ICHEP 2022
BOLOGNA

Recent XYZ Results at BESIII

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on behalf of BESIII Collaboration

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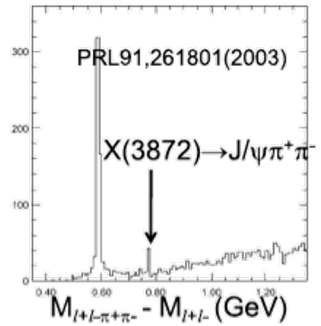
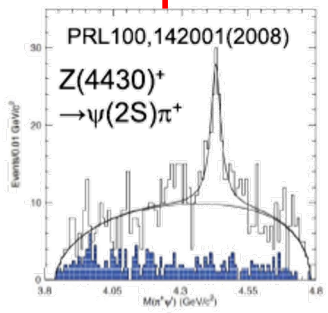
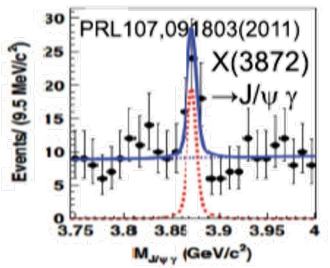
9 July 2022

New exotic resonances

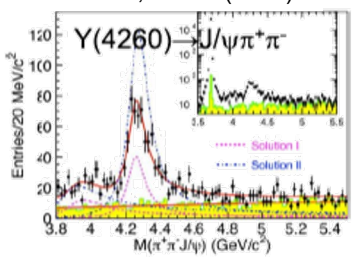
Starting from 2003, in heavy quarkonia,
a long list of states not following the conventional potential model

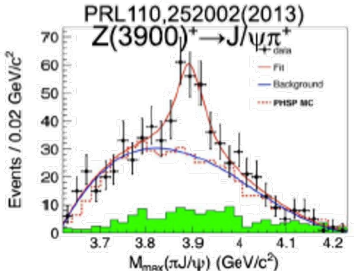


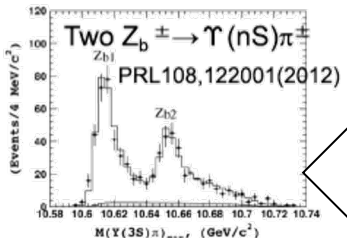




PRL95,142001(2005)







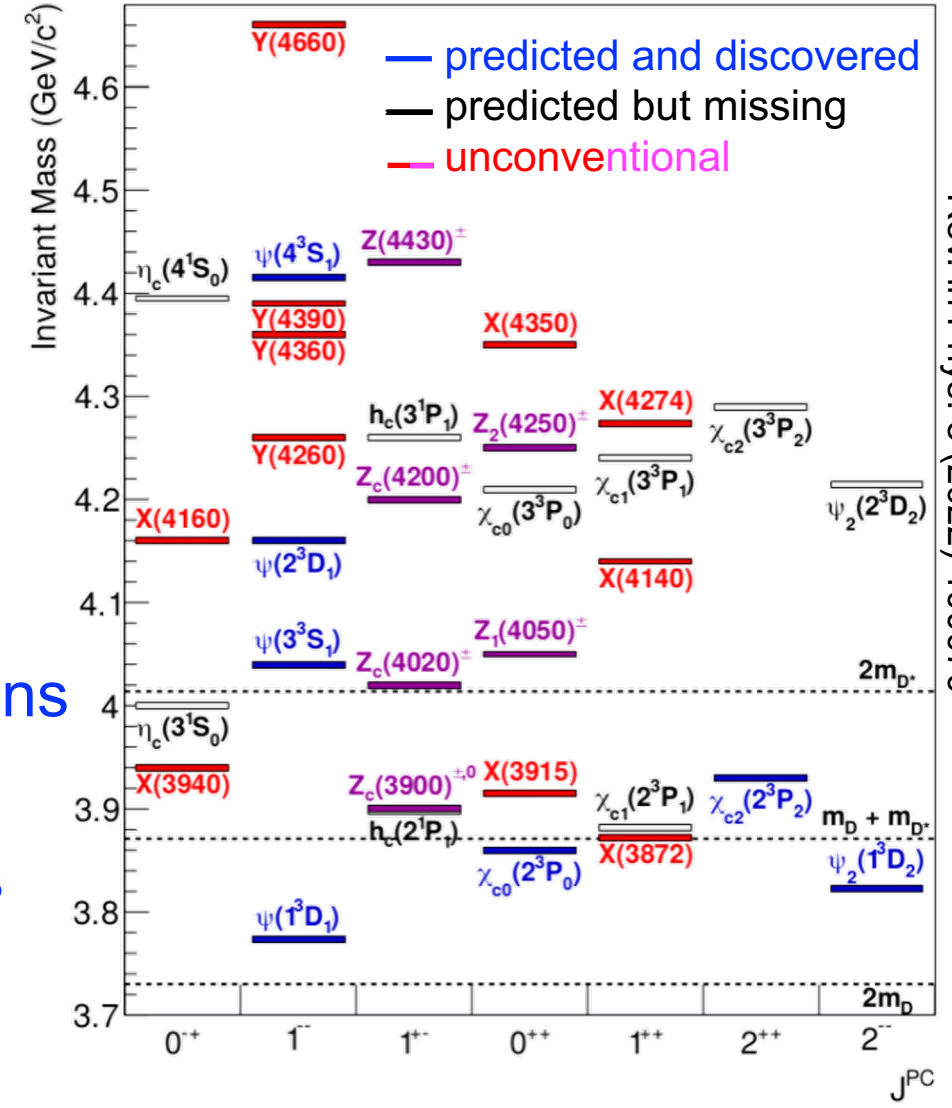
also in the bottomonium sector

the exotic alphabet

Y – 1^- states in e^+e^- collisions

Z – charged states

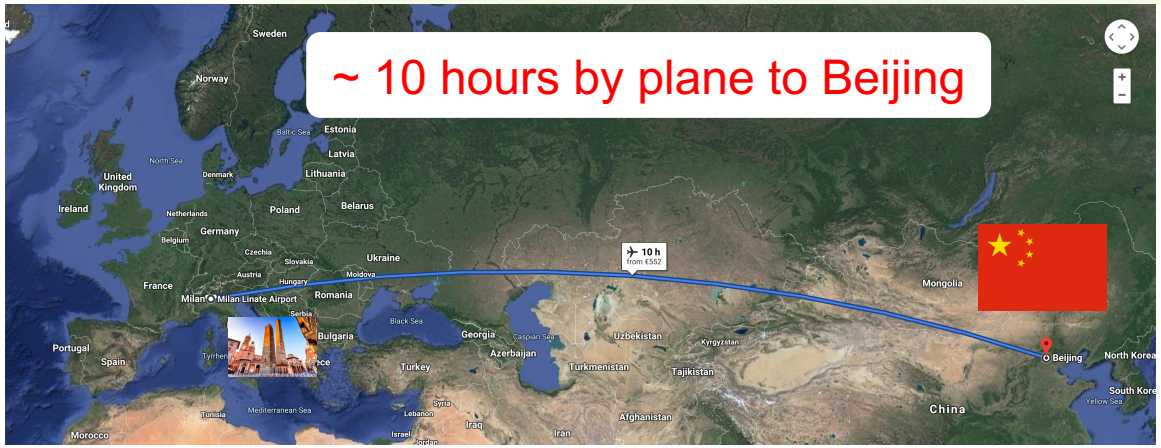
X – all the remaining cases

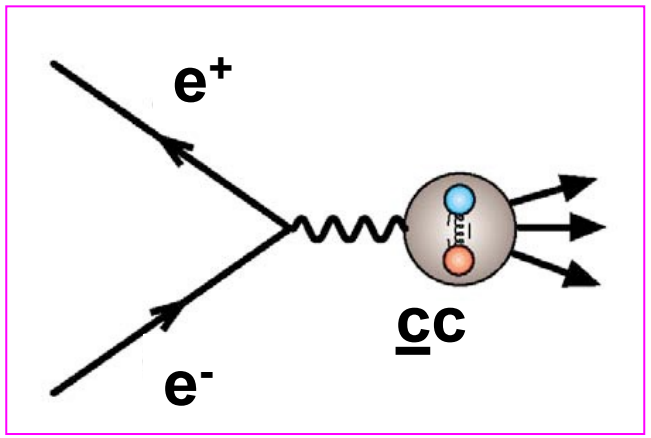


Rev. in Phys. 8 (2022) 100070

… even if PDG has recently changed the name scheme

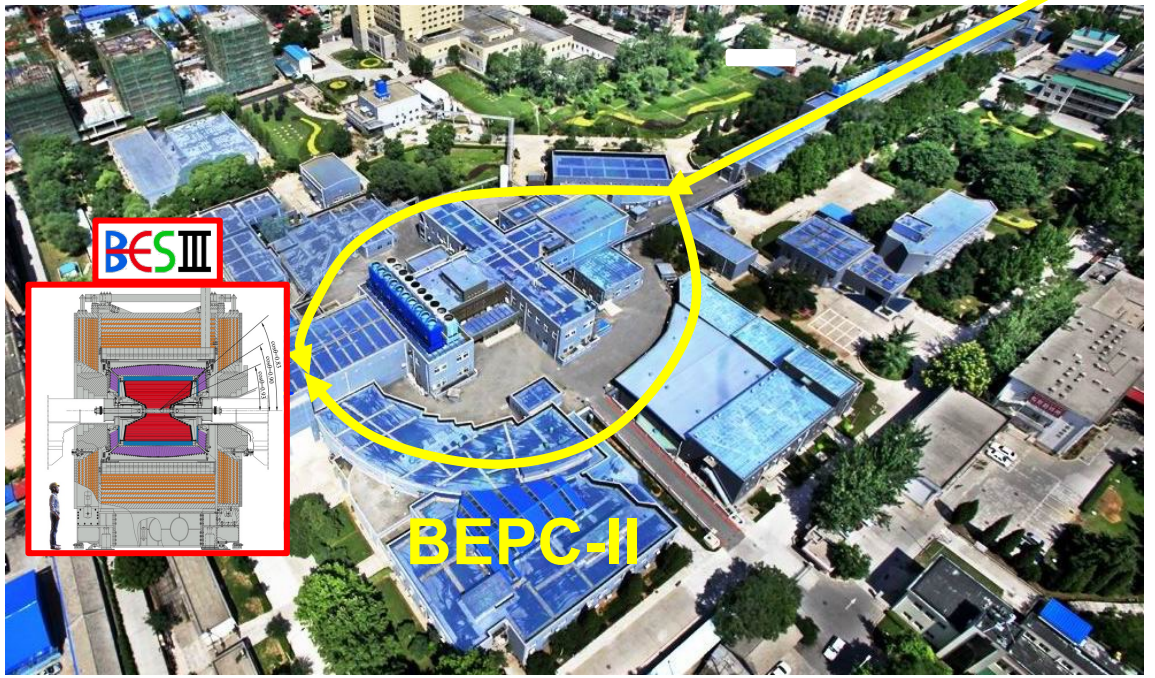
Charmonium(-like) Spectroscopy with BEPC-II and BESIII





The concept:

Formation of 1^{--} states, which decay into lighter charmonium(-like) states



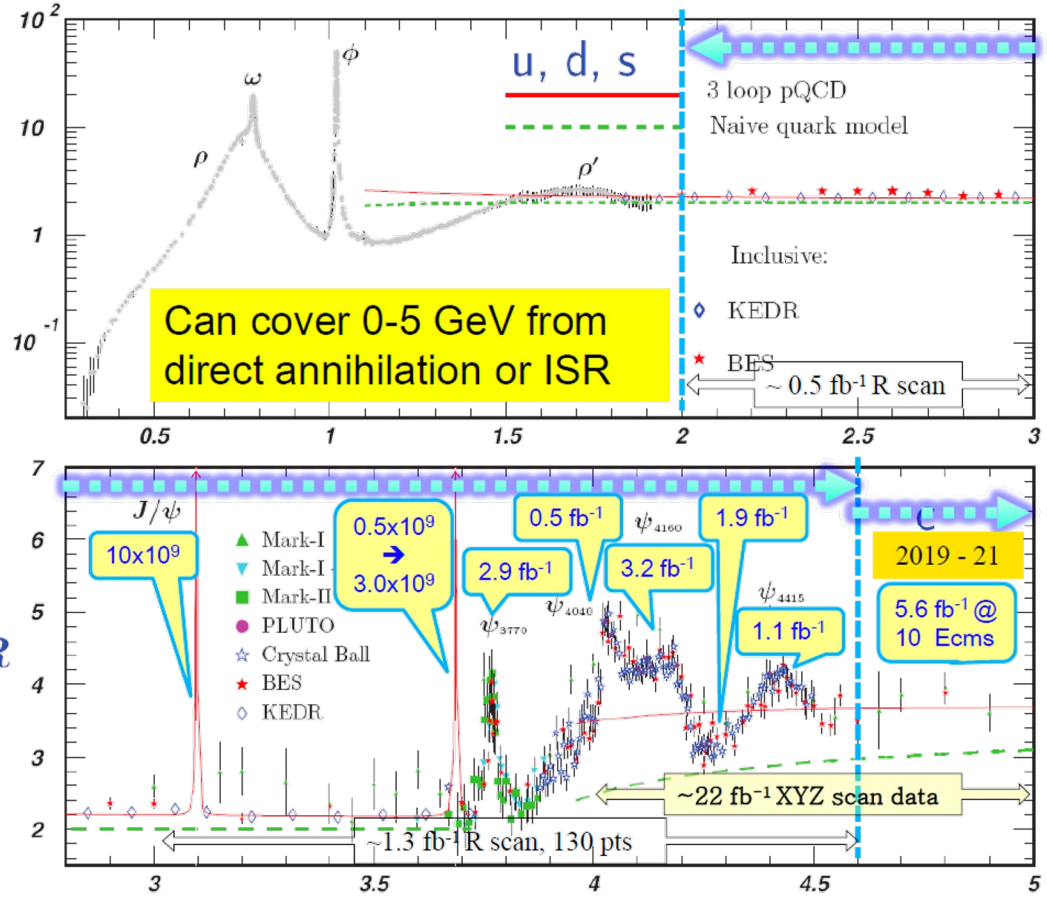
E_{CM} = 2-4.6 GeV (2-4.9 GeV from 2019)

$L_{peak} = 1.0 \times 10^{33}/cm^2s^{-1}$

BESIII Data Sample

Successful data taking since 2009

The XYZ search of this talk focus on

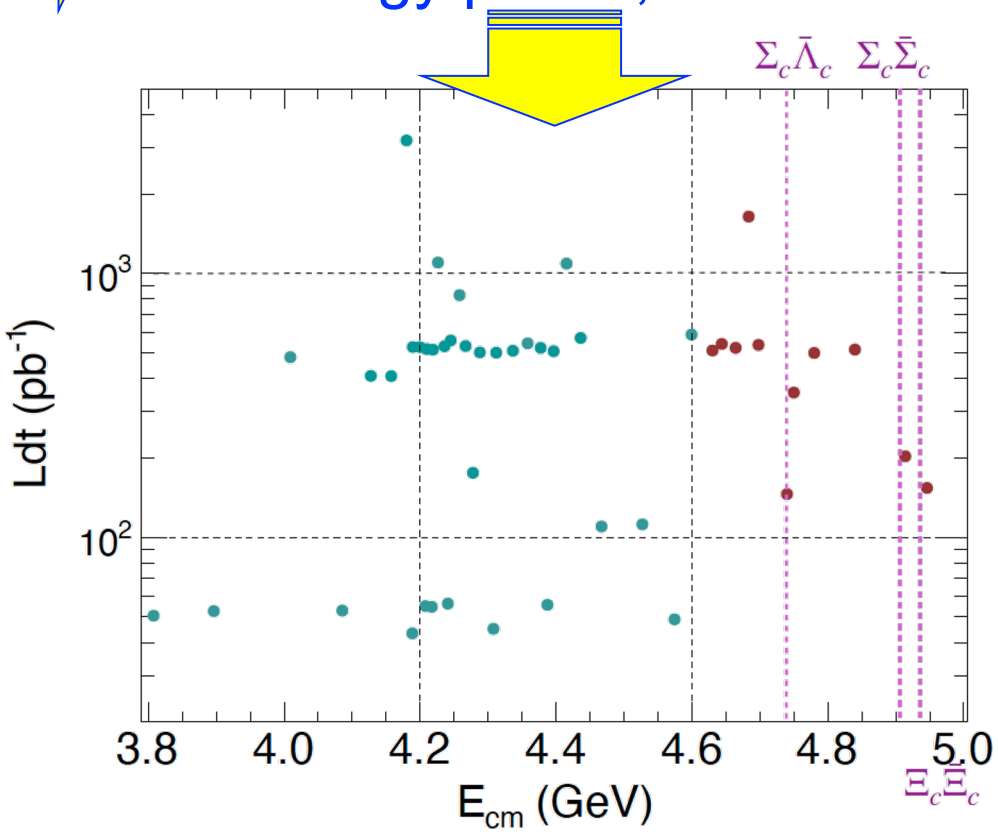


46 data samples L ~21.9 fb^{-1}

29 with L_i > 0.4 fb^{-1}

Small R scan sample:

104 energy points, L ~ 0.8 fb^{-1}



Let's start with X(3872) aka $\chi_{c1}(3872)$

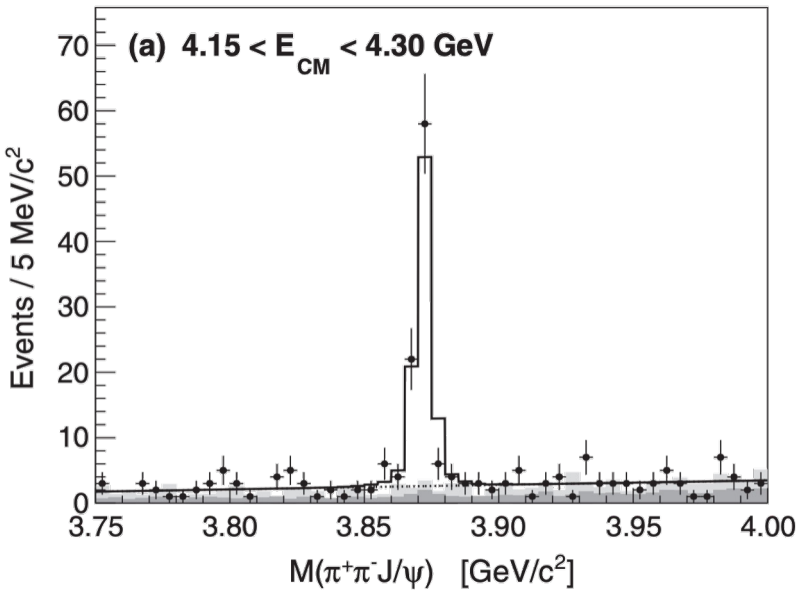
The best studied exotic state

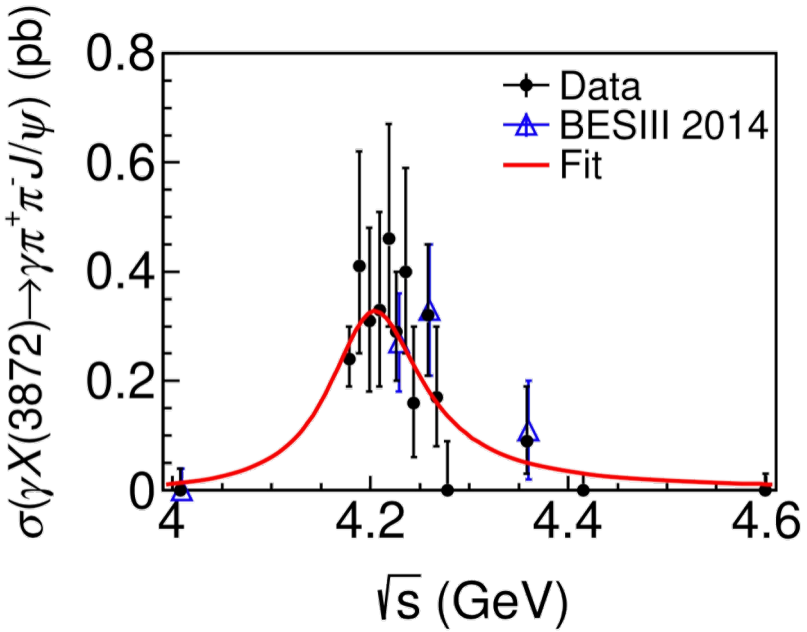
What we know so far

- ✓ Very close do the D^0D^{*0} threshold: $M_{X(3872)} - M_{D^0D^{*0}} = 0.01 \pm 0.14 MeV$
- ✓ Very narrow: $\Gamma^{BW}_{X(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21 MeV$
- ✓ $J^{PC} = 1^{++}$
- ✓ Charged partner not found (yet) – iso-singlet state?
- ✓ Large isospin breaking $B(X \to \rho J/\psi) \simeq B(X \to \omega J/\psi)$
- ✓ Produced in B decays, in hadron collisions, in $e^+e^- \to Y(4230) \to \gamma X(3872)$?

$e^+e^- \to \gamma X(3872); \quad X(3872) \to \pi^+\pi^- J/\psi$

[PRL 122, 232002 (2019)]





Favorite interpretation: molecule mixed with charmonium, but other options are not ruled out

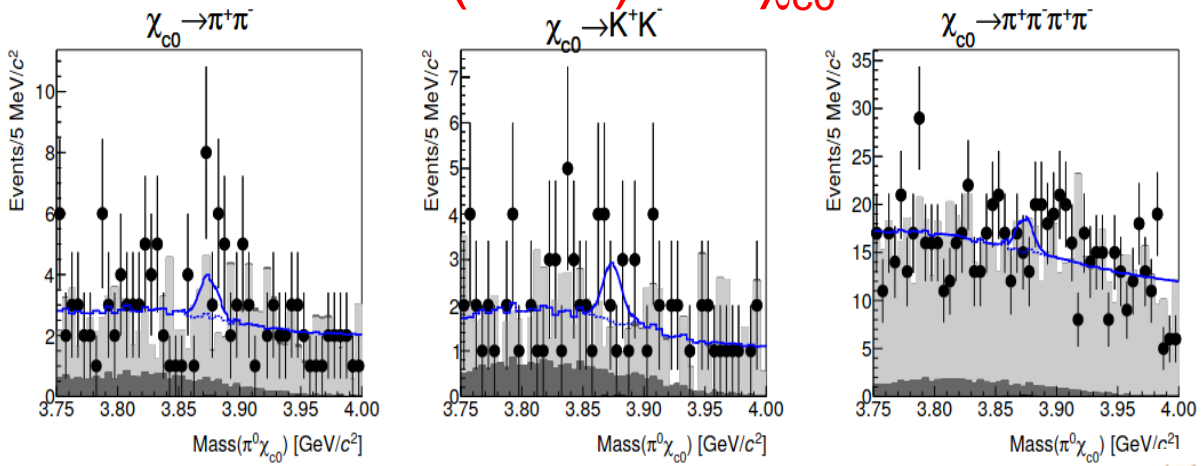
Search for X(3872)→π°χc0 and X(3872)→ππχc0

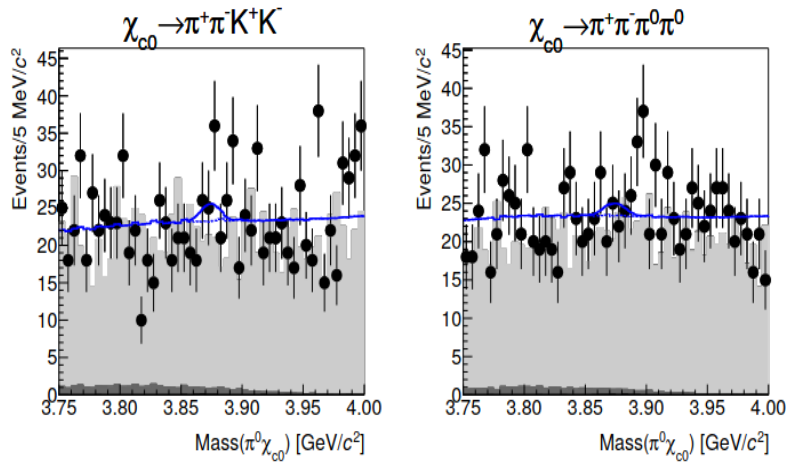
The ratios $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$ and $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$ sensitive to physical interpretation

	Interpretation	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$
1)	Four-quark/molecule	...	2.97
1)	$\chi_{c1}(2P)$	0.0	0.0
2)	$D^0\bar{D}^{0*}$	...	2.84–2.98
3)	$D^0\bar{D}^{0*} + D^+D^{-*}$	1.3–2.07	1.65–1.77
4)	$D^0\bar{D}^{0*} + D^+D^{-*}$	...	3.72
5)	$D^0\bar{D}^{0*} + D^+D^{-*} + \chi_{c1}(2P)$	0.094	1.15

1)PRD77,014013(2008) 2)PRD78,094019(2008) 3)EPJC81,193(2021)
4)PRD79,094013(2009) 5)PRD100,094025(2019)

X(3872)→π°χc0





No significant results (<< 3σ)

→ Upper limits

Ratio	90% C.L. upper limit
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	3.6
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$	4.5
$\frac{\mathcal{B}(X(3872)\to\pi^+\pi^-\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.56
$\frac{\mathcal{B}(X(3872)\to\pi^0\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	1.7

New statistics will be collected after BEPC-II upgrade

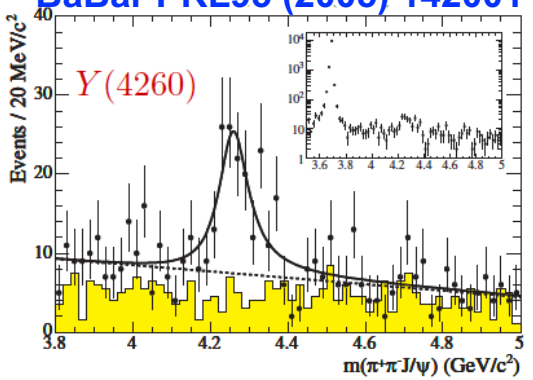
PHYS. REV. D 105, 072009 (2022)

Moving to Y states

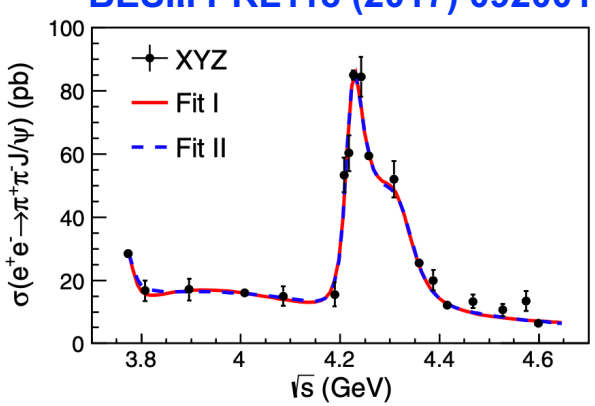
Y(4260) firstly seen by BaBar searching for X(3872), afterwards split into two states Y(4230) and Y(4360) by BESIII

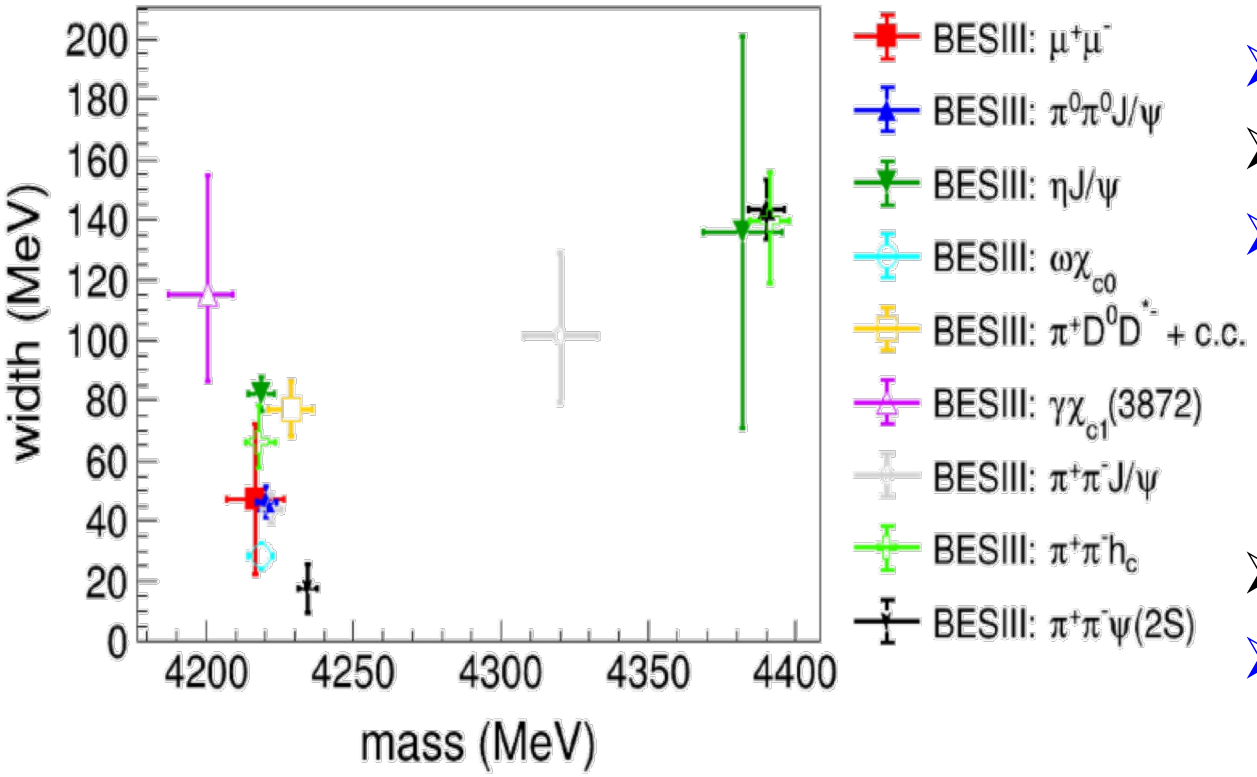
…now called ψ(4230) and ψ(4360) by PDG

BaBar PRL95 (2005) 142001



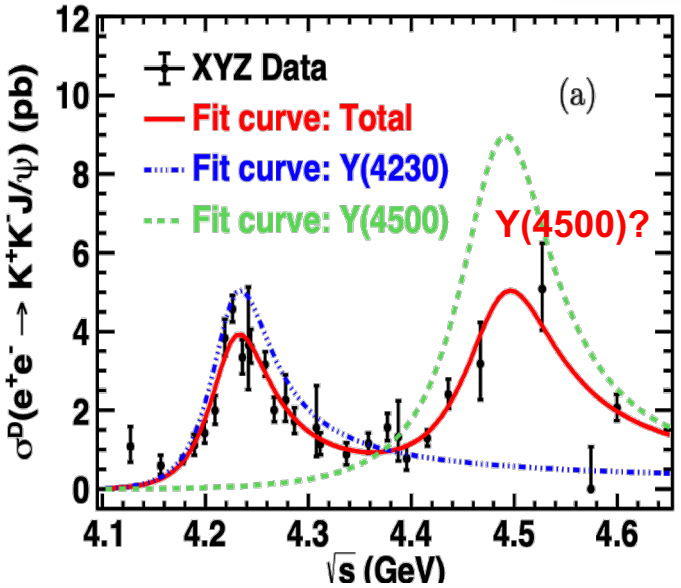
BESIII PRL118 (2017) 092001

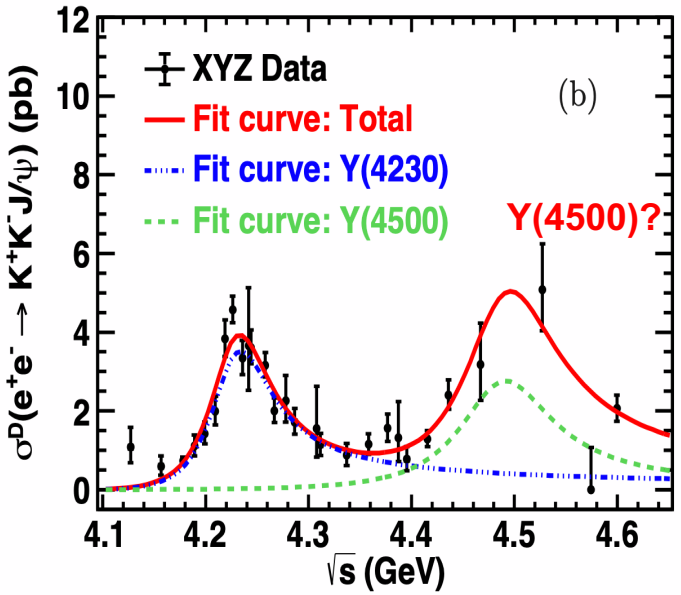




- Inconsistent with all 1^{--} quark model states
- Very suppressed open charm decays
- Candidates for exotic matter
  - ? Hybrids?
  - ? Tetraquark?
  - ? Hadronic molecules?
- Well established
- Experimentally easy to produce using e^+e^- collisions → Initial State Radiation

Searching for Y(4230) in $e^+e^- \to K^+K^-J/\psi$





Investigating the strange content inside Y(4230)

✓ First observation of $Y(4230) \to K^+K^-J/\psi$ peak

$$0.02 < \frac{\mathcal{B}(Y(4230) \to K^+K^-J/\psi)}{\mathcal{B}(Y(4230) \to \pi^+\pi^-J/\psi)} < 0.26$$

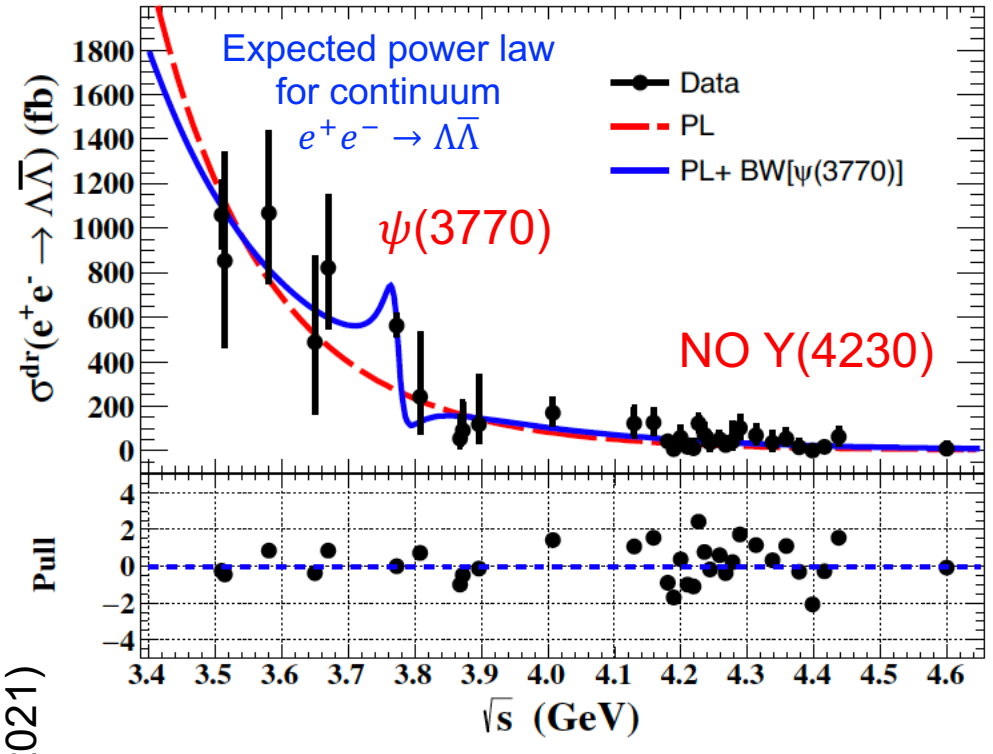
✓ Resonance Y(4500) > 5σ, consistent with the predictions of:

- 5S-4D mixing scheme (PRD99,114003 (2019))
- heavy-antiheavy hadronic molecules model (ProgrPhys41,65(2021))
- Lattice QCD result for a $(cs\bar{c}\bar{s})$ state (PRD73,094510 (2006))

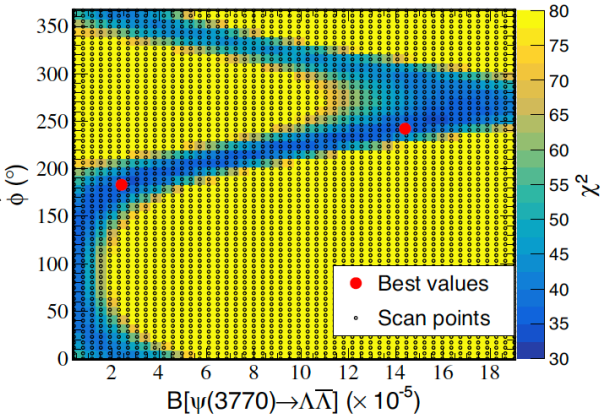
	Parameters	Solution I	Solution II
$Y(4230)$	M(MeV)	$4225.3 \pm 2.3 \pm 21.5$	
	Γ_{tot}(MeV)	$72.9 \pm 6.1 \pm 30.8$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$0.42 \pm 0.04 \pm 0.15$	$0.29 \pm 0.02 \pm 0.10$
$Y(4500)$	M(MeV)	$4484.7 \pm 13.3 \pm 24.1$	
	Γ_{tot}(MeV)	$111.1 \pm 30.1 \pm 15.2$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$1.35 \pm 0.14 \pm 0.06$	$0.41 \pm 0.08 \pm 0.13$
phase angle	φ(rad)	$1.72 \pm 0.09 \pm 0.52$	$5.49 \pm 0.35 \pm 0.58$

arXiv:2204.07800 submitted to PRL

Searching for Y(4230) in $e^+e^- \to \Lambda\bar{\Lambda}$



PRD 104, L091104 (2021)



	PL	PL+BW [$\psi(3770)$]	
σ_0 (fb)	379 ± 22	320^{+750}_{-340}	
n	8.8 ± 0.4	8.2 ± 0.6	
ϕ (°)	...	183^{+57}_{-40}	240^{+17}_{-115}
σ_ψ (fb)	0 (fixed)	240^{+1470}_{-190}	1440^{+270}_{-1390}
χ^2/ndof	62.0/31	34.6/29	
$\mathcal{B}$ ($\times 10^{-5}$)	...	$2.4^{+15.0}_{-1.9}$	$14.4^{+2.7}_{-14.0}$

Investigating the charmless decays

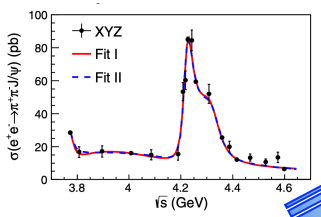
- ✓ No signal for $\Upsilon(4230) \to \Lambda\bar{\Lambda}$
- ✓ First evidence of $\psi(3770) \to \Lambda\bar{\Lambda}$ with 4.6-4.9σ
  - ➢ 2.4×10^{-6} < BF < 1.8×10^{-4} at 90% CL
  - ➢ much larger than the prediction based on electronic width scaling (BF ~ 5×10^{-7})

Nature of $\psi(3770)$ still under debate:

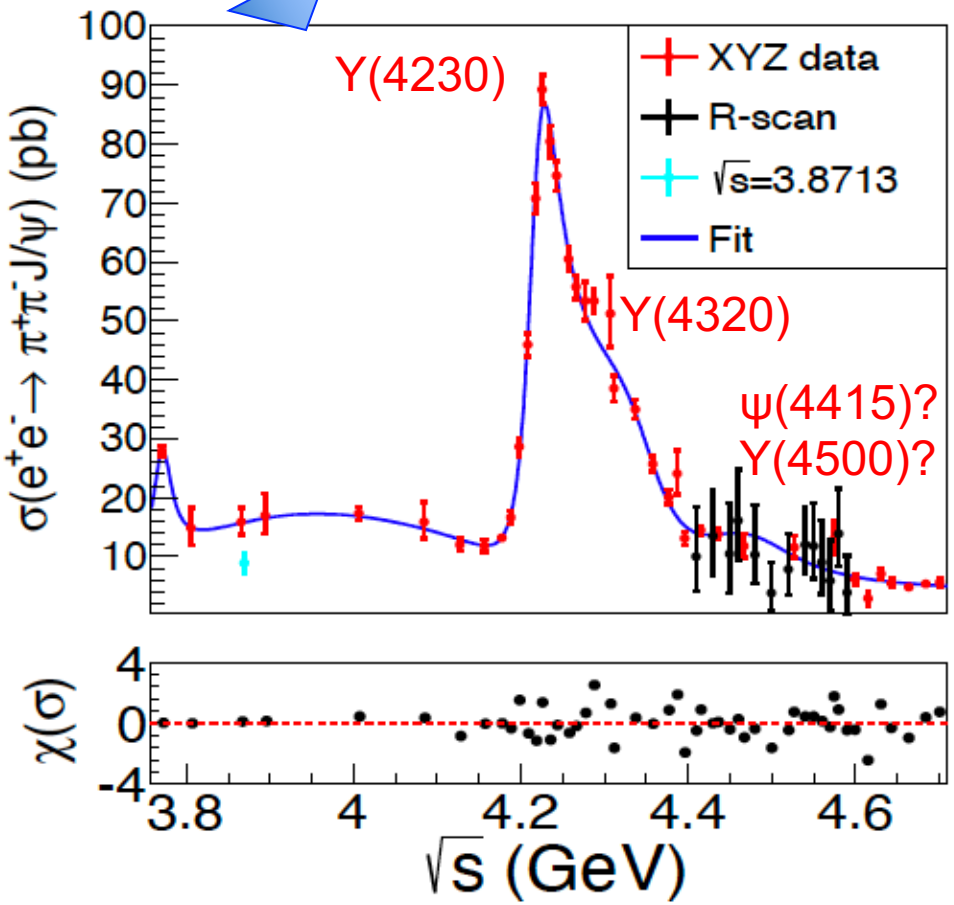
- ➢ conventional 1D charmonium state
- ➢ 2S+1D mixing?
- ➢ tetraquark?

A multi-quark content could explain enhanced decays into light quark systems

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



Higher statistics, higher precision, higher energies, better fit



- ✓ Y(4230) and Y(4320) observed with > 10σ
- ✓ Structure around 4 GeV better fit by a BW (before exp)
- ✓ Evidence ~3σ of a structure at higher energies
  ψ(4415)? The new Y(4500)?
- ✓ By including the high energy state in the fit, the Y(4320) parameters change

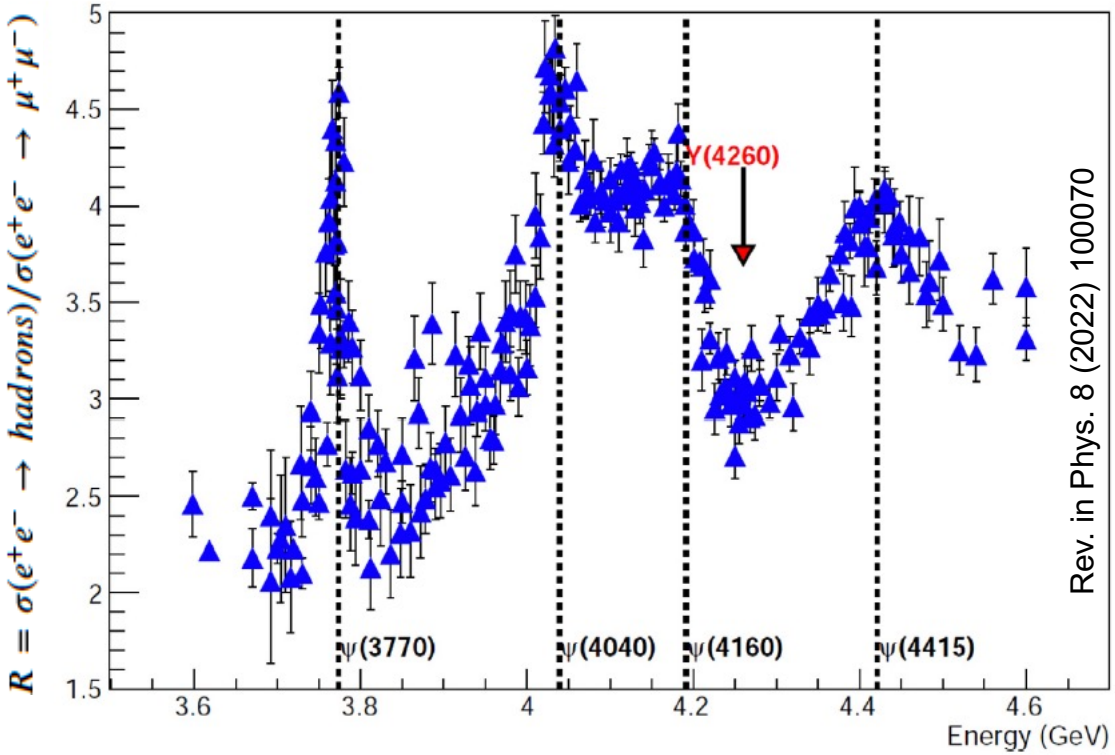
$M_{Y(4230)}$	=	$4221.4 \pm 1.5 \pm 2.0$ MeV/c^2
$\Gamma_{Y(4230)}$	=	$41.8 \pm 2.9 \pm 2.7$MeV

$M_{Y(4320)}$	=	$4298 \pm 12 \pm 26$ MeV/c^2
$\Gamma_{Y(4320)}$	=	$127 \pm 17 \pm 10$ MeV

arXiv:2206.08554v1, submitted to PRD

Open charm production

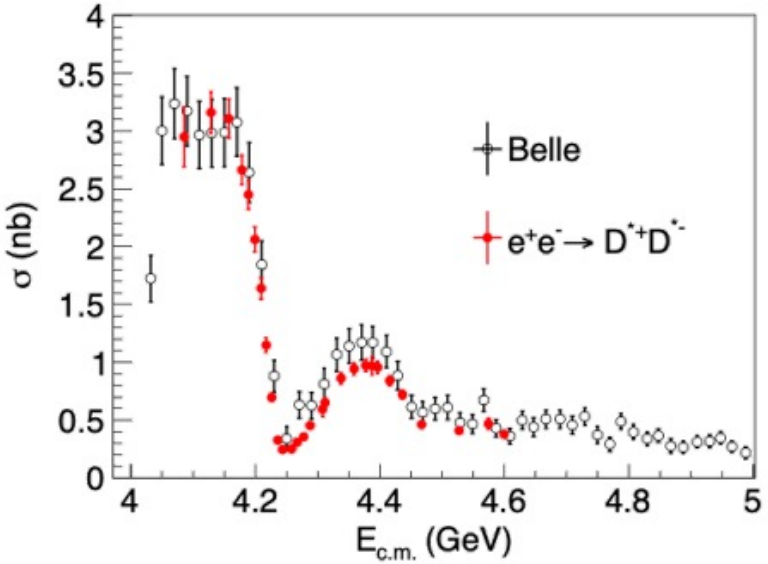
- Conventional states above threshold match well quark potential model
  - ✓ main decays in open charm mesons
- Charmonium-like states (Y) disagree with quark model
  - ✓ main decay in hidden-charm mesons

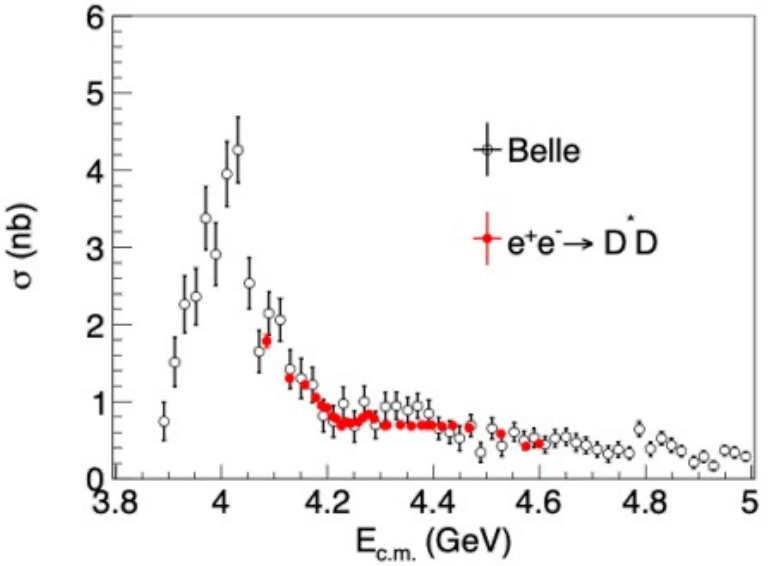


Open charm cross section measurements essential to fully understand XYZ states

Important input for coupled-channel analysis

Measurement of $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^{*+}D^-$

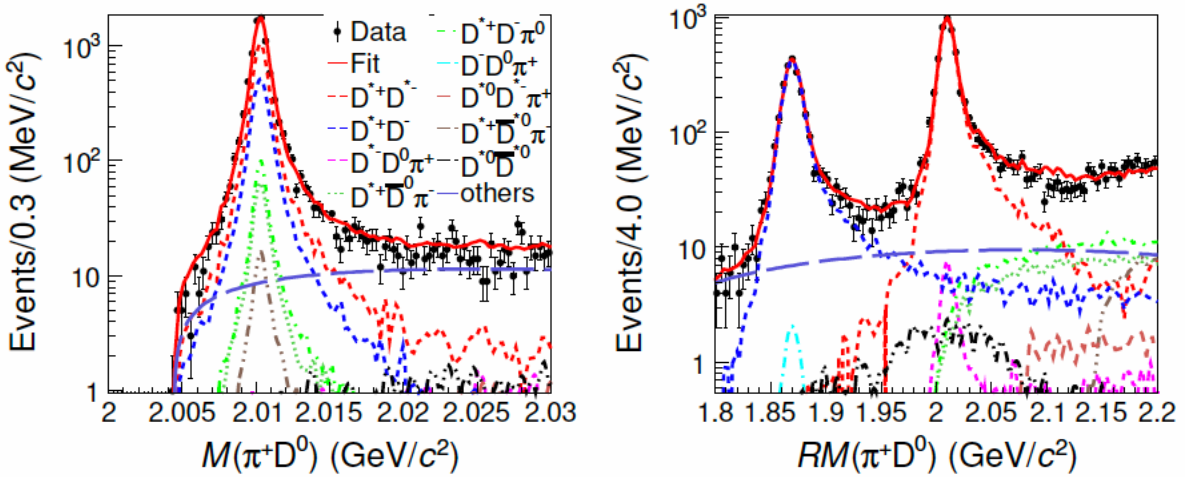




- ✓ Results consistent with Belle BaBar and CLEO and more precise
- ✓ The structures in the cross section are confirmed

With the new and more precise data, a simultaneous fit of combined measurements allows to test different hypotheses for the Y(4230) and for the other charmonium(-like) states

D^{*+} candidates at 4.416 GeV

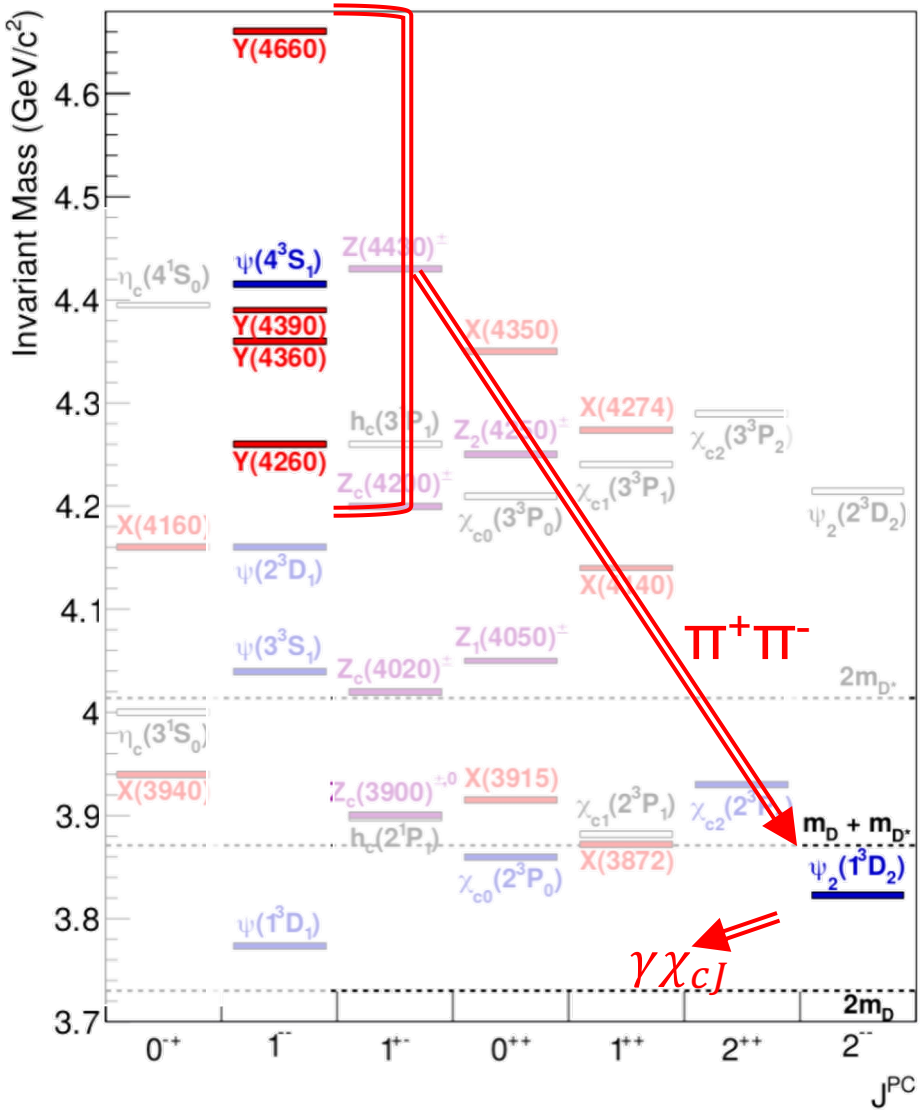


JHEP2022, 55 (2022)

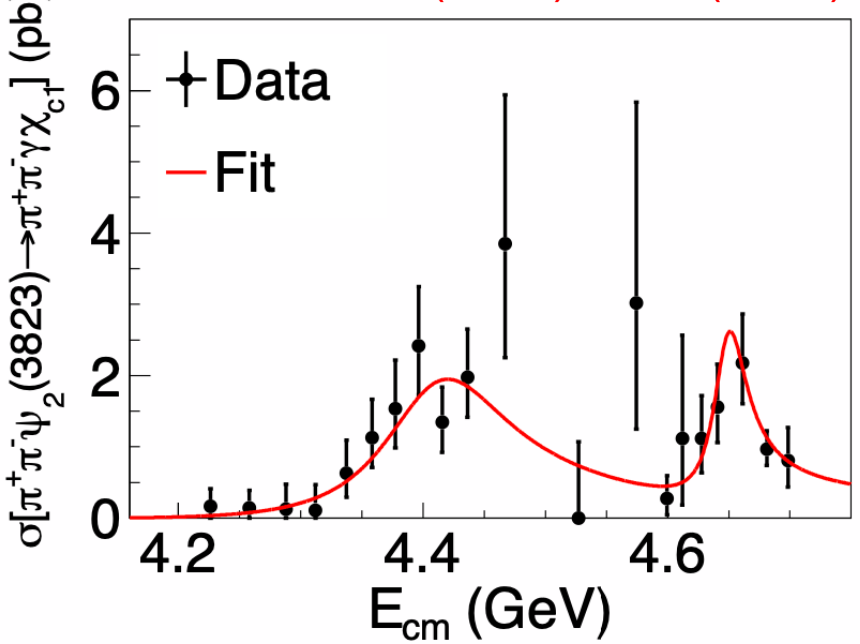
Resonance structures in $e^+e^- \to \pi^+\pi^-\psi_2(3823)$

first observation of vector Y states decaying to D-wave charmonium state

arXiv:2203.05815



Consistent with Y(4360) and Y(4660)



Most precise measurement

mass and width of $\psi_2(3823)$:

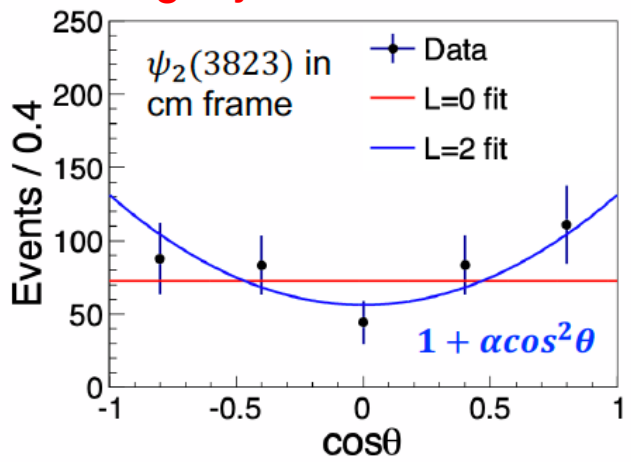
$m = 3823.12 \pm 0.43 \pm 0.13\ \mathrm{MeV}/c^2$

$\Gamma < 2.9\ \mathrm{MeV}$ (at 90% CL)

See also poster session:

Yong Xie: Observation of new charmonium decays at BESIII

$L = 2$ slightly favored over $L = 0$

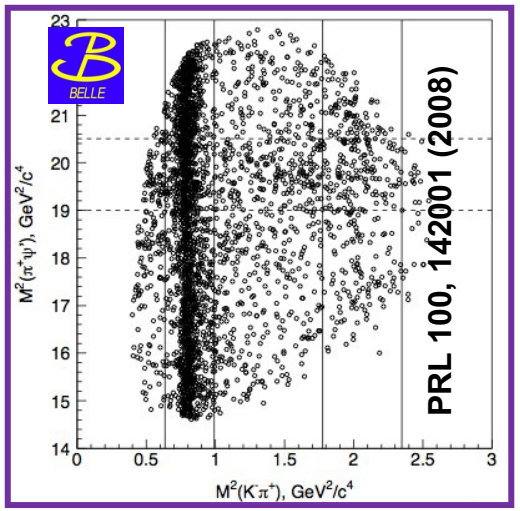


Moving to Z states

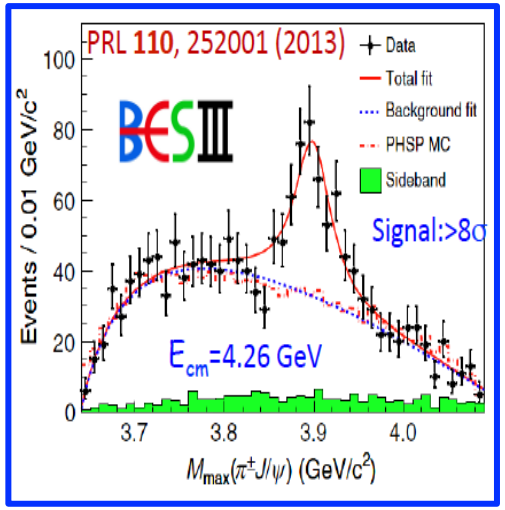
- ✓ Charged non conventional states
- ✓ Produced in e^+e^- collisions and in B decays
- ✓ Decays typically in hadron + charmonium
- ✓ Intrinsic nature unclear - exotic states? kinematic effects?
- ✓ Correlated to Y states?

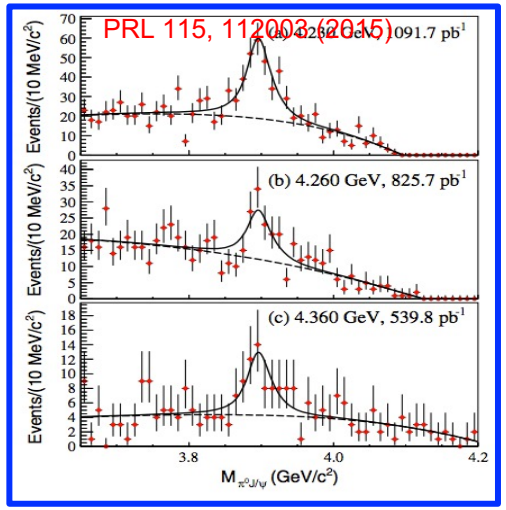
State	M (MeV/c^2)	Γ (MeV)	J^{PC}	Process	Experiment
$Z_c(3900)^{(\pm,0)}$	3888.4 ± 2.5	28.3 ± 2.5	1^{+-}	$e^+e^- \to \pi^{(+,0)}(\pi^{(-,0)}J/\psi)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)}(D\bar{D}^*)^{(-,0)}$	BESIII
				$H_b \to X\pi^+(\pi^- J/\psi)$	D0
				$e^+e^- \to \pi^+(\eta_c\rho^-)$	BESIII
$Z_c(4020)^{(\pm,0)}$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e^- \to \pi^{(+,0)}(\pi^- h_c)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)}(D^*\bar{D}^*)^{(-,0)}$	BESIII
$Z(4050)^{\pm}$	4051^{+24}_{-40}	82^{+50}_{-28}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4055)^{\pm}$ 3.5σ	4054 ± 3.2	45 ± 13	$?^{?-}$	$e^+e^- \to \pi^+(\pi^-\psi(2S))$	Belle
$Z(4100)^{\pm}$ 3.4σ	4096 ± 28	152^{+80}_{-70}	$?^{??}$	$B^0 \to K^+(\pi^-\eta_c)$	LHCb
$Z(4200)^{\pm}$	4196^{+35}_{-32}	370^{+100}_{-150}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle, LHCb
$Z(4250)^{\pm}$	4248^{+190}_{-50}	177^{+320}_{-70}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4430)^{\pm}$ first/2008	4478^{+15}_{-18}	181 ± 31	1^{+-}	$B^0 \to K^+(\pi^-\psi(2S))$	Belle, LHCb
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle
$R_{c0}(4240)$	4239^{+50}_{-21}	220^{+120}_{-90}	0^{-+}	$B^0 \to K^+\pi^-\psi(2S)$	LHCb
$Z_{cs}(3985)^{\pm}$	$3982.5^{+2.8}_{-3.4}$	$12.8^{+6.1}_{-5.3}$	$?$	$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$	BESIII
$Z_{cs}(4000)^{\pm}$	4003^{+6}_{-15}	131 ± 30	1^+	$B^+ \to \phi(J/\psi K^+)$	LHCb
$Z_{cs}(4220)^{\pm}$	4216^{+49}_{-38}	233^{+110}_{-90}	1^+	$B^+ \to \phi(J/\psi K^+)$	LHCb

The first: Z(4430)±

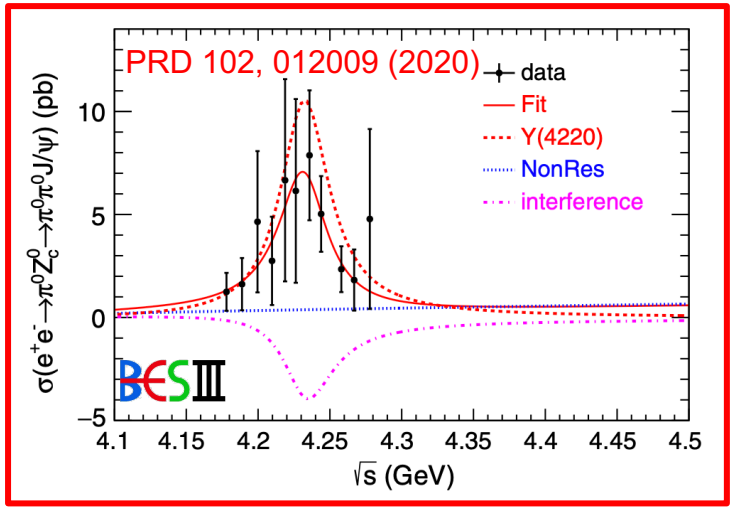


$Z_c(3900)$ isospin triplet



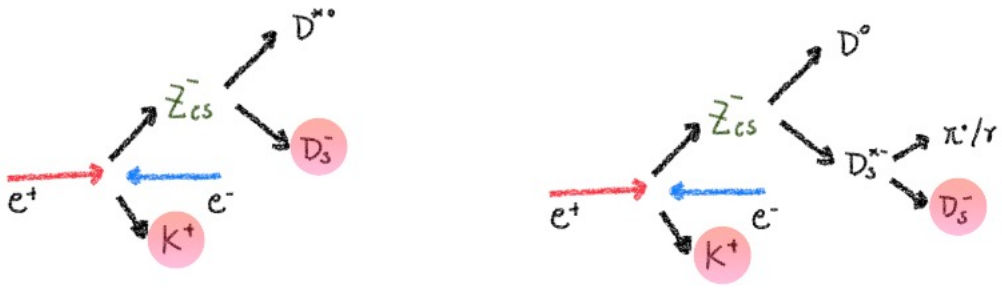


$e^+e^- \to Y(4230) \to \pi^0 Z_c(3900)^0$

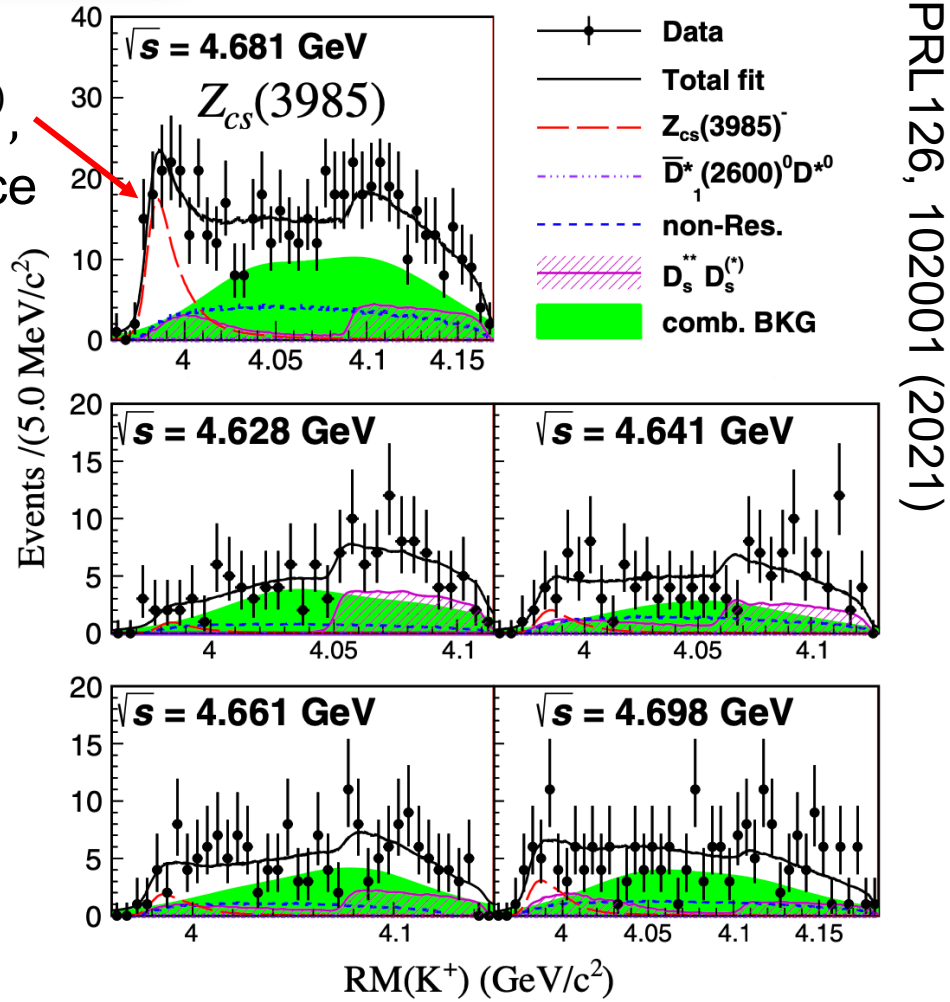


The charged $Z_{cs}(3985)$ state

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

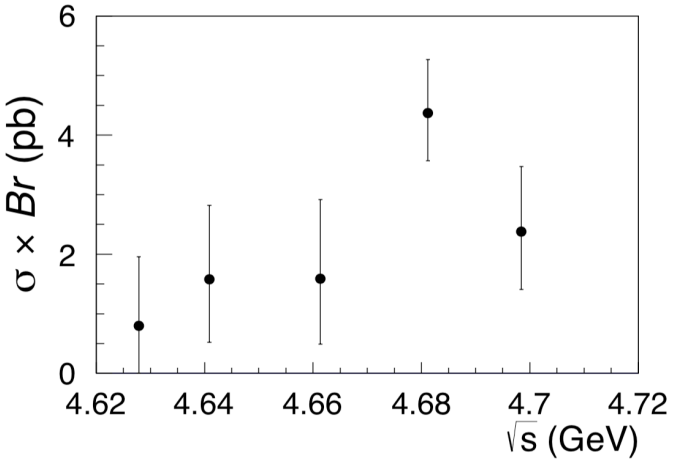


Enhancement not explained by $D_s^{**} D_s^{(*)}$, neither by interference



PRL126, 102001 (2021)

- Added a new resonance in the fit, assuming $J^P=1^+$
- Significance: 5.3σ
- Minimal quark content $c\bar{c}s\bar{u}$?
- Similar to $Z_{cs}(4000)$ seen by LHCb (widths differ)



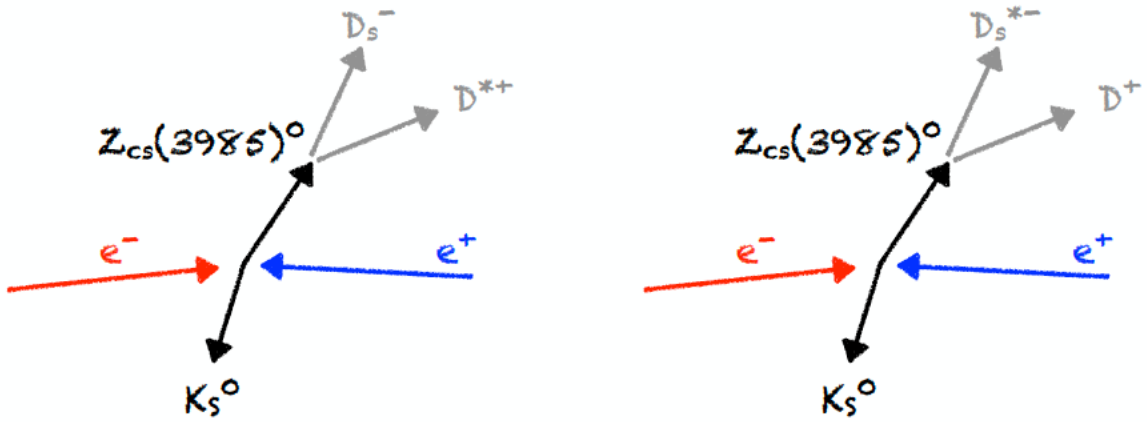
PRL127, 082001 (2021)

Coupling with Y state
$e^+e^- \to Y \to K Z_{cs}(3895)$
?

$$m_{\text{pole}}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$
$$\Gamma_{\text{pole}}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}.$$

The neutral $Z_{cs}(3985)$ state

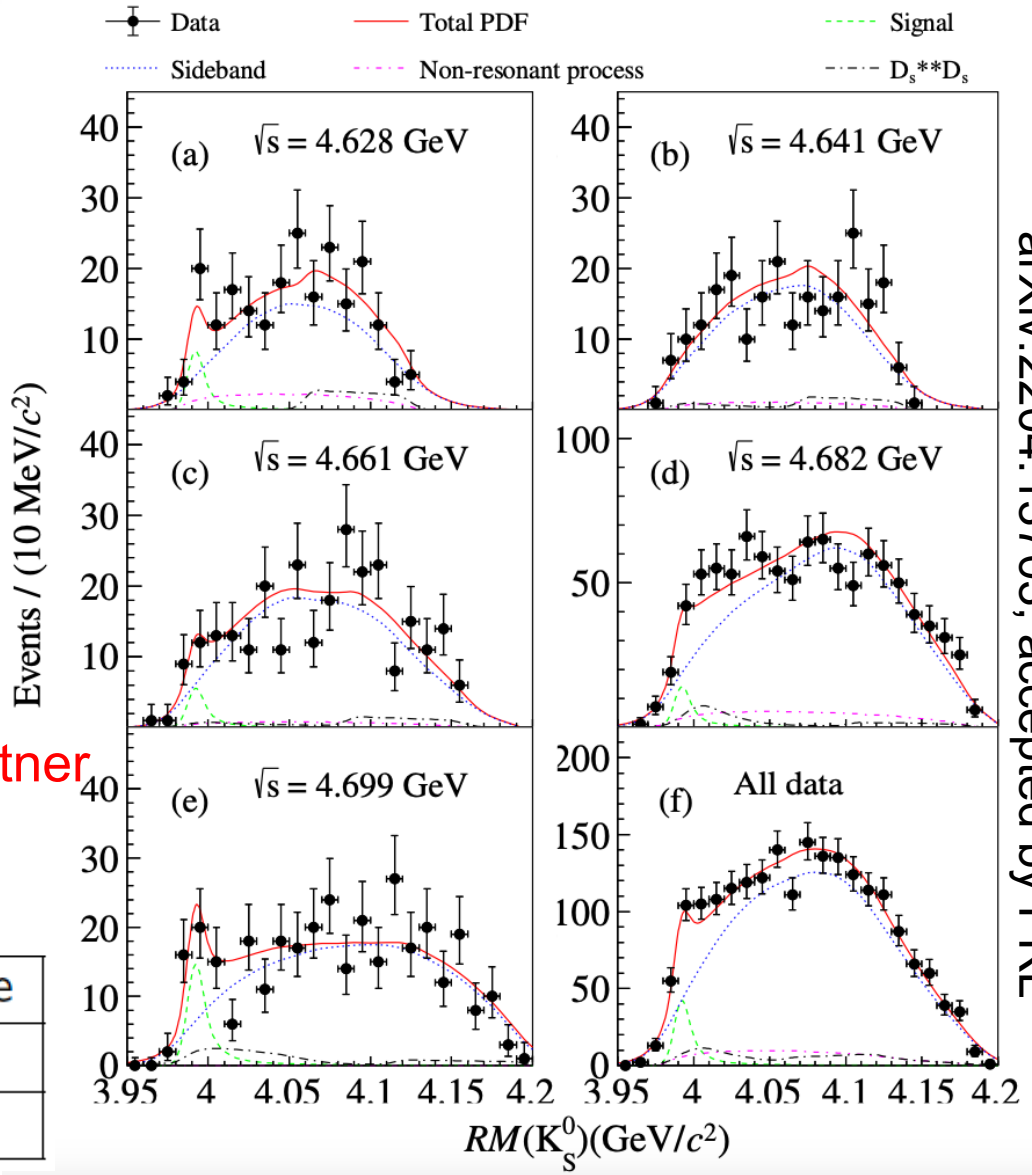
$$e^+e^- \to K_S^0 \left(D_S^- D^{*+} + D_S^{*-} D^+\right)$$



- Significance: 4.6σ
- Minimal quark content $c\bar{c}s\bar{d}$?
- Mass and width consistent with charged Z_{cs} → isospin partner

NPB 968, 115450 (2021): $M(Z_{cs}^+) < M(Z_{cs}^\circ)$

State	Mass (MeV/c^2)	Width (MeV)	Significance
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$	5.3σ
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$	4.6σ



arXiv:2204.13703, accepted by PRL

Trying to summarize

The XYZ Spectroscopy is a key component of the BESIII physics program

- Studies of X(3872) continue thanks to the $e^+e^- \to Y(4230) \to \gamma X(3872)$ process
- We continue to map Y structures through exclusive e^+e^- cross sections
- The Z_c family has expanded with the new and strange $Z_{cs}(3985)$ triplet

In the next future crucial upgrades will improve BESIII capabilities

- Increase in maximum CMS energy
- Increase in integrated luminosity in XYZ region
- New TOF and CGEM for better performances