



# BESIII和LHCb实验上 重味奇特强子态研究进展

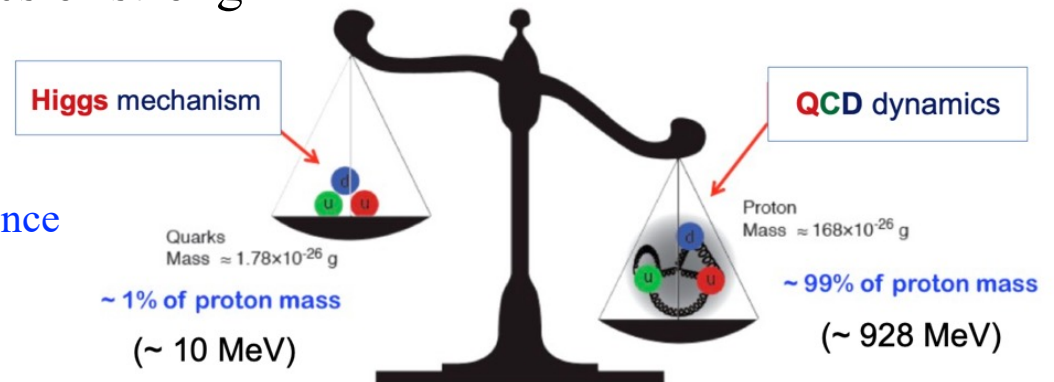
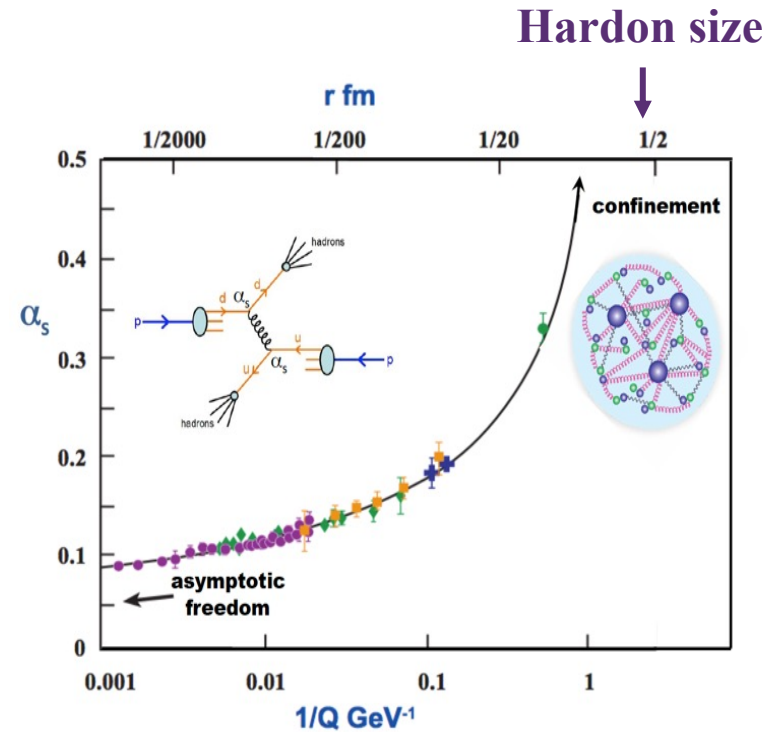
吕晓睿

(中国科学院大学)

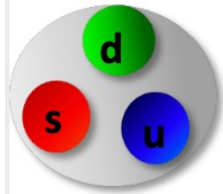
第八届全国重味物理与  
量子色动力学研讨会

# Introduction

- Quarks and gluons not isolated in nature.
  - Formation of colorless bound states: “**Hadrons**”
  - **1-fm scale** size of hadrons?
- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence



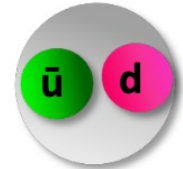
# Different types of hadrons to be explored



Baryons are red-blue-green triplets

$$\Lambda = usd$$

Mesons are color-anticolor pairs

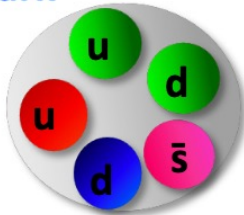


$$\pi = \bar{u}d$$

Other possible combinations of quarks and gluons :

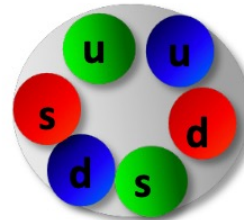
## Pentaquark

$S = +1$   
Baryon



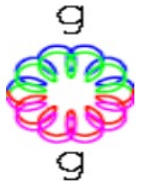
## H di-Baryon

Tightly bound  
6 quark state



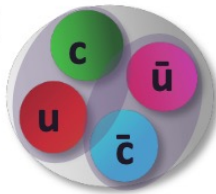
## Glueball

Color-singlet multi-gluon bound state



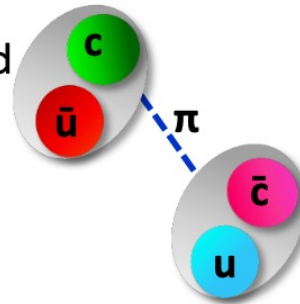
## Tetraquark

Tightly bound  
diquark &  
anti-diquark

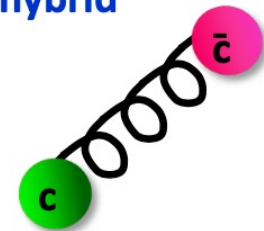


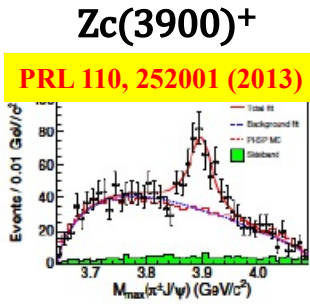
## Molecule

loosely bound  
meson-  
antimeson  
"molecule"

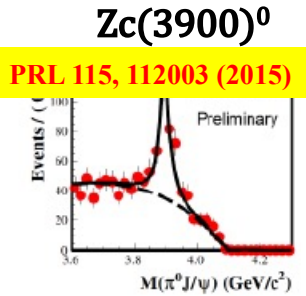


$q\bar{q}$ -gluon hybrid  
mesons

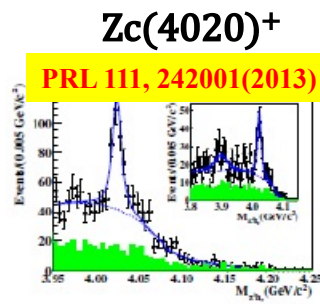




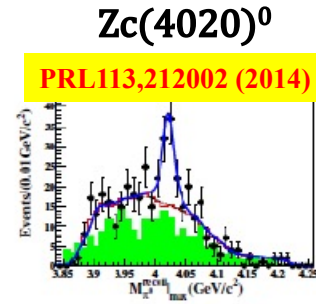
$$e^+e^- \rightarrow \pi^- \pi^+ J/\psi$$



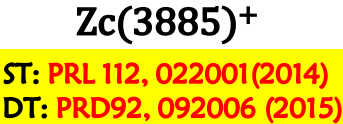
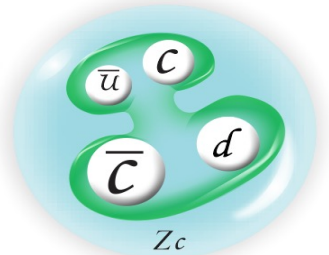
$$e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$$



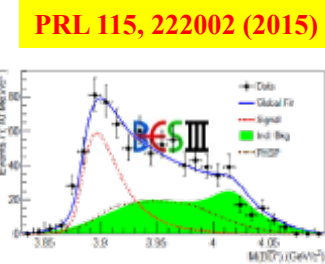
$$e^+e^- \rightarrow \pi^- \pi^+ h_c$$



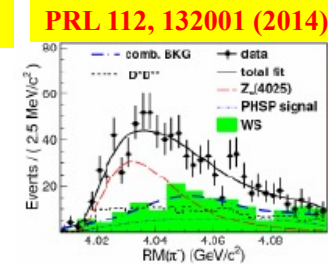
$$e^+e^- \rightarrow \pi^0 \pi^0 h_c$$



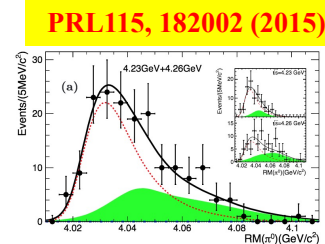
$$e^+e^- \rightarrow \pi^- (D\bar{D}^*)^+$$



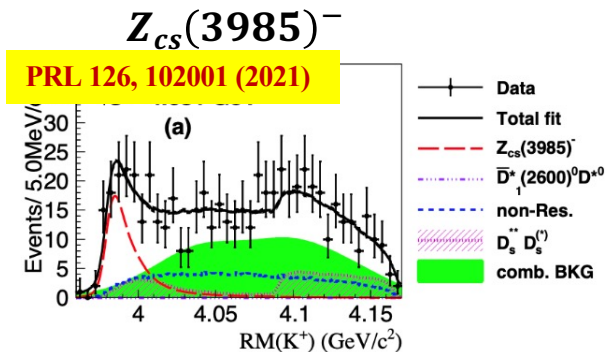
$$e^+e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0$$



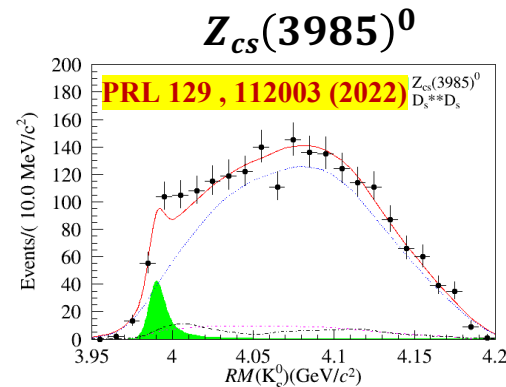
$$e^+e^- \rightarrow \pi^- (D^* \bar{D}^*)^+$$



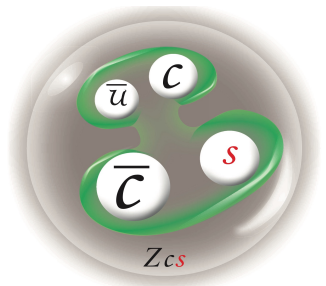
$$e^+e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0$$



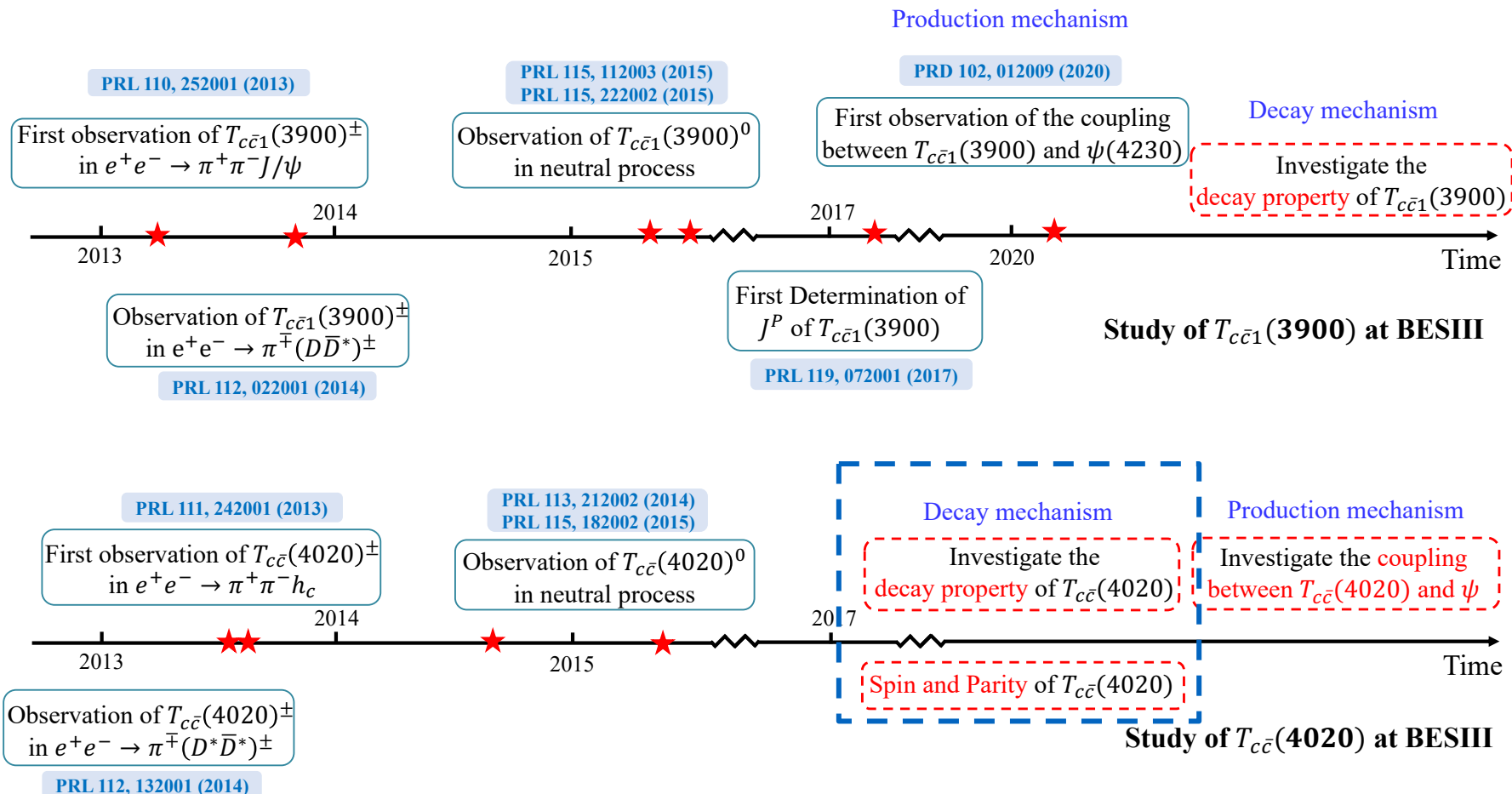
$$e^+e^- \rightarrow K^+ (D^{*0} D_s^- + D^0 D_s^{*-})$$



$$e^+e^- \rightarrow K_s^0 (D^{*+} D_s^+ + D^- D_s^{*+})$$



# To explore the property of the $T_{c\bar{c}}(4020)$



PDG naming:  $Z_c(3900/3885) = T_{c\bar{c}1}(3900)$ ,  $Z_c(4020/4025) = T_{c\bar{c}}(4020)$

# Multi-channel joint analysis for $T_{c\bar{c}}(4020)$

Three Channels:  $e^+e^- \rightarrow D^{*0}D^{*-}\pi^+, \pi^+\pi^-J/\psi, \pi^+\pi^-h_c$

PRL 112, 132001 (2014)

PRL 118, 092001 (2017)

PRL 111, 242001 (2013)

- For  $D^{*0}D^{*-}\pi^+$ : Double-tag method is used, details in Appendix.  $D^{*0}D^{*-}\pi^+ \rightarrow [D^0\pi^0(\gamma)][\bar{D}^0\pi^-]\pi^+$  ✓ The charge conjugated channels are implied.

- For  $\pi^+\pi^-J/\psi$ : Full reconstruction method is used.

$$J/\psi \rightarrow l^+l^- \quad (l = e, \mu)$$

- For  $\pi^+\pi^-h_c$ : Full reconstruction method is used.

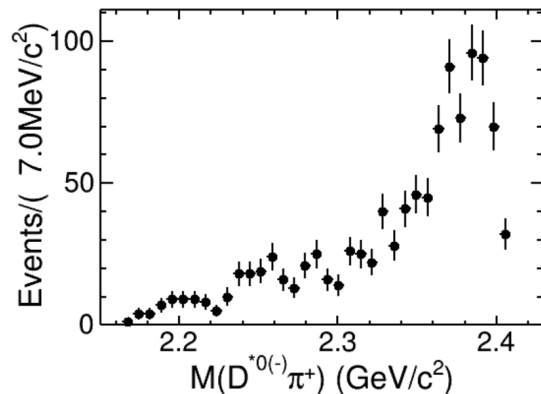
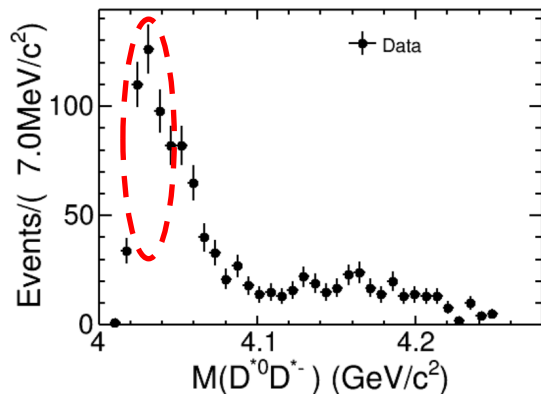
$$h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow 16 \text{ channels}$$

$$\eta_c \rightarrow p\bar{p}, 2(\pi^+\pi^-), 2(K^+K^-), \pi^+\pi^-K^+K^-, \pi^+\pi^-p\bar{p}, 3(\pi^+\pi^-), 2(\pi^+\pi^-)K^+K^-, K_S^0K^\pm\pi^\mp, K_S^0K^\pm\pi^\mp\pi^+\pi^-, K_S^0K^\pm\pi^\mp\pi^+\pi^-, K^+K^-\pi^0, p\bar{p}\pi^0, K^+K^-\eta, \pi^+\pi^-\eta, 2(\pi^+\pi^-)\eta, \pi^+\pi^-\pi^0\pi^0 \text{ and } 2(\pi^+\pi^-)\pi^0$$

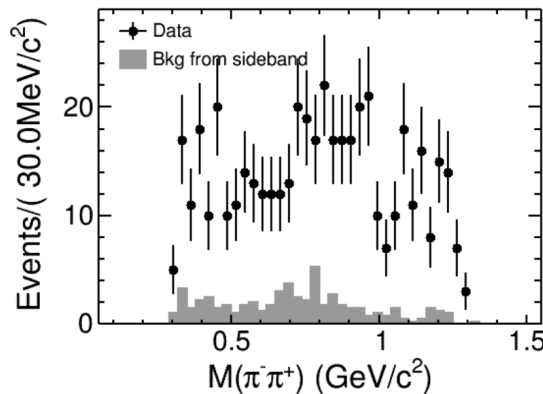
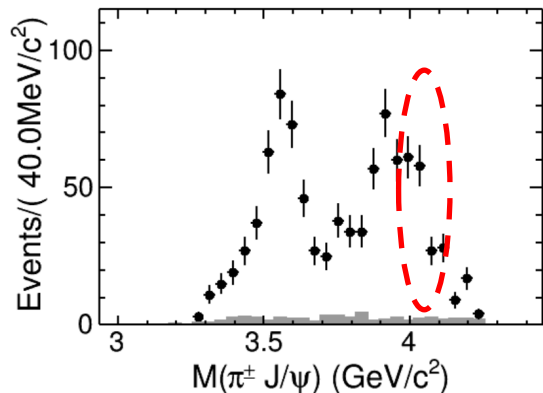
**The event selection criteria are consistent with published results.**

- Data samples collected at 4.395 and 4.416 GeV are used

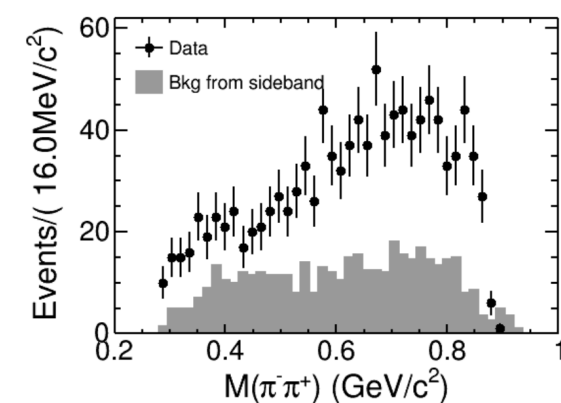
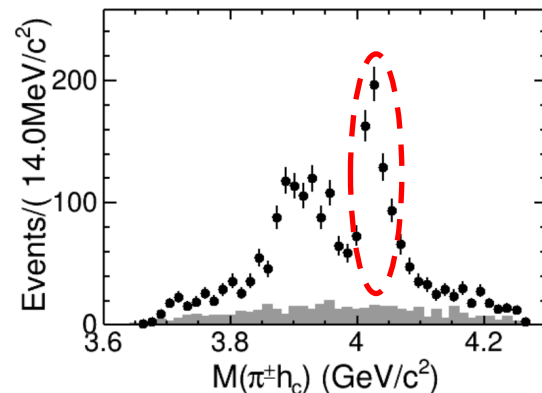
$D^{*0}D^{*-}\pi^+$



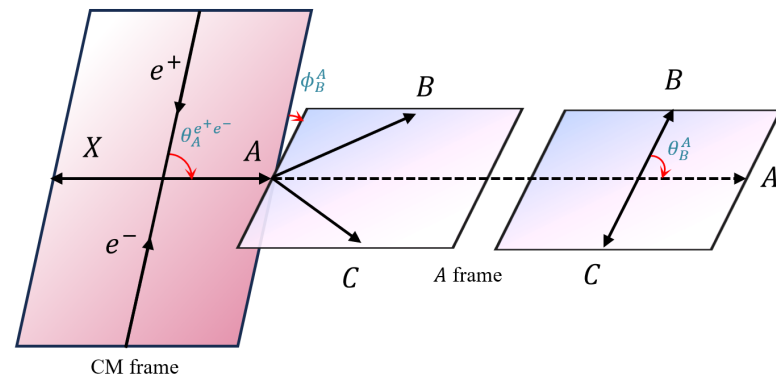
$\pi^+\pi^-J/\psi$



$\pi^+\pi^-h_c$



- Full procedure uses helicity amplitude formalism based on [TF-PWA](#) package
- Simultaneously fit on samples at 4.395 GeV and 4.416 GeV with sharing parameters of the decay dynamics of the  $T_{c\bar{c}}(4020)^-$



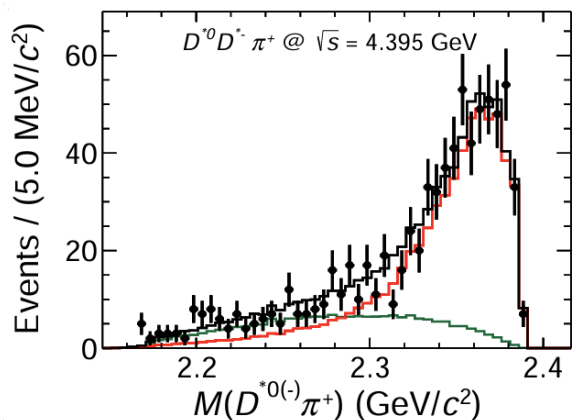
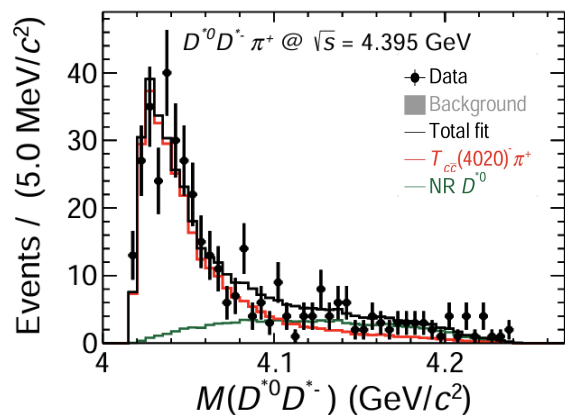
### Baseline model:

$D^{*0}D^{*-}\pi^+$ :  $T_{c\bar{c}}(4020)^-\pi^+$ ,  $D^*\bar{D}_1(2420)$ ,  $NRD^{*0}$

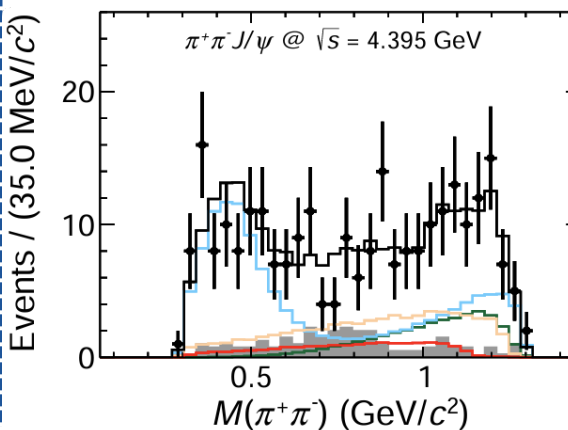
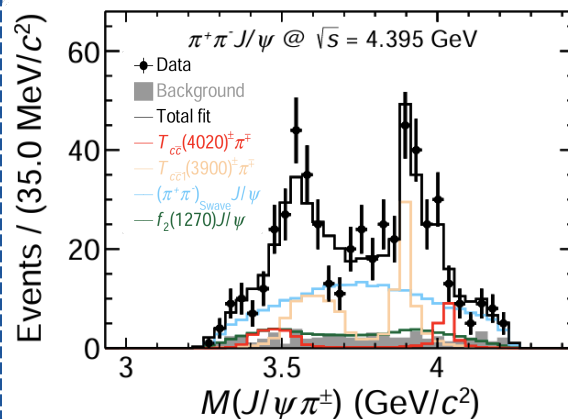
$\pi^+\pi^-J/\psi$ :  $T_{c\bar{c}}(4020)^{\mp}\pi^{\pm}$ ,  $T_{c\bar{c}1}(3900)^{\mp}\pi^{\pm}$ ,  $\sigma J/\psi$ ,  $f_0(980)J/\psi$ ,  $f_0(1370)J/\psi$ ,  $f_2(1270)J/\psi$

$\pi^+\pi^-h_c$ :  $T_{c\bar{c}}(4020)^{\mp}\pi^{\pm}$ ,  $\sigma h_c$ ,  $f_0(980)h_c$

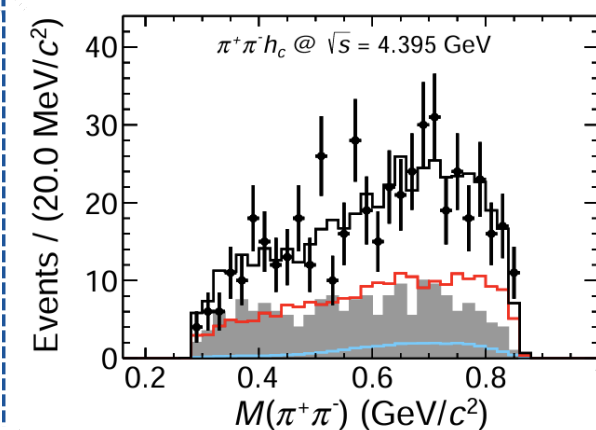
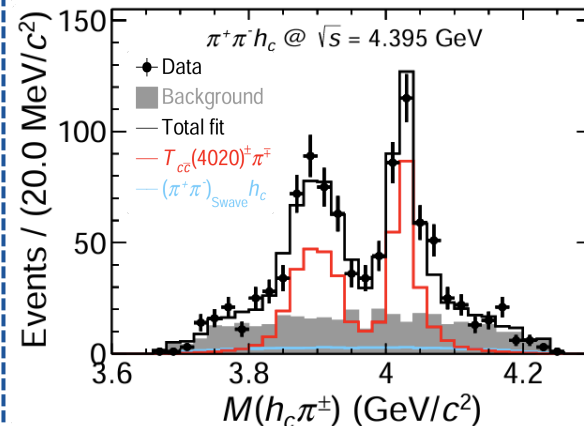
$D^{*0}D^{*-}\pi^+$

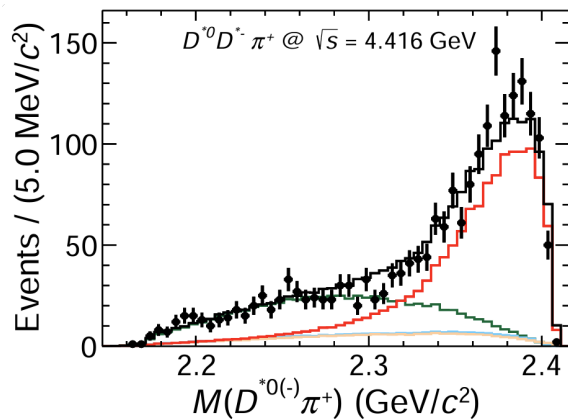
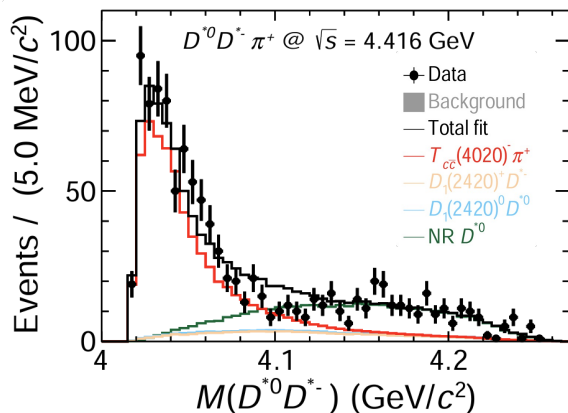
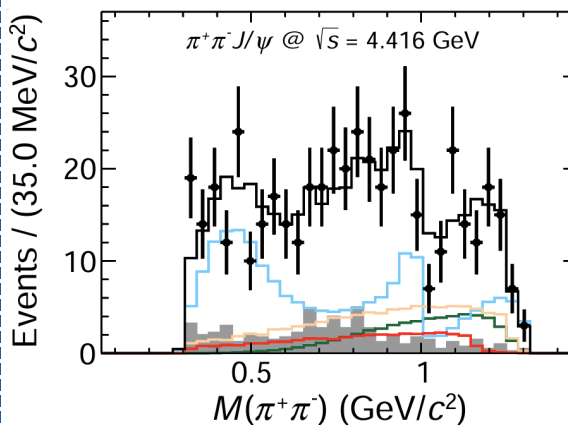
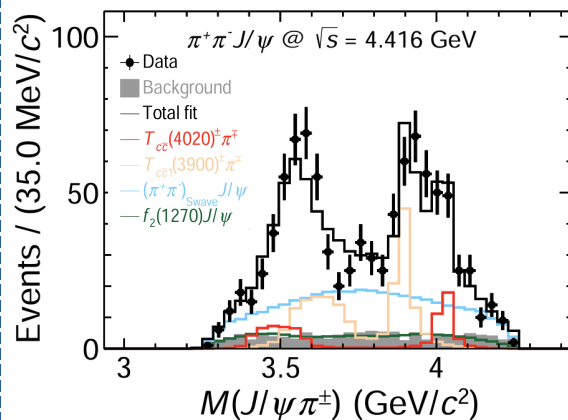
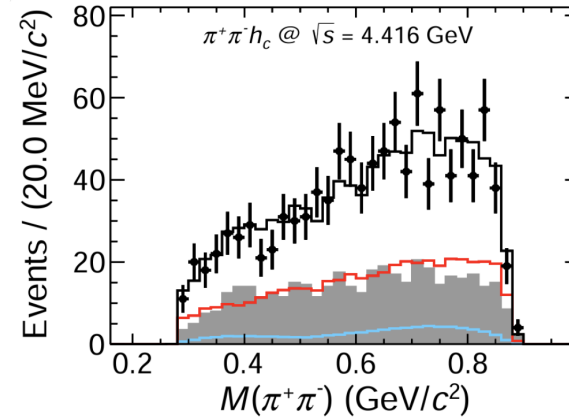
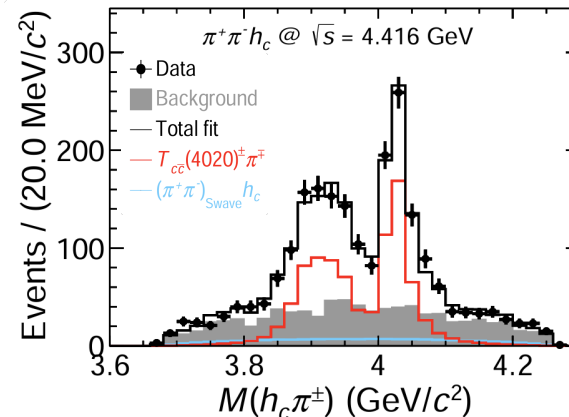


$\pi^+\pi^-J/\psi$



$\pi^+\pi^-h_c$



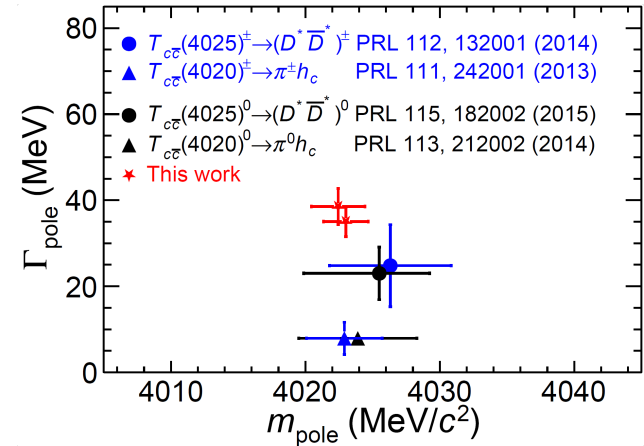
$D^{*0}D^{*-}\pi^+$  $\pi^+\pi^-J/\psi$  $\pi^+\pi^-h_c$ 

# BESIII $T_{c\bar{c}}$ (4020) resonance parameters and spin-parity



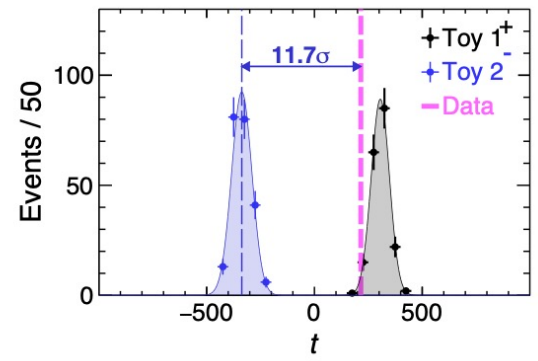
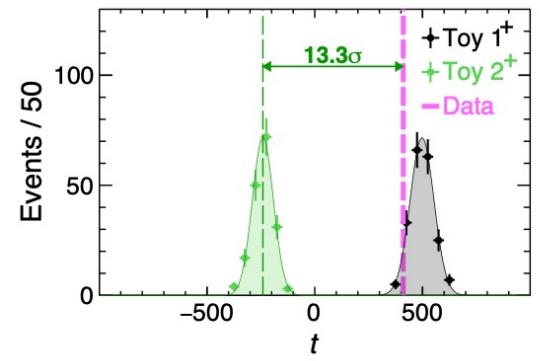
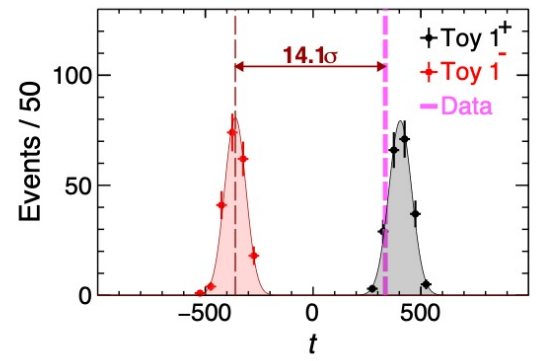
arXiv:2603.05564

Pole	$M_{\text{pole}} \text{ (MeV}/c^2)$	$\Gamma_{\text{pole}} \text{ (MeV)}$	Imag.( $p$ )
1	$4022.44 \pm 1.55$	$38.54 \pm 2.94$	(-, -, -)
2	$4023.01 \pm 1.35$	$35.02 \pm 2.20$	(-, +, -)
3	$4029.39 \pm 0.86$	$0.03 \pm 15.66$	(-, +, +)
4	$4029.87 \pm 0.95$	$2.85 \pm 14.56$	(-, -, +)
5	$4022.44 \pm 1.55$	$-38.54 \pm 2.94$	(-, -, -)
6	$4023.01 \pm 1.35$	$-35.02 \pm 2.20$	(-, +, -)
7	$4029.39 \pm 0.86$	$-0.03 \pm 15.66$	(-, +, +)
8	$4029.87 \pm 0.95$	$-2.85 \pm 14.56$	(-, -, +)



$$R(m) = \frac{1}{m^2 - M^2 + im[\Gamma_{D^*0D^{*-}}(m) + \Gamma_{J/\psi\pi}(m) + \Gamma_{h_c\pi}(m) + \Gamma_X(m)]}$$

$$\Gamma(m) = \frac{1}{8\pi} \sum_{\lambda_B, \lambda_C} |H_{\lambda_B, \lambda_C}^J|^2 \frac{|\mathbf{p}|}{m^2}$$



$J^P = 1^+$  with  $> 11.7\sigma$        $T_{c\bar{c}}(4020) \rightarrow T_{c\bar{c}1}(4020)$

	Simultaneously Fit	$\sqrt{s} = 4.395 \text{ GeV}$	$\sqrt{s} = 4.416 \text{ GeV}$
$D^{*0}D^{*-}\pi^+$	FF( $T_{c\bar{c}}^-\pi^+$ ) (%)	$75.1 \pm 4.3$	$61.4 \pm 4.6$
$\pi^+\pi^-J/\psi$	FF( $T_{c\bar{c}}^+\pi^-$ ) (%)	$4.4 \pm 1.4$	$5.1 \pm 1.5$
	FF( $T_{c\bar{c}}^-\pi^+$ ) (%)	$4.4 \pm 1.4$	$5.1 \pm 1.5$
$\pi^+\pi^-h_c$	FF( $T_{c\bar{c}}^+\pi^-$ ) (%)	$35.0 \pm 6.4$	$33.5 \pm 4.7$
	FF( $T_{c\bar{c}}^-\pi^+$ ) (%)	$35.0 \pm 6.4$	$33.5 \pm 4.7$
$\sigma_{2body}^B \cdot B[T_{c\bar{c}}(4020)^\pm \rightarrow D^{*0}D^{*-}(\text{c. c.})]$ (pb)		$335.2 \pm 21.0$	$336.4 \pm 25.7$
$\sigma_{2body}^B \cdot B[T_{c\bar{c}}(4020)^\pm \rightarrow \pi^\pm J/\psi]$ (pb)		$1.1 \pm 0.3$	$1.4 \pm 0.3$
$\sigma_{2body}^B \cdot B[T_{c\bar{c}}(4020)^\pm \rightarrow \pi^\pm h_c]$ (pb)		$30.4 \pm 4.5$	$29.6 \pm 3.3$

- The relative branching fractions of  $T_{c\bar{c}}(4020)^\pm$  combining two datasets (weighted by yields) :

*first evidence!*

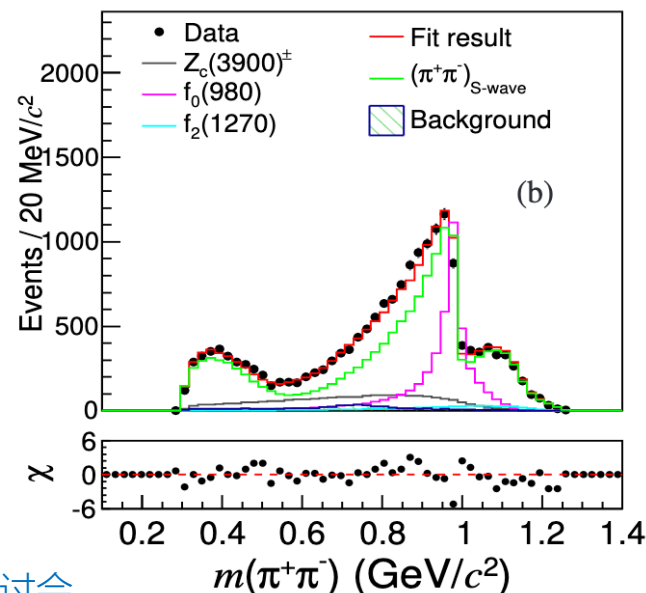
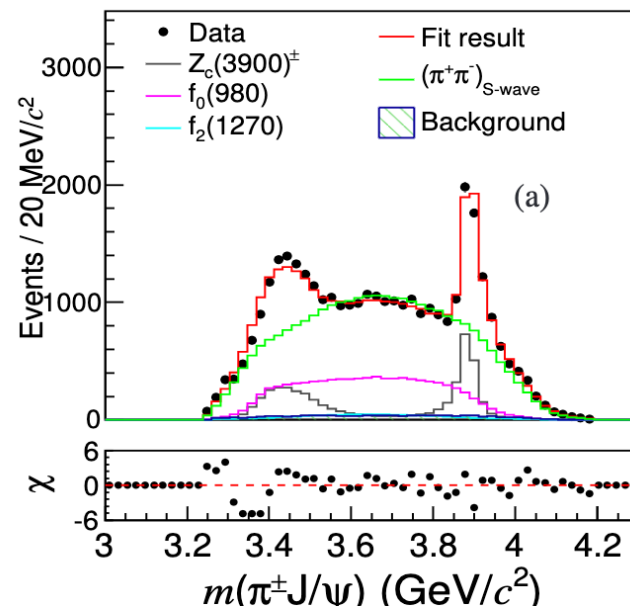
$$B[T_{c\bar{c}1}(4020)^- \rightarrow \pi^- J/\psi]/B[T_{c\bar{c}1}(4020)^- \rightarrow D^{*0}D^{*-}] = (3.6 \pm 0.6 \pm 1.6) \times 10^{-3}$$

$$B[T_{c\bar{c}1}(4020)^- \rightarrow \pi^- h_c]/B[T_{c\bar{c}1}(4020)^- \rightarrow D^{*0}D^{*-}] = (8.9 \pm 1.3 \pm 2.3) \times 10^{-2}$$

- Based on  $12.0 \text{ fb}^{-1}$  of  $e^+e^-$  collision data between 4.1271 and 4.3583 GeV
- $Z_c(3900)$ : BW model with constant width
- $f_0(980)$  seen at all energy points

Sample	$M$ (MeV/ $c^2$ )	$\Gamma$ (MeV)
4.1567 – 4.1989	$3883.5 \pm 1.6$	$38.6 \pm 3.6$
4.2091 – 4.2357	$3884.0 \pm 1.0$	$37.8 \pm 1.6$
4.2438 – 4.2776	$3884.9 \pm 1.8$	$34.2 \pm 3.3$
4.2866 – 4.3583	$3890.0 \pm 2.3$	$36.1 \pm 4.2$
Average	$3884.6 \pm 0.7 \pm 3.3$	$37.2 \pm 1.3 \pm 6.6$

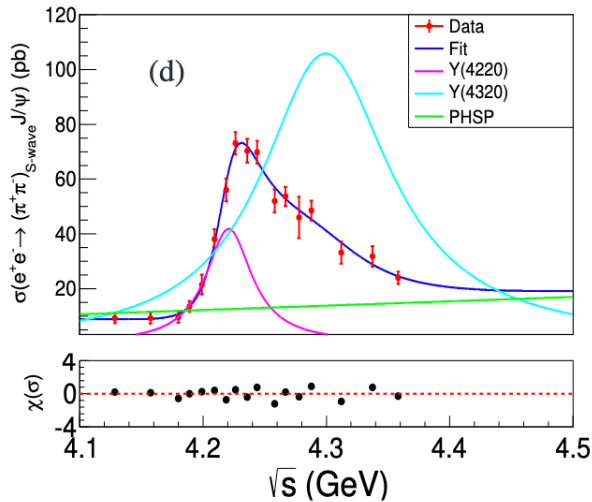
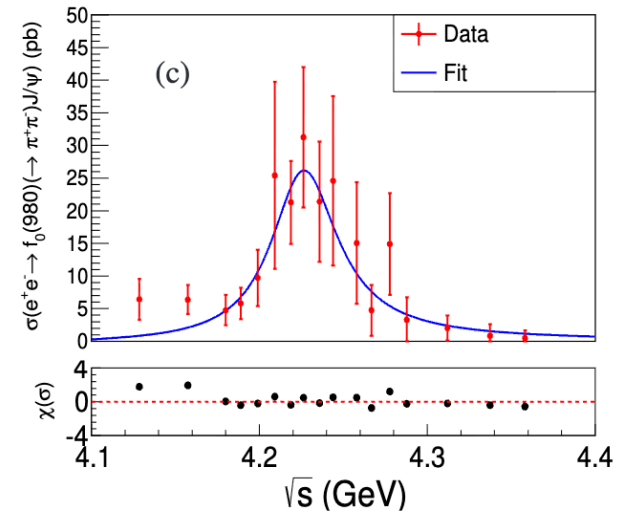
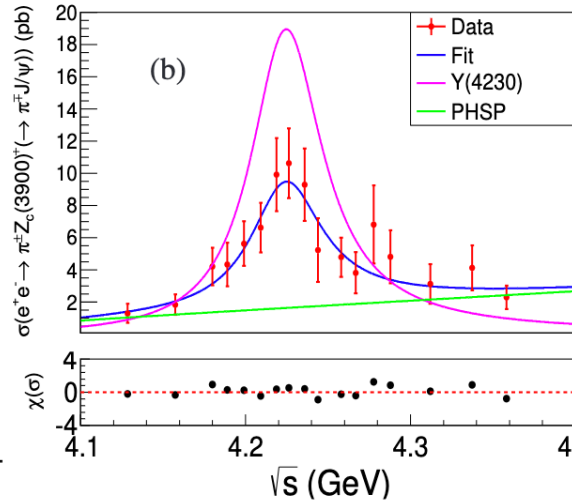
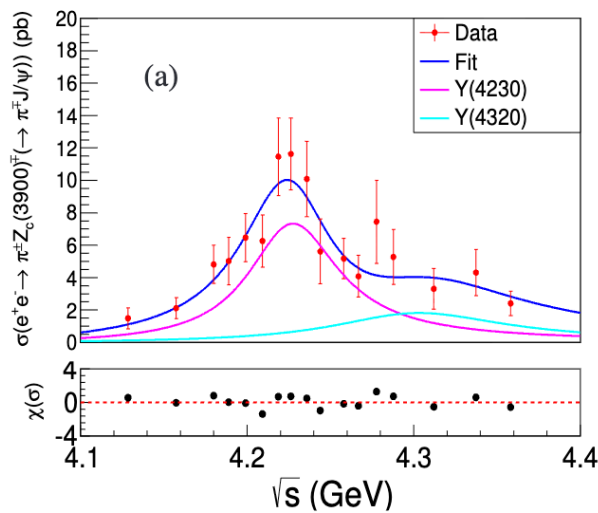
State	Mass (MeV/ $c^2$ )	Width (MeV)	Decay	Process
$Z_c(3885)^\pm$	$3883.9 \pm 1.5 \pm 4.2$ Single D tag	$24.8 \pm 3.3 \pm 11.0$ Single D tag	$(D\bar{D}^*)^\pm$	$e^+e^- \rightarrow (D\bar{D}^*)^\pm \pi^\mp$
	$3881.7 \pm 1.6 \pm 2.1$ Double D tag	$26.6 \pm 2.0 \pm 2.3$ Double D tag	$(D\bar{D}^*)^\pm$	$e^+e^- \rightarrow (D\bar{D}^*)^\pm \pi^\mp$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	$e^+e^- \rightarrow (D\bar{D}^*)^0 \pi^0$



# BESIII Cross sections of $e^+e^- \rightarrow \pi^+ Z_c(3900)^-$



PRD112, 092013 (2025)

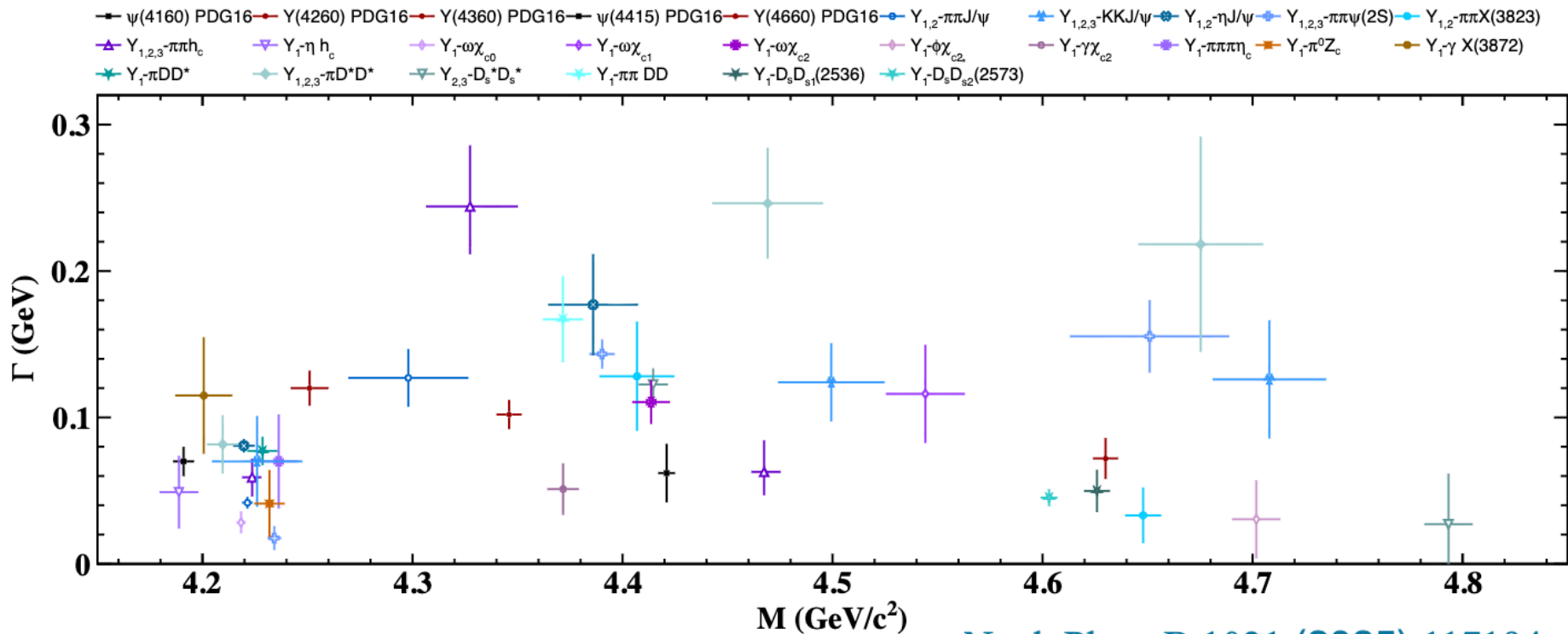


	Y(4220)	Y(4320)	
<b>Process</b>	$M$ (MeV/ $c^2$ )	$\Gamma$ (MeV)	<b>Significance</b>
$\pi^\pm Z_c(3900)^\mp$ (model I)	$4225.7 \pm 6.8 \pm 6.8$	$66.5 \pm 16.1 \pm 24.1$	$2.1\sigma$
$\pi^\pm Z_c(3900)^\mp$ (model II)	$4223.1 \pm 6.4 \pm 0.6$	$53.8 \pm 19.1 \pm 0.3$	$2.0\sigma$
$f_0(980)J/\psi$ (model III)	$4225.6 \pm 4.5 \pm 0.6$	$48.4 \pm 9.8 \pm 0.2$	$0.5\sigma$
$(\pi^+\pi^-)_{S\text{-wave}}J/\psi$ (model IV)	$4218.8 \pm 3.4 \pm 3.7$	$43.5 \pm 5.3 \pm 5.0$	$11.7\sigma$
$Y(4220)^{\text{ave}}$	$4225.7 \pm 4.1 \pm 3.4$	$57.5 \pm 9.4 \pm 12.1$	

# Vector Charmonium-like States



Over the past two decades, a series of charmoniumlike states with  $J^{PC} = 1^{--}$ , referred to as the Y states, have been observed by a number of experiments.

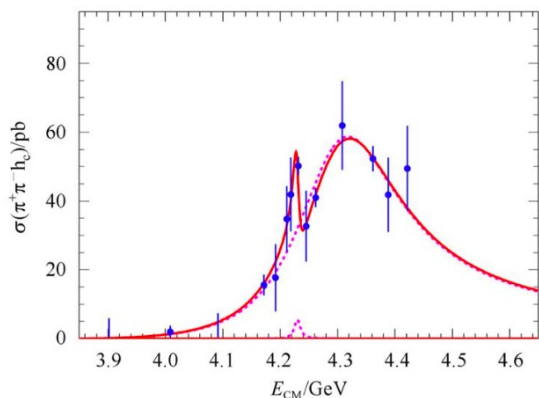


Nucl. Phys. B 1021 (2025) 117194

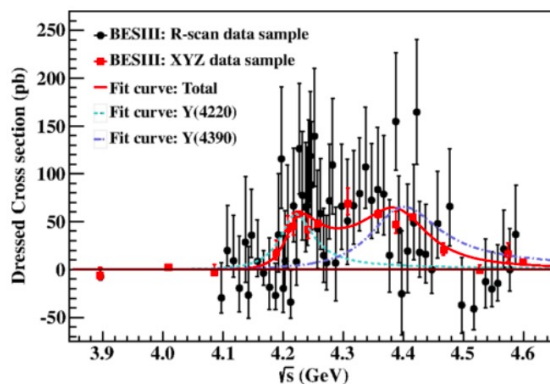
# Improved measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c)$

PRL135, 071901 (2025)

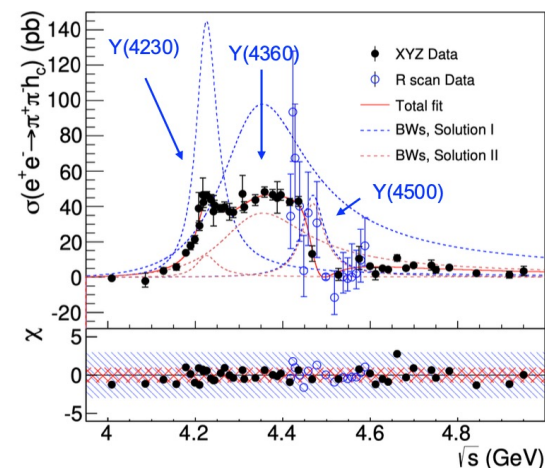
- Initially observed by CLEO-c at  $\sqrt{s}=4.17$  GeV [PRL107, 041803 (2011)]
- Cross sections of  $e^+e^- \rightarrow \pi^+\pi^-h_c$  obtained by BESIII at 3.9-4.6 GeV, found two structures [PRL118, 092002 (2017)]
- New data collected by BESIII between 4.18-4.95 GeV (27 data samples)**



PRL107, 041803 (2011) – CLEO-c  
PRL111, 242001 (2013) – BESIII  
CPC 38, 043001 (2014)



PRL118, 092002 (2017) - BESIII



PRL135, 071901 (2025)

Y(4230)

Y(4360)

Parameter	$R_1$	$R_2$	$R_3$
$M$ (MeV/ $c^2$ )	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	$4467.4^{+7.2+3.2}_{-5.4-2.7}$
$\Gamma$ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	$244.1^{+34.0+24.2}_{-27.1-18.3}$	$62.8^{+19.2+9.9}_{-14.4-7.0}$

a bit larger width

$$\Gamma_{Y(4360)} = 120 \pm 21 \text{ MeV}$$

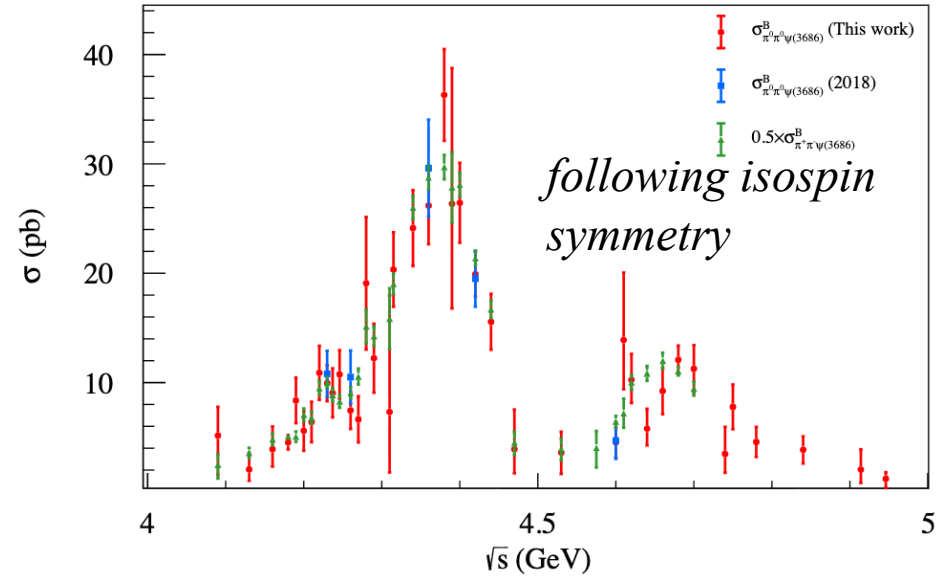
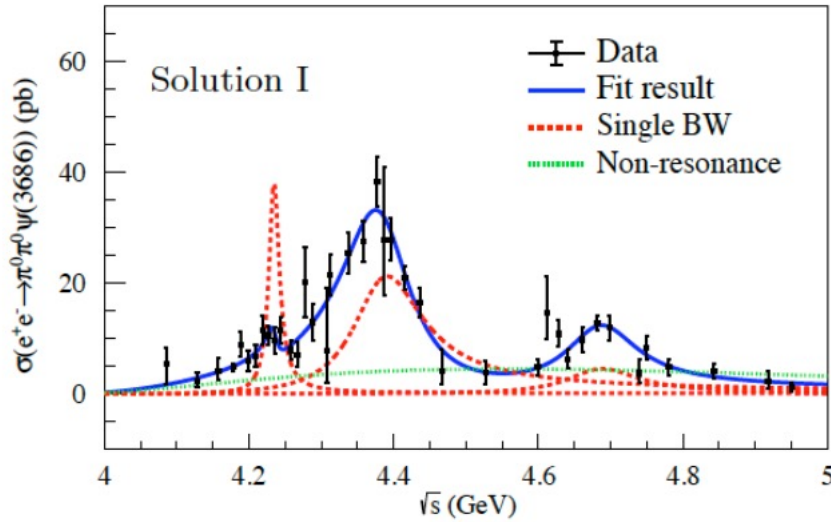
$>5\sigma$

Y(4500)

# BES III Study of $\sigma(e^+e^- \rightarrow \pi^0\pi^0\psi(3686))$



arXiv:2601.02136



Parameter	Solution I	Solution II	Solution III	Solution IV
$M(Y4230)$ (MeV/ $c^2$ )		4234.4 (fixed)		
$\Gamma^{\text{tot}}(Y4230)$ (MeV)		17.6 (fixed)		
$B\Gamma^{ee}(Y4230)$ (eV)	$0.81 \pm 0.07 \pm 0.37$	$0.02 \pm 0.01 \pm 0.01$	$0.87 \pm 0.08 \pm 0.43$	$0.02 \pm 0.01 \pm 0.01$
$M(Y4390)$ (MeV/ $c^2$ )		$4383.0 \pm 8.6 \pm 1.9$		
$\Gamma^{\text{tot}}(Y4390)$ (MeV)		$117.4 \pm 20.7 \pm 4.8$		
$B\Gamma^{ee}(Y4390)$ (eV)	$3.18 \pm 1.21 \pm 0.57$	$2.92 \pm 1.07 \pm 0.36$	$9.90 \pm 1.42 \pm 0.76$	$9.03 \pm 1.22 \pm 0.09$
$M(Y4660)$ (MeV/ $c^2$ )		$4684.0 \pm 17.3 \pm 1.9$		
$\Gamma^{\text{tot}}(Y4660)$ (MeV)		$119.5 \pm 47.1 \pm 9.1$		
$B\Gamma^{ee}(Y4660)$ (eV)	$0.80 \pm 0.73 \pm 0.14$	$0.79 \pm 0.70 \pm 0.13$	$5.36 \pm 1.60 \pm 0.39$	$5.31 \pm 1.58 \pm 0.23$

- About  $T_{c\bar{c}1}(4430)^+$

- Discovered by Belle in 2007 in  $B^{+,0} \rightarrow K^{0,-} \pi^+ \psi(2S)$

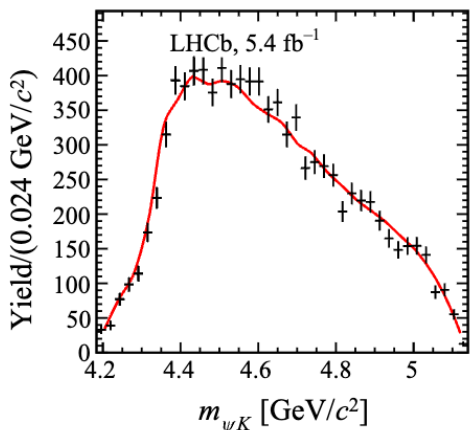
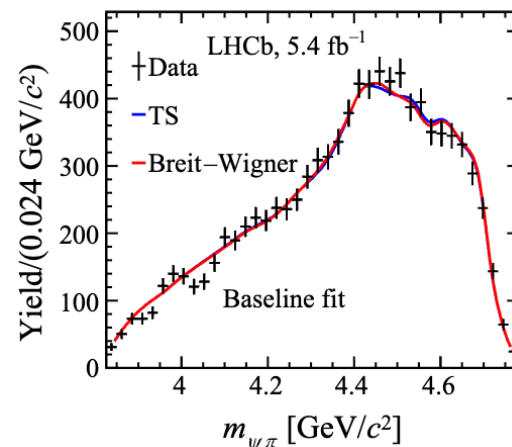
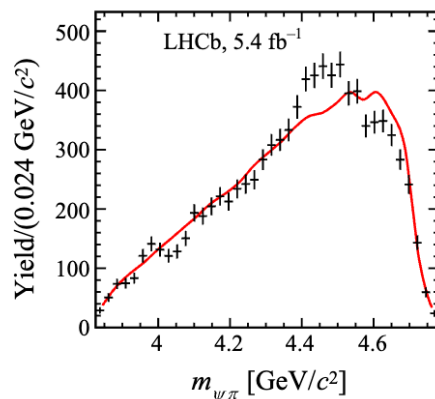
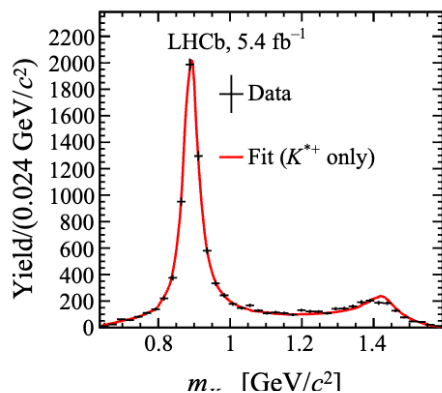
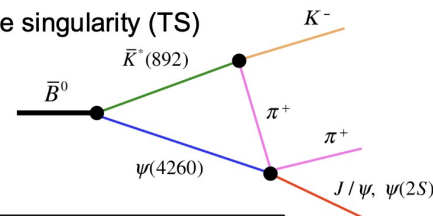
PRL 100 (2008) 142001

- Confirmed by LHCb  $J^P = 1^+$  in  $B^0$  decays.

PRL12 (2014) 22, 222002

4-dimensional amplitude analysis based on RUN 2 data

Triangle singularity (TS)



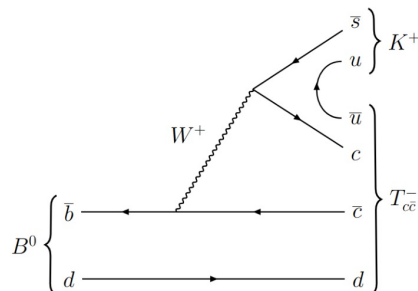
$K^*$  states alone cannot describe the  $\psi(2S)\pi^+$  enhancement around 4.4 GeV in data

model with a rel. BW state

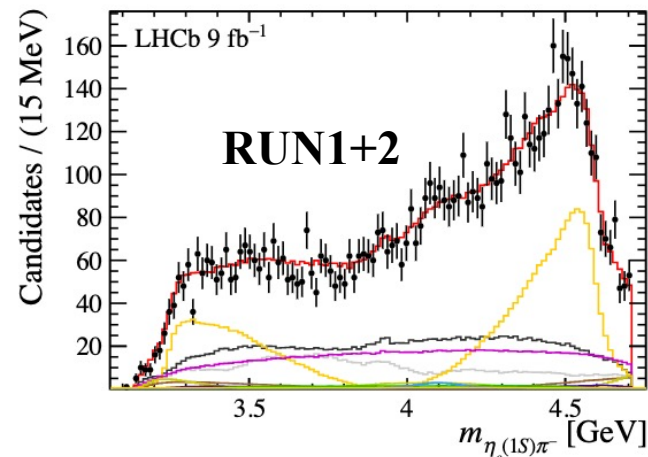
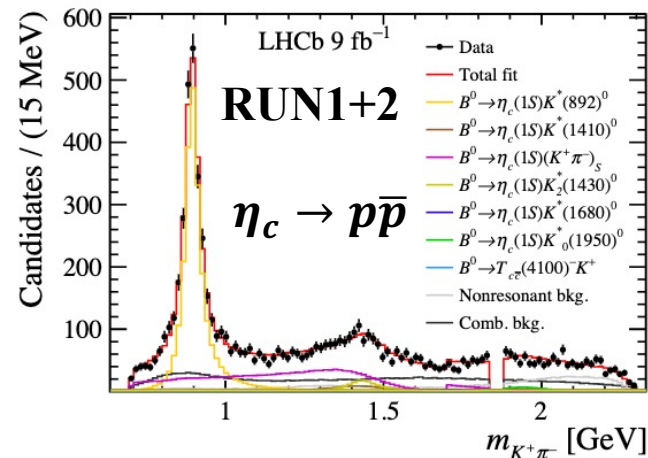
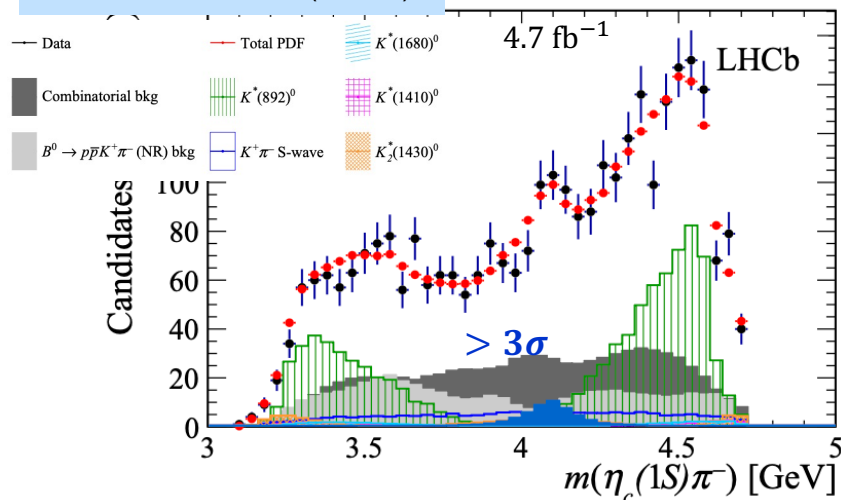
$m(\text{GeV}/c^2)$	$\Gamma(\text{GeV})$
$4.452 \pm 0.016_{-0.033}^{+0.023}$	$0.174 \pm 0.019_{-0.020}^{+0.075}$

- $J^P = 1^+$  is determined unambiguously
- consistent with previous measurements

An evidence of a charged  $T_{c\bar{c}}(4100)$  was reported previously with 2011, 2012 and 2016 data



EPJC78, 1019 (2018)

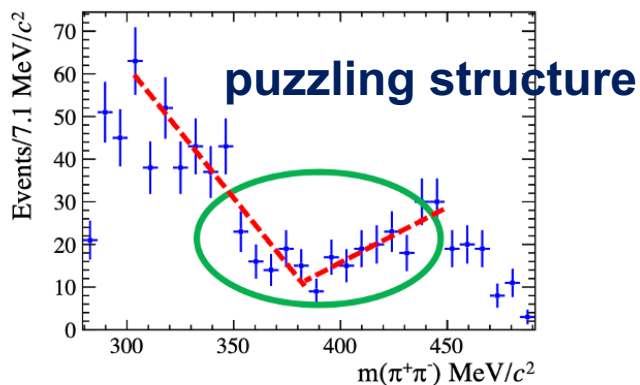
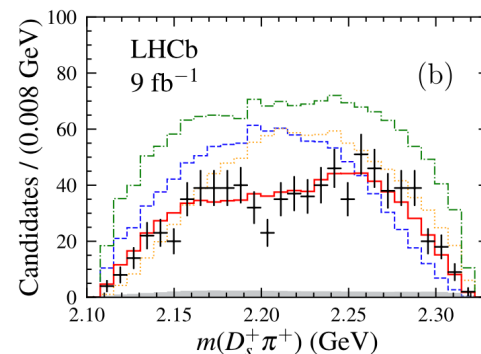
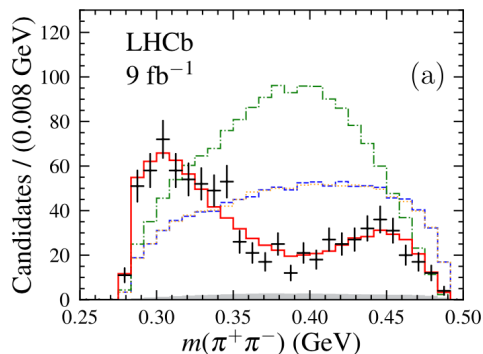
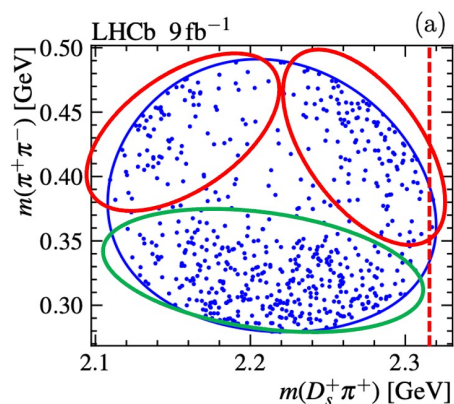


While a better description of the data is achieved when including  $T_{c\bar{c}}(4100)$ , the contribution is not significant

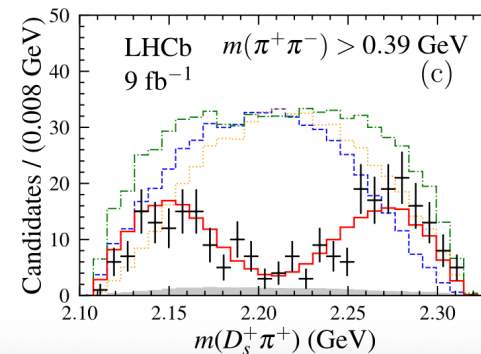
## Joint amplitude analysis of the three channels

Sci. Bull. 70, 1432 (2025)

$$B^+ \rightarrow \bar{D}^0 D_{s1}(2460)^+, B^0 \rightarrow D^{(*)-} D_{s1}(2460)^+ (D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-)$$



---  $T_{c\bar{s}}^{++}$   
 ---  $T_{c\bar{s}}^0$   
 - - -  $f_0(500)$   
 ■ Background  
 — Total fit  
 + Data



- $T_{c\bar{s}}^{0/++}$  is observed with significance larger than  $10\sigma$
- $J^P$  favours  $0^+$

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$474 \pm 30 \pm 18$	$224 \pm 23 \pm 16$	$248^{+40}_{-54} \pm 39$
$T_{c\bar{s}}^{++/0}$ ( $K$ -matrix)	$2327 \pm 13 \pm 13$	$96 \pm 16 \pm 23$	$156^{+27}_{-38} \pm 25$

## Joint amplitude analysis of the three channels

Sci. Bull. 70, 1432 (2025)

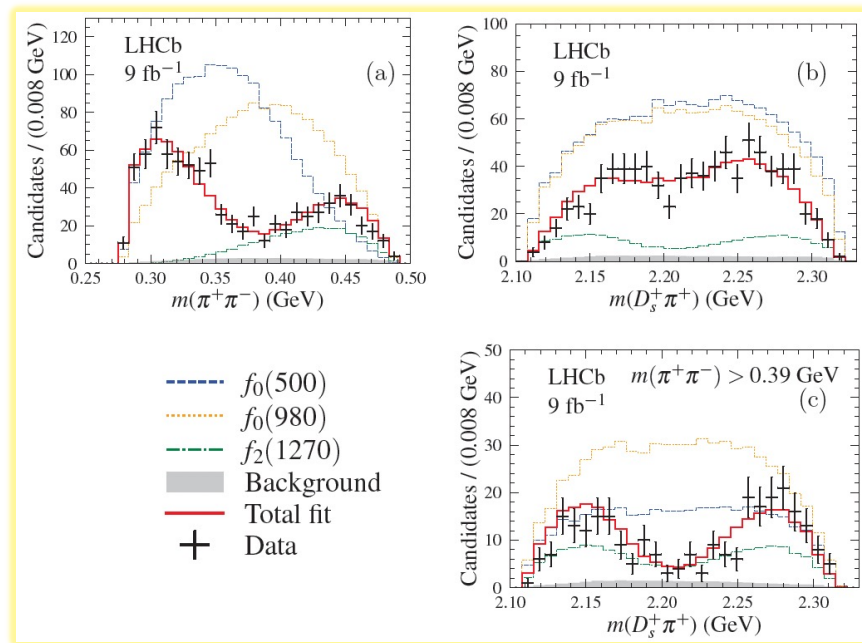
$$B^+ \rightarrow \bar{D}^0 D_{s1}(2460)^+, B^0 \rightarrow D^{(*)-} D_{s1}(2460)^+ (D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-)$$

An alternative model:  $f_0(500) + f_0(980) + f_2(1270)$

Not a favorite model:

- Very large interference between  $f_0(500)$  and  $f_0(980)$  to present the double-peak lineshape in  $m(\pi\pi)$ .
- Large contribution from the tail of the  $f_2(1270)$  and  $f_0(980)$
- The mass and width of  $f_0(500)$  are different from other measurements

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$





# Summary

- An exciting period of finding new hadrons, among which most of them are candidates of exotic hadrons
- **Exotic heavy hadrons:**
  - Unique feature of exotic hadron candidates
  - Thorough studies on the properties of the  $T_{c\bar{c}}(4020)$ : spin-parity, pole position and relative branching fractions
  - advances in studying  $T_{c\bar{c}}(4430)$  in a new channel and in scenario of hadronic molecule or triangle diagram
  - $T_{c\bar{s}}^{0/++}$  observed  $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$
  - ...
- More results based on higher statistics data can be expected regarding to the ongoing **3xL upgraded BEPCII-U** and **LHC RUN3**.



Thank you!

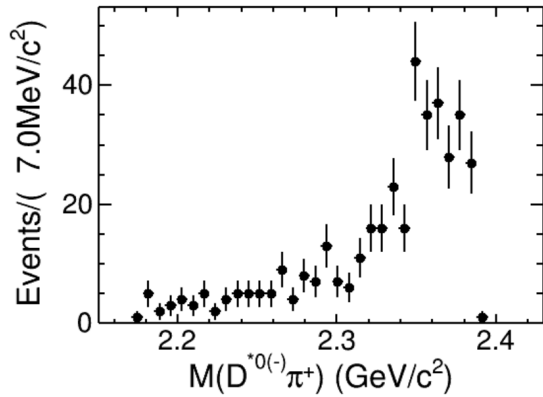
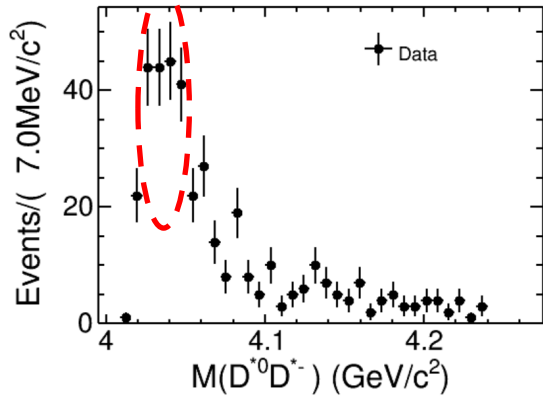
谢谢!



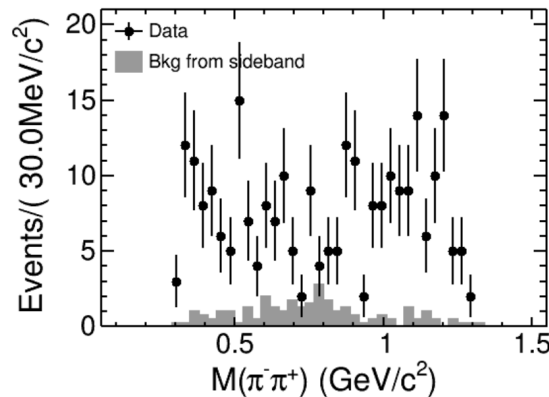
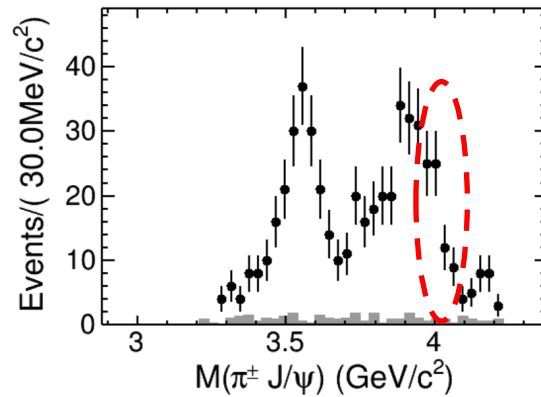
# Backup

# Samples Summary ( $\sqrt{s} = 4.395 \text{ GeV}$ )

$D^{*0}D^{*-}\pi^+$



$\pi^+\pi^-J/\psi$



$\pi^+\pi^-h_c$

