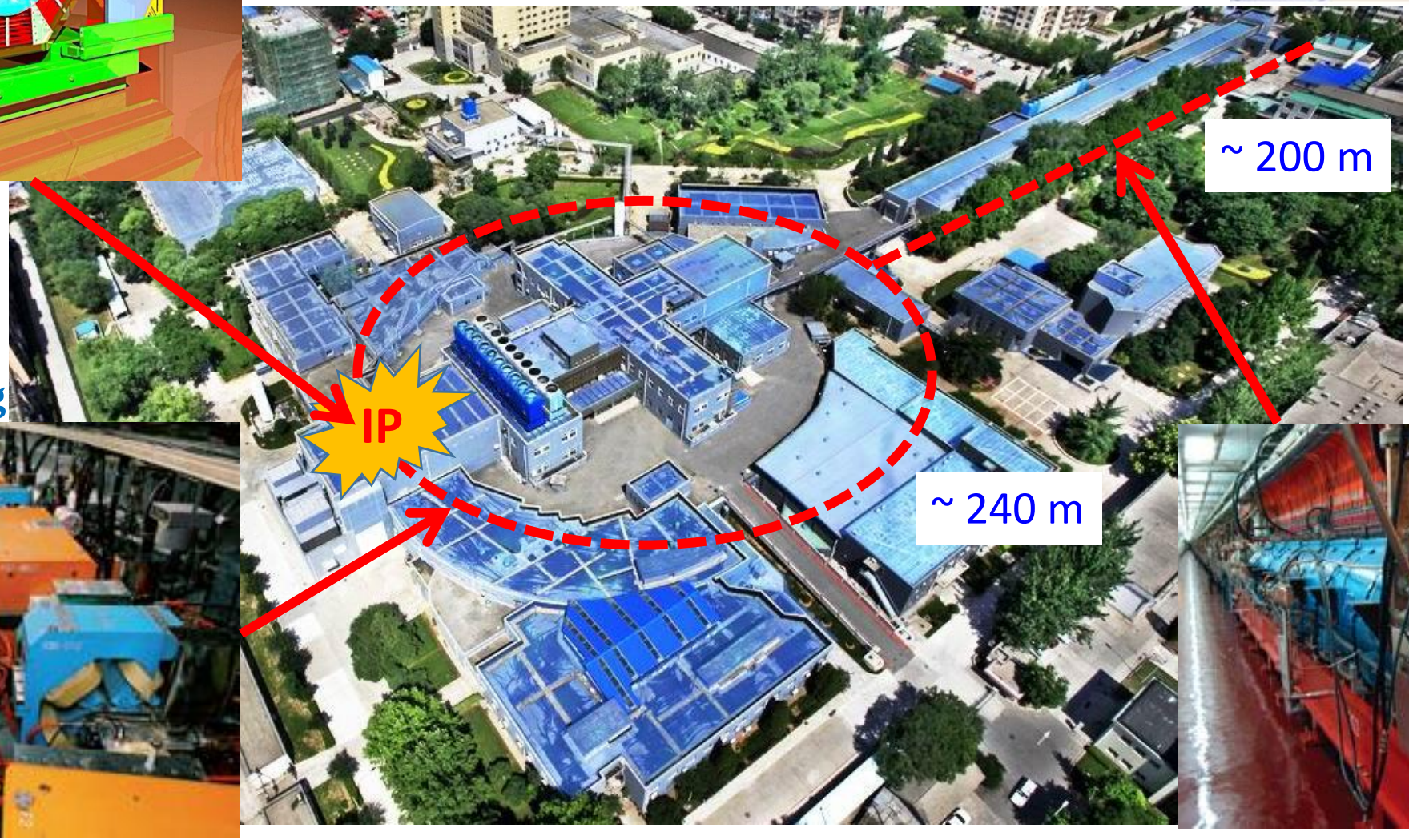


- BEPCII: τ-charm factory
- Center of Mass Energy: 2 – 4.95 GeV
- Achieved design Luminosity $L_{design} = 1 \times 10^{33}\ cm^{-2}s^{-1}$

2016/04/05 22:29:47		
Luminosity	10.00	E32/cm^2/s
	e+	e−
Energy [GeV]	1.8831	1.8831
Current [mA]	849.18	852.31
Lifetime [hr]	1.53	2.30
Inj.Rate [mA/min]	0.00	0.00

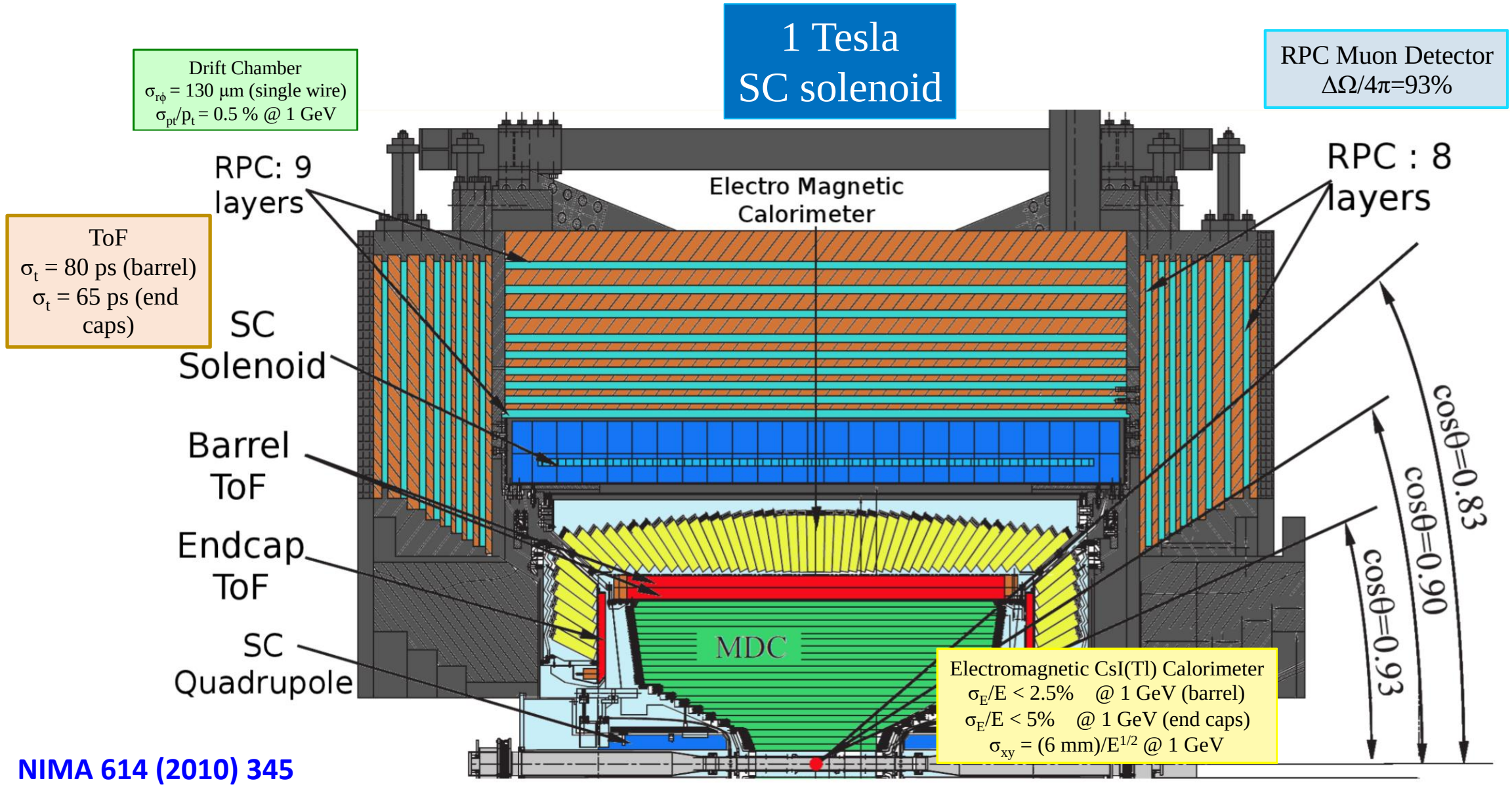
BESIII experiment

BEPC-II e^+e^- storage ring



injection LINAC

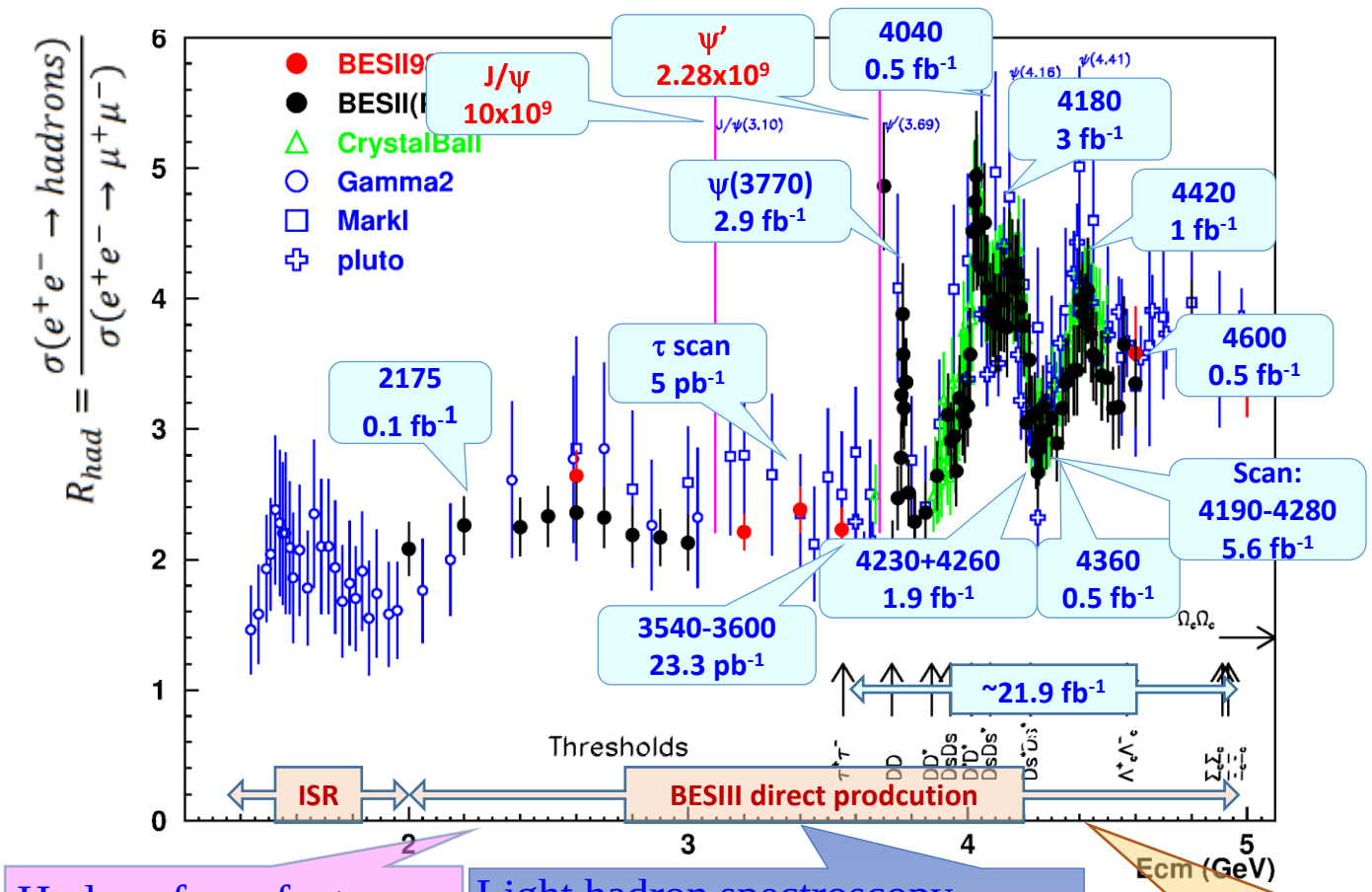
BESIII Spectrometer

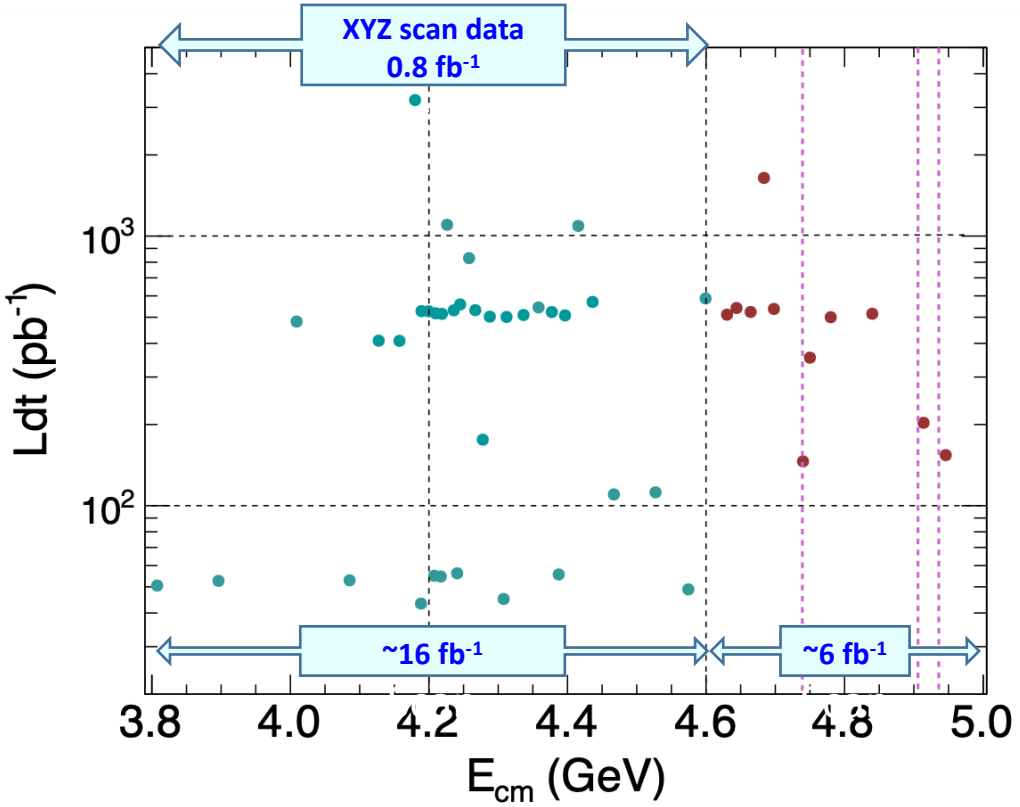


NIMA 614 (2010) 345

Excellent scenario for XYZ Physics

World's largest data samples directly produced from e^+e^- collision @ J/ψ and ψ(2S)





Hadron form factors
Y(2175)
Zs states?
QCD test

Light hadron spectroscopy
Glueballs, hybrids, multi-quark states
Rare decays
Tau Physics

XYZ
D and Ds Physics
(f_D and f_{Ds}, mixing, CP)
Charmed baryons

XYZ data:

- **46 energy points (21.9 fb^{-1})**
- **29 energy points with L_i > 0.4 fb^{-1}**

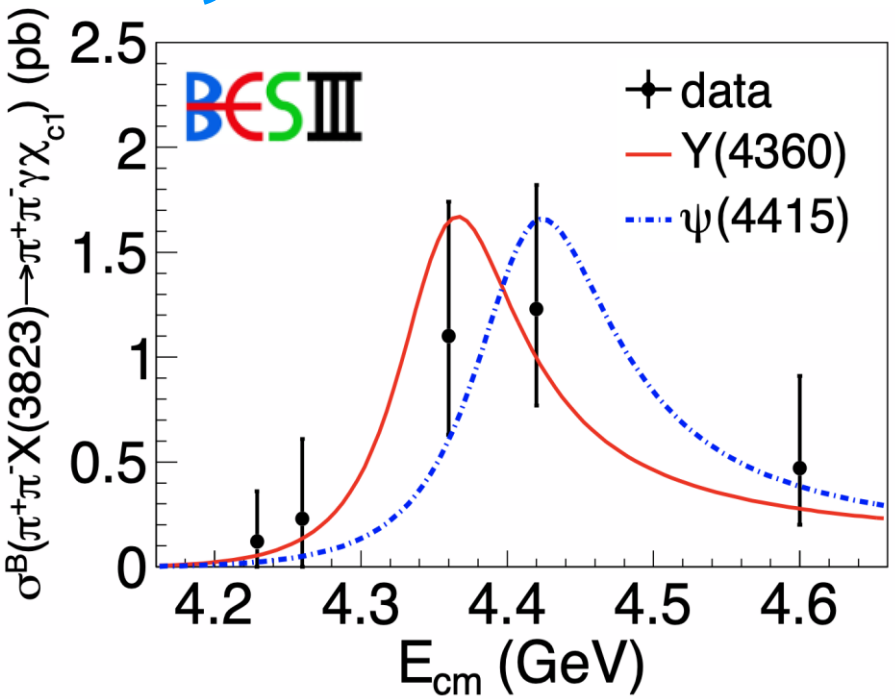
Small scan sample:

- **104 energy points (0.8 fb^{-1})**

X *states*

1^3D_2 states $-\psi_2(3823)$

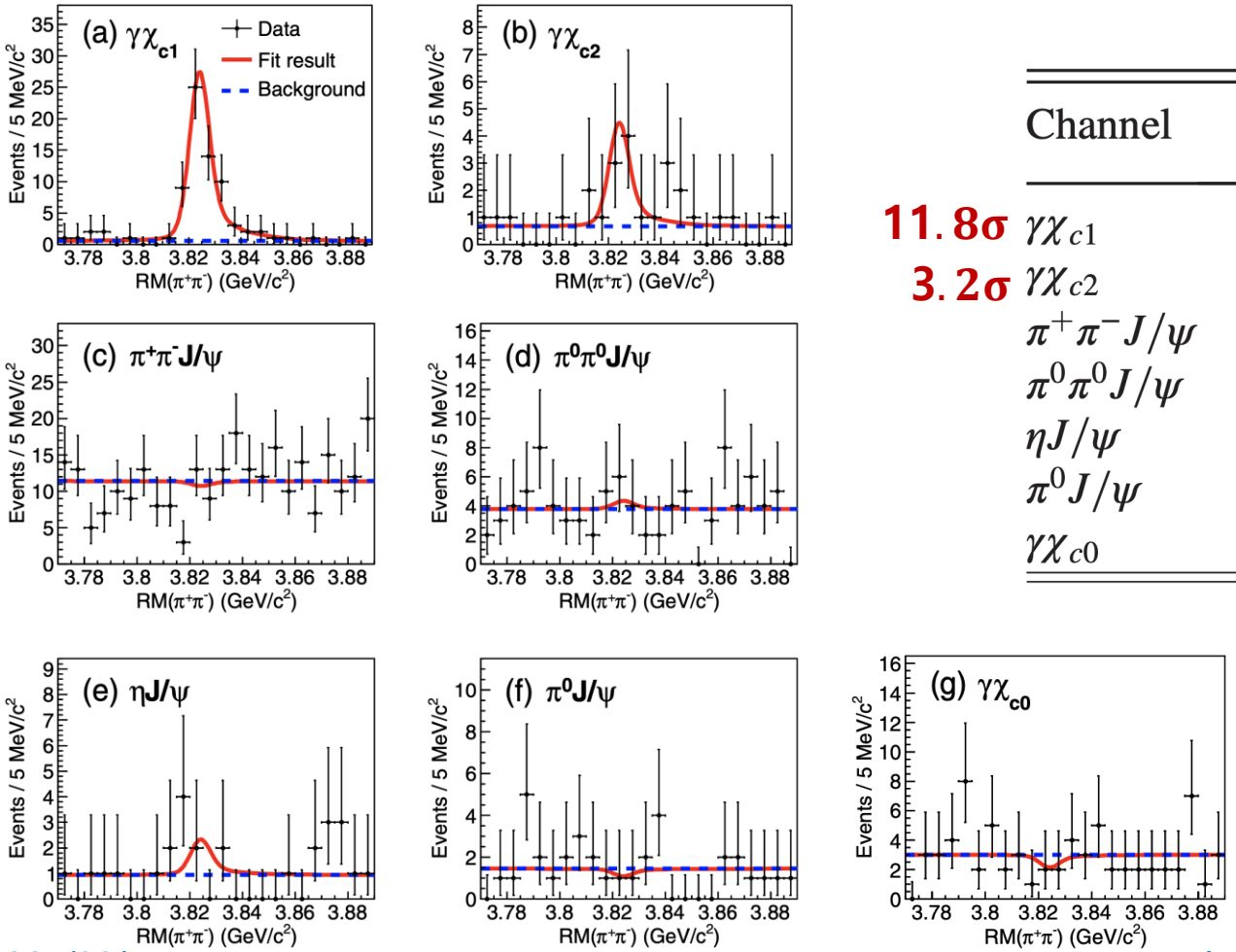
- $B \to (\psi_2(3823) \to \gamma\chi_{c1})K$
  - first evidence from Belle: **PRL 111, 032001 (2013)**
    - 772×10^6 $B\overline{B}$ events, 3.8σ
    - $M = (3823.1 \pm 1.8 \pm 0.7)$ MeV, $\Gamma_{\rm tot} < 24$ MeV
- $e^- \to \pi^+\pi^-\psi_2(3823), \psi_2(3823) \to \gamma\chi_{c1}$
  - observed from BESIII: **PRL 115, 011803 (2015)**
    - Scan data sample at $\sqrt{s} = 4.23,4.26,4.36,4.42,4.60$ GeV, 6.2σ
    - $M = (3821.7 \pm 1.3 \pm 0.7)$ MeV, $\Gamma_{\rm tot} < 16$ MeV
- $\psi_2(3823) \to \gamma\chi_{c2}, \pi^+\pi^- J/\psi, ggg, \gamma gg$
  - predicted by several theoretical works:
    - $\Gamma_{\psi_2(3823)\to\gamma\chi_{c1}} \sim 200 - 350$ keV
    - $\Gamma_{\psi_2(3823)\to\gamma\chi_{c2}} \sim 40 - 90$ keV
    - $\Gamma_{\psi_2(3823)\to\gamma\chi_{c2}}/\Gamma_{\psi_2(3823)\to\gamma\chi_{c1}} \sim 0.19 - 0.32$
    - $\Gamma_{\psi_2(3823)\to\pi\pi J/\psi} \sim 45 - 200$ keV
    - $\Gamma_{\psi_2(3823)\to\pi^+\pi^- J/\psi}/\Gamma_{\psi_2(3823)\to\gamma\chi_{c1}} \sim 0.12 - 0.39$



PRD 55, 4001 (1997)
PRL 89, 162002 (2002)
PRD 67, 014027 (2003)
PRD 69, 054008 (2004)
PRD 72, 054026 (2005)
PRD 79, 094004 (2009)
PRD 94, 034005(2016)
Front. Phys. 11, 111402 (2016)
arXiv:1510.08269

New $\psi_2(3823)$ decay modes

- $e^+ e^- \to \pi^+ \pi^- \psi_2(3823)$ **PRD 103, L091102(2021)**
  - 9 fb^{-1} scan data between 4.30 and 4.70 GeV
  - investigation of decays: $\psi_2(3823) \to \gamma\chi_{c0,1,2}$, $\pi\pi J/\psi$, $\eta J/\psi$, $\pi^0 J/\psi$



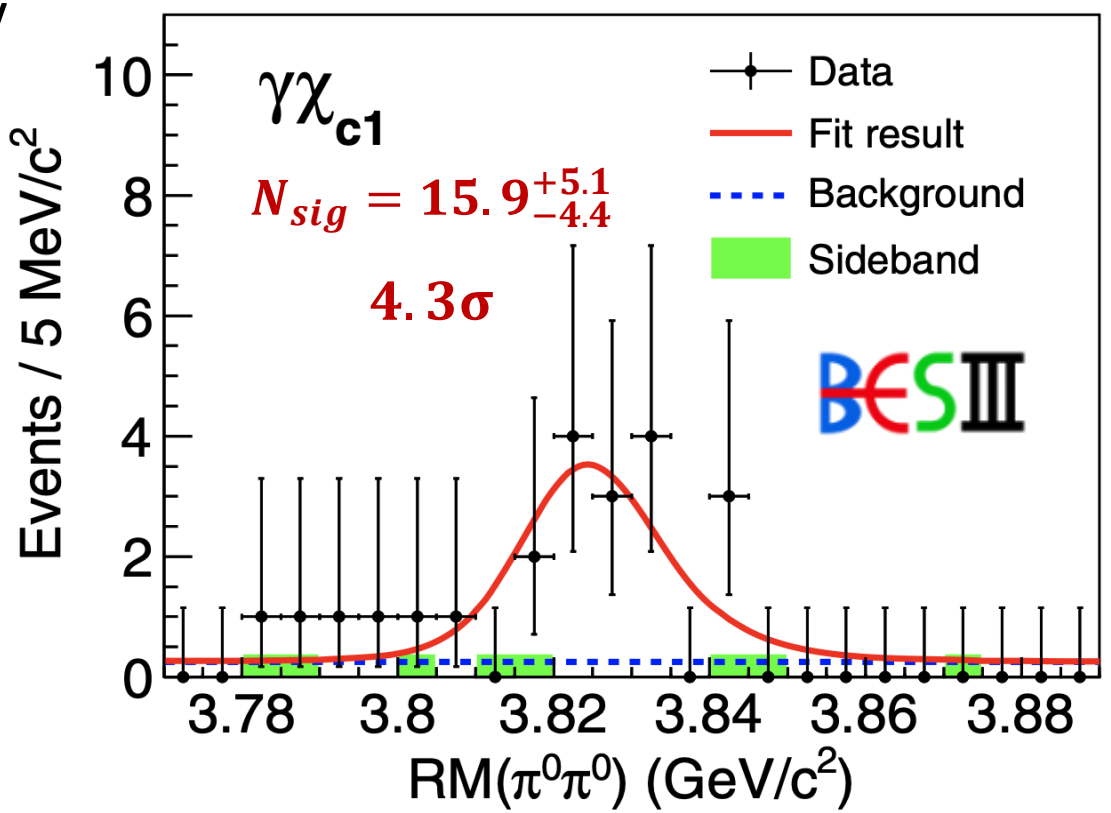
Channel	$N^{\psi_2(3823)}$	$\frac{\mathcal{B}(\psi_2(3823)\to\cdots)}{\mathcal{B}(\psi_2(3823)\to\gamma\chi_{c1})}$
11.8σ $\gamma\chi_{c1}$	63.1 ± 8.5	$\cdots$
3.2σ $\gamma\chi_{c2}$	$8.8^{+4.3}_{-3.4}$	$0.28^{+0.14}_{-0.11} \pm 0.02$
$\pi^+\pi^- J/\psi$	<21.0	<0.06
$\pi^0\pi^0 J/\psi$	<10.0	<0.11
$\eta J/\psi$	<9.8	<0.14
$\pi^0 J/\psi$	<5.6	<0.03
$\gamma\chi_{c0}$	<6.3	<0.24

lower than prediction

consistent with theoretical prediction

New $\psi_2(3823)$ decay modes

- $e^+ e^- \to \pi^0 \pi^0 \psi_2(3823)$ **PRD 103, L091102(2021)**
  - 9 fb^{-1} scan data between 4.30 and 4.70 GeV
  - search for decay: $\psi_2(3823) \to \gamma\chi_{c1}$
  - $\frac{\sigma[e^+e^- \to \pi^0\pi^0\psi_2(3823)]}{\sigma[e^+e^- \to \pi^+\pi^-\psi_2(3823)]} = 0.64^{+0.22}_{-0.20} \pm 0.05$

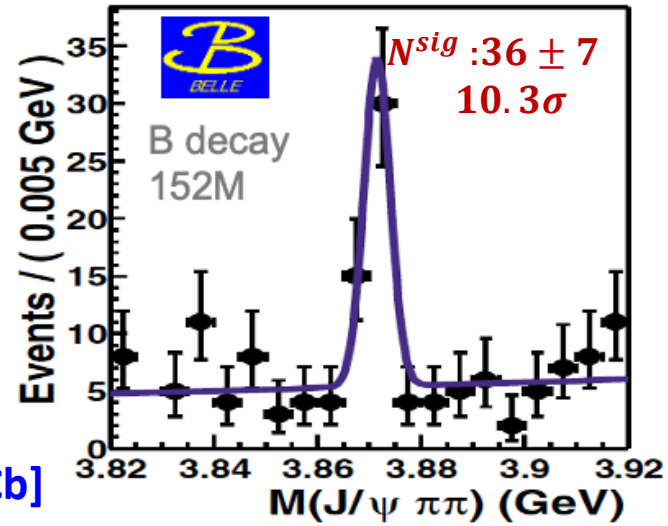


- $e^+ e^- \to \pi^+ \pi^- \psi_3(3842)$ **PRD 103, L091102(2021)**
  - $\psi_3(1^3D_3)$ observed by LHCb in 2019 ([JHEP 07, 035 (2019)])
  - no evidence in any decay mode

$X(3872)$

- $B^{\pm} \to K^{\pm} X(3872) \to K^{\pm}\pi^{+}\pi^{-}J/\psi$
  - first evidence from Belle: **PRL 91, 262001 (2003)**
  - confirmed by CDF and D0 **PRL 93, 072001 (2004) ; PRL 93, 162002 (2004)**
- $X(3872)$
  - mass:
    - $M = (3871.65 \pm 0.06)$ MeV **PDG2020, dominated by JHEP08, 123 (2020) [LHCb]**
    - very close to $D^0\overline{D}^{*0}$ mass threshold [(3871.69 ± 0.01) MeV]
  - width:
    - $\Gamma_{BW} = (1.19 \pm 0.21)$ MeV **PRD 102, 092005 (2020)**
  - J^{PC}: 1^{++} **PRL 110, 222001 (2013)**
  - produced in:
    - B decays, B_s decays, Λ_b decays, $p\overline{p}$ collision, pp collision, $PbPb$ collision, e^+e^- radiative transition, $\gamma\gamma^*$ processes
  - decay modes:
    - $D^0\overline{D}^{*0}$, $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0J/\psi$, $\pi^0\chi_{cJ}$, $\gamma J/\psi$, $\gamma\psi(2S)$[?]

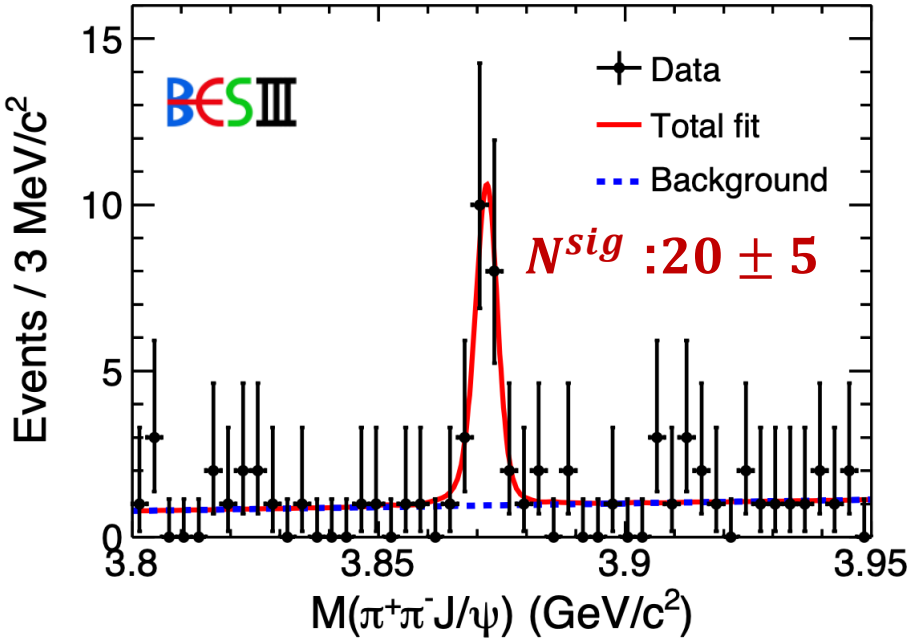
PRL 91, 262001 (2003)



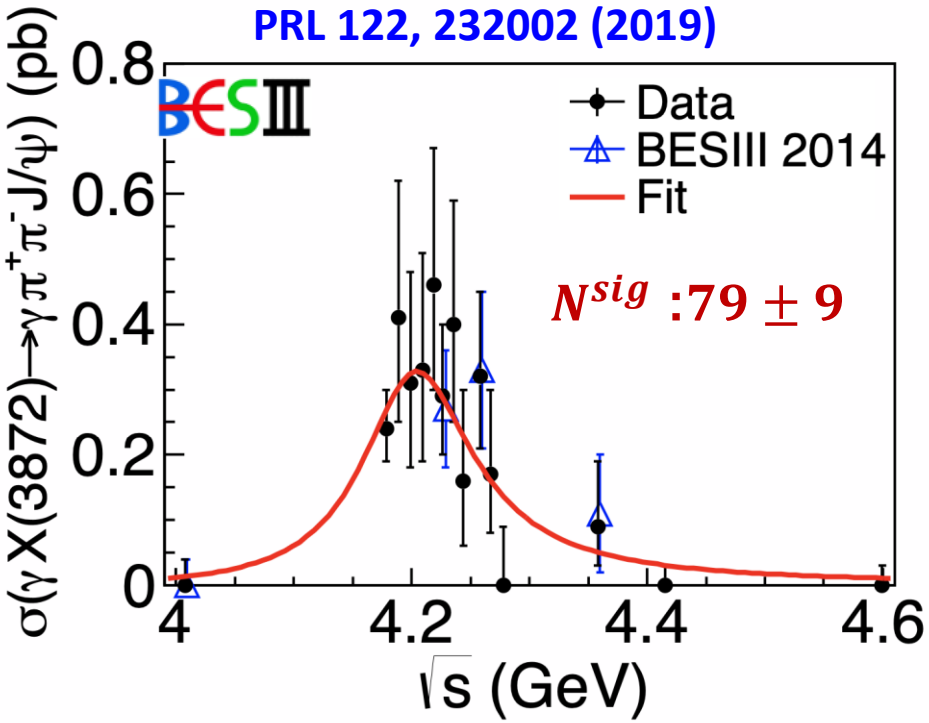
$X(3872)$

- $e^+ e^- \to \gamma X(3872) \to \gamma \pi^+ \pi^- J/\psi$
  - 4 data samples between 4.01 and 4.42 GeV
  - first observation at BESIII: 6.3σ **PRL 112, 092001 (2014)**
- $e^+ e^- \to \gamma X(3872) \to \gamma \omega J/\psi$ **PRL 122, 232002 (2019)**
  - 11.6 fb^{-1} data between 4.01 and 4.60 GeV
  - first observation in $\omega J/\psi$: $> 5\sigma$

PRL 112, 092001 (2014)

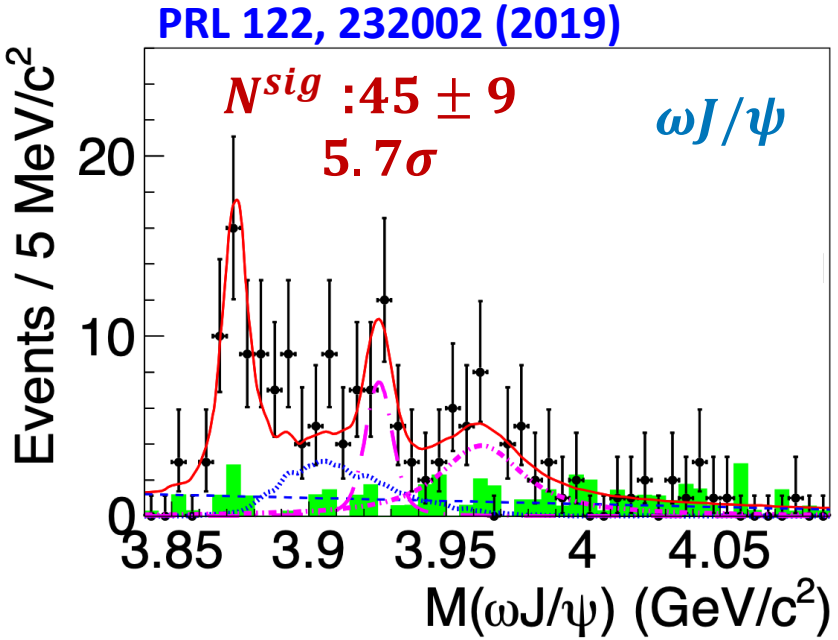


PRL 122, 232002 (2019)

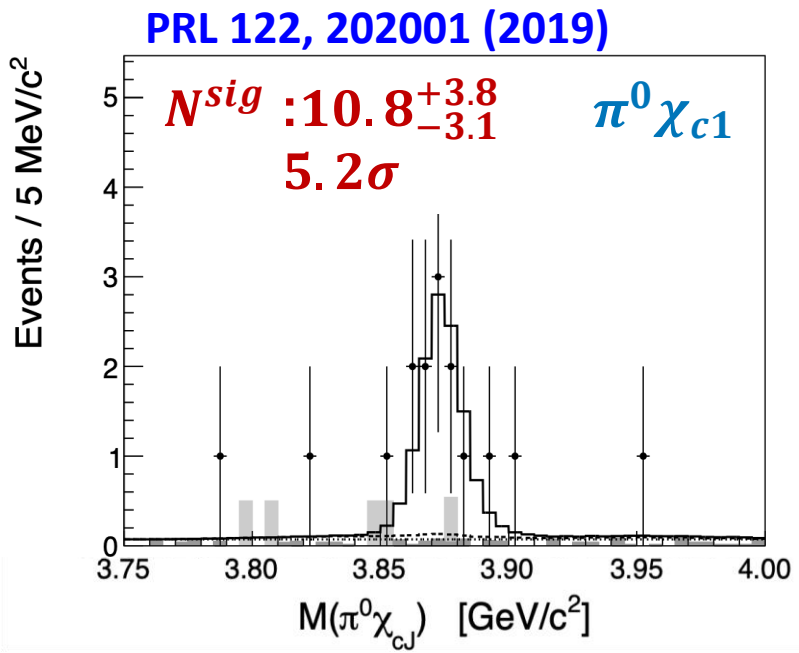


$X(3872)$ decays

- $e^+ e^- \to \gamma X(3872) \to \gamma\, \omega J/\psi$ **PRL 122, 232002 (2019)**
  - 11.6 fb^{-1} data between 4.01 and 4.60 GeV
  - cross section peaks around 4.2 GeV
  - first observation in $\omega J/\psi$: $> 5\sigma$
  - $M = (3873.3 \pm 1.1 \pm 1.0) MeV/c^2$
  - $\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} = 1.6^{+0.4}_{-0.3} \pm 0.2$



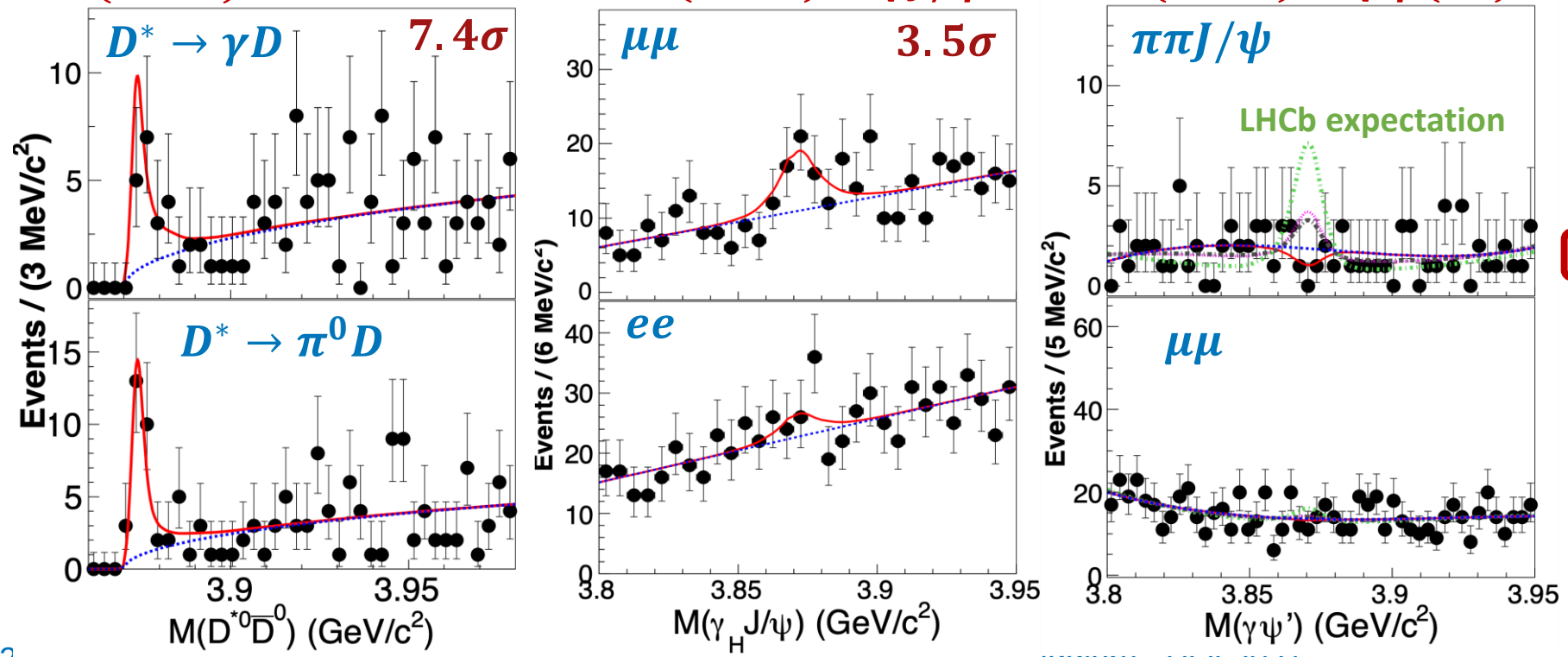
- $e^+ e^- \to \gamma X(3872) \to \gamma \pi^0 \chi_{cJ}$ **PRL 122, 202001 (2019)**
  - 9.0 fb^{-1} data between 4.15 and 4.30 GeV
  - first observation of $X(3872) \to \pi^0 \chi_{c1}$ $> 5\sigma$
  - $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} = 0.88^{+0.33}_{-0.27} \pm 0.10$
  - $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c2})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} < 19$
  - $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} < 1.1$



$X(3872)$ decays

- $e^+ e^- \to \gamma X(3872)$, $X(3872) \to \gamma J/\psi,\ \gamma\psi(2S), D^{*0}\bar{D}^0 + c.c.$ **PRL 124, 242001 (2020)**
  - 9.0 fb^{-1} data between 4.15 and 4.30 GeV
  - $X(3872) \to D^{*0}\bar{D}^0 + c.c.$ **7.4σ**
  - $X(3872) \to \gamma J/\psi$ **3.5σ**
  - no evidence for $X(3872) \to \gamma\psi(2S), D^+D^-$

$X(3872) \to D^{*0}\bar{D}^0 + c.c.$ **$X(3872) \to \gamma J/\psi$** **$X(3872) \to \gamma\psi(2S)$**



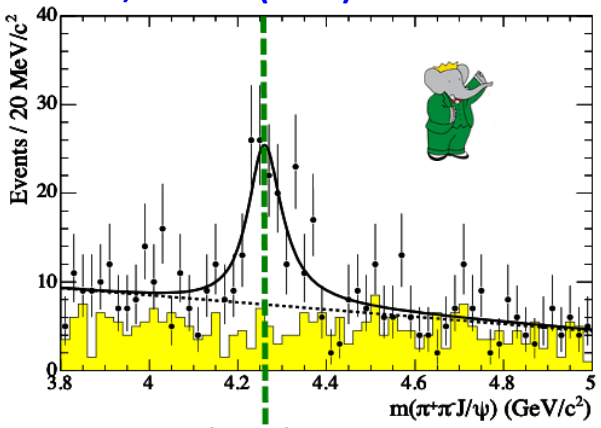
Mode	Ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	...
$\gamma\psi'$	-0.03 ± 0.22	< 0.42
$\gamma D^0\bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0\bar{D}^0$	-0.13 ± 0.47	< 1.16
$D^{*0}\bar{D}^0$ + c.c.	11.77 ± 3.09	...
γD^+D^-	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	...
$\pi^0\chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [27]	...

$Y\ states$

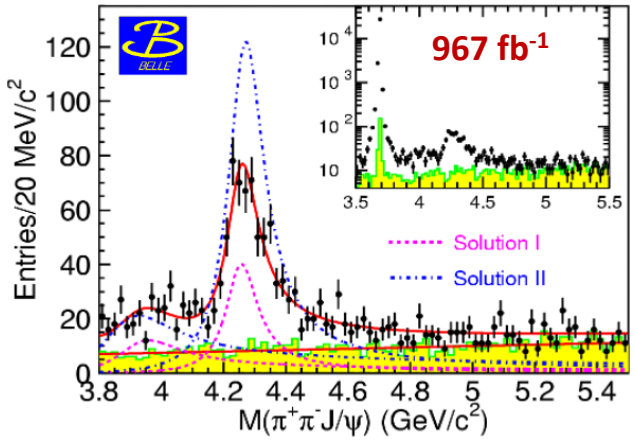
Y states

- $Y(4260)$
  - discovered first
  - in ISR processes by BaBar
  - no evidence in:
    - inclusive hadron cross section
    - open charm pair cross section
  - confirmed by CLEO and Belle

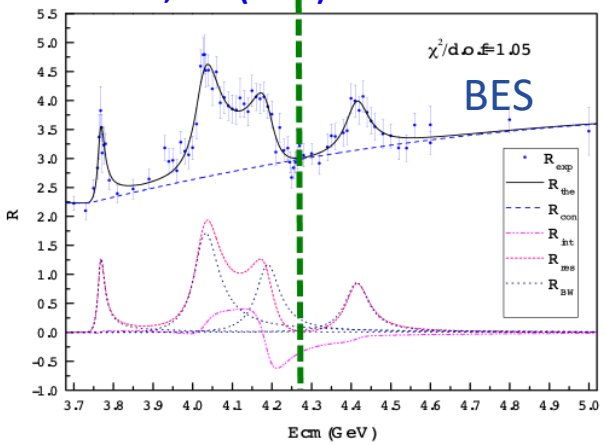
PRL 95, 142001 (2005)



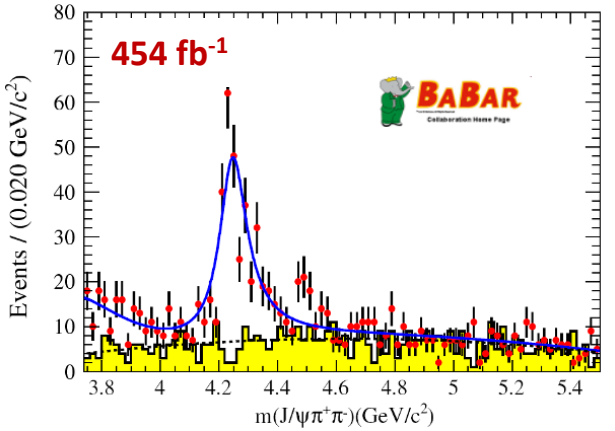
PRL 110, 252002 (2013)



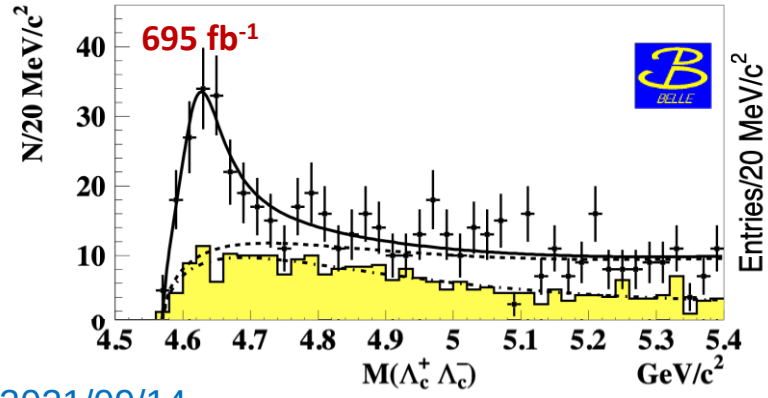
PLB 660, 315 (2008)



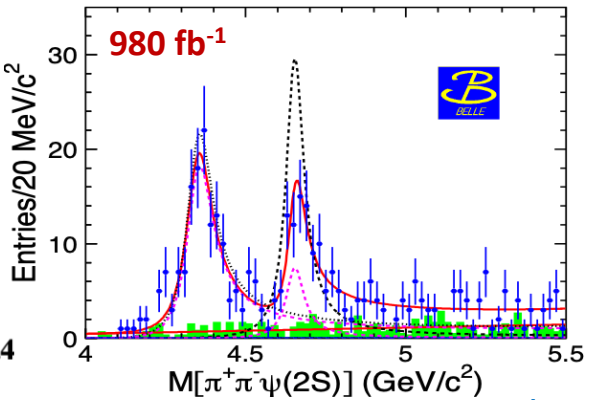
PRD 86, 051102 (2012)



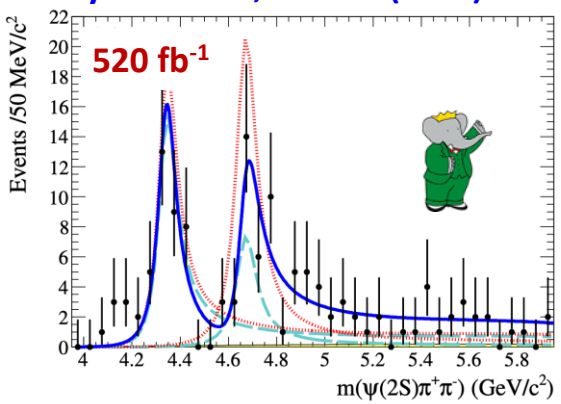
Phys.Rev.Lett. 101, 172001 (2008)



PRD 91, 112007 (2014)



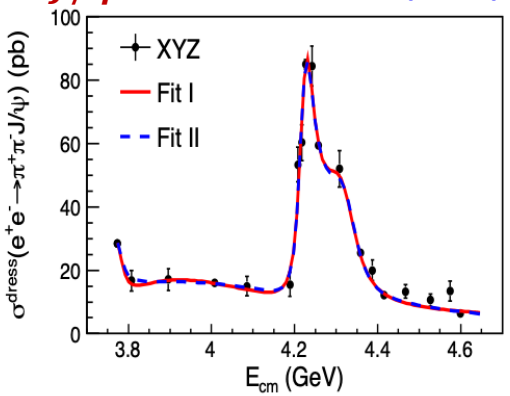
Phys.Rev.D 89, 111103 (2014)



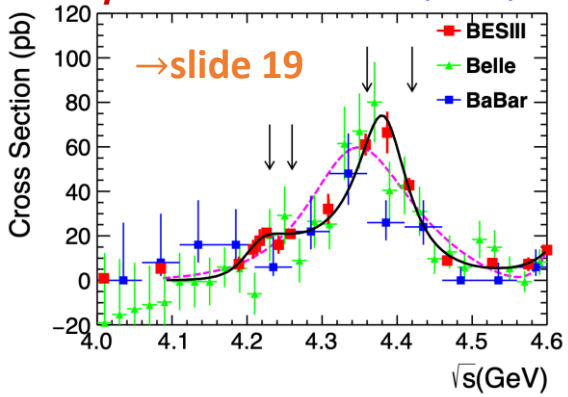
- $Y(4360), Y(4660)$
  - discovered later
  - in ISR processes

Y(4260→4230)

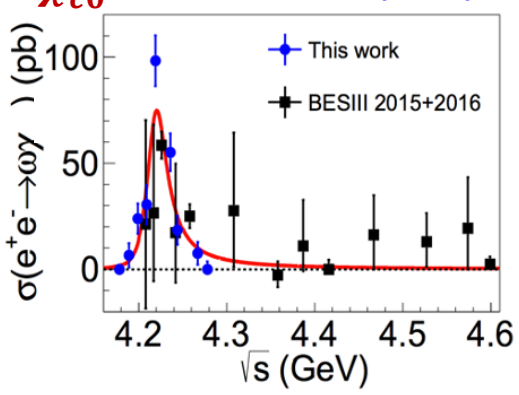
$\pi\pi J/\psi$ PRL 118, 092001 (2017)



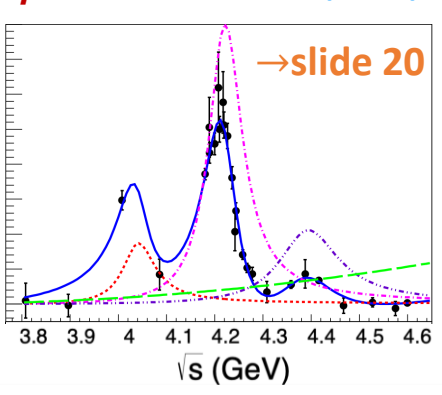
$\pi\pi\psi'$ PRD 96, 032004 (2017)



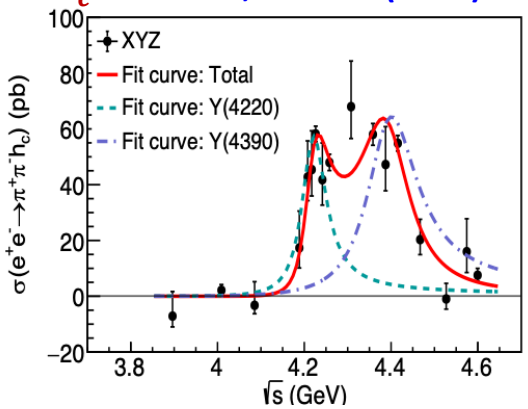
$\omega\chi_{c0}$ PRD 99, 091103 (2019)



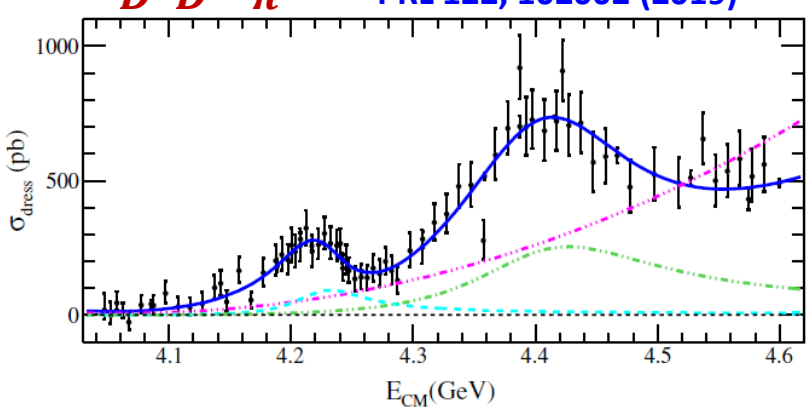
$\eta J/\psi$ PRD 102, 031101 (2020)



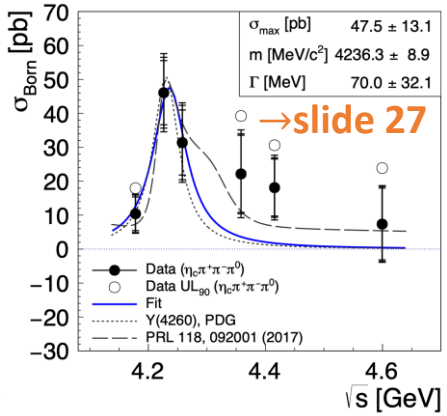
$\pi\pi h_c$ PRL 118, 092002 (2017)



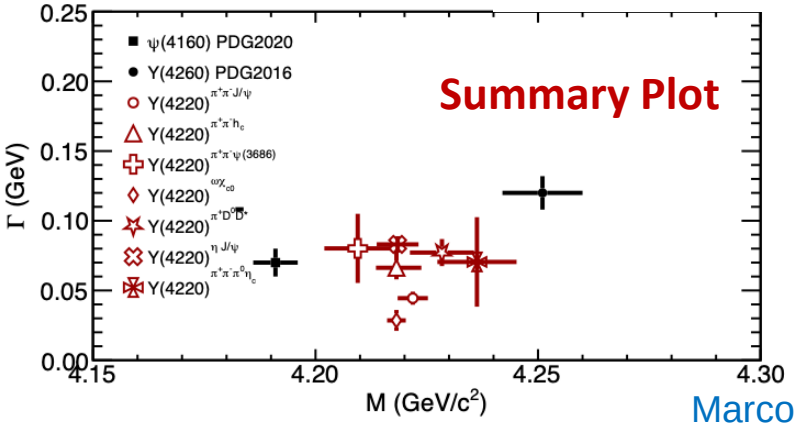
$D^0D^{*-}\pi^+$ PRL 122, 102002 (2019)

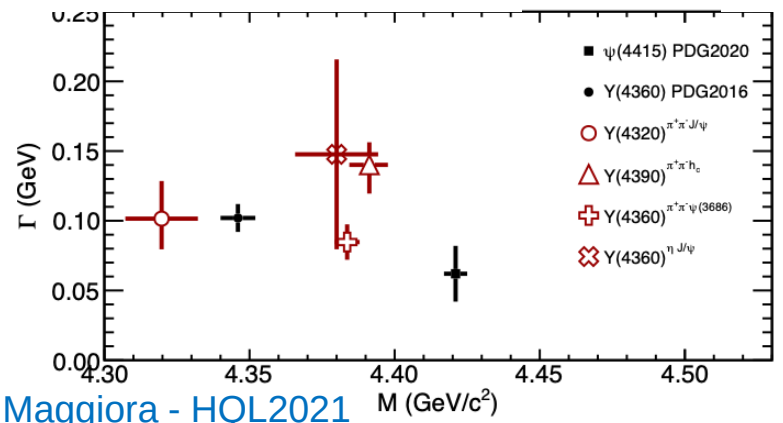


$\eta_c\pi^+\pi^-\pi^0$ PRL 103, 032006 (2021)



Summary Plot



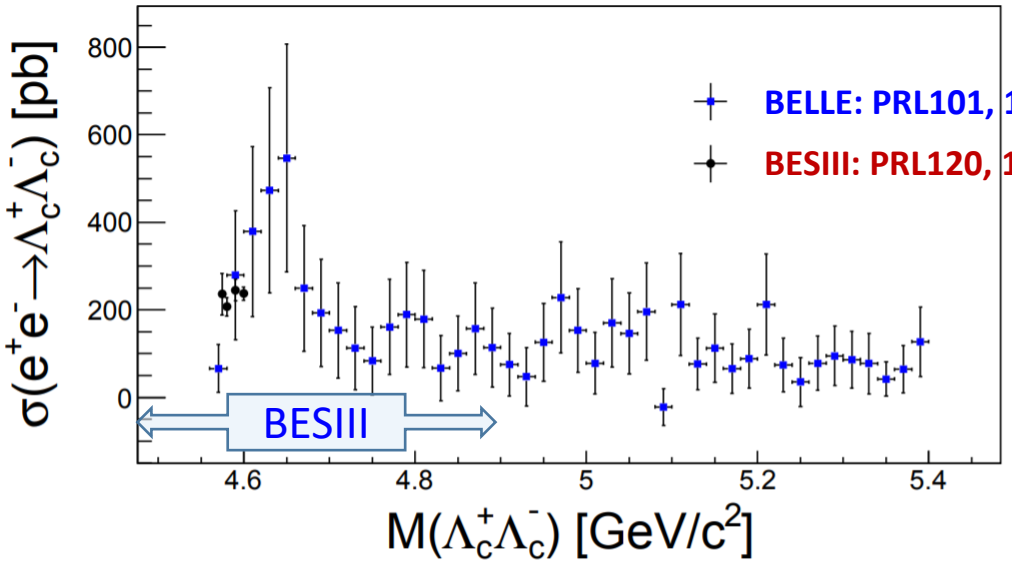


ψ(4260) MASS PDG 2019

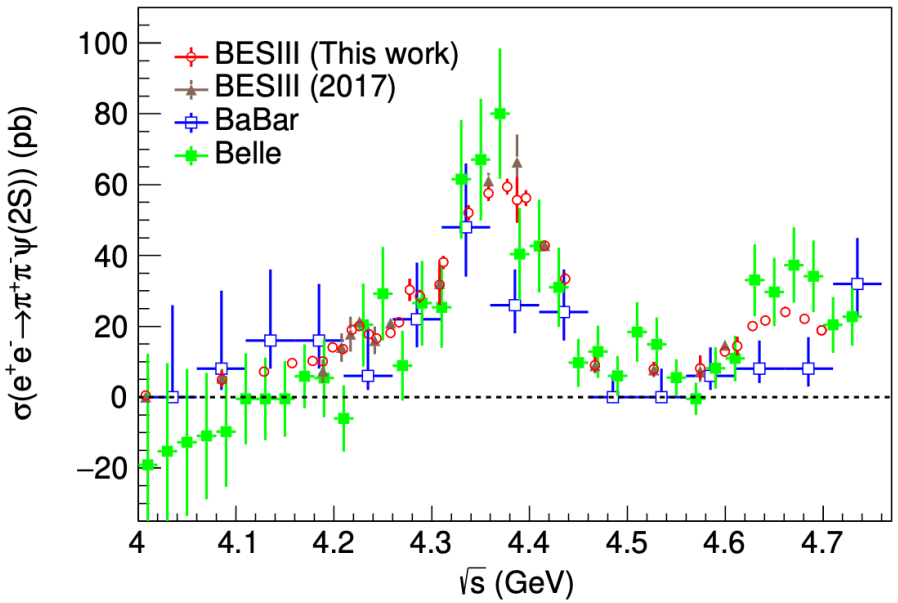
VALUE (MeV)	EVTS	DOC
4230 ± 8	OUR AVERAGE	

Y(4660)

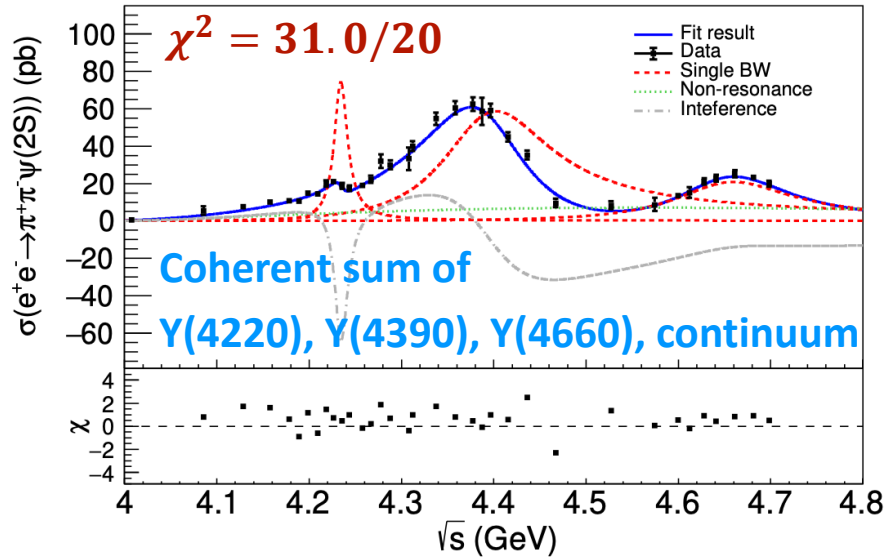
$\Lambda_c\bar{\Lambda}_c$: first observation from Belle



$e^+ e^- \to \pi^+ \pi^- \psi(3686)$: first time in BESIII

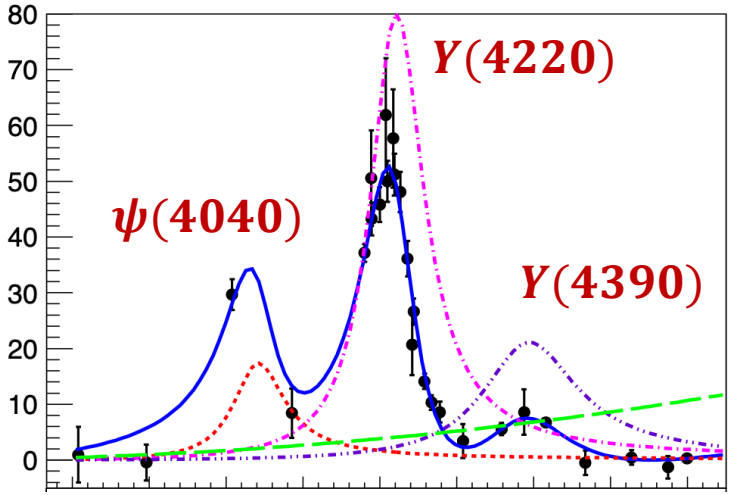


- $e^+ e^- \to \pi^+ \pi^- \psi(3686)$ **arXiv:2107.09210**
  - 20.1 fb^{-1} data between 4.01 and 4.70 GeV
  - in agreement with previous data but…
  - much improved precision in cross section:
    - first observation of Y(4660), Y(4220) and Y(4390) confirmed
    - higher precision w.r.t. Belle and BaBar
    - new 2020-2021 data sample: $4.70 < \sqrt{s} < 4.95\ GeV$
  - challenging parameterization of σ line-shape

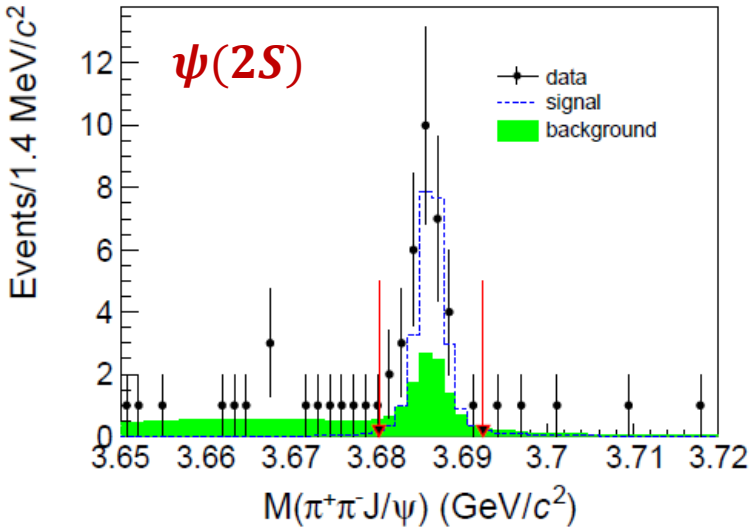


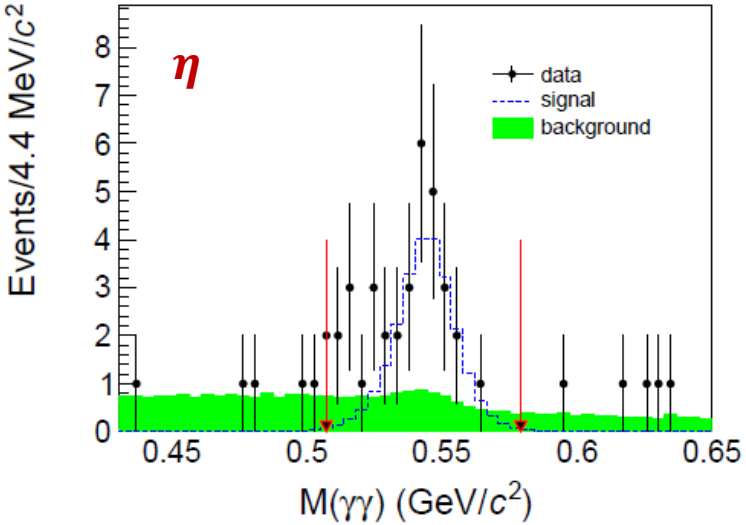
$e^+e^- \to \eta + J/\psi\,, \psi(2S)$

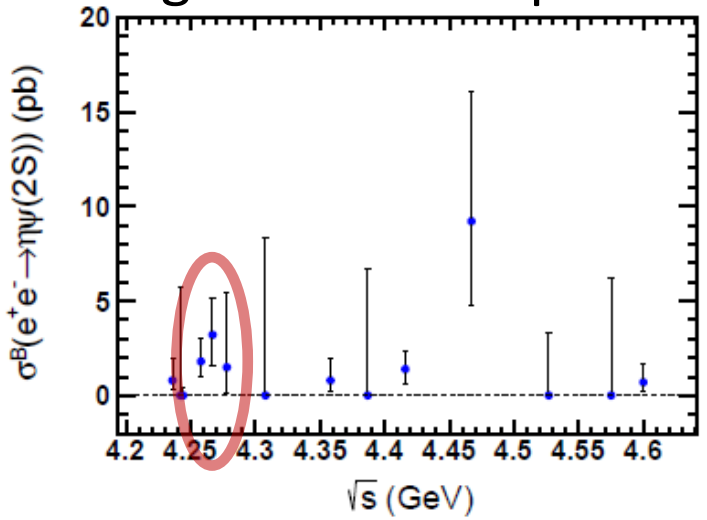
- $e^+e^- \to \eta J/\psi$ **PRD 102, 031101 (2020)**
  - 13.1 fb^{-1} data between 3.81 and 4.60 GeV
  - first observation of Y(4220) and Y(4390) states in $\eta J/\psi$
  - significance $> 6\sigma$



- $e^+e^- \to \eta\psi(2S)$ **arXiv: 2103.01480**
  - 5.25 fb^{-1} data between 4.24 and 4.60 GeV
  - first observation with 5σ significance (only $\sigma^{\text{up}}_{4.26GeV} = 25pb$ from CLEOc [PRL96, 162003 (2006)])
  - no significant structure in $\eta\psi(2S)$: more data expected and missing track technique

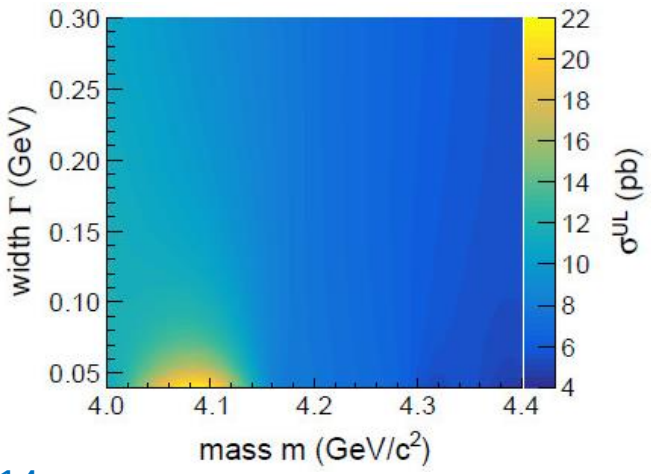


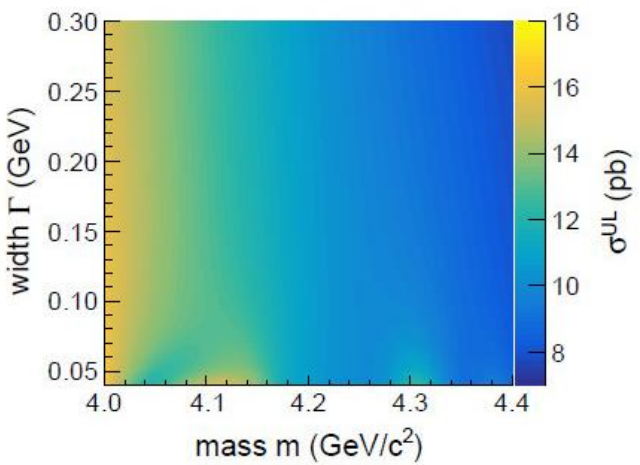


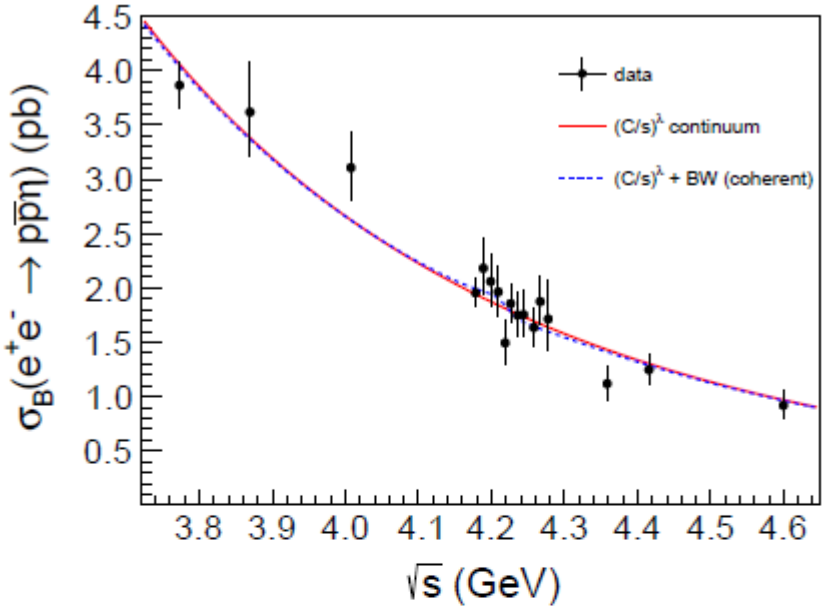


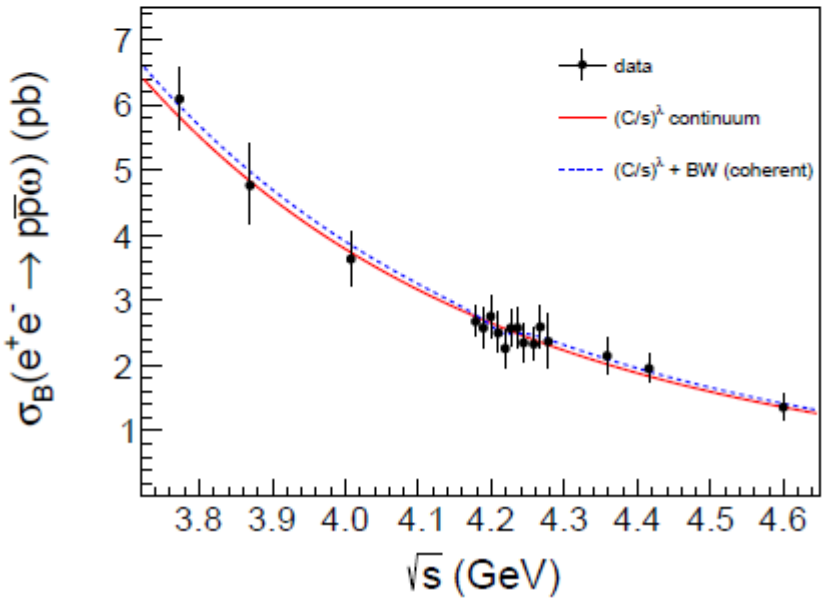
Search for Y(4260) → light hadrons

- $e^+e^- \to p\bar{p} + \eta, \omega$ **arXiv: 2102.04268**
  - 14.7 fb^{-1} data between 3.77 and 4.60 GeV
  - final states with $p\bar{p}$ are very interesting:
    - $\psi \to p\bar{p}h \quad \leftrightarrow \quad p\bar{p} \to \psi h, h = \eta, \omega$ $(\to \bar{P}ANDA)$
  - no resonant production through a vector state V:
    - $e^+e^- \to V \to p\bar{p}\eta, \quad e^+e^- \to V \to p\bar{p}\omega$
    - $e^+e^- \to V \to p\bar{p}\eta'$ in progress
  - Born cross section upper limits at 90% C.L.:
    - $\sigma^{\text{up}}_{e^+e^- \to \psi(4260) \to p\bar{p}\eta} = 7.5pb$, $\sigma^{\text{up}}_{e^+e^- \to \psi(4260) \to p\bar{p}\omega} = 10.4pb$
    - $\sigma^{\text{up}}_{e^+e^- \to V \to p\bar{p}\eta}$: $\sigma^{\text{up}}_{e^+e^- \to V \to p\bar{p}\omega}$:



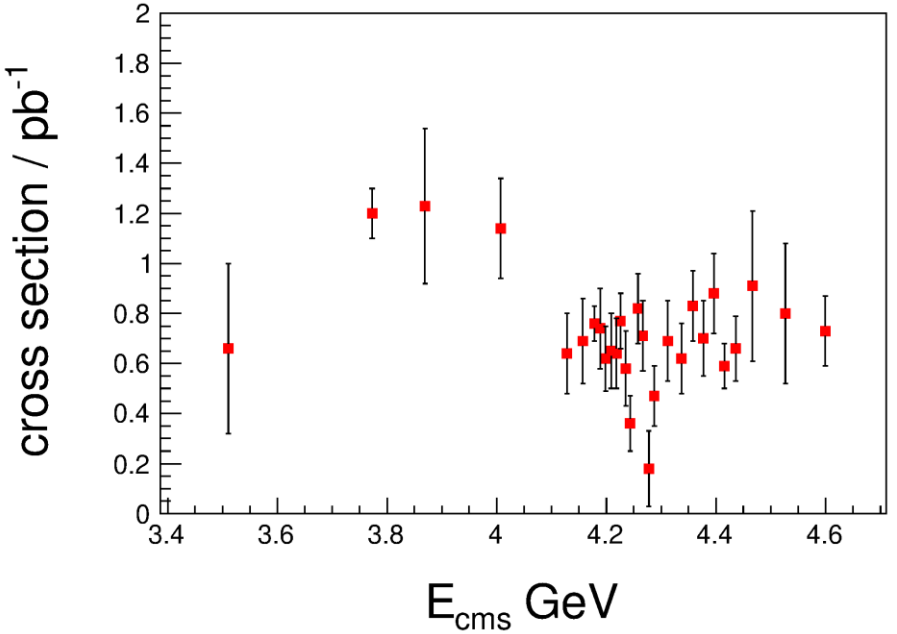






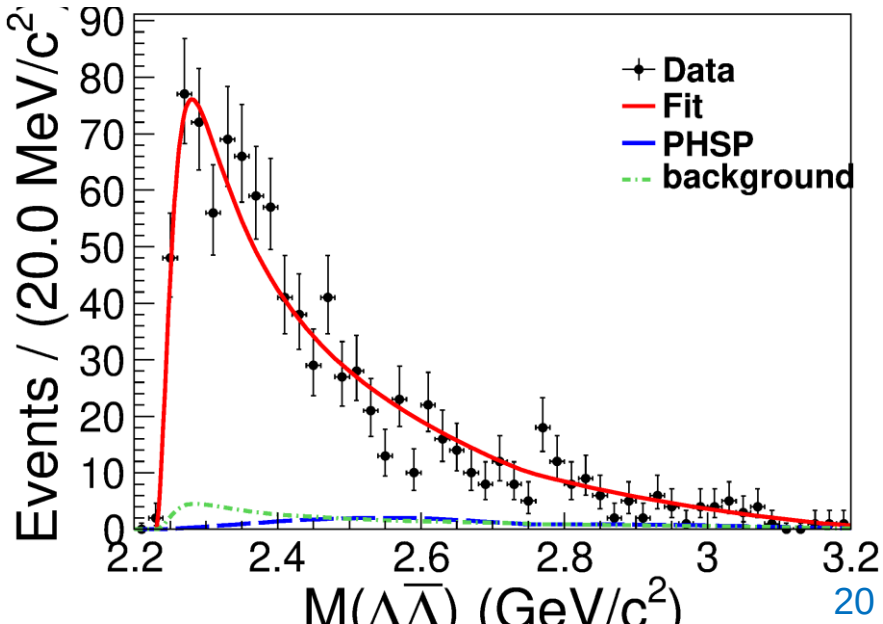
Search for Y(4260) → $\phi\Lambda\bar{\Lambda}$

- $e^+e^- \to \phi\Lambda\bar{\Lambda}$ **arXiv: 2104.08754**
  - 19.5 fb^{-1} data between 3.51 and 4.60 GeV
  - Y(4260):
    - interpreted as a $[cs][\bar{c}\bar{s}]$state [PRD72, 031502 (2005)]
    - decays to final states including $\bar{s}\bar{s}$
    - explains large $Y(4260) \to f_0(980)J/\psi$ in $Y(4260) \to \pi^+\pi^- J/\psi$
    - if $\bar{c}\bar{c}$ annihilate, $Y(4260) \to \phi\Lambda\bar{\Lambda}$ possible
  - fit to cross section:
    - large interference b/w resonant and non resonant contributions



- near threshold enhancement observed - X(2260) - $> 25\sigma$:
  - $M = (2262 \pm 4 \pm 28) MeV/c^2$
  - $\Gamma = (72 \pm 5 \pm 43) MeV/c^2$

  } no match in PDG!
  - J^{PC}: $1^{++}, 2^{-+}$(favoured), $2^{++}; 0^{-+}$ rejected (7σ , no $\eta(2225)$)



Search for vector resonant contributions to $D_S^* D_{sJ}$ around 4.6 GeV

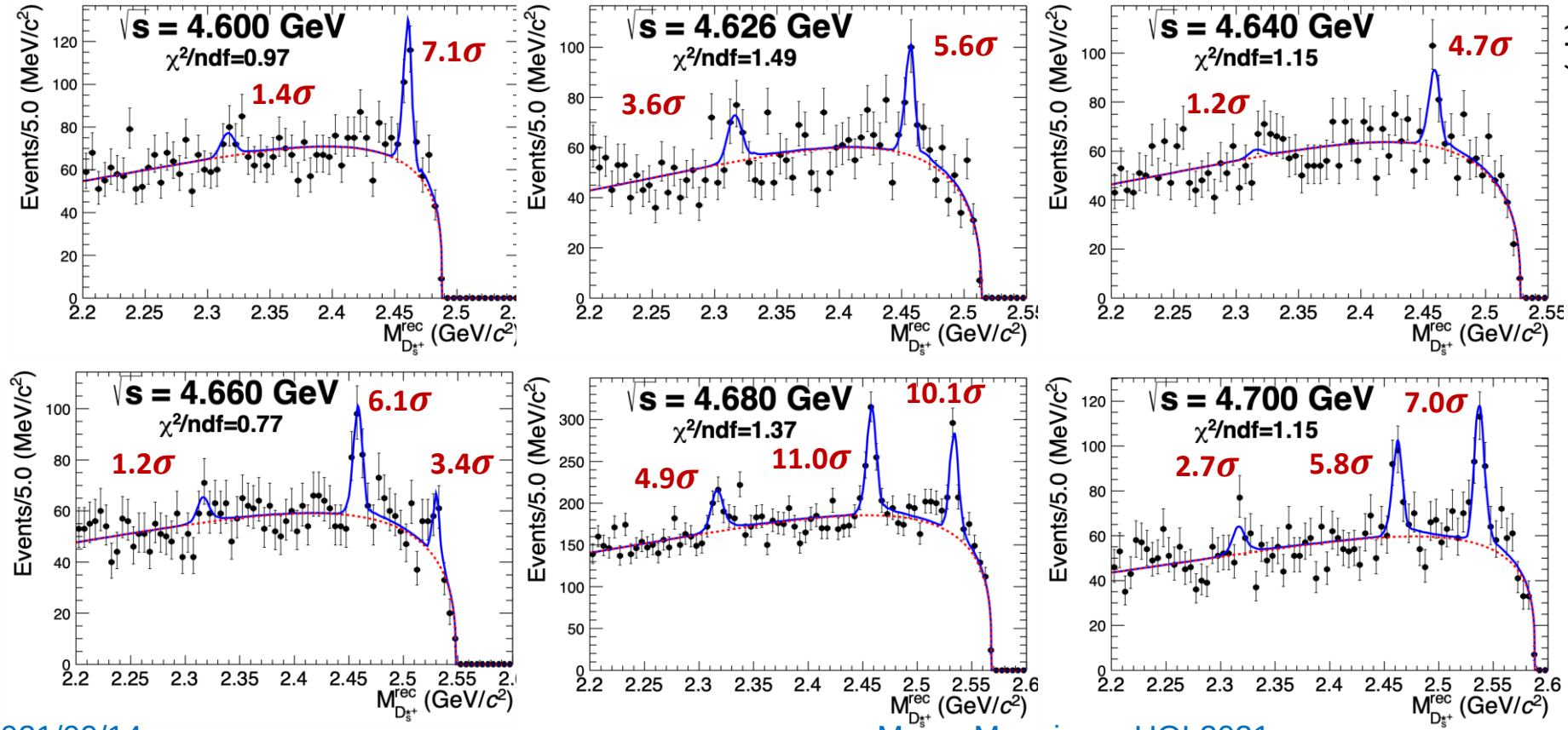
PRD 100, 111103 (2019)

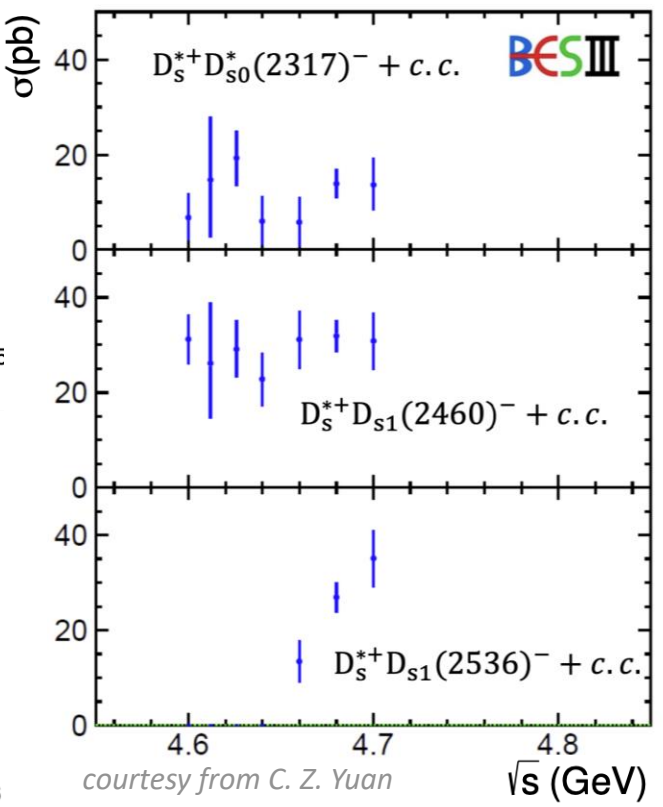
- Belle: $e^+e^- \to D_s^{\pm} D_{s1}(2536)^{\mp}$
  - enhancement just above 4.6 GeV observed

PRD 101, 091101 (2020)

- Belle: $e^+e^- \to D_s^{\pm} D_{s2}^*(2573)^{\mp}$
  - evidence seen above 4.6 GeV

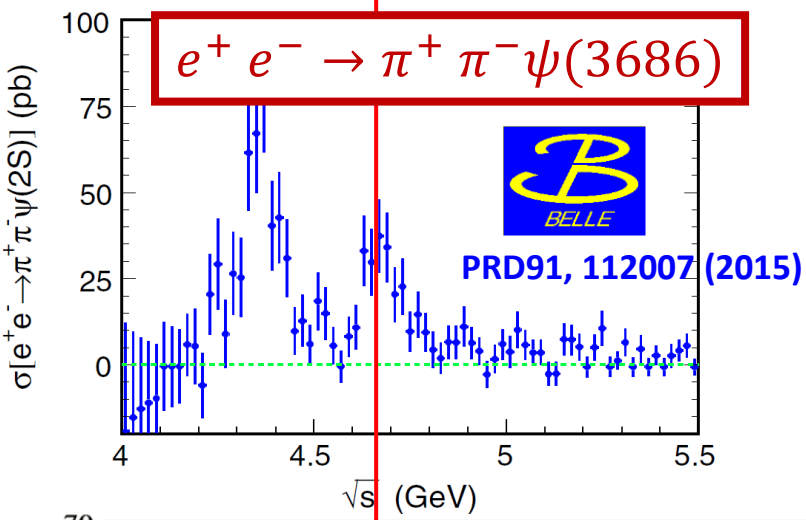
- $e^+e^- \to D_s^{*\pm} D_{s0}^{*\mp}(2317), D_s^{*\pm} D_{s1}(2460)^{\mp}, D_s^{*\pm} D_{s1}(2536)^{\mp}$ **PRD 104, 032012 (2021)**
  - clear $D_s^* D_{sJ}$ signal, no significant resonant structures in cross section line-shape

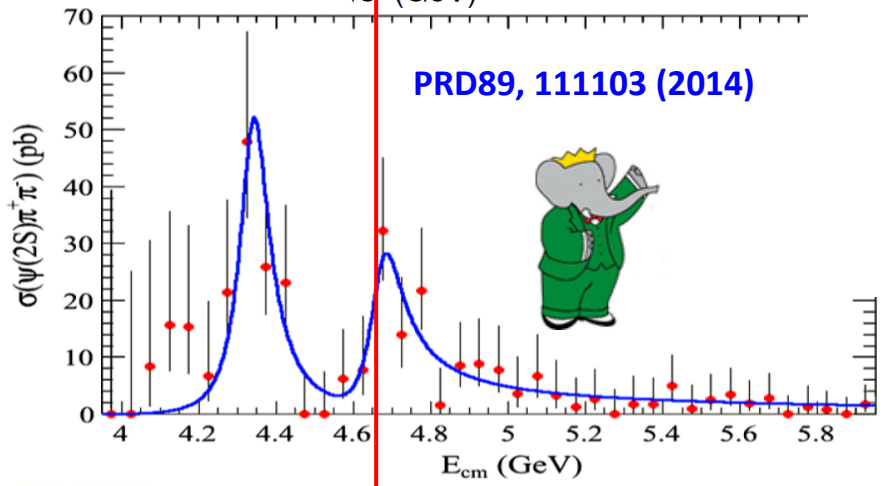


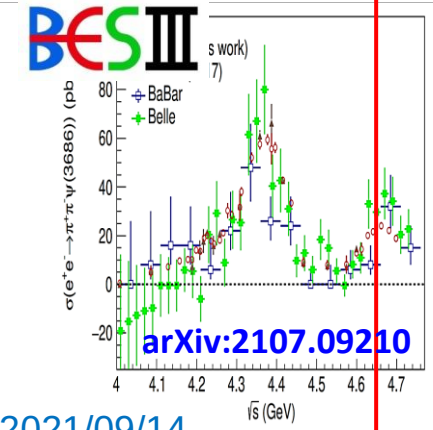


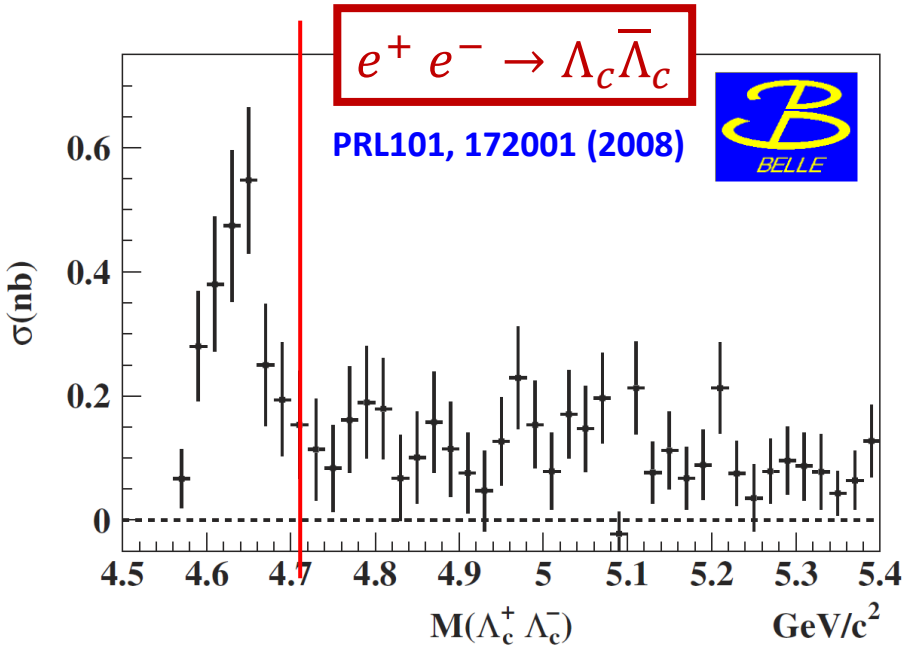
courtesy from C. Z. Yuan

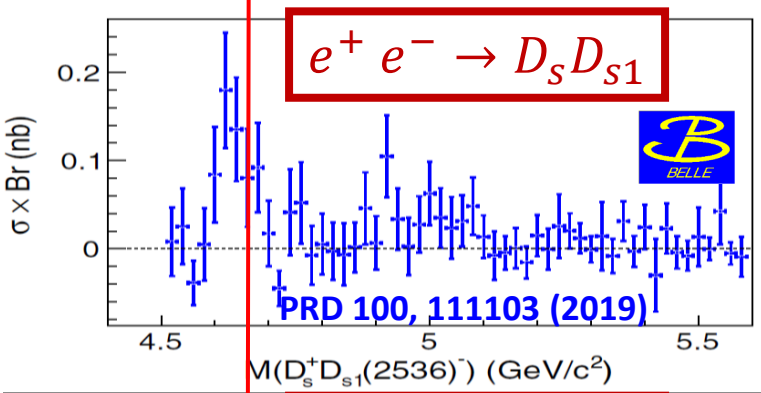
Y(4630) or Y(4660)?

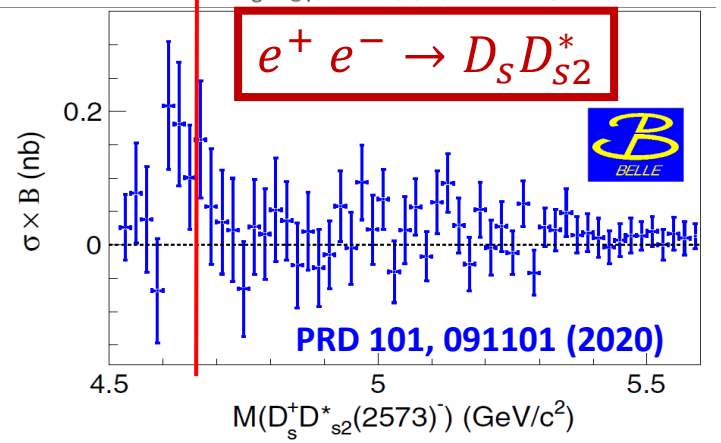








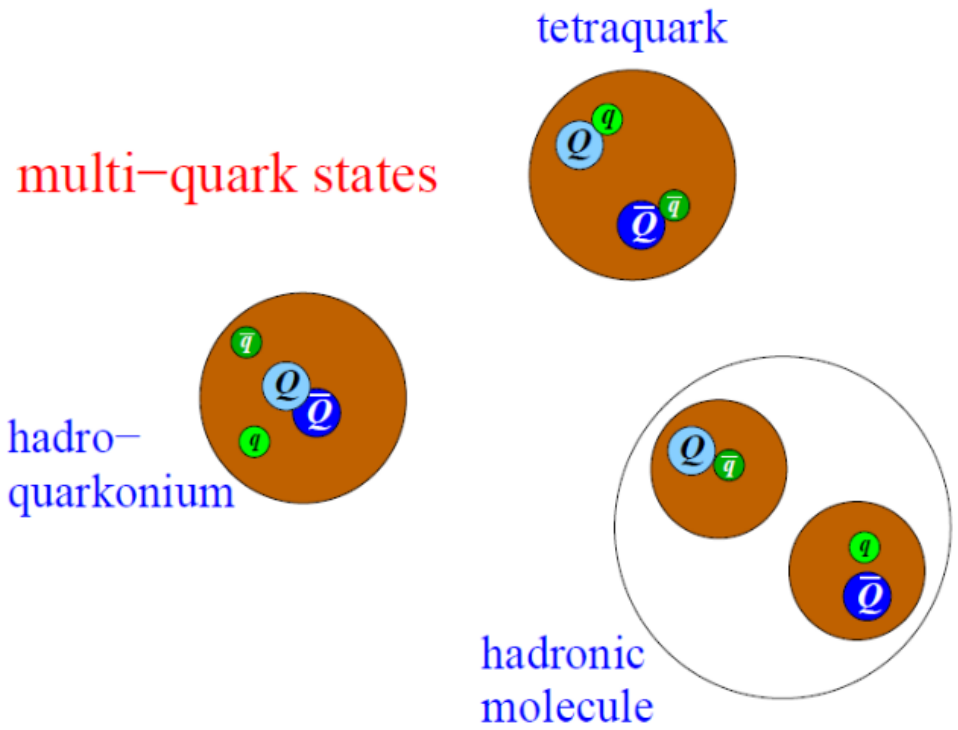




- tension between open charm and charmonium modes
- parametrisation affects resonance parameters

Experiment	Mass (MeV)	Width (MeV)
Belle, $\pi\pi\psi'$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi\pi\psi'$	$4669\pm21\pm3$	$104\pm48\pm10$
BESIII, $\pi\pi\psi'$	$4651\pm38\pm2$	$155\pm25\pm1$
Belle, $\Lambda^+_c\Lambda^-_c$	$4634\ ^{+8}_{-7}\ ^{+5}_{-8}$	$92\ ^{+40}_{-24}\ ^{+10}_{-21}$
Belle, D_sD_{s1}	$4625.9\ ^{+6.2}_{-6.0}\pm0.4$	$49.8\ ^{+13.9}_{-11.5}\pm4.0$
Belle, $D_sD^*_{s2}$	$4619.8\ ^{+8.9}_{-8.0}\pm2.3$	$47.0\ ^{+31.3}_{-14.8}\pm4.6$

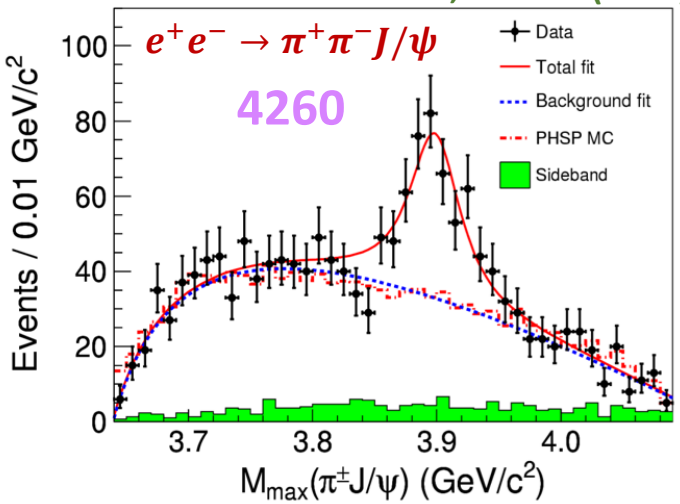
Z_c and Z_{cs} states



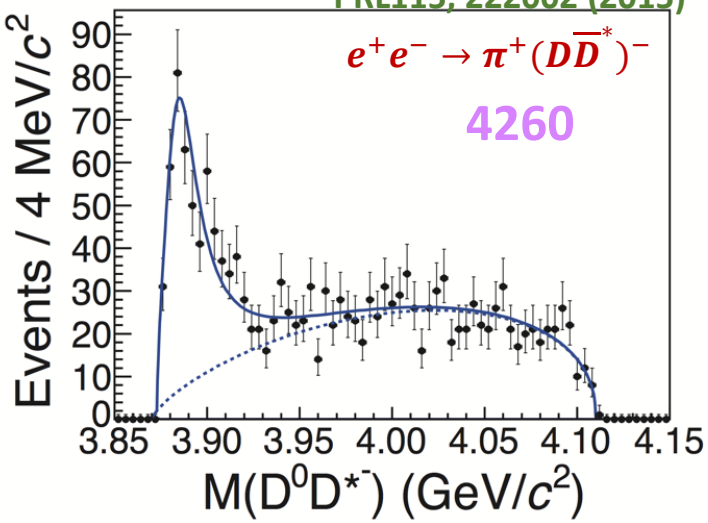
Z_c states from e^+e^- annihilations

$Z_c(3900)/Z_c(3885)$

PRL110, 252001 (2013)
PRL115, 112003 (2015)

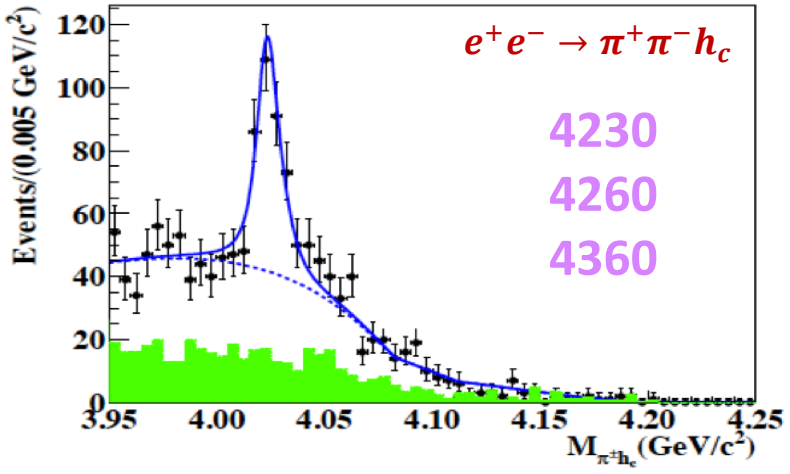


PRL112, 252001 (2014)
PRL115, 222002 (2015)

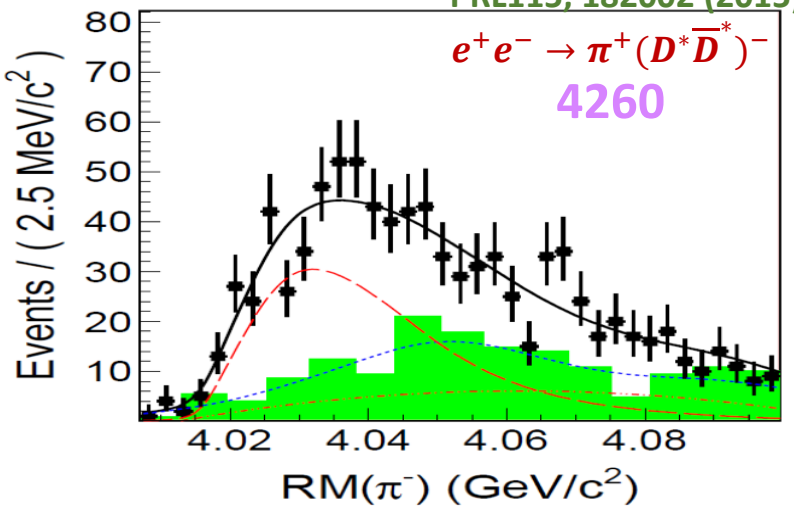


$Z_c(4020)/Z_c(4025)$

PRL111, 242001 (2013)
PRL113, 212002 (2014)



PRL112, 132001 (2014)
PRL115, 182002 (2015)



Observed both in
charged and neutral modes

Inspired by

$Z_c(3900)^{\pm 0}$ in $e^+e^- \to \pi\pi J/\psi$

$Z_c(4020)^{\pm 0}$ in $e^+e^- \to \pi\pi h_c$

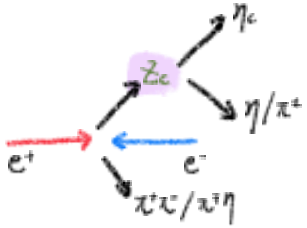
search for unobserved new
Z_c states via:

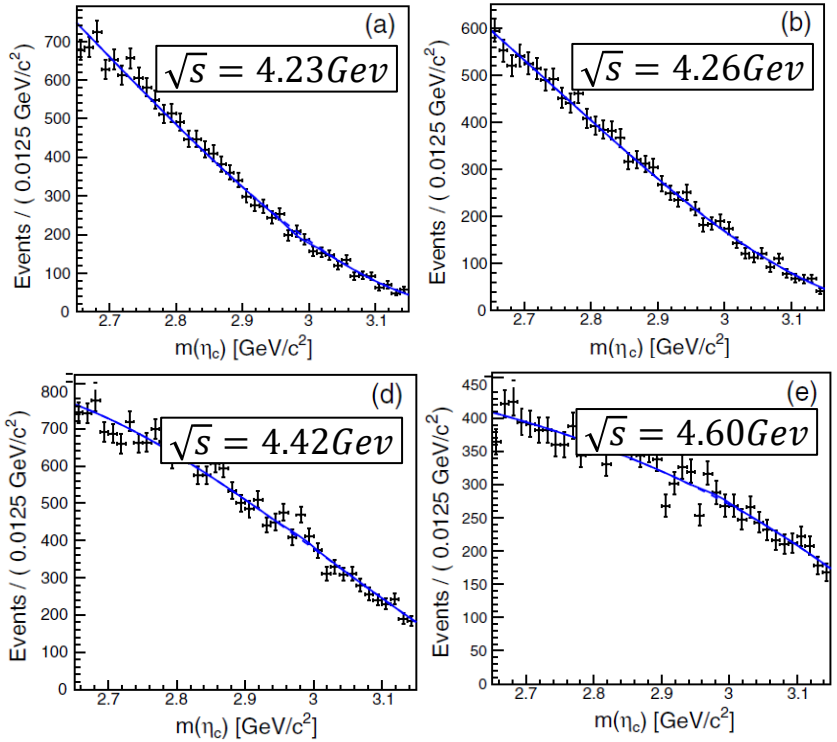
$e^+e^- \to \pi^+\pi^-\eta_c\eta$

- Iso-triplet $Z_c^{\pm 0}$ decay into $\pi^{\pm o}\eta_c$
- Iso-singlet $Z_c^{\ 0}$ decay into $\eta\eta_c$

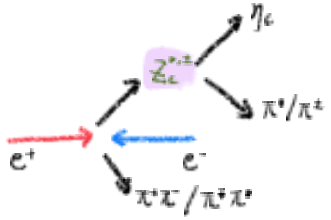
$Z_c \to \pi\eta_c$ and $Z_c \to \eta\eta_c$

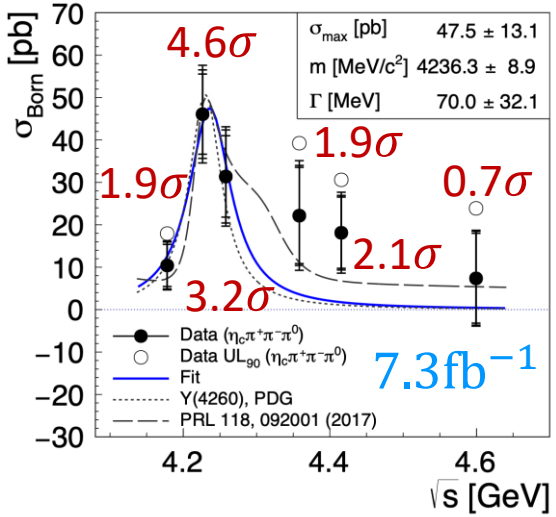
- $e^+e^- \to \pi^+\pi^-\eta_c\eta$ **PRD 103, 032004 (2021)**
  - 4.1 fb^{-1} data between 4.23 and 4.60 GeV
  - 16 η_c decay modes
  - no significant signal for $\pi^+\pi^-\eta_c\eta$ (η_c or Z_c production)
  - no 0^{++} iso-singlet $3.7 < M(\eta\eta_c) < 3.9\ GeV$
  - $\sigma^{\text{up}}_{4.23GeV} = 6.2\ pb$, $\sigma^{\text{up}}_{4.26GeV} = 10.8\ pb$, $\sigma^{\text{up}}_{4.36GeV} = 27.6\ pb$, $\sigma^{\text{up}}_{4.42GeV} = 22.6\ pb$, $\sigma^{\text{up}}_{4.60GeV} = 23.7\ pb$ at 90%C.L.





- $e^+e^- \to \eta_c\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-, \eta_c\pi^0\gamma$ **PRD 103, 032006 (2021)**
  - 7.3 fb^{-1} data between 4.18 and 4.60 GeV
  - $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$ observed at 4230 compatible with intermediate Y(4260)
  - looking for Z_c close to $m(D\overline{D})$
  - useful to investigate $Z_c^{\pm,0} \to \eta_c\pi^{\pm,0}$

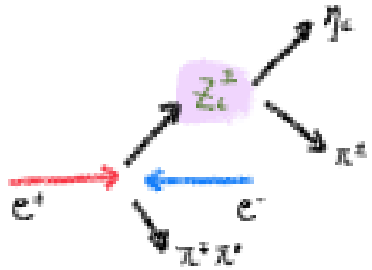


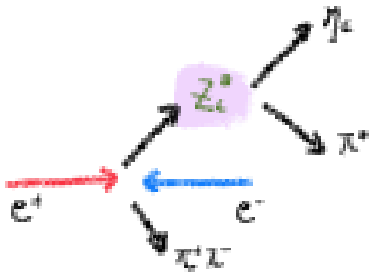


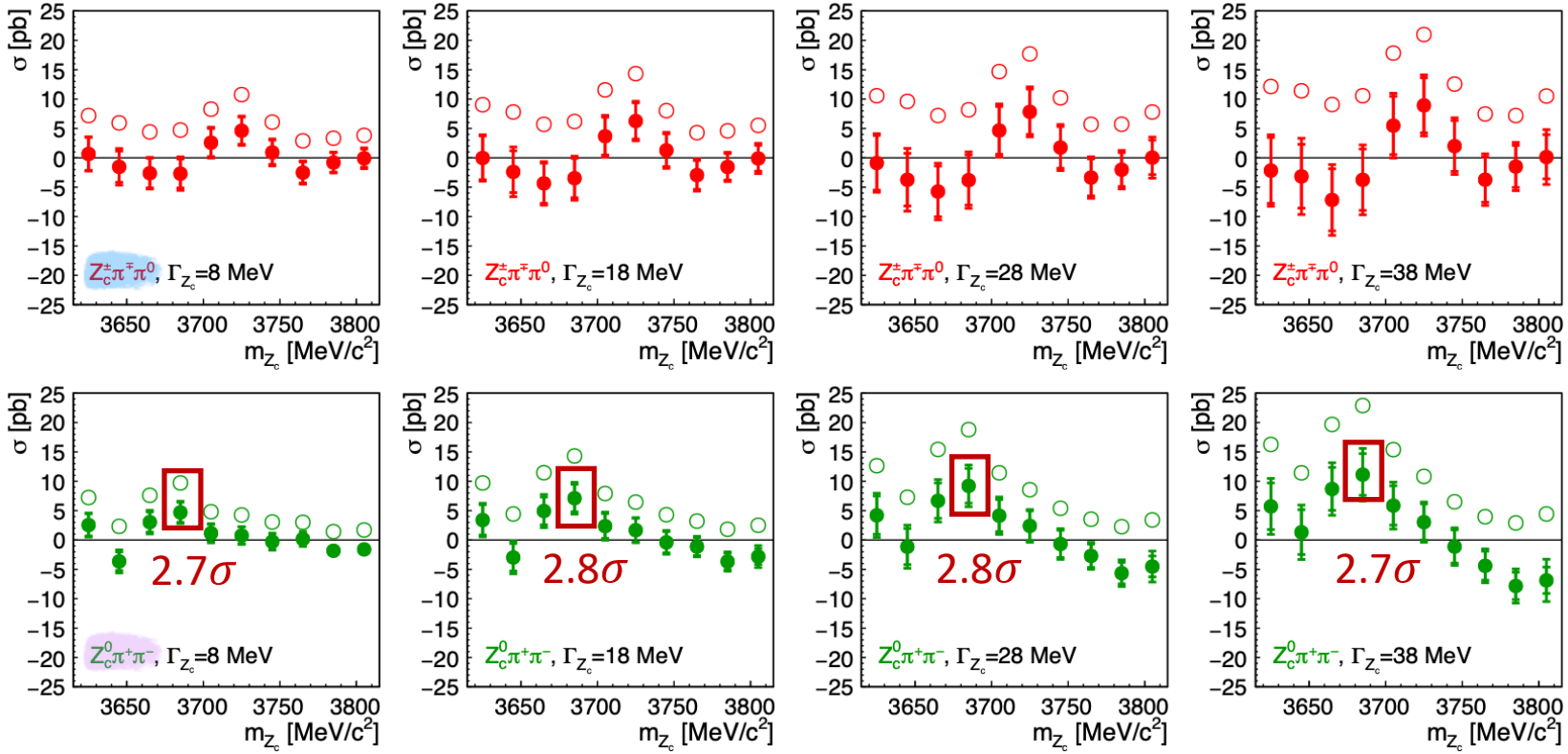
$Z_c \to \pi\eta_c$ and $Z_c \to \eta\eta_c$

- $e^+e^- \to Z_c[\to \eta_c \pi^{\pm,0}]\pi\pi$
  - 7.3 fb^{-1} data between 4.18 and 4.60 GeV
  - looking for Z_c close to $m(D\overline{D})$
  - no signal found for $Z_c^{\pm} \to \eta_c\pi^{\pm}$
  - more significant cross sections for $Z_c^0 \to \eta_c\pi^0$, but more statistics is needed

PRD 103, 032006 (2021)





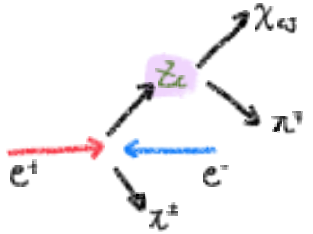


$Z_c \to \pi^{\pm}\chi_{cJ}$

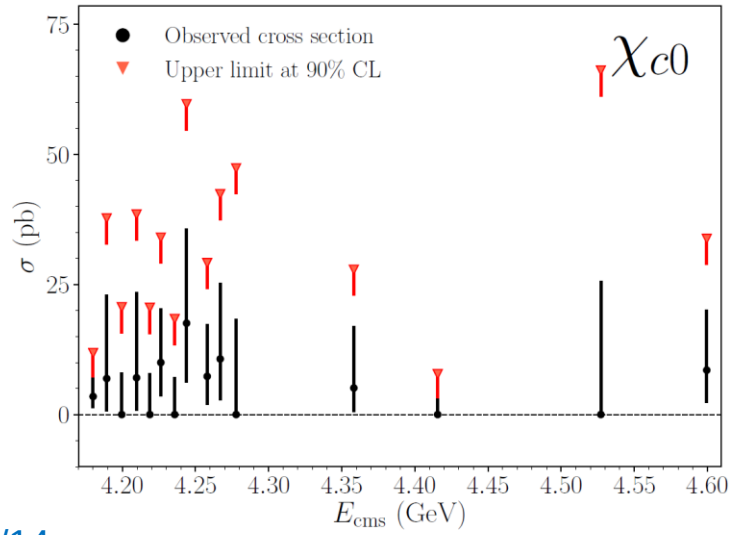
$Z_c(4050)$ and $Z_c(4250)$ in $\pi^{\pm}\chi_{c1}$:

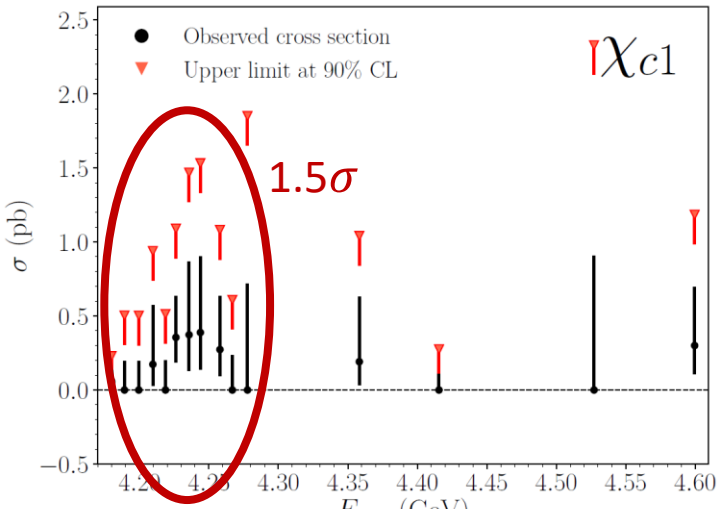
- observed from B decays by Belle **PRD 78, 072004 (2008)**
- no evidence from BaBar **PRD 85, 052003 (2012)**

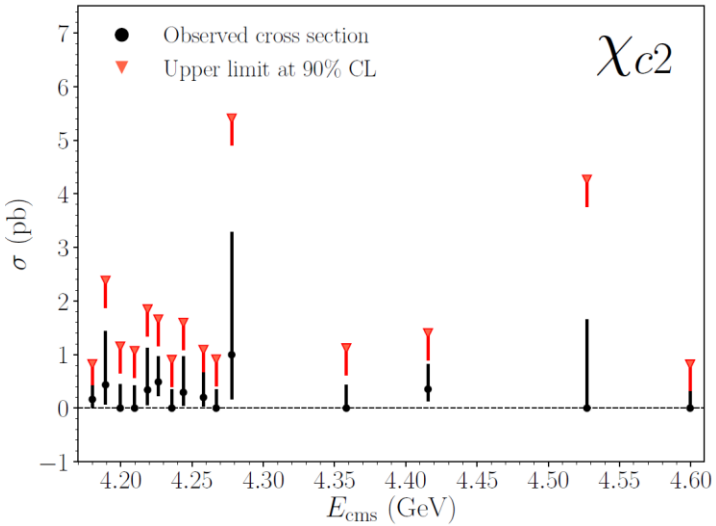
Looking for $Z_c(4050)$ and $Z_c(4250)$ in e^+e^- annihilations @ BESIII



- $e^+e^- \to \pi^+\pi^-\chi_{cJ}$ **PRD 103, 052010 (2021)**
  - 15 data samples for a total of 11.23 fb^{-1}
  - no obvious signal found for $e^+e^- \to \pi^+\pi^-\chi_{cJ}$, slight enhancement: 1.5σ at 4226
  - upper limits at 90% CL for $e^+e^- \to (Z_{c1,2}\pi \to)\ \pi^+\pi^-\chi_{cJ}$



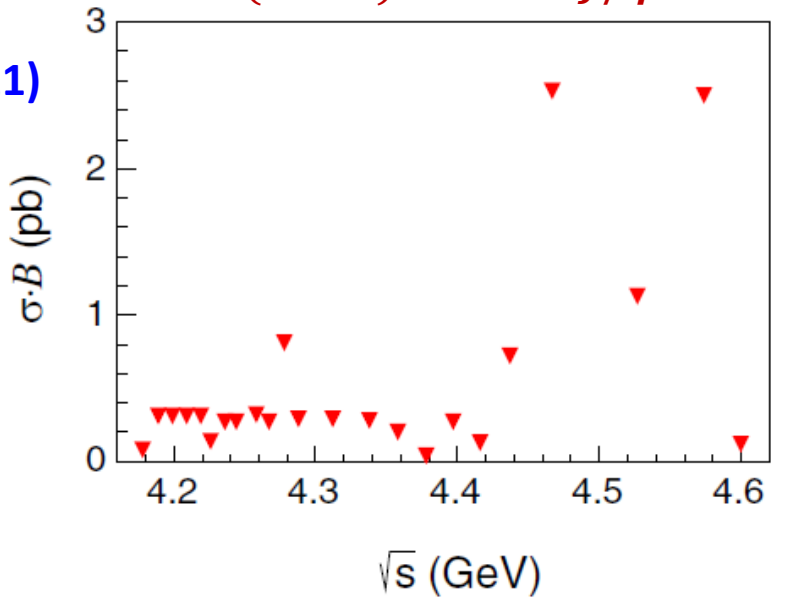




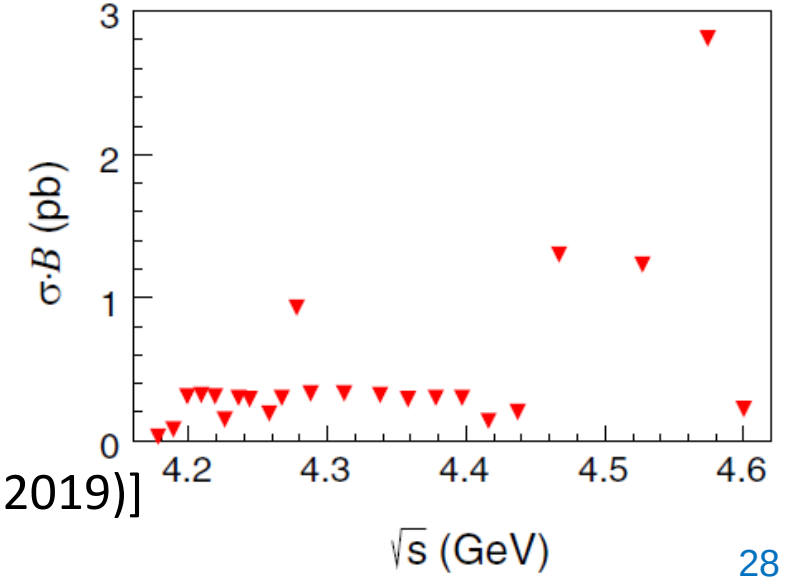
$Z_c(4020)^0 \to X(3872)\gamma$

- $e^+ e^- \to \pi^0 Z_c(4020)^0 \to \pi^0 X(3872)\gamma$ **PRD 104, 012001 (2021)**
  - 14.4 fb^{-1} data between 4.18 and 4.60 GeV
  - proposed $Z_c(4020)^0$ radiative transition to $X(3872)$
    [PRD 99, 054028 (2019)]
  - no significant signal for $X(3872) \to \pi^+\pi^- J/\psi$
  - $\sigma(e^+ e^- \to \pi^0 X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$
    - upper limit at 90% C.L.: $\langle \sigma\mathcal{B} \rangle < 1.6\ fb$
    - predicted $\mathcal{O}(0.1\ fb)$ [PRD 102, 114041 (2020)]
  - no significant signal for $Z_c(4020)^0 \to X(3872)\gamma$
  - $\sigma(e^+ e^- \to \pi^0 Z_c(4020)^0) \cdot \mathcal{B}(Z_c(4020)^0 \to X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$
    - upper limit at 90% C.L.:
  - $$\frac{\mathcal{B}(Z_c(4020)^0 \to X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}{\mathcal{B}(Z_c(4020)^0 \to (D^*\bar{D}^*)^0)} < 0.15\%$$
    - $\mathcal{B}(Z_c(4020)^0 \to (D^*\bar{D}^*)^0)$ from BESIII [PRL 115, 182002 (2015)]
    - compatible with predictions from molecular picture [PRD 99, 054028 (2019)]

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

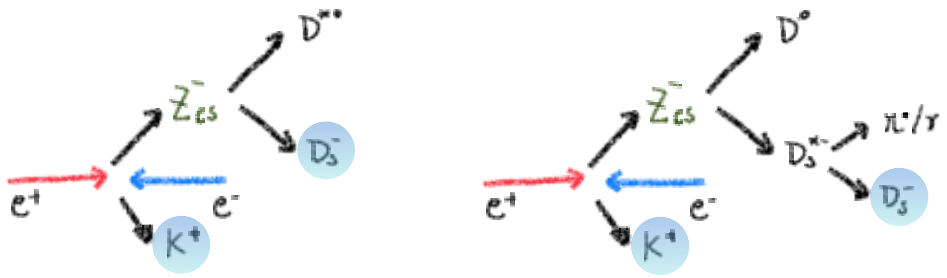


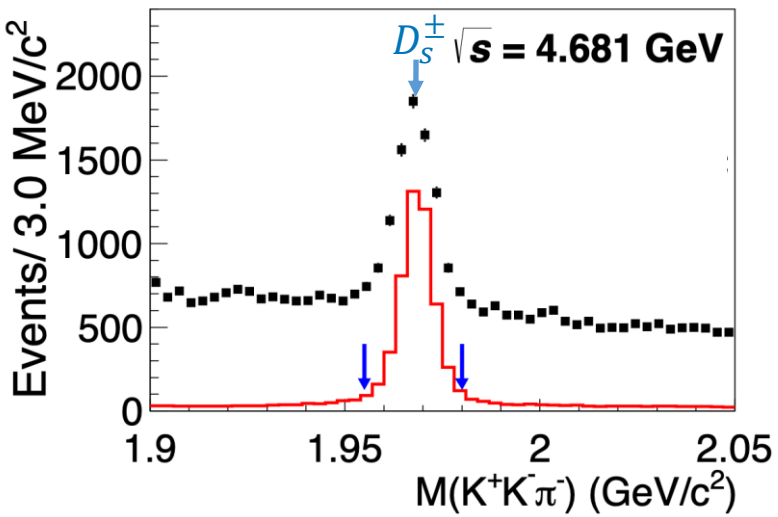
$Z_c(4020)^0 \to X(3872)\gamma$

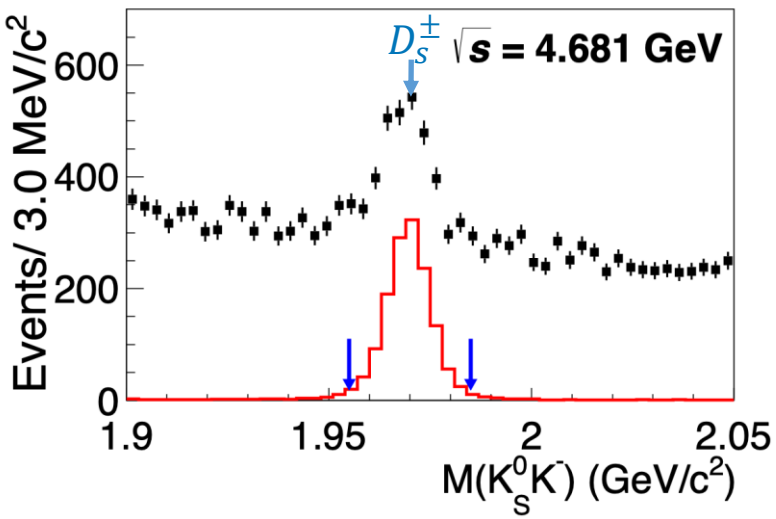


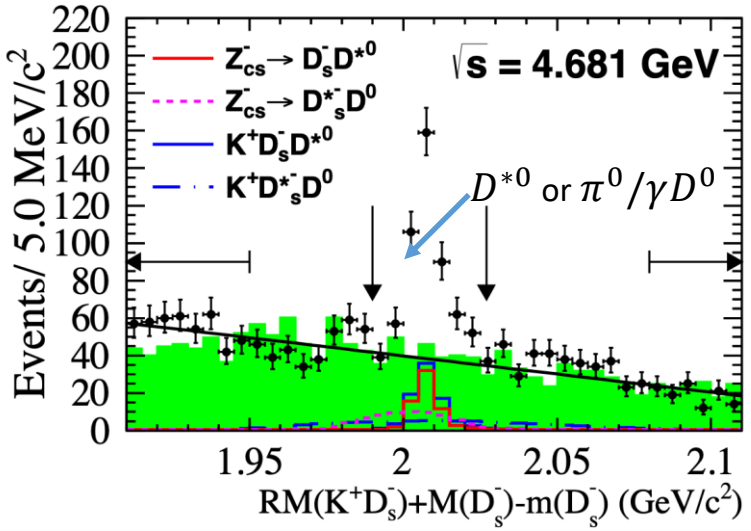
$Z_{cs}(3985)$ from e^+e^- annihilations

- $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ **PRL 126, 102001 (2021)**
  - 5 data samples for a total of 3.7 fb^{-1} (at 4628, 4640, 4660, 4680, and 4700)
  - partial reconstruction of final state, K and D_s^- tag
  - reconstructing $D_s^- \to [\Phi\pi^-, K^*K] \to K^+ K^-\pi^-$ or $D_s^- \to K_s^0 K^-$
  - clear signal for both decay modes
  - wrong sign (WS) events provide good description of combinatorial background
  - Fit to $RM(K^+D_s^-)$ provides absolute contribution in signal region







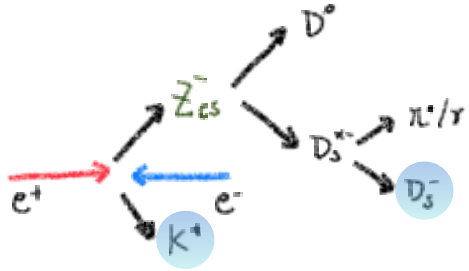


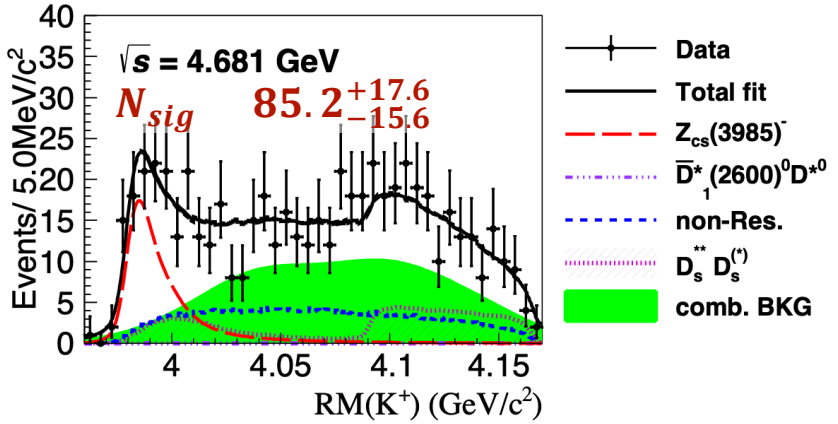
$Z_{cs}(3985)$ from e^+e^- annihilations

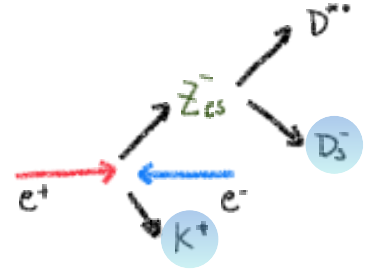
- $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ **PRL 126, 102001 (2021)**
  - enhancement around 3.98 GeV
  - cannot be described by:
    - $D_s^{(*)-} D_s^{**+}$ and $D^{(*)0}\overline{D}^{**0}$
    - interference between two of them
  - assume $J^P = 1^+$
  - simultaneous fit to 5 data samples
  - signal component ($f = 0.5$: 2 decay modes):

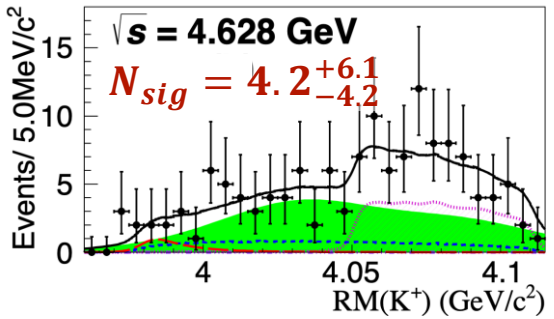
$$\left| \frac{\sqrt{q \cdot p_j}}{M^2 - m_0^2 + i m_0 (f\Gamma_1(M) + (1-f)\Gamma_2(M))} \right|^2$$

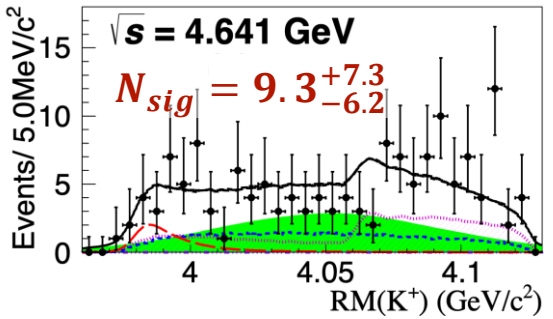
  - Pole (**5.3σ** significance):
    - $m = 3982.5^{+1.8}_{-2.6} \pm 2.1\text{MeV}/c^2$
    - $\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0\text{MeV}$
  - **at least four quarks ($c\bar{c}s\bar{u}$)**

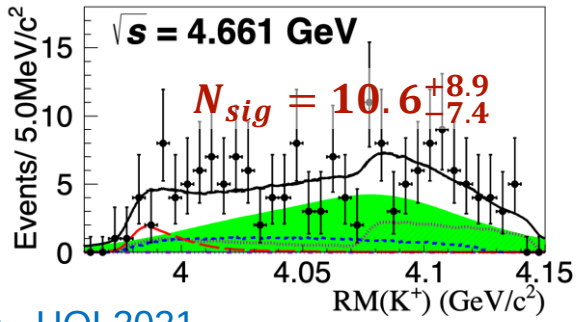


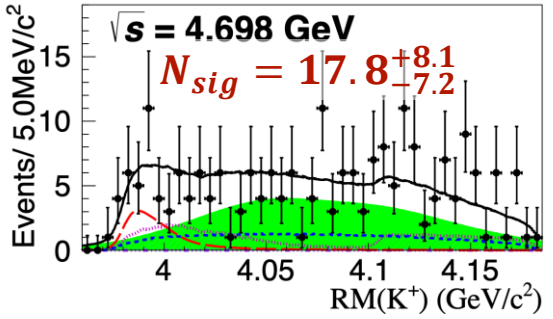








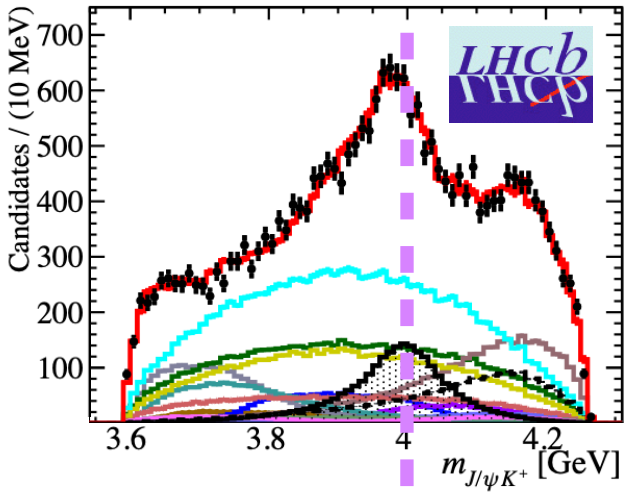




$Z_{cs}(3985)$ vs $Z_{cs}(4000)$

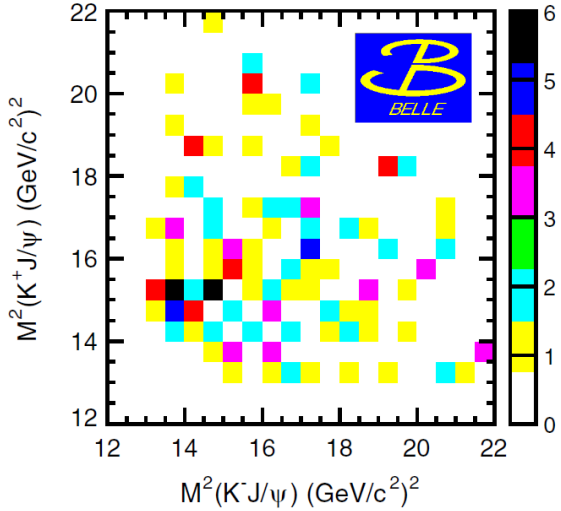
$B^+ \to J/\psi\phi K^-$

PRL 127, 082001 (2021)



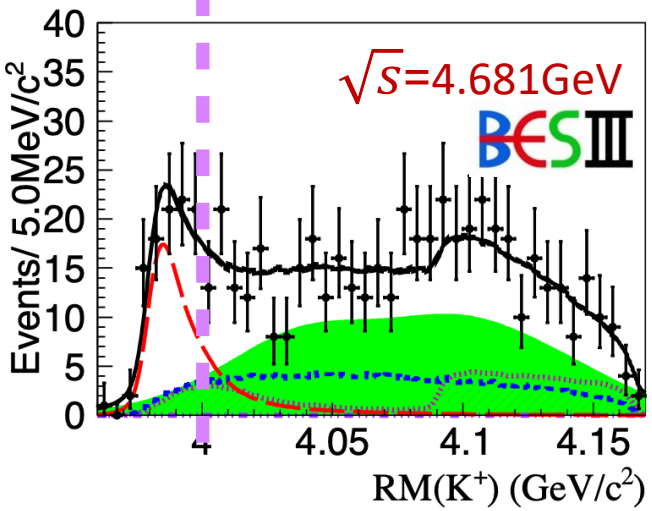
$e^+e^- \to K^+K^-J/\psi$

PRD 89, 072015 (2014)



$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$

PRL 126, 102001 (2021)



State	Signif.	JP	M_0 (MeV)	Γ_0 (MeV)
$Z_{cs}(3985)$	5.3σ	??	$3985^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$
$Z_{cs}(4000)$	15σ	1+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

$Z_{cs}(3985)$ vs $Z_{cs}(4000)$:

- mass consistent within 1σ
- width differs significantly

} not the same state!

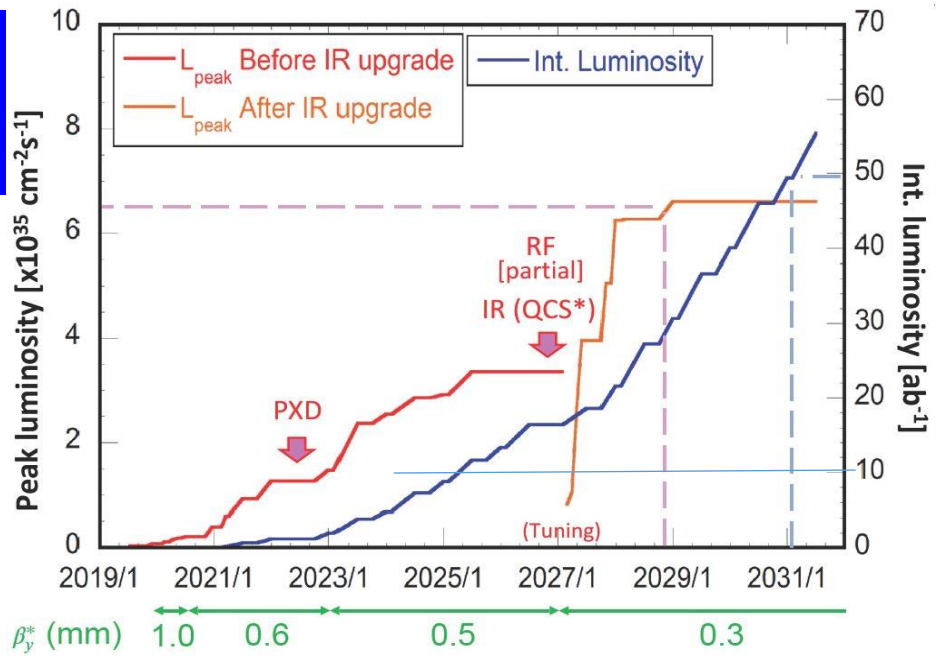
Missing data:

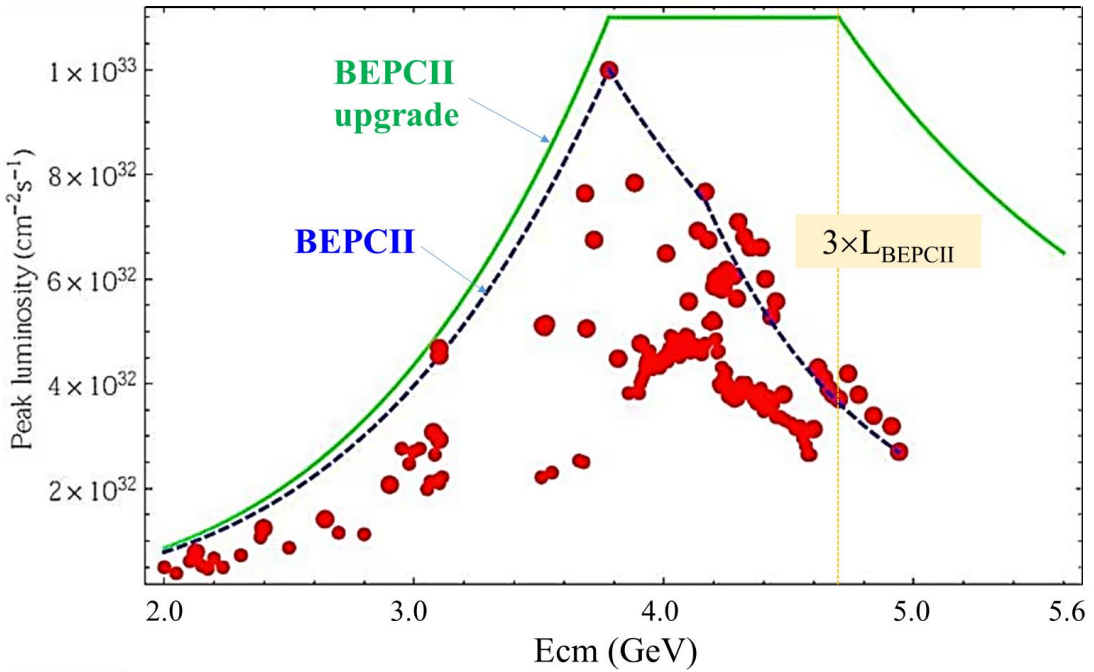
- $B^+ \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$
- $e^+e^- \to K^+K^-J/\psi$

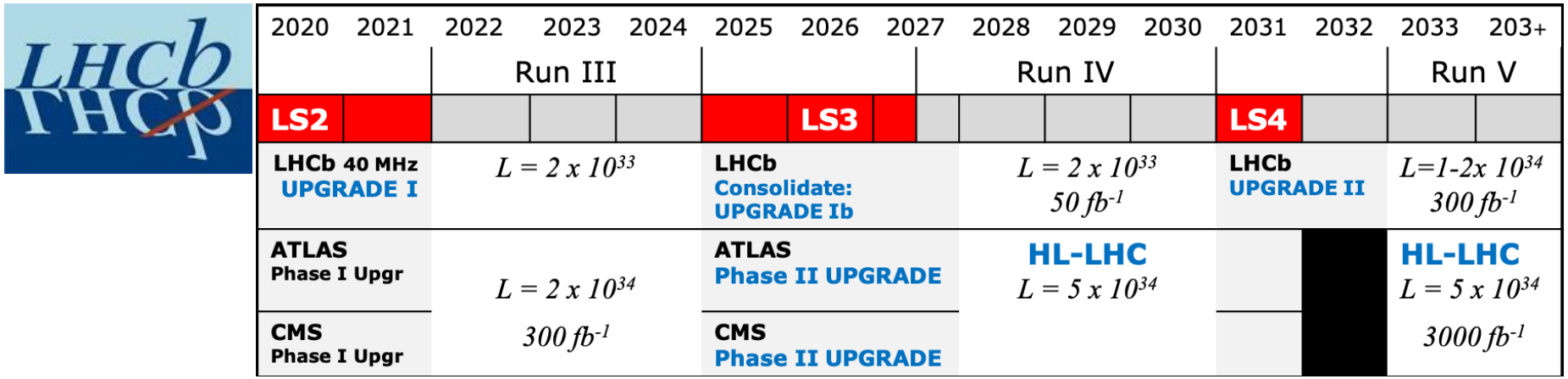
waiting for BESIII results on same data sample

The near future

The near future







Summary

Conclusions

- BESIII provides an ideal environment to investigate XYZ states
- lots of progress in the experimental study of XYZ
- investigation of excited charmonium states:
  - new $\psi_2(3823)$ decays modes observed
- charmonium-like states:
  - decay modes of X(3872)
  - high precision measurements of cross section for Y states investigation
  - decay modes of Z_c states
  - observation of new Z_{cs} states
- more results to come, and lots of opportunities and challenges ahead

Thank you!

Backup

BESIII detector performance

Experiments	**MDC** Spatial resolution	**MDC** dE/dx resolution	**EMC** Energy resolution
CLEOc	110 μm	5%	2.2-2.4 %
Babar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII	115 μm	<5% (Bhabha)	2.4%

Experiments	**TOF** Time resolution
CDFII	100 ps
Belle	90 ps
BESIII	68 ps (BTOF) 60 ps (ETOF)