Exotic Charmonium at BESIII

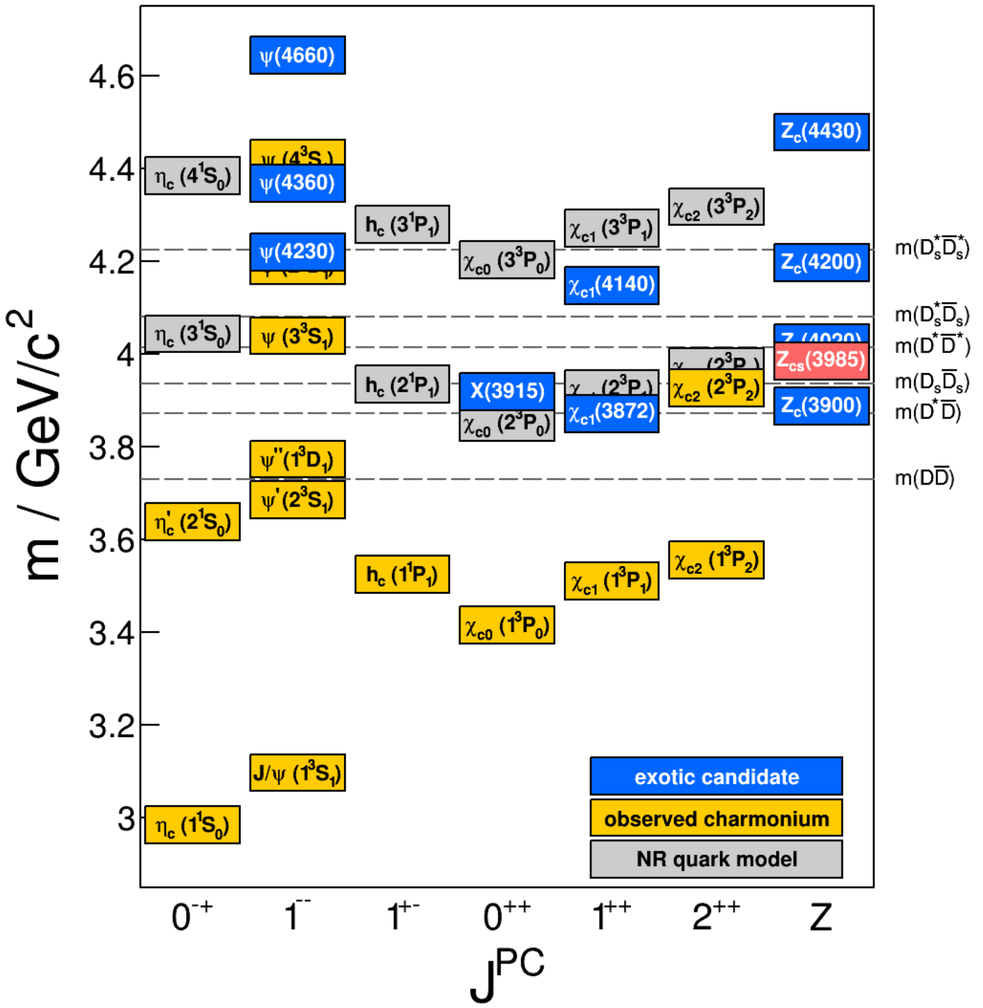
G. Cibinetto (INFN Ferrara) on behalf of the BESIII collaboration

IPA2022 - Wien, Sep 5-9, 2022

Exotic Charmonium Spectroscopy

- Exotic searches
  - states with exotic quantum numbers
  - states with internal exotic structure
- Heavy-quark exotics cleaner than light-quark sector
- Important interplay with advancements in theory (non-relativistic EFT and LQCD)

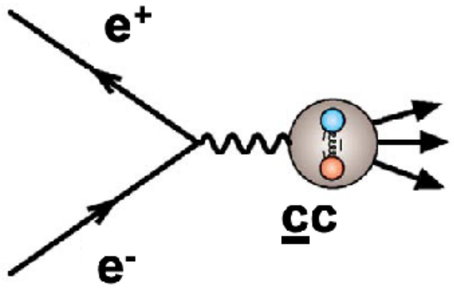
- Naming scheme used in this presentation
  - Y —> 1^{--} states
  - Z —> charged states
  - X —> all the remaining states



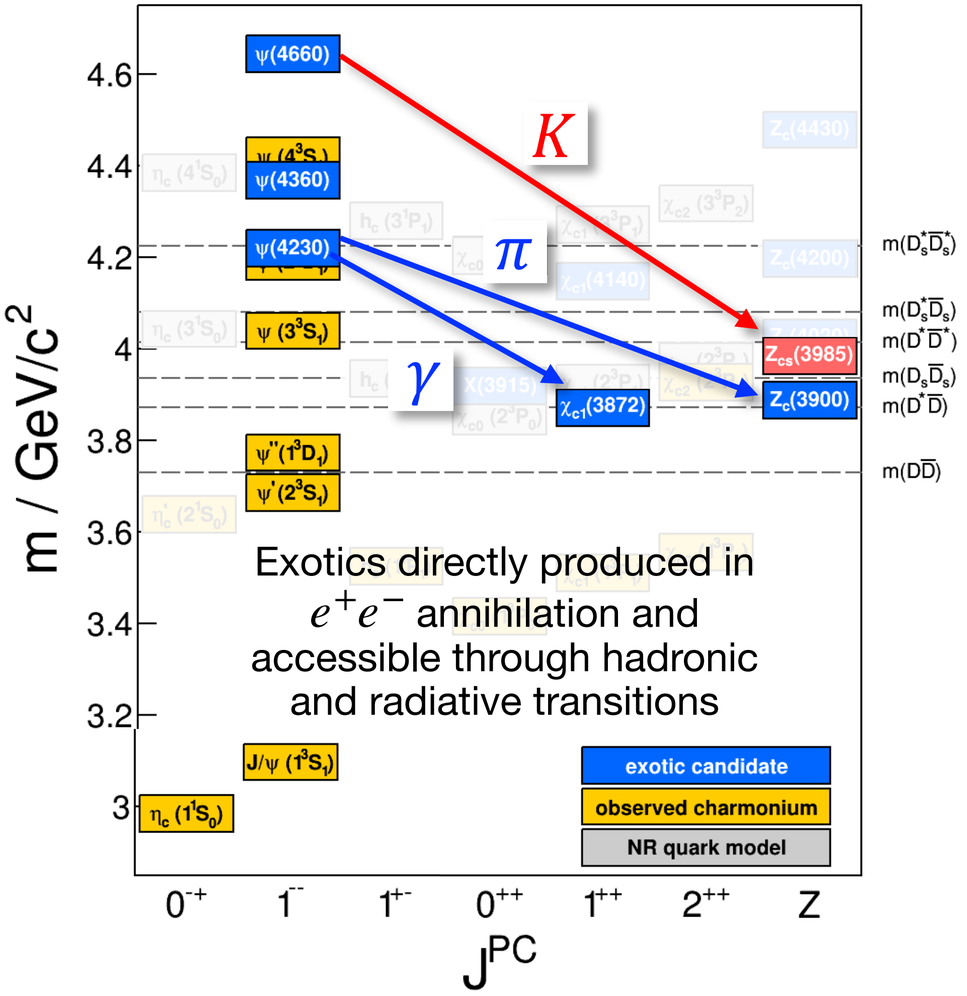
Exotic Charmonium Spectroscopy @ BESIII

Experimental environment

- At BEPCII Electron-Positron collider
- $E_{CM} = 2 - 4.95\ GeV$
- $\mathscr{L}_{peak} = 1.0 \times 10^{33}\ cm^{-2}s^{-1}$



Physics data taking ongoing since 2009



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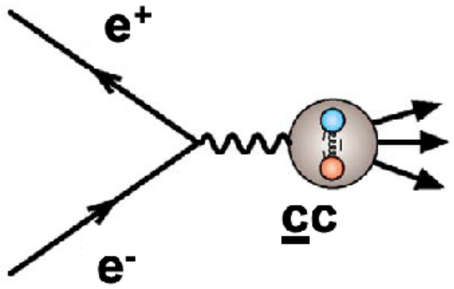
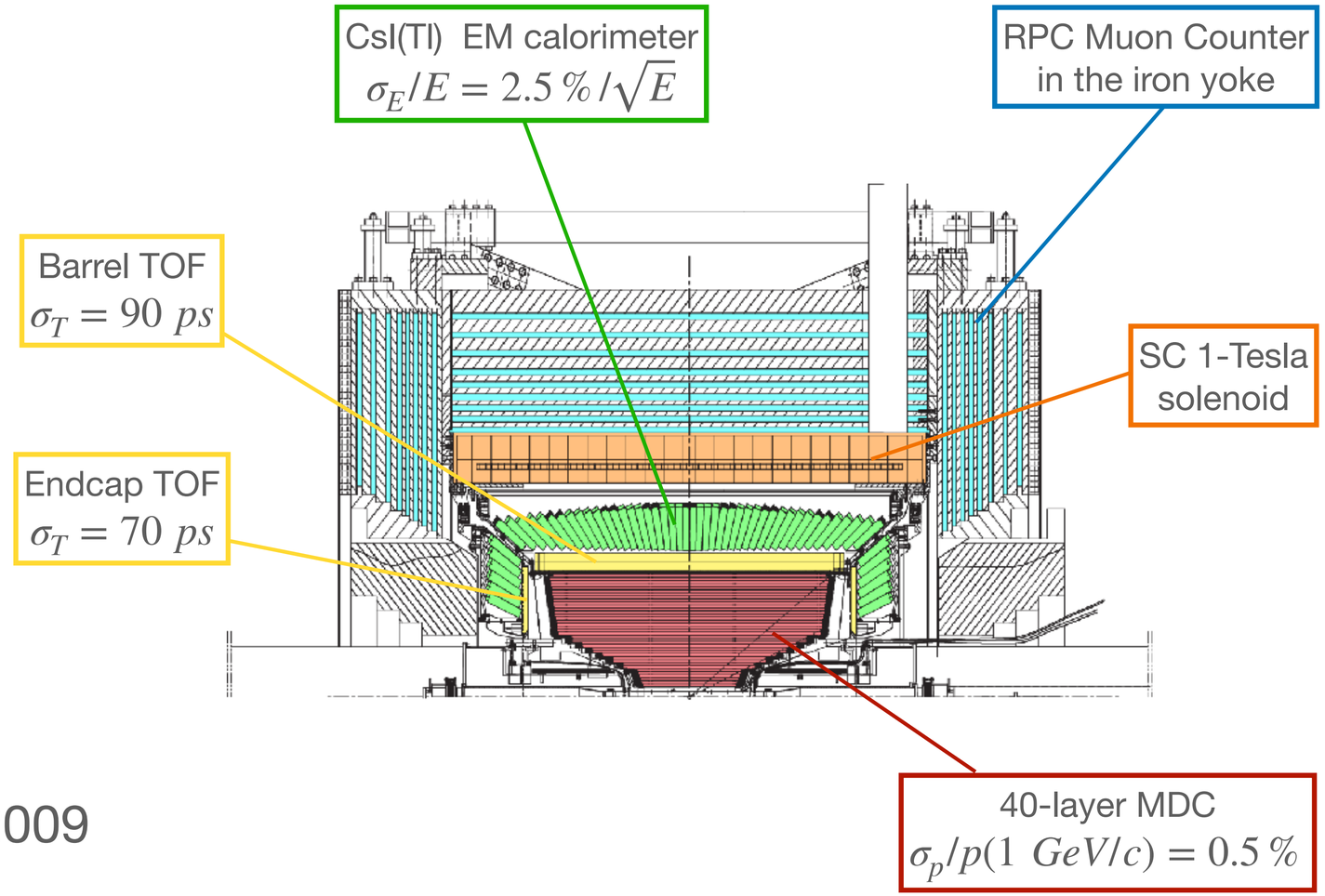
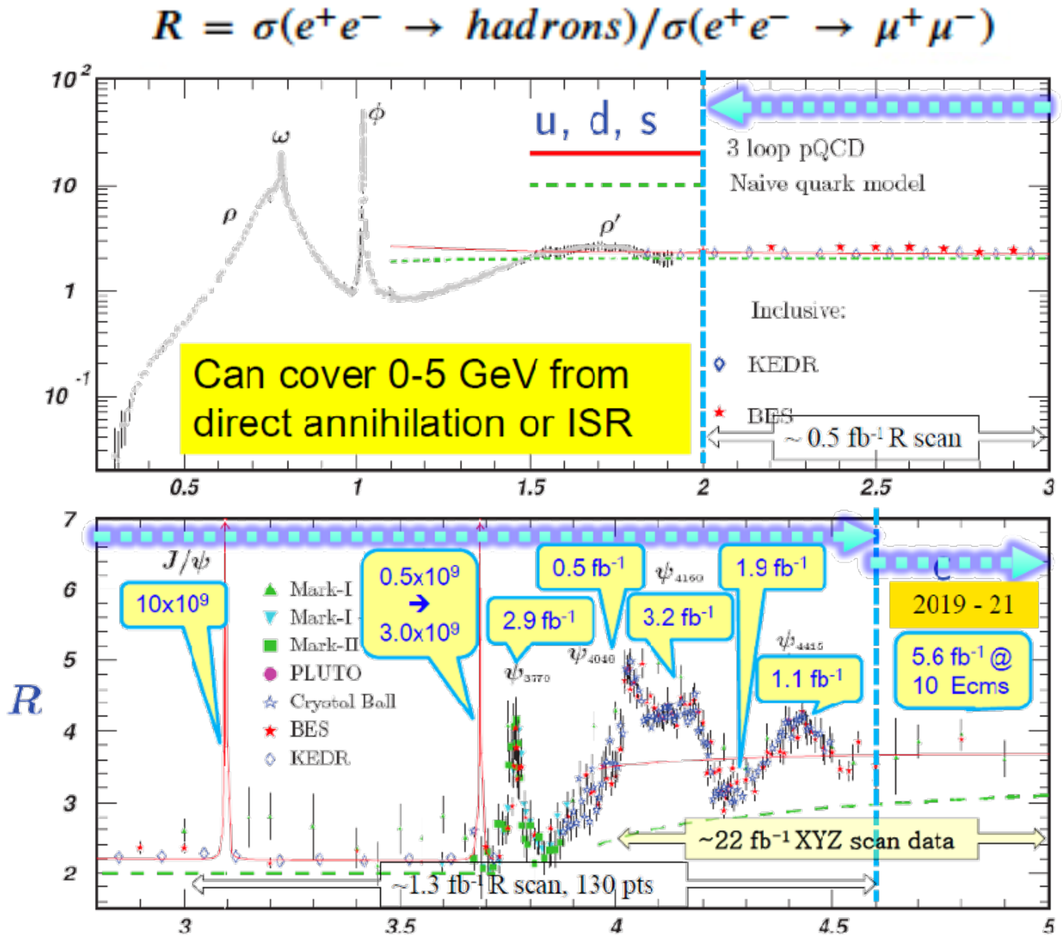




Physics data taking ongoing since 2009

Exotic Charmonium Spectroscopy @ BESIII

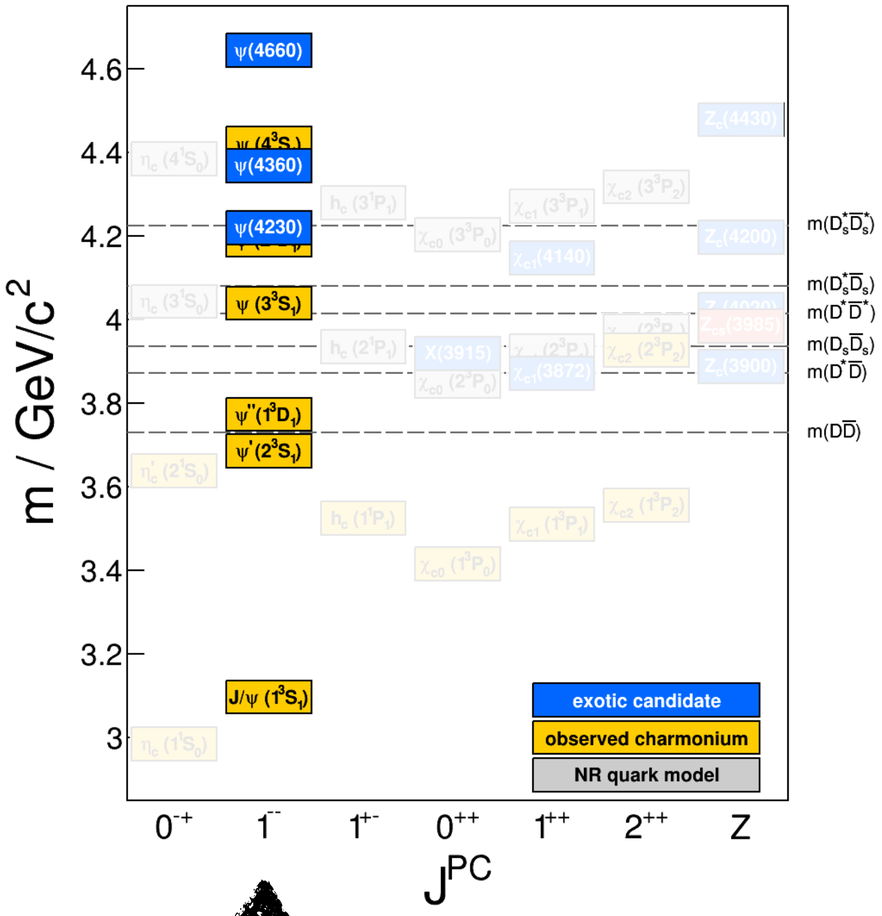
Datasets and physics potential



- Center-of-mass energy spanning the τ-charm sector
- Region below 2 GeV directly accessible (via ISR)
- World's largest sample of
  - J/ψ —> 10 billions
  - $\psi(2S)$ —> 3 billions
  - $\psi(3770)$ —>2.9 fb^{-1} (20 fb^{-1} with next data taking)
- About 22 fb^{-1} of data for Exotic Charmonium Spectroscopy
- 46 XYZ data samples $\mathscr{L}_i$ ~21.9 fb^{-1}
  - 29 with $\mathscr{L}_i$ > 0.4 fb^{-1}
- Used also a smaller R scan sample
  - 104 energy points, $\mathscr{L}_i$ ~ 0.8 fb^{-1}
- Machine upgrade to unlock more data and energies

Vectorial exotics

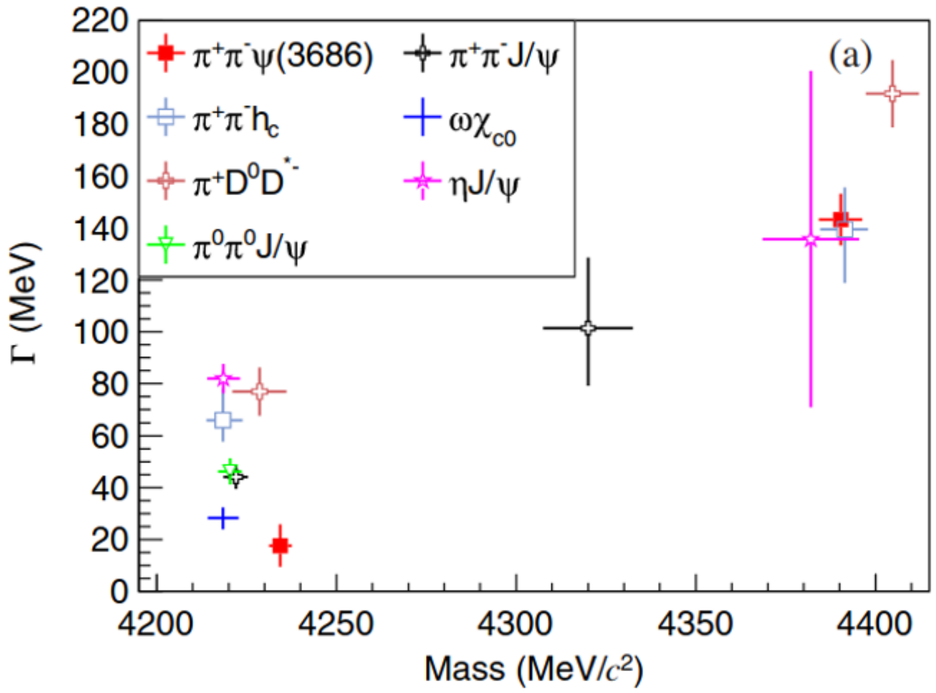
The Y states



Directly produced in e^+e^- annihilation

- Y(4260) first such-a-state discovered by BaBar PRL95 (2005) 142001
  - Inconsistent with all 1^{--} quark model states
  - Very suppressed open charm decays
  - Decays into other exotics
- Cross section for different processes studied at BESIII

PRD 104 (2021) 5, 052012



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

Investigating the strange content inside Y(4230)

$\mathscr{L}_i = 15.6\ fb^{-1}$ ArXiv: 2204.07800

- First observation of Y(4230) in K^+K^-J/ψ

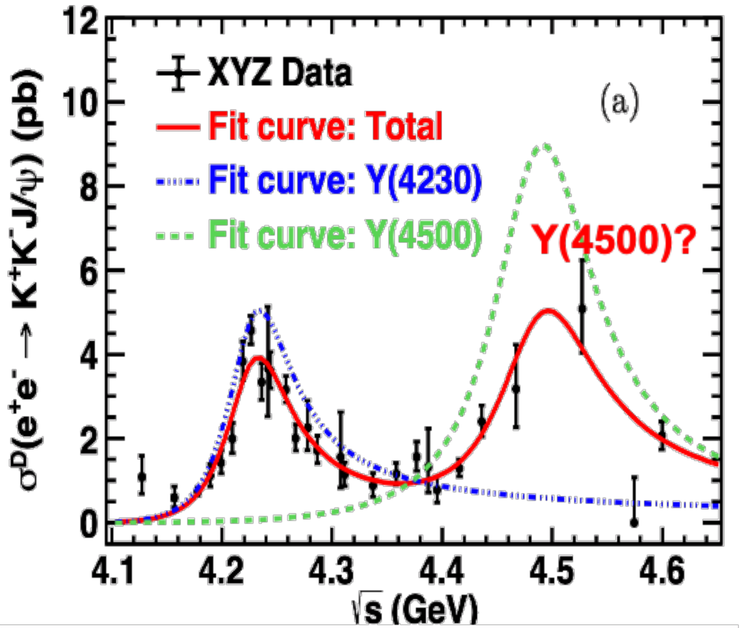
$$0.02 < \frac{\mathcal{B}(Y(4230) \to K^+K^-J/\psi)}{\mathcal{B}(Y(4230) \to \pi^+\pi^-J/\psi)} < 0.26$$

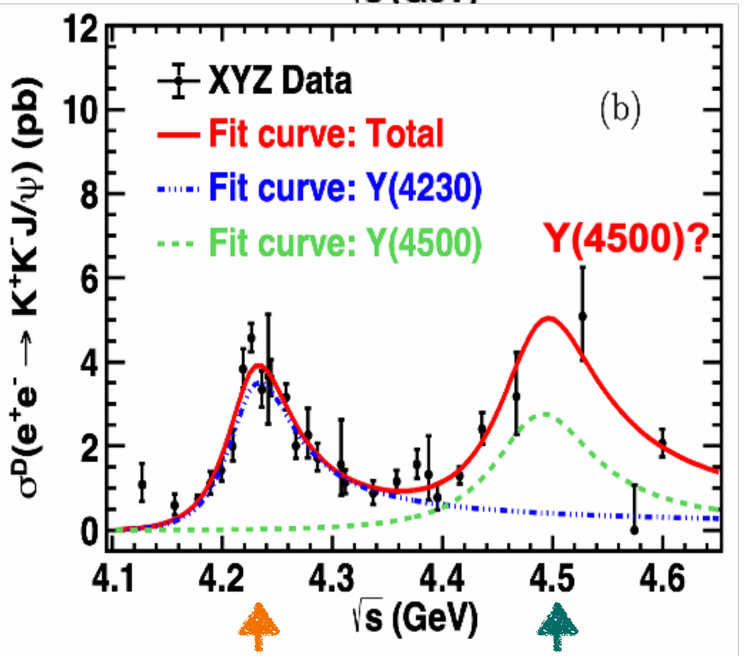
Large range due to multiple solutions in $\pi^+\pi^-J/\psi$

- Structure around 4.5 GeV observed for first time!
- New structure compatible with:
  - 5S/4D mixing
  - D_sD_{s1} hadronic molecule
  - lattice $c\bar{c}s\bar{s}$ structure
- $K_s^0K_s^0J/\psi$ paper in preparation

$M_{Y(4230)} = 4225.3 \pm 2.3 \pm 21.5\ MeV/c^2$
$\Gamma_{Y(4230)} = 72.9 \pm 6.1 \pm 30.8\ MeV$

$M_{Y(4500)} = 4487.7 \pm 13.3 \pm 24.1\ MeV/c^2$
$\Gamma_{Y(4500)} = 111.1 \pm 30.1 \pm 15.2\ MeV$



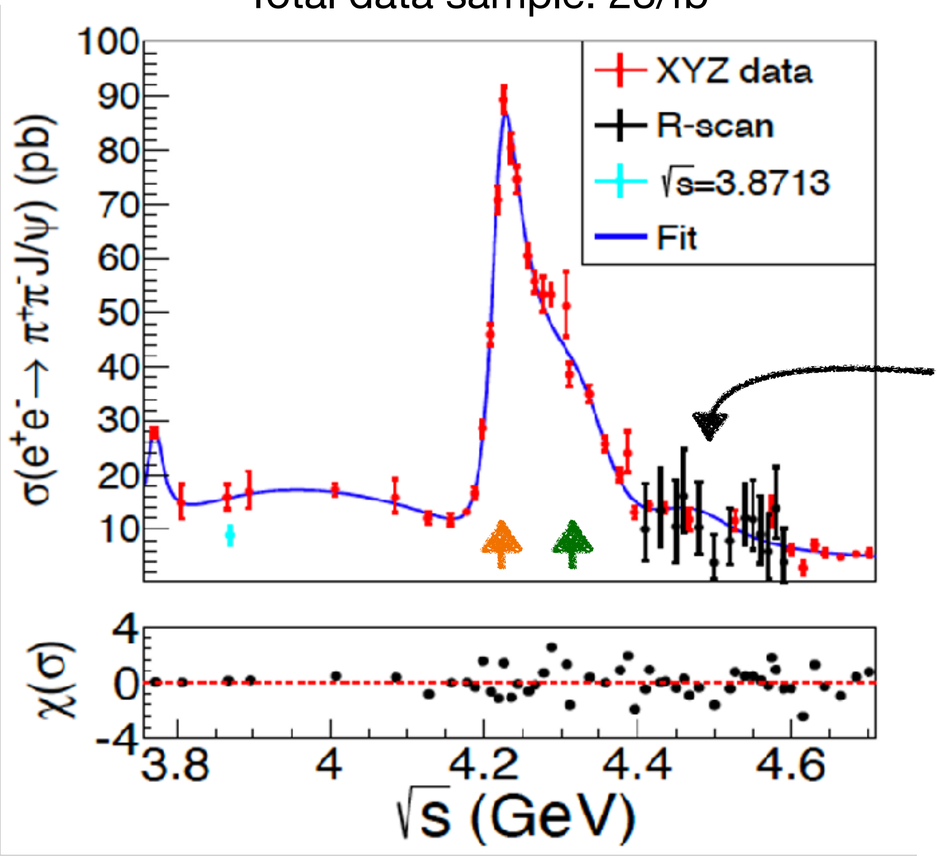


arXiv:2206.08554v1

Update of $e^+e^- \to \pi^+\pi^- J/\psi$ cross section

Higher statistics, higher precision, higher energies, better fit

Total data sample: 23/fb



- Structure around 4 GeV favors BW rather than exponential parametrization
- Large fluctuation at 3.8713 GeV - X(3872) not included in the fit
- Y(4230) and Y(4320) observed with > 10σ
- Evidence ~3σ of a structure at higher energies
  - ψ(4415)? A new state at 4.5 GeV?
- With the high energy state in the fit, the Y(4320) parameters change

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

$\Gamma_{Y(4230)} = 41.8 \pm 2.9 \pm 2.7\ MeV$

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

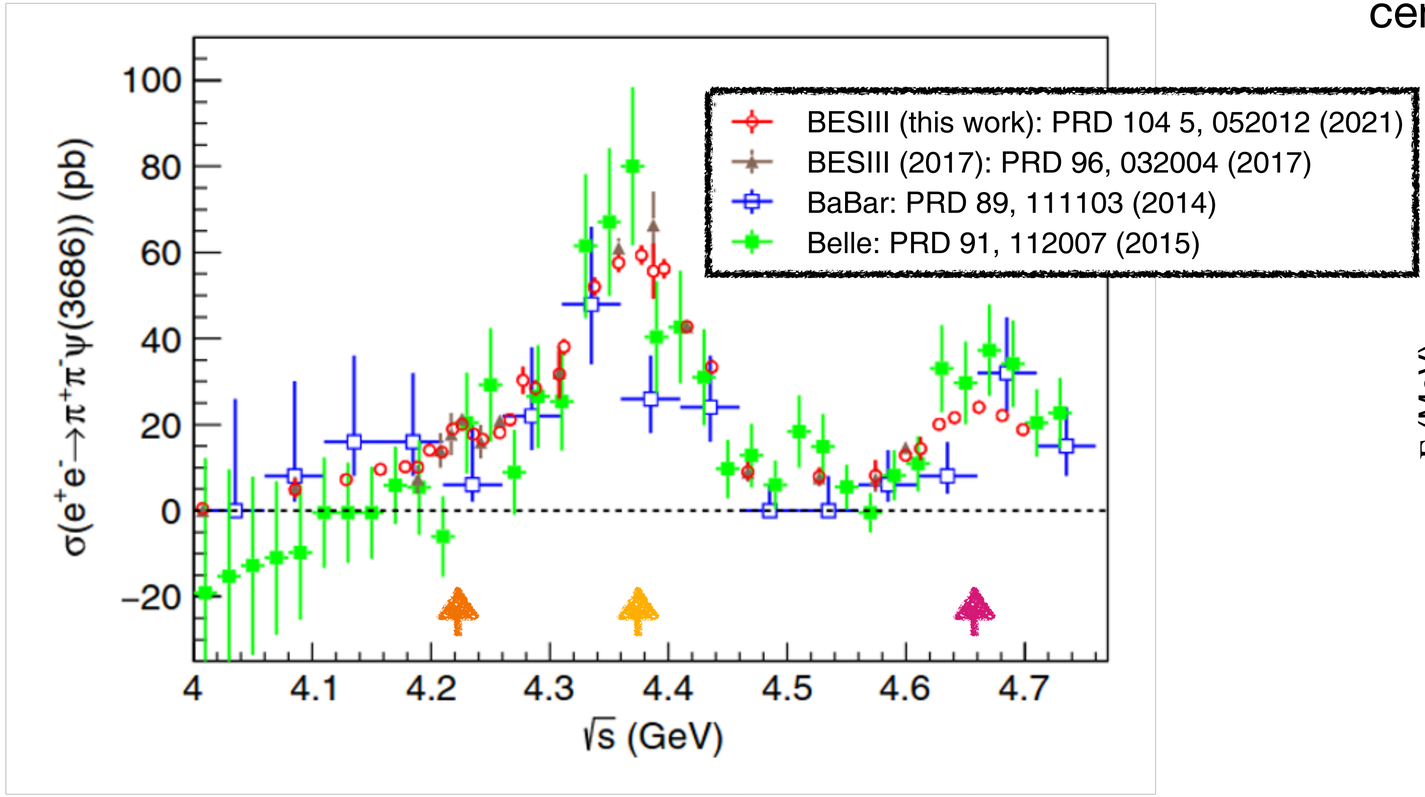
$\Gamma_{Y(4320)} = 127 \pm 17 \pm 10\ MeV$

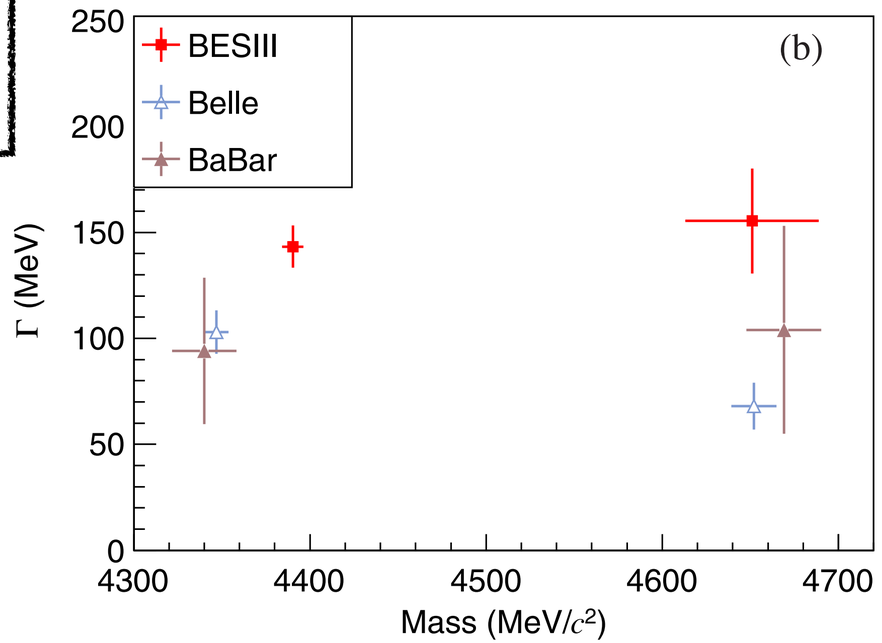
$e^+e^- \to \pi^+\pi^-\psi(2S)$

PRD 104 (2021) 5, 052012

Updated result up to 4.7 GeV based on 20.1/fb

- Confirmed both Y(4220) and Y(4390) contribution
- First observation of Y(4660) at BESIII thanks to the center of mass upgrade!





$M_{Y(4230)} = 4234.4 \pm 3.2 \pm 0.2\ MeV/c^2$

$\Gamma_{Y(4230)} = 17.6 \pm 8.1 \pm 0.9\ MeV$

$M_{Y(4390)} = 4390.3 \pm 6.0 \pm 0.7\ MeV/c^2$

$\Gamma_{Y(4390)} = 143.3 \pm 10.0 \pm 0.5\ MeV$

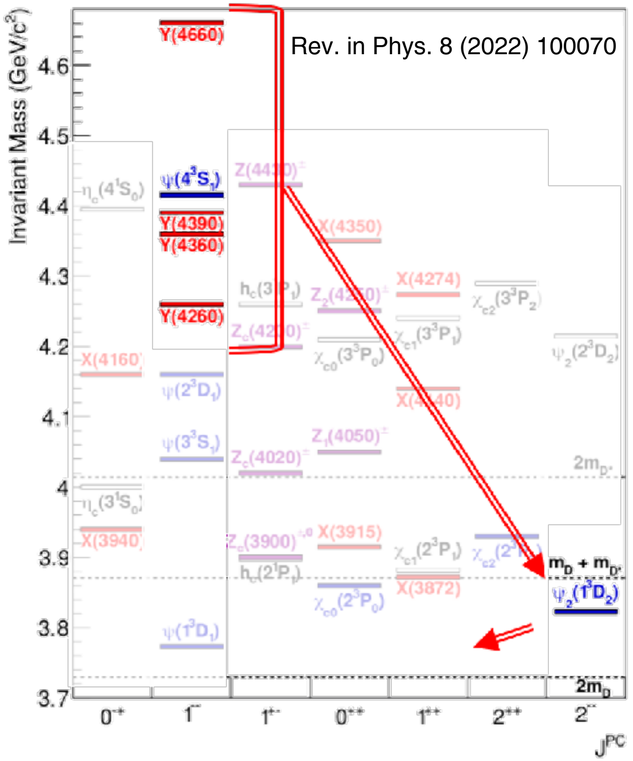
$M_{Y(4660)} = 4651.0 \pm 37.8 \pm 2.1\ MeV/c^2$

$\Gamma_{Y(4660)} = 155.4 \pm 24.8 \pm 0.8\ MeV$

Study of $e^+e^- \to \pi^+\pi^-\psi_2(3823)$

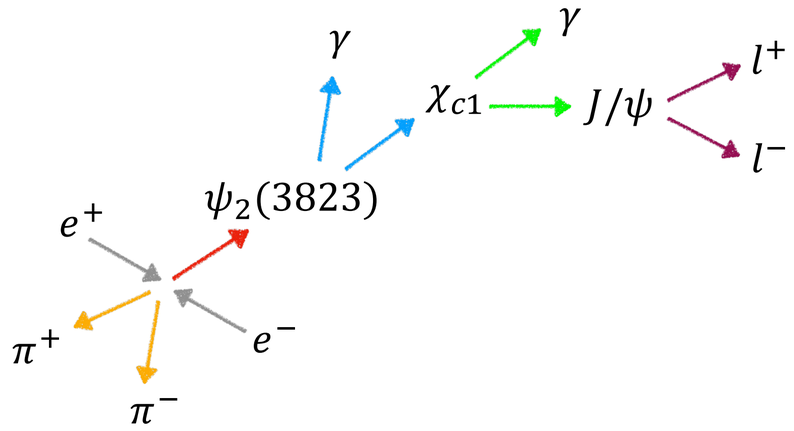
$\mathscr{L}_i = 11.3\ fb^{-1}$ arXiv:2203.05815

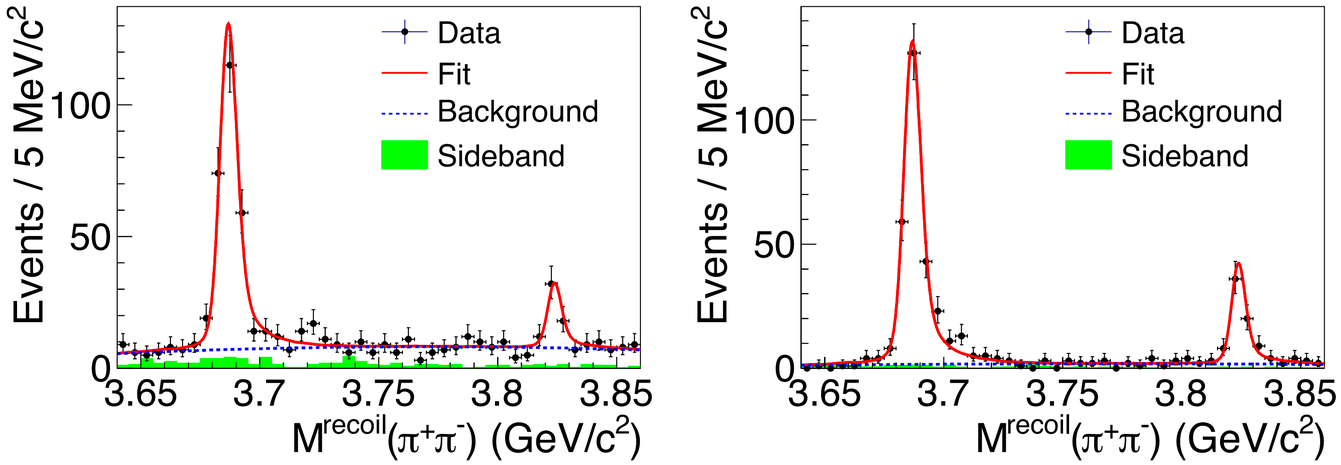
First observation of vector Y states decaying to D-wave charmonium



mass and width of $\psi_2(3823)$:
$m = 3823.12 \pm 0.43 \pm 0.13\ \mathrm{MeV}/c^2$
$\Gamma < 2.9$ MeV (at 90% CL)

- Study the internal structure of Y states by measuring their coupling with D-wave charmonia
- $\psi_2(3823)$ candidates reconstructed in $\gamma\chi_{c1,2}$





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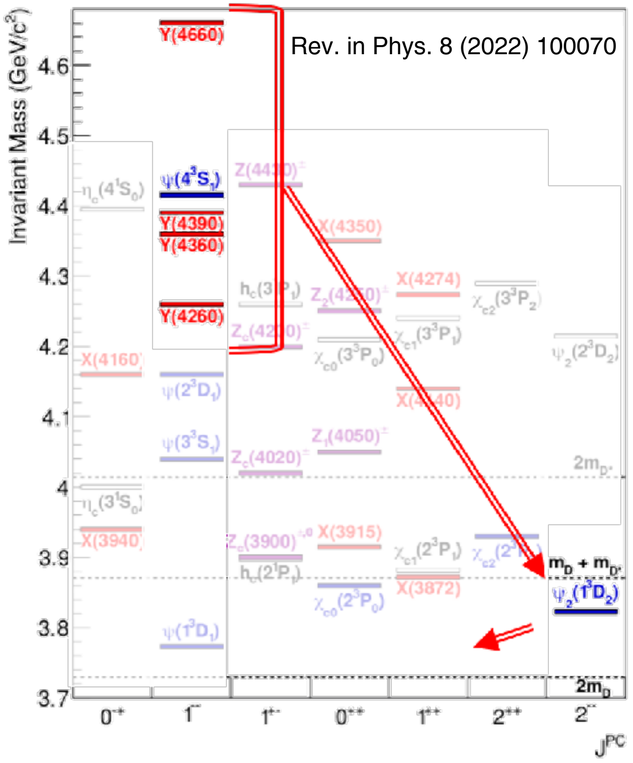

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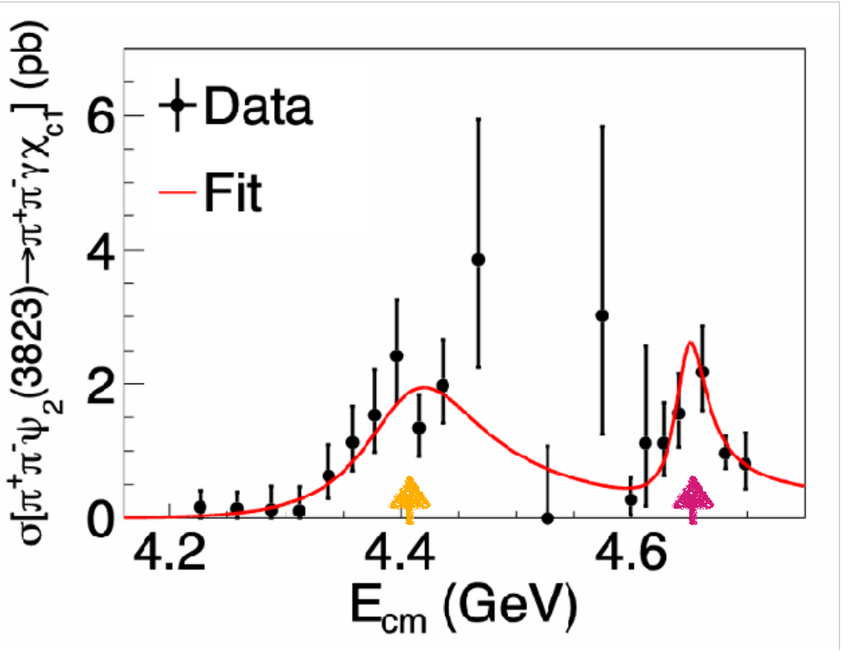
- Study the internal structure of Y states by measuring their coupling with D-wave charmonia
- $\psi_2(3823)$ candidates reconstructed in $\gamma\chi_{c1,2}$
- Two resonances hypothesis favored:
  - to single resonance by 2.6σ
  - to only continuum by more than 5σ
- Consistent with Y(4390) and Y(4660)
- Second largest BF of Y(4660)
- Best mass measurement of $\psi_2(3823)$



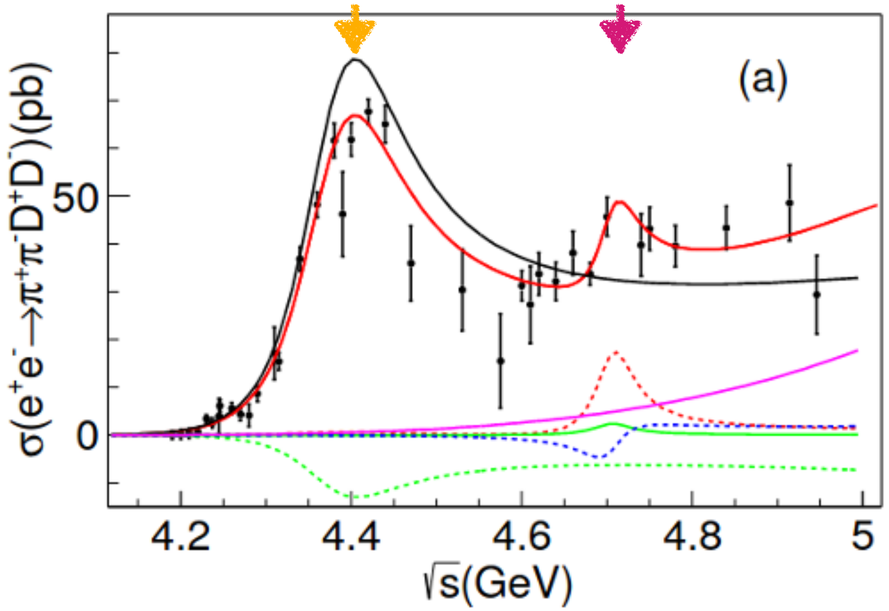
$M_{Y(4390)} = 4406.9 \pm 17.2 \pm 4.5\ MeV/c^2$
$\Gamma_{Y(4390)} = 128.1 \pm 37.2 \pm 2.3\ MeV$

$M_{Y(4660)} = 4647.9 \pm 8.6 \pm 0.8\ MeV/c^2$
$\Gamma_{Y(4660)} = 33.1 \pm 18.6 \pm 4.1\ MeV$

ArXiv: 2208.00099

Study of the $\pi^+\pi^- D^+ D^-$ lineshape

$\mathscr{L}_i = 17.4\ fb^{-1}$



- Study the 4-body final state to search for clues about vector resonance in the region 4-4.7 GeV
- 3 subprocesses accounted for: PHSP, $\pi\pi\psi(3770)$, $D_1(2420)D$
- Fit to 37 energy values
- Partial reconstruction method (one $D \to K\pi\pi$, one in recoil mass)

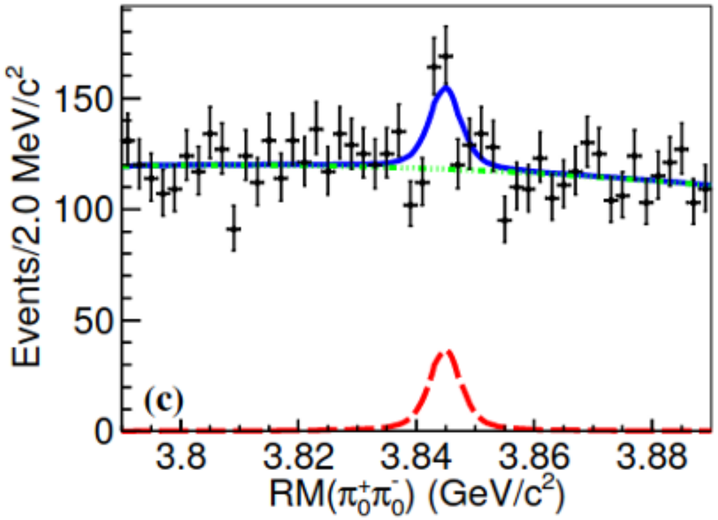
$M_{R1} = 4373.1 \pm 4.0 \pm 2.2\ MeV/c^2$

$\Gamma_{R1} = 146.5 \pm 7.4 \pm 1.3\ MeV$

$M_{R2} = 4706 \pm 11 \pm 4\ MeV/c^2$

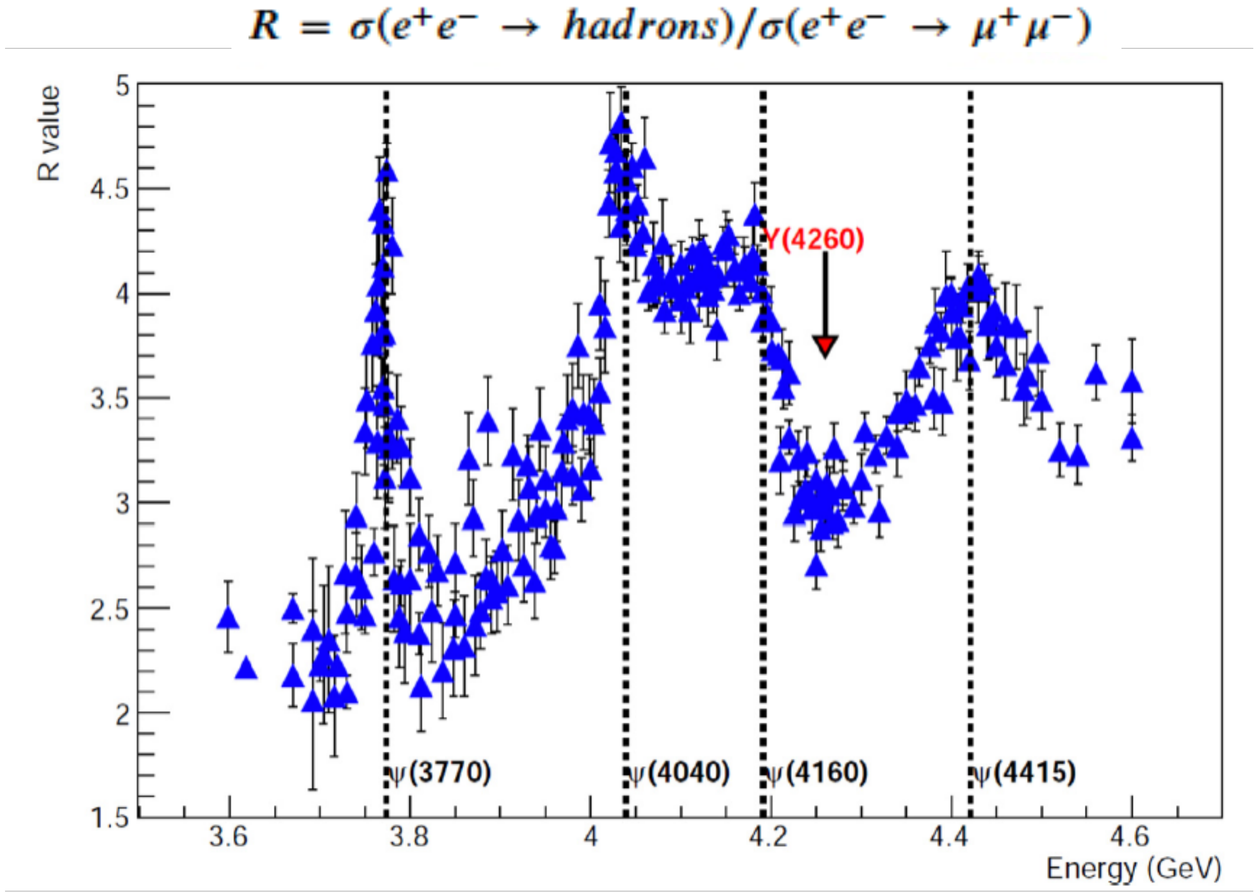
$\Gamma_{R2} = 45 \pm 28 \pm 9\ MeV$

- Search for spin-3 partner of ψ(3770) and ψ(3823) in its DD decay
- Signal shape extracted using $e^+e^- \to f_0(500)\psi(3842)$ MC
- Combining all dataset in 4.6-4.7 GeV evidence of ππψ(3842) at 4.2σ level



Y decays to open Charm

- Conventional charmonium 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

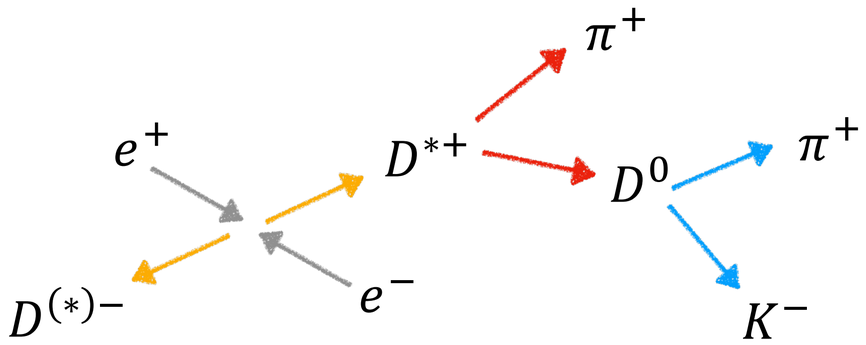


Rev. in Phys. 8 (2022) 100070

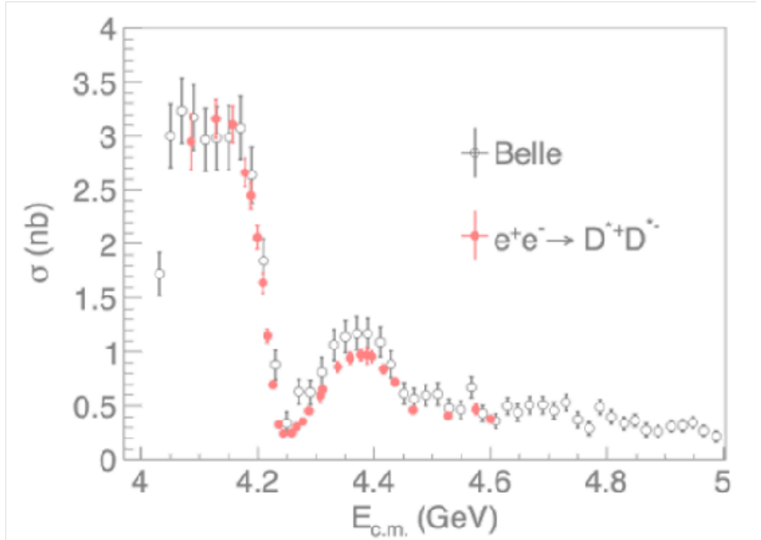
$e^+e^- \to D^*D^{(*)}$

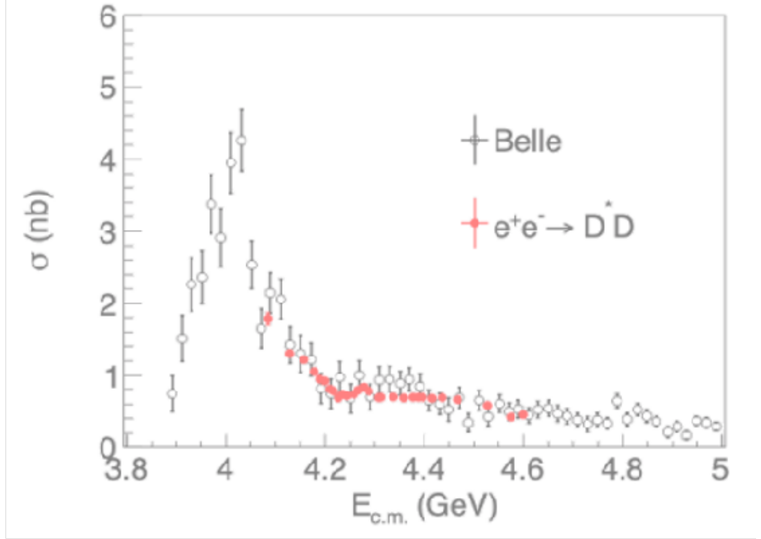
JHEP 2022, 155 (2022)

15.7 fb^{-1} collected between 4.085 and 4.6 GeV



- Reconstructed $D^{*+} \to \pi^+ D^0$ with $D^0 \to K^-\pi^+$
- $D^{(*)-}$ inferred kinematically





- Good agreement with existing measurements
- Confirmed structure around 4.39 GeV in D*D*
- Results can provide information to improve modelization of the cross section between 4.2 and 4.3 GeV (*e.g.* Eur. Phys. J. C 81 (2021) 83)
- 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

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JHEP 2022, 155 (2022)

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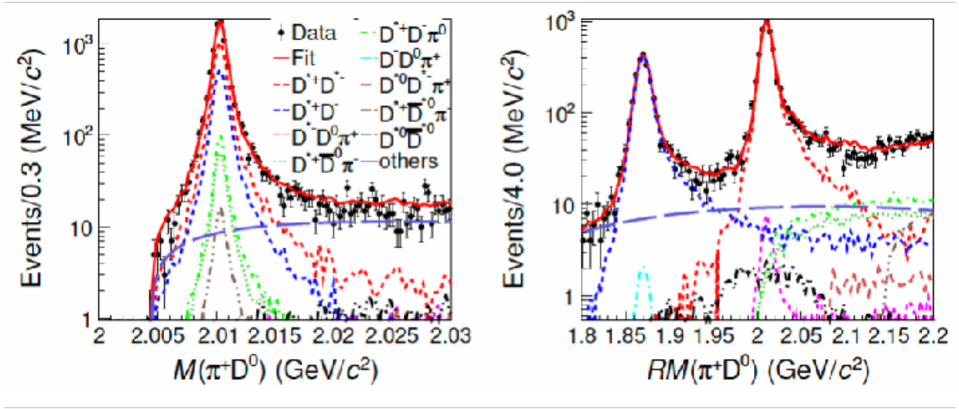

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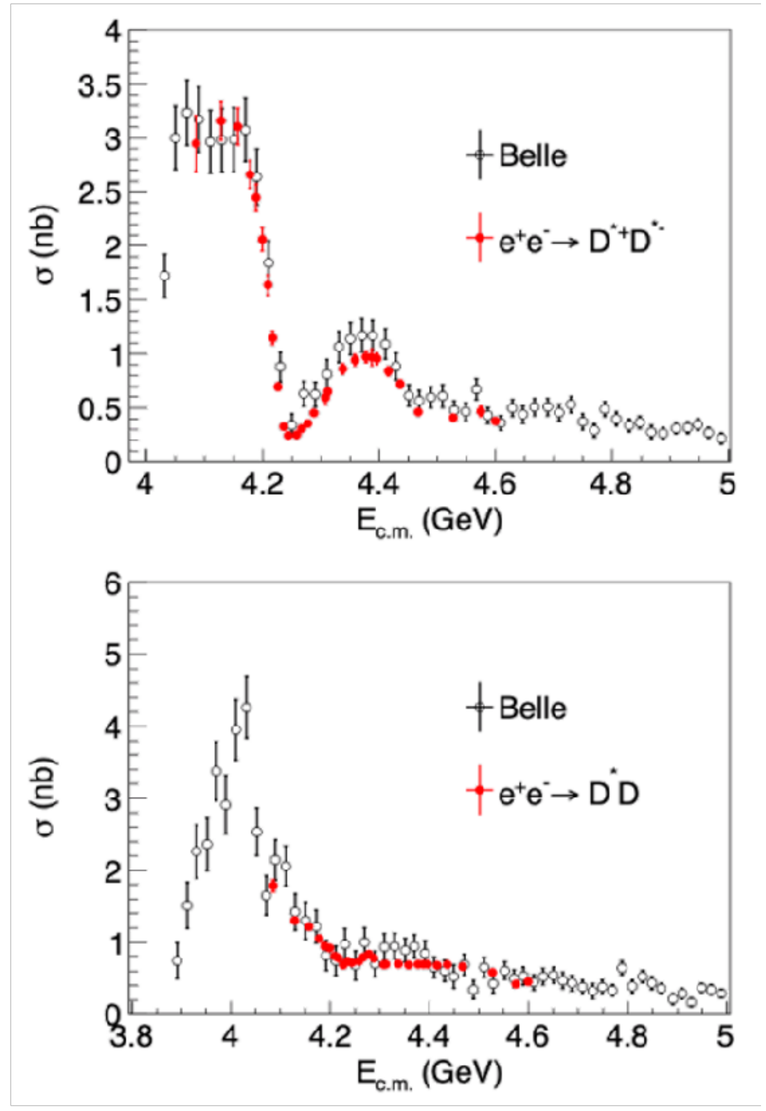

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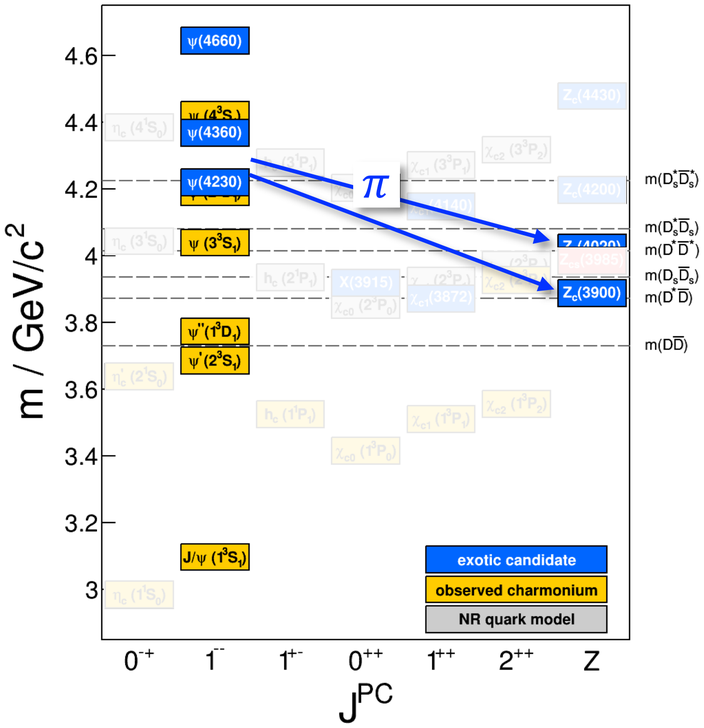
D*+ candidates at 4.416 GeV

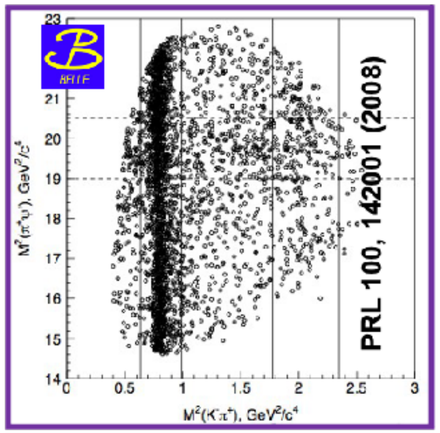
Charged exotics

Charged charmonium-like states

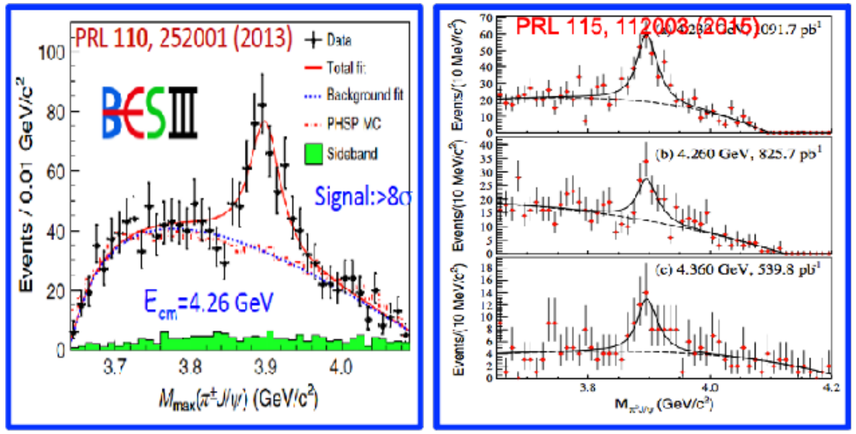
- Produced in e^+e^- collisions and in B decays
- Decays typically in hadron + charmonium
- Intrinsic nature unclear - exotic states? kinematic effects?
- Correlated to Y states?



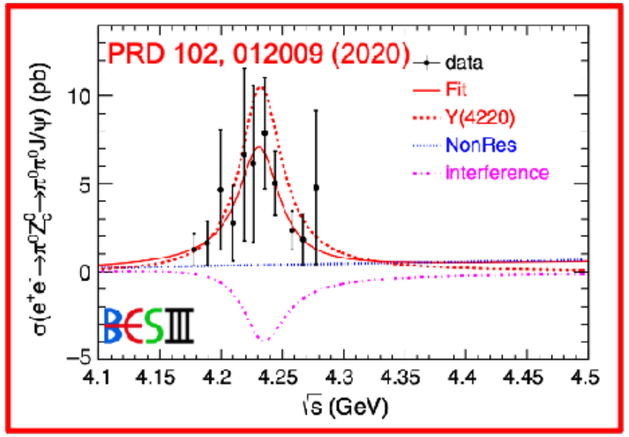
The first: Z(4430)±



$Z_c(3900)$ isospin triplet



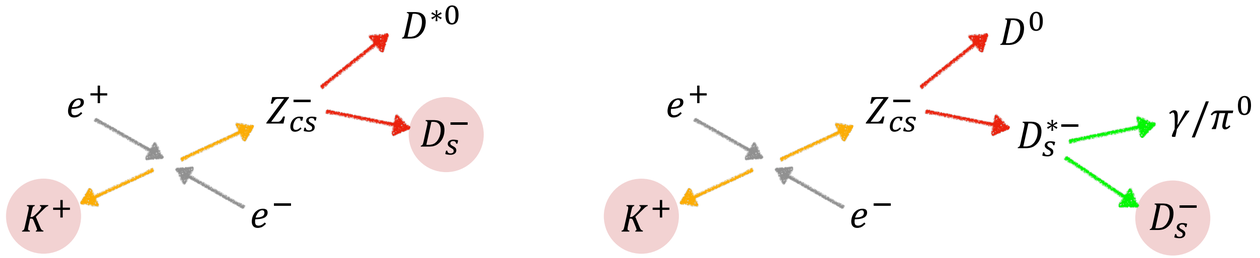
$e^+e^- \to Y(4230) \to \pi^0 Z_c(3900)^0$



$\mathscr{L}_i = 3.7\ fb^{-1}$ PRL 126, 102001 (2021)

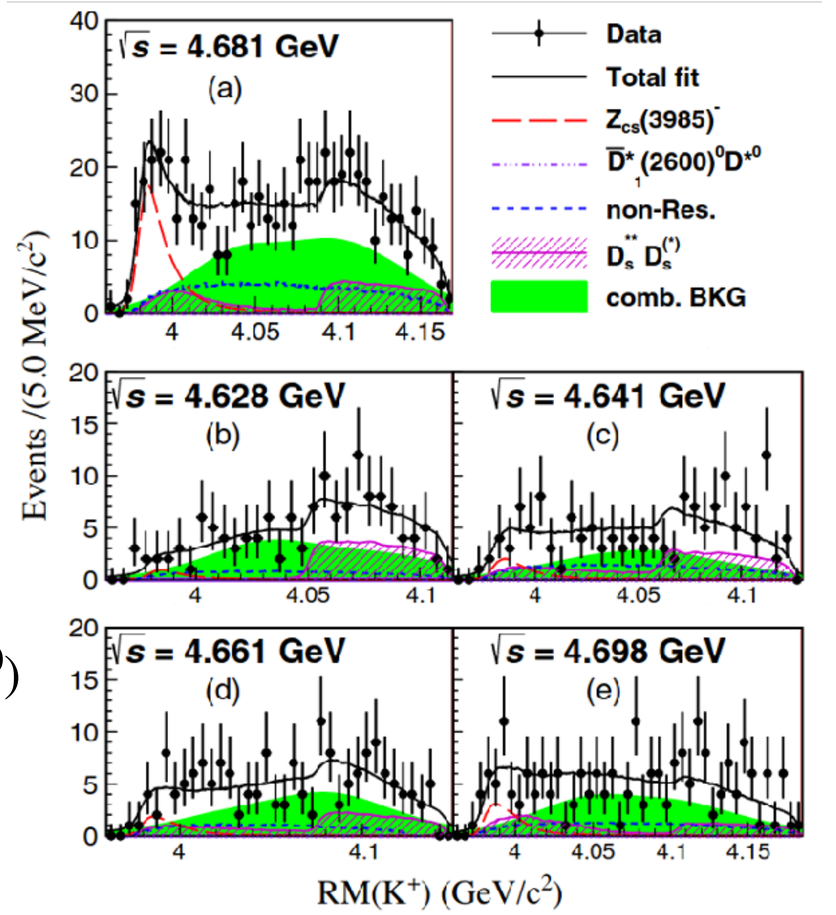
$Z_{cs}(3985)^{\pm}$ @ BESIII

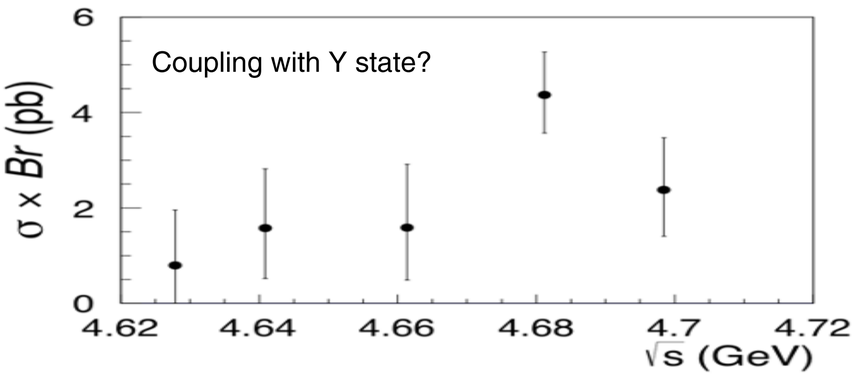
Search for “strange” partner of the Zc(3900)



- Discovered by studying the K^+ recoil mass in $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$
- Significance: 5.3σ
- Minimal quark content $c\bar{c}s\bar{d}$?
- Similar to $Z_{cs}(4000)$ seen by LHCb (widths differ) PRL127, 082001 (2021)

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





$Z_{cs}(3985)^0$ @ BESIII

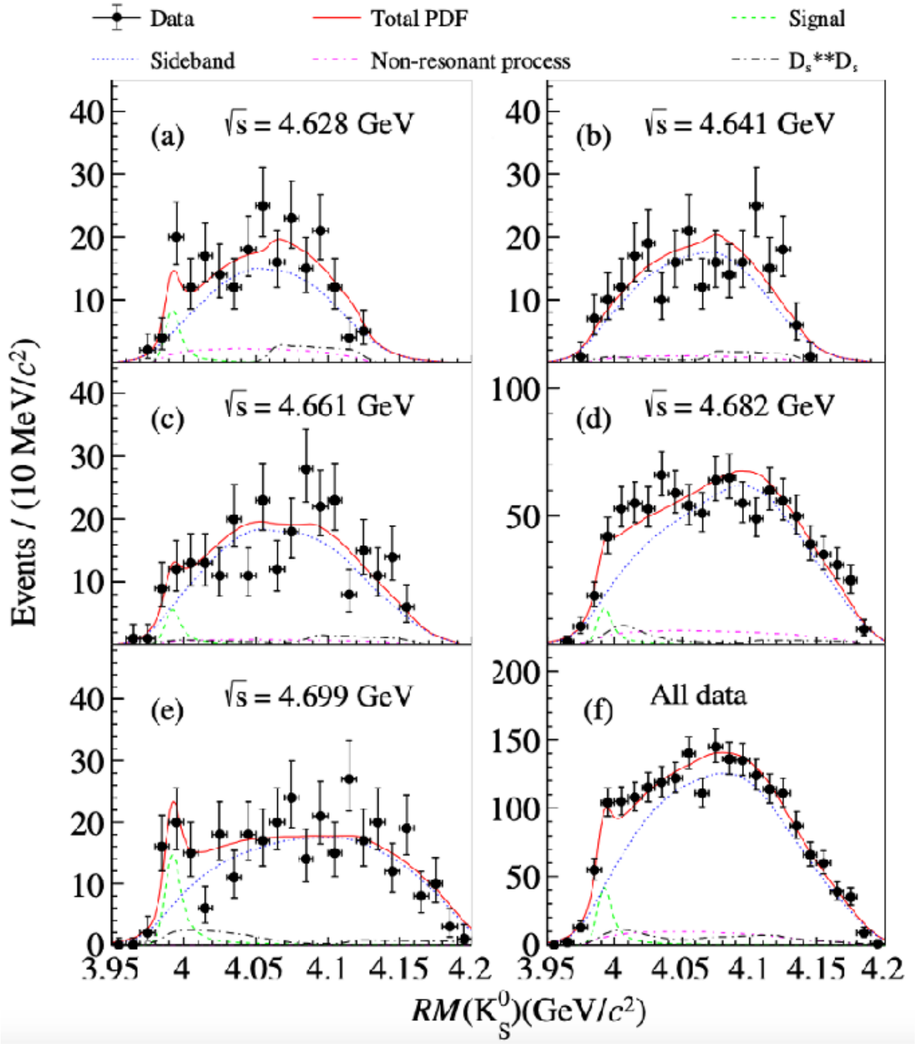
Neutral partner of $Z_{cs}(3985)^{\pm}$ useful to assess their nature

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

- Studied with partial reconstruction method in K_s recoil mass
- Evidence at 4.6σ level. Compatible with isospin predictions
- Minimal quark content $c\bar{c}s\bar{d}$?
- Mass and width consistent with charged Z_{cs} → isospin partner
  - NPB 968, 115450 (2021): $M(Z_{cs}^+) < M(Z_{cs}^0)$

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

$\mathscr{L}_i = 3.8\ fb^{-1}$ arXiv:2204.13703



$\sqrt{s}$ (MeV)	$\sigma^{\mathrm{Born}} \times \mathcal{B}$ (pb) $K^0 Z_{cs}(3985)^0$	$K^- Z_{cs}(3985)^+$	χ^2	χ^2_{total}/ndf
4628	$4.4^{+2.6}_{-2.2} \pm 2.0$	$0.8^{+1.2}_{-0.8} \pm 0.6$	1.2	
4641	$0.0^{+1.6}_{-0.0} \pm 0.2$	$1.6^{+1.2}_{-1.1} \pm 1.3$	0.5	
4661	$2.8^{+1.8}_{-1.6} \pm 0.6$	$1.6^{+1.3}_{-1.1} \pm 0.8$	0.3	5.1/5
4682	$2.2^{+1.2}_{-1.0} \pm 0.8$	$4.4^{+0.9}_{-0.8} \pm 1.4$	1.0	
4699	$7.0^{+2.2}_{-2.0} \pm 1.8$	$2.4^{+1.1}_{-1.0} \pm 1.2$	2.1	

The X(3872)

Almost twenty years of X(3872)

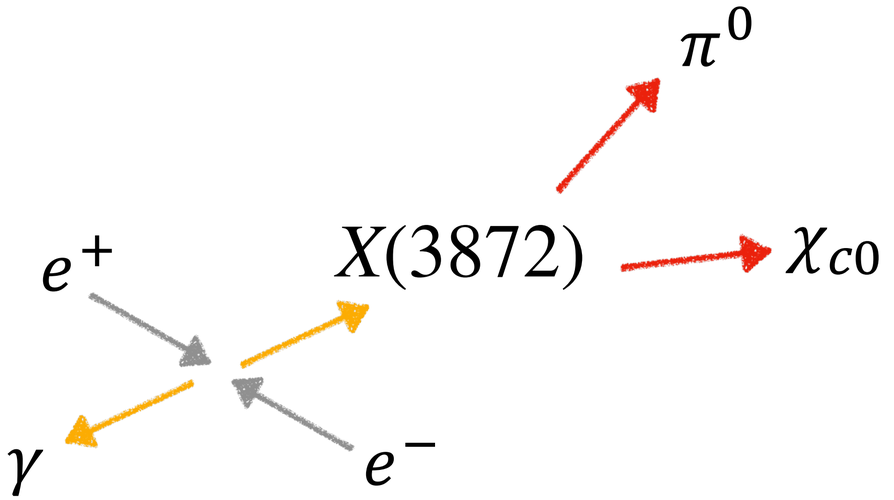
The best studied exotic state

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

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

Search for $X(3872) \to \pi^0\chi_{c0}$ and $X(3872) \to \pi\pi\chi_{c0}$

- To understand the nature of X(3872), verify prediction to test the charmonium-ness of the state
- χ_{c0} reconstructed in 5 hadronic channels



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

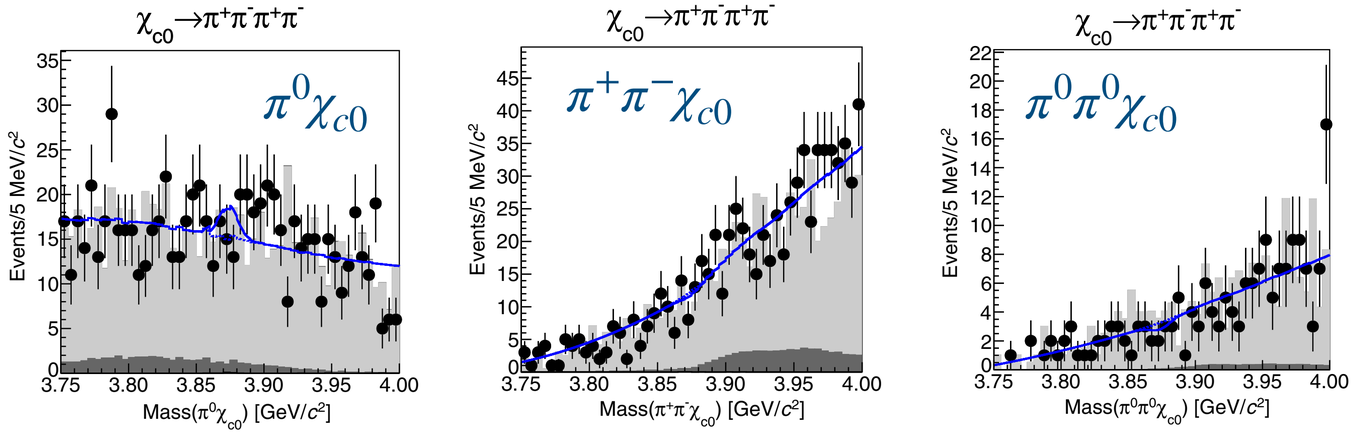
	Interpretation	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$
1)	Four-quark/molecule	...	2.97
1)	$\chi_{c1}(2P)$	0.0	0.0
2)	$D^0\bar{D}^{0*}$	...	2.84–2.98
3)	$D^0\bar{D}^{0*}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

$\mathscr{L}_i = 9.9\ fb^{-1}$ PRD 105 (2022) 7, 072009

Search for $X(3872) \to \pi^0\chi_{c0}$ and $X(3872) \to \pi\pi\chi_{c0}$

- To understand the nature of X(3872), verify prediction to test the charmonium-ness of the state
- χ_{c0} reconstructed in 5 hadronic channels
- No significant results —> Upper Limits



$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$ 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	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$
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4)	$D^0\bar{D}^{0*} + D^+D^{-*}$	...	3.72
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1)PRD77,014013(2008) 2)PRD78,094019(2008) 3)EPJC81,193(2021)
4)PRD79,094013(2009) 5)PRD100,094025(2019)

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

Upper limits (90% C.L.) still not conclusive.
New statistics will be collected with BEPCII-U

Conclusions

Outlook

Other results not shown

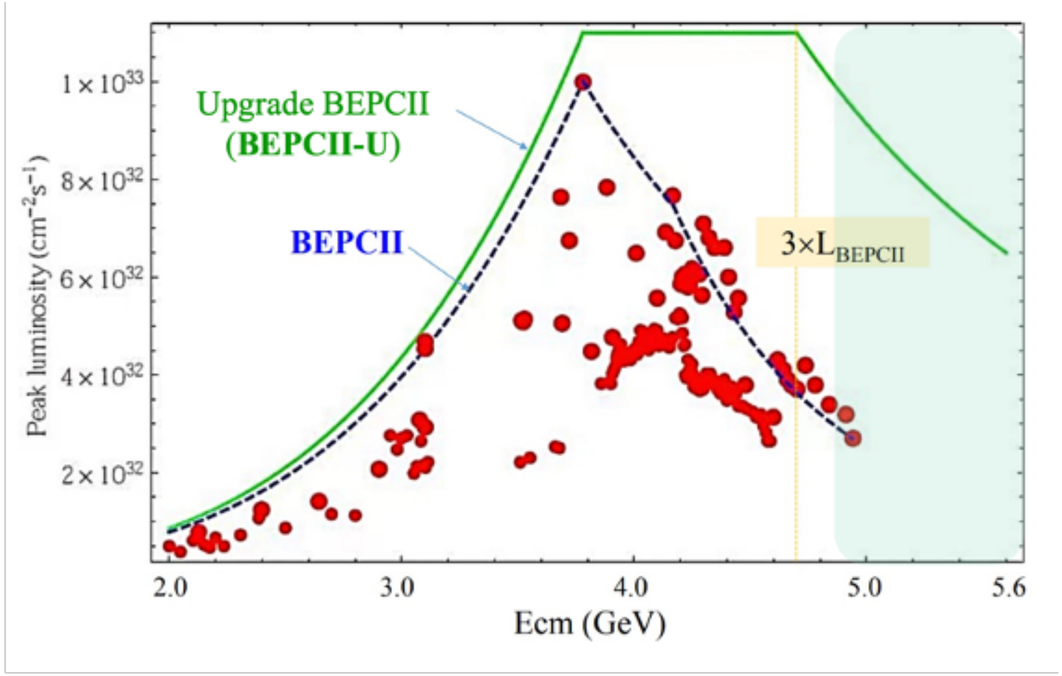
- Many other great results have been recently published
  - e.g. exotics' decay to light hadrons and baryons

PRD 104, 112009 (2021)
PRD 104, L091104 (2021)

- Connections between exotic states are also investigated at BESIII
  - $e^+e^- \to \gamma X(3872);\ X(3872) \to \pi^+\pi^- J\psi$ PRL 122, 232002 (2019)
  - $e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$ PHYS. REV. D 102, 012009 (2020)
  - $e^+e^- \to \pi^0 Z_c;\ Z_c \to \gamma X(3872)$ PRD 104, 012001 (2021)

Summary

- Exciting results from new XYZ data are presented
  - Studies of $X(3872)$ continue thanks to the $e^+e^- \to Y(4230) \to \gamma X(3872)$ process
  - Mapping out fine structures of Y states
  - $Z_{cs}(3985)$ triplet
- Data with unprecedented statistical accuracy from BESIII provides great opportunities to study QCD exotics. Will continue to run until ~2030
- Further upgrade in energy (5.6 GeV) and luminosity (BEPCII-U) coming



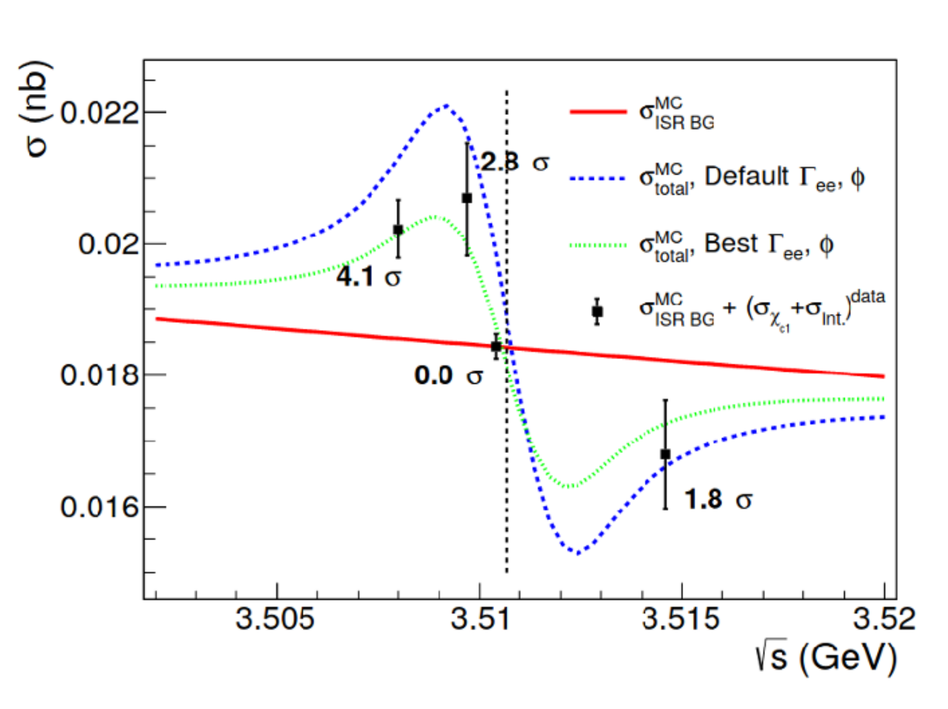
BESIII White paper: arXiv:1912.05983 Chin. Phys. C 44, 040001 (2020)

Thanks for your attention!

ArXiv: 2203.13782

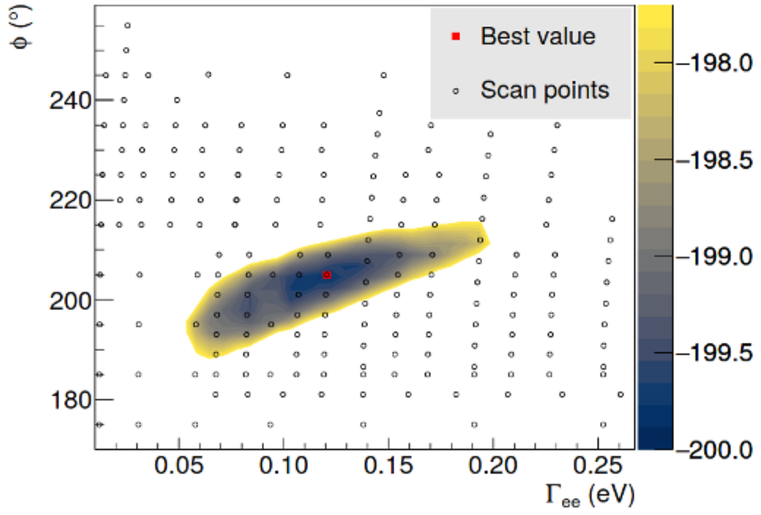
$\chi_{c1}(1P)$ direct production

First observation (5σ) of $\chi_{c1}(1P)$ direct production at e^+e^- collider



- Study of $e^+e^- \to \gamma J/\psi$ to extract interference pattern
- Electronic width same order of magnitude with theoretical calculation

$$\Gamma_{ee} = (0.12^{+0.13}_{-0.08})\ \text{eV}$$



- Similar approach for X(3872). Paper in preparation!