University of Chinese Academy of Sciences

Multi-channel joint analysis of the exotic charmonium-like state $T_{c\bar{c}}(4020)$

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(on behalf of the BESIII collaboration)

arXiv: 2603.05564

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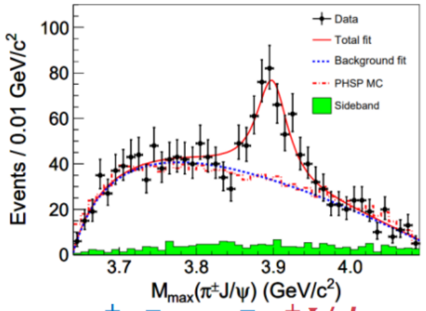
Motivation

- The charmoniumlike iso-vector resonances $T_{c\bar{c}1}(3900/3885)^{\pm(0)}, T_{c\bar{c}}(4020/4025)^{\pm(0)}$ are observed at BESIII.

$Z_c(3900)^+$

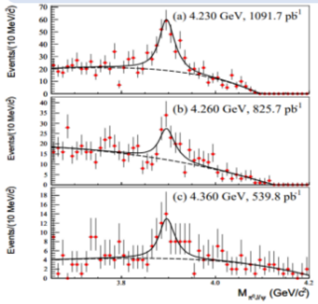
PRL 110, 252001 (2013)



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

$Z_c(3900)^0$

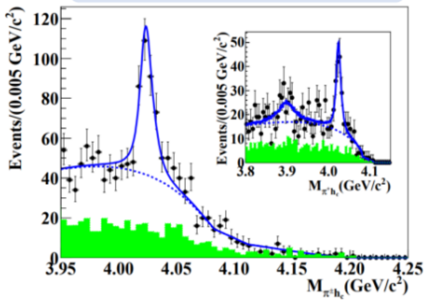
PRL 115, 112003 (2015)



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

$Z_c(4020)^+$

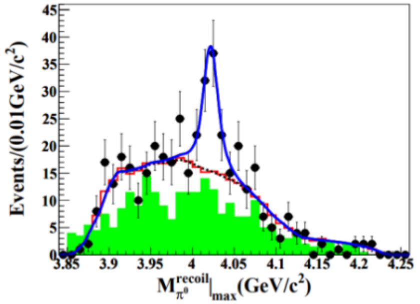
PRL 111, 242001 (2013)



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

$Z_c(4020)^0$

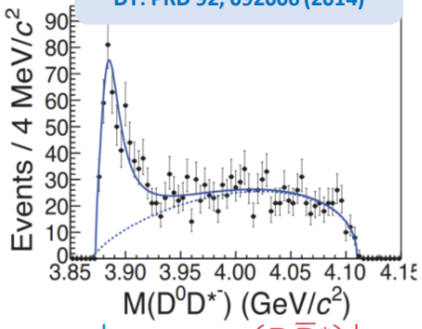
PRL 113, 212002 (2014)



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

$Z_c(3885)^+$

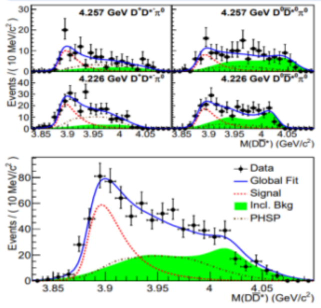
ST: PRL 112, 022001 (2014)
DT: PRD 92, 092006 (2014)



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

$Z_c(3885)^0$

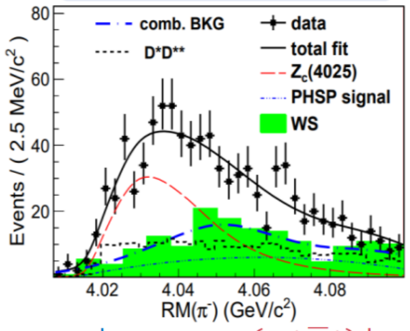
PRL 112, 022001 (2014)



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

$Z_c(4025)^+$

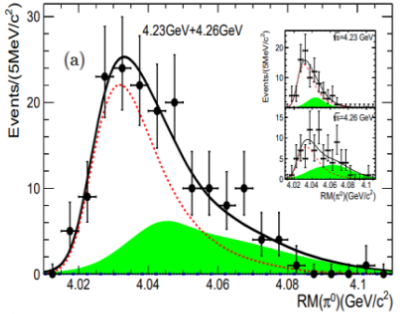
PRL 112, 132001 (2014)



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

$Z_c(4025)^0$

PRL 115, 182002 (2015)

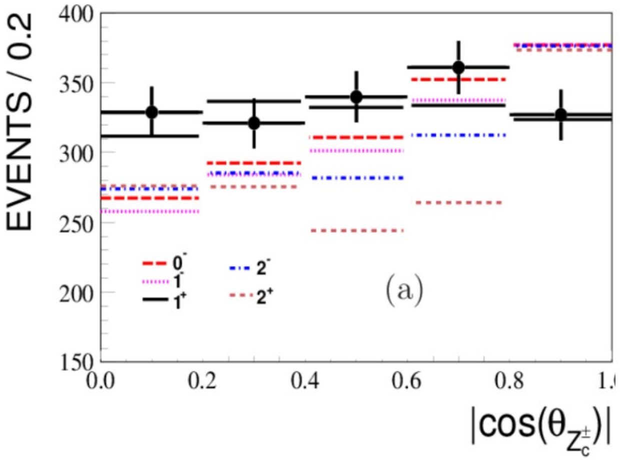


$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

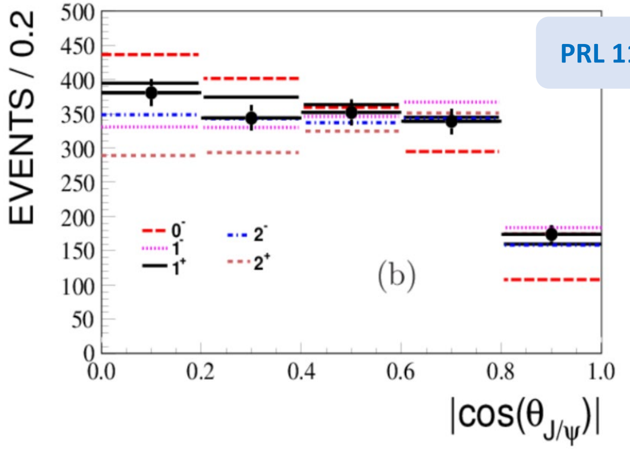
- Many theoretical explanations have been proposed.
- More experimental information is needed.

Motivation

- The spin and parity of $T_{c\bar{c}1}(3900)^{\pm}$ are determined as 1^{+} with significance >7.5σ at BESIII.



θ_{Z_c} : Polar angle of $T_{c\bar{c}1}(3900)^{\pm}$



PRL 119, 072001 (2017)

$\theta_{J/\psi}$: Helicity angle of J/ψ

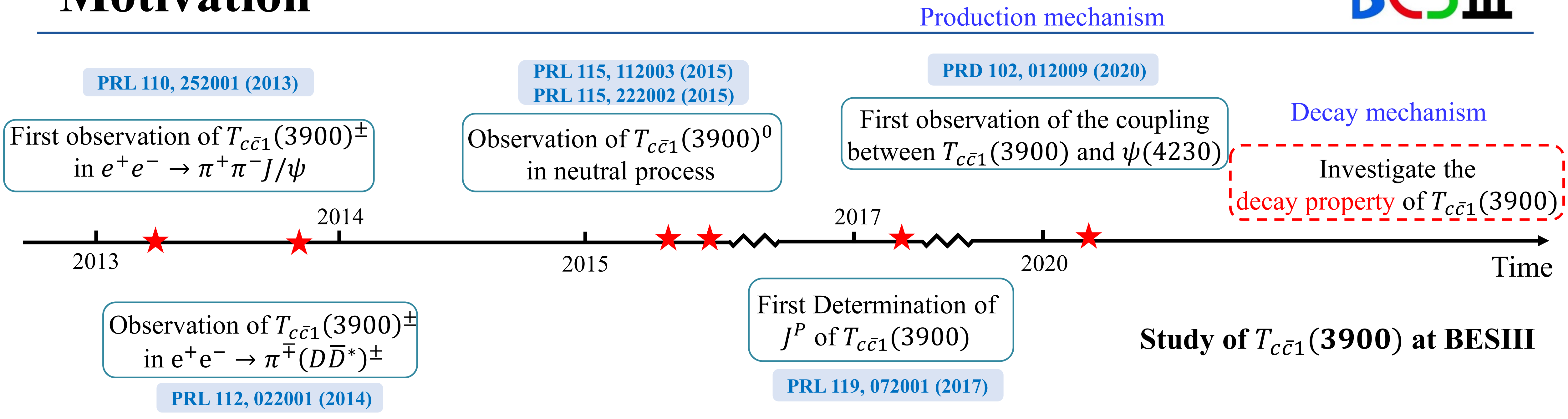
What is the J^P quantum number of $T_{c\bar{c}}(4020/4025)$?

$T_{c\bar{c}}(4020)$ $\quad I^G(J^{PC}) = 1^+(?^{?-})$

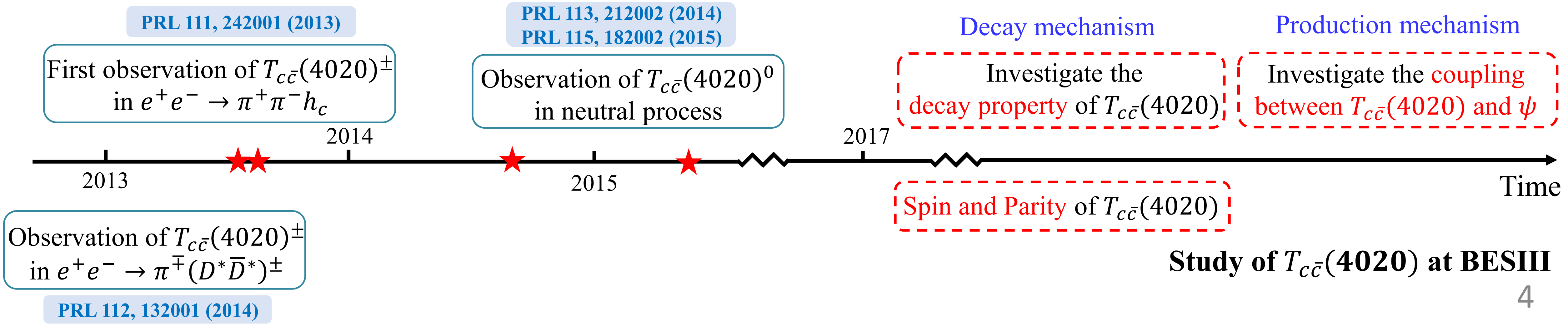
From PDG

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

Motivation



Production mechanism
PRL 110, 252001 (2013)
First observation of $T_{c\bar{c}1}(3900)^{\pm}$ in $e^+e^- \to \pi^+\pi^- J/\psi$
PRL 115, 112003 (2015)
PRL 115, 222002 (2015)
Observation of $T_{c\bar{c}1}(3900)^0$ in neutral process
PRD 102, 012009 (2020)
First observation of the coupling between $T_{c\bar{c}1}(3900)$ and $\psi(4230)$
Decay mechanism
Investigate the decay property of $T_{c\bar{c}1}(3900)$
2013
2014
2015
2017
2020
Time
Observation of $T_{c\bar{c}1}(3900)^{\pm}$ in $e^+e^- \to \pi^{\mp}(D\bar{D}^*)^{\pm}$
PRL 112, 022001 (2014)
First Determination of J^P of $T_{c\bar{c}1}(3900)$
PRL 119, 072001 (2017)
Study of $T_{c\bar{c}1}(3900)$ at BESIII



PRL 111, 242001 (2013)
First observation of $T_{c\bar{c}}(4020)^{\pm}$ in $e^+e^- \to \pi^+\pi^- h_c$
PRL 113, 212002 (2014)
PRL 115, 182002 (2015)
Observation of $T_{c\bar{c}}(4020)^0$ in neutral process
Decay mechanism
Investigate the decay property of $T_{c\bar{c}}(4020)$
Production mechanism
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2013
2014
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2017
Time
Spin and Parity of $T_{c\bar{c}}(4020)$
Observation of $T_{c\bar{c}}(4020)^{\pm}$ in $e^+e^- \to \pi^{\mp}(D^*\bar{D}^*)^{\pm}$
PRL 112, 132001 (2014)
Study of $T_{c\bar{c}}(4020)$ at BESIII

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

Decay mechanism

Investigate the
decay property of $T_{c\bar{c}}(4020)$

Spin and Parity of $T_{c\bar{c}}(4020)$

Data Samples

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

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.

  $D^{*0}D^{*-}\pi^+ \to [D^0\pi^0(\gamma)][\bar{D}^0\pi^-]\pi^+$

✓ **The charge conjugated channels are implied.**

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

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

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

  $h_c \to \gamma\eta_c, \eta_c \to$ 16 channels

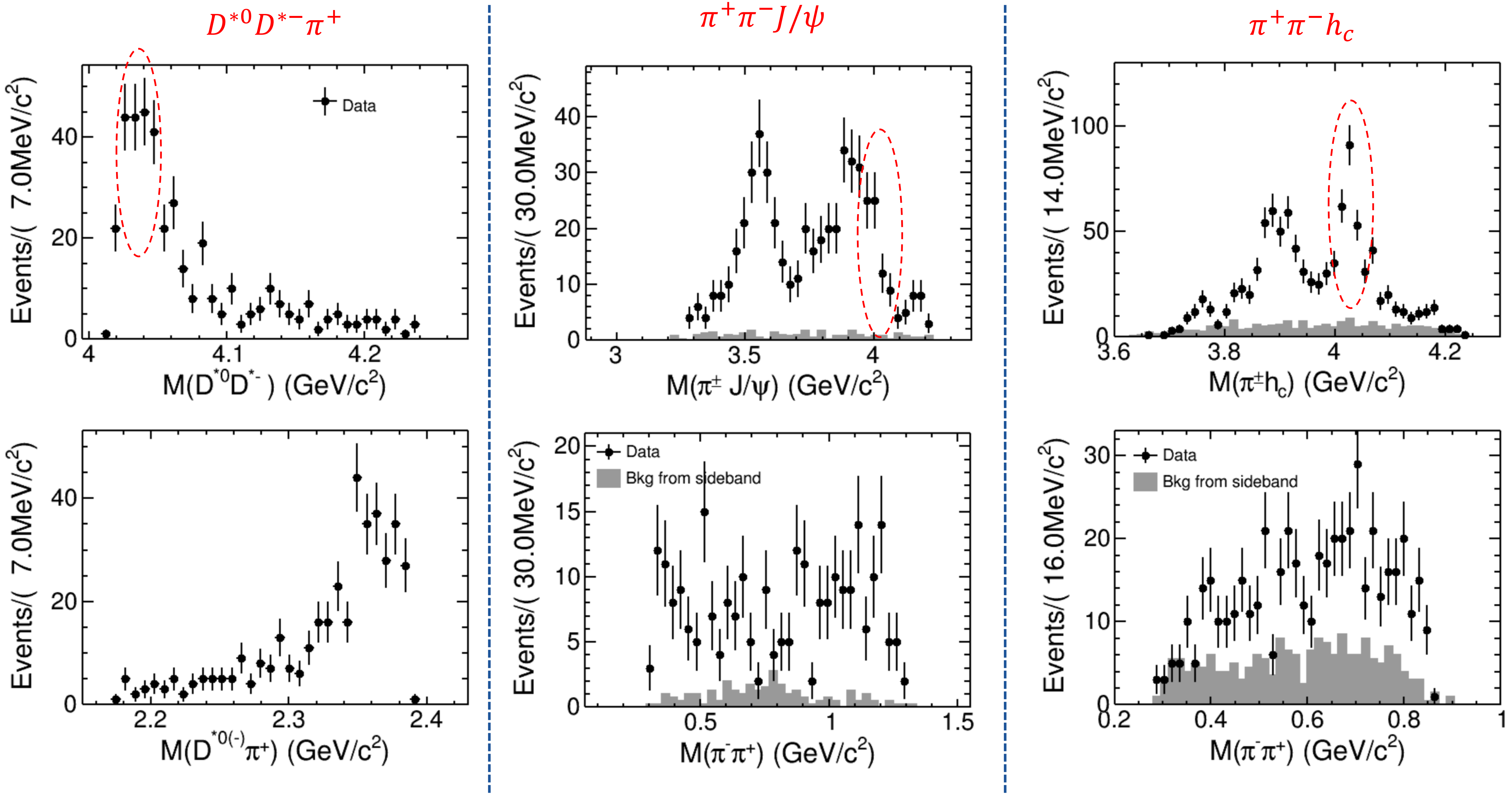
  $\eta_c \to p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-p\bar{p}$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^\pm\pi\mp$, $K_S^0K^\pm\pi\mp\pi^+\pi^-$, $K_S^0K^\pm\pi\mp$, $K_S^0K^\pm\pi\mp\pi^+\pi^-$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $2(\pi^+\pi^-)\eta$,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

The event selection criteria are consistent with published results.

- Keep the balance of **integrated luminosity** and **3-body cross sections** of $e^+e^- \to D^{*0}D^{*-}\pi^+, \pi^+\pi^-J/\psi, \ \pi^+\pi^-h_c$.

  Two datasets: $\sqrt{s} = 4.395$ GeV, $L_{\text{int}} = 508.18 \text{ pb}^{-1}$; $\sqrt{s} = 4.416$ GeV, $L_{\text{int}} = 1090.70 \text{ pb}^{-1}$.

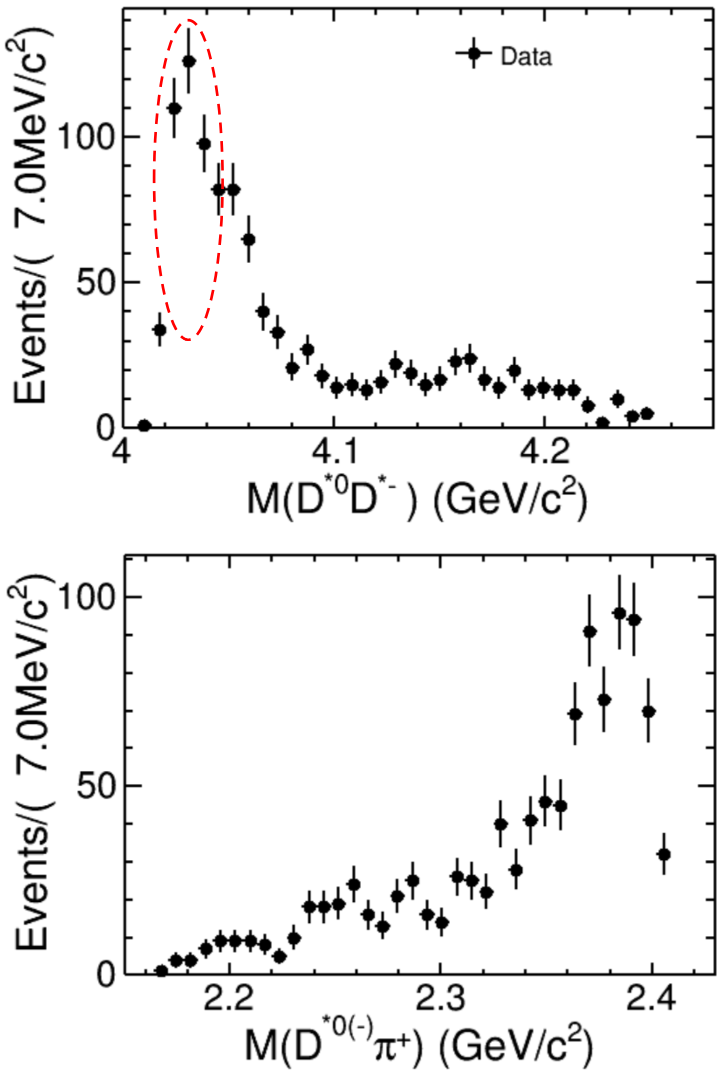
Samples Summary ($\sqrt{s} = 4.395$ GeV)



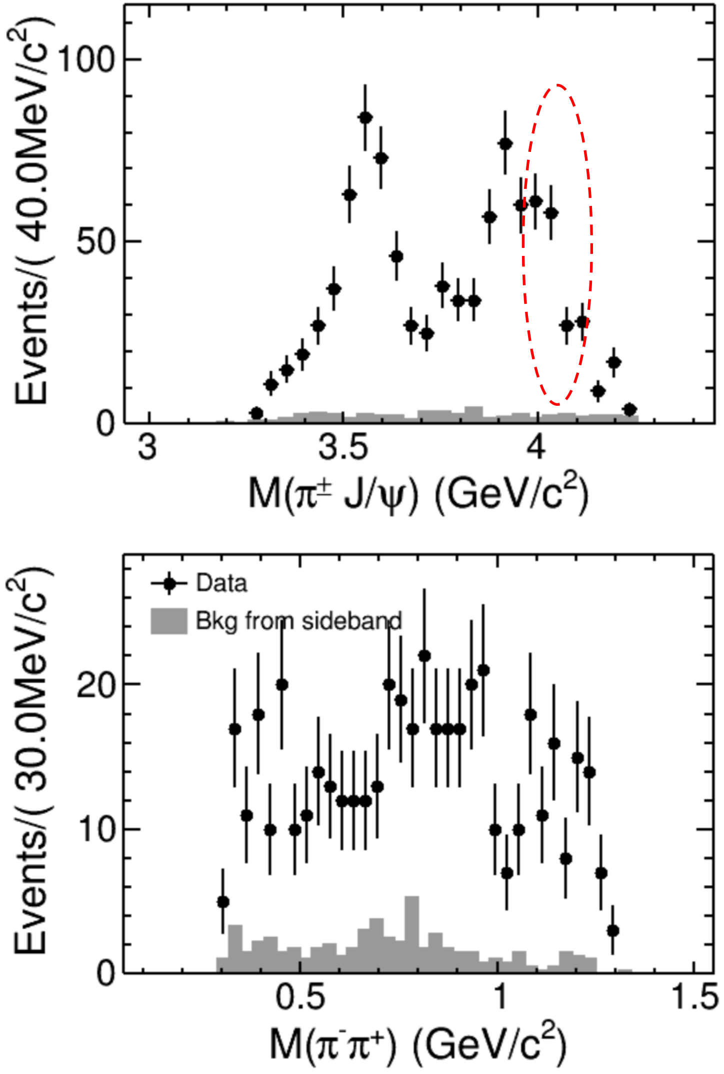
Samples Summary ($\sqrt{s} = 4.416$ GeV)

BESIII

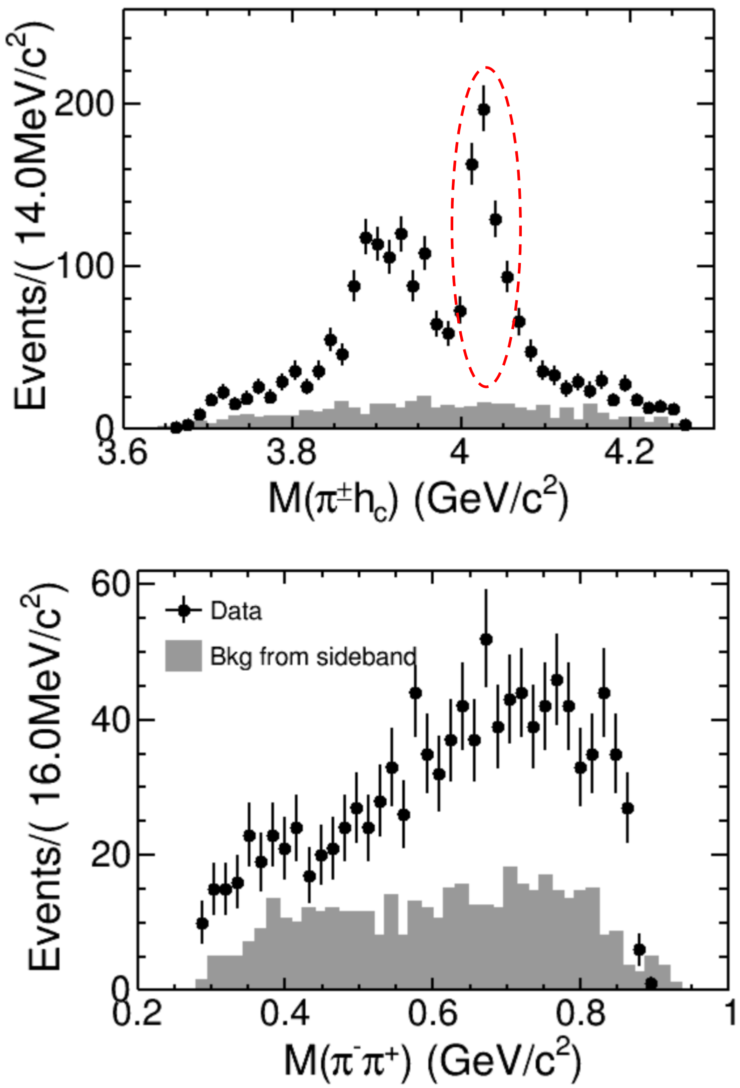
$D^{*0}D^{*-}\pi^{+}$



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



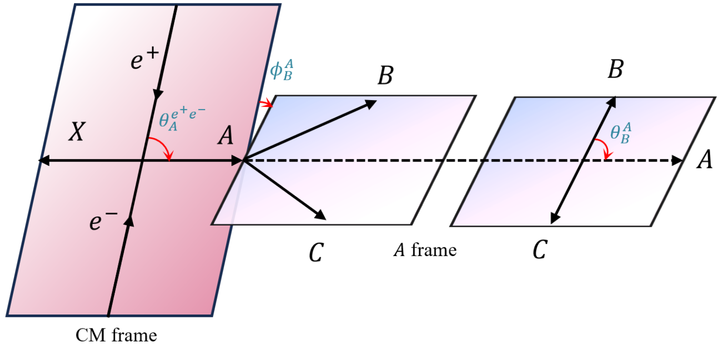
$\pi^{+}\pi^{-}h_{c}$



Helicity Amplitude

- Full procedure uses helicity amplitude formalism[1] based on TF-PWA package.

For decay: $A[\,(spin)J, (parity)\eta_J\,] \rightarrow B\,[s_b, \eta_b] + C\,[s_c, \eta_c]$



The decay amplitudes are given by: $A^J_{\lambda_B,\lambda_C}(\theta,\phi;M) \propto D^{J*}_{M,\lambda_B-\lambda_C}(\phi,\theta,0)H^J_{\lambda_B,\lambda_C}$

- λ_B, λ_C: Helicity of the daughter particle B and C.
- θ, ϕ: Corresponding helicity angles.
- M: Z-projection of spin-J.
- D: Wigner-D function. $[D^J_{a,b}(\phi,\theta,0) = e^{-ia\phi}\, d^J_{a,b}(\theta)]$
- H: Helicity-coupling amplitude.

In the LS-coupling scheme, we use the Chung's formula [*]:

$$H^J_{\lambda_B,\lambda_C} = \sum_{LS} g_{LS}\left(\frac{2L+1}{2J+1}\right)^{\frac{1}{2}} \langle L0\, S\delta \,|\, J\delta\rangle\langle s_b\lambda_B\ s_c -\lambda_C\,|S\delta\rangle r^L B'_L(r,r_0,d)$$

- g_{LS}: Coupling constants (complex), free parameters, determined by fitting.

[1] Phys. Rev. D 78, 074027 (2008)

Propagator

- Resonance $f_0(1370)/f_2(1270)$ is parametrized by relativistic Breit-Wigner function[1] .
- Resonance σ for E791 type[2]:

$$R(m) = \frac{1}{m^2 - m_0^2 + im\Gamma_X(m)}, \Gamma_X(m) = \sqrt{1 - \frac{4m_\pi^2}{m^2}}\Gamma,$$

- $f_0(980)$ is parametrized by the Flatte-formula[3]:

$$R(m) = \frac{1}{m^2 - m_0^2 + i[g_1\rho_{\pi\pi}(m) + g_2\rho_{K\bar{K}}(m)]}$$

$\rho(s) = \frac{2k}{\sqrt{s}}$, the k is the center of mass momentum of the π or K in the resonance rest frame. The g_1 and g_2 are coupling strength, which fixed to the BESII results [3]. $(g_2/g_1 = 4.45)$

- If assuming $T_{c\bar{c}1}(3900)$ is dominated by the decay to $\pi J/\psi$ and $\bar{D}D^*$, it also can be parametrized by the Flatte-formula:

$$R(m) = \frac{1}{m^2 - m_0^2 + i[g_1'\rho_{\pi J/\psi}(m) + g_2'\rho_{D^*\bar{D}}(m)]}$$

$\rho(s) = \frac{2k}{\sqrt{s}}$, the k is the center of mass momentum of the π or D in the $T_{c\bar{c}1}$ rest frame, and g_1' and g_2' are coupling strength, which fixed to the BESIII results [4]. $(g_2'/g_1' = 27.1)$

- For non-resonance (NR): $\mathrm{BW}(m) = 1$

[1] Phys. Lett. B 607, 243 (2005)
[2] Phys. Rev. Lett. 86, 770 (2001)
[3] PLB 598, 149 (2004)
[4] PRL 119, 072001 (2017)

Propagator

- For $T_{c\bar{c}}(4020)^-$, to take into consideration of multi-channel, its line-shape with Breit-Wigner is defined as[1]:

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

$\Gamma_{D^{*0}D^{*-}}(m), \Gamma_{J/\psi\pi}(m)$, $\Gamma_{h_c\pi}(m)$ and $\Gamma_X(m)$:
the $T_{c\bar{c}}(4020)$ partial decay width for $D^{*0}D^{*-}, J/\psi\pi$, $h_c\pi$ and missing decays, respectively.

- They are calculated with the standard formula for two-body decays :

$$\Gamma(m) = \frac{1}{8\pi} \overline{\sum_{\lambda_B,\lambda_C}} \left|H^J_{\lambda_B,\lambda_C}\right|^2 \frac{|\mathbf{p}|}{m^2}$$

Helicity amplitude: $H^J_{\lambda_B,\lambda_C} = H(g_{LS})$

✓ $|\mathbf{p}|$: the momentum magnitude of final state.
i$|\mathbf{p}|$ will be used for below threshold events.

✓ $\overline{\sum_{\lambda_B,\lambda_C}}$: the average is taken over spin−J.

- For missing decay, the sum of helicity amplitude, H_X, is assumed as a constant, determined in the fit.
Momentum dependence: $\pi J/\psi$ mode.

- To further constrain the coupling parameters used in calculation of $\Gamma(m)$. Extended likelihood method[*] is used.

[1] Phys. Rev. D 94, 114019 (2016).
[*] In Appendix

Fit Method

BESIII

- Four-vector momentum as input : $x_i = (p_1,\ p_2,\ p_3)$
- The signal probability density function can be written as:

$$p^{(i)} = \epsilon(x_i)|A(x_i)|^2,$$

$$|A|^2 = \begin{cases} \sum_{\lambda_{\gamma^*},\lambda_{\pi^0(\gamma)}} \left|A_D(\lambda_{\gamma^*},\lambda_{\pi^0(\gamma)})\right|^2, \\ \sum_{\lambda_{\gamma^*},\lambda_{l^+},\lambda_{l^-}} |A_J(\lambda_{\gamma^*},\lambda_{l^+},\lambda_{l^-})|^2, \\ \sum_{\lambda_{\gamma^*},\lambda_{\gamma}} |A_H(\lambda_{\gamma^*},\lambda_{\gamma})|^2. \end{cases}$$

- The extended negative log likelihood (NLL) is formed using the background subtraction method:

$$-\ln\mathcal{L}_n = -\alpha\left(\sum_{i=1}^{N_{\rm data}} \ln p_{\rm data}^{(i)} - \mathcal{W}_{\rm bkg}\sum_{i=1}^{N_{\rm bkg}} \ln p_{\rm bkg}^{(i)} - \mu\right)$$

normalization factor: $\alpha = \dfrac{N_{\rm data} - N_{\rm bkg}w_{\rm bkg}}{N_{\rm data} + N_{\rm bkg}w_{\rm bkg}^2}$

- The μ will converge to the signal events in each channel, where $\mu = \frac{1}{N_{MC}}\sum_{i=1}^{N_{MC}}\left(\frac{d\sigma}{d\Phi}\right)_i \cdot L_{int}\cdot\epsilon\cdot B\cdot V_{PHSP}(\times 2)$

✓ -ln L is minimized by **MINUIT.**

- Fitting data to obtain the complex parameters c_i and g_{LS}.

$$H^J_{\lambda_B,\lambda_C} = \sum_{LS} g_{LS}\left(\frac{2L+1}{2J+1}\right)^{\frac{1}{2}}\langle L0\ S\delta\,|\,J\delta\rangle\langle s_b\lambda_B\ s_c -\lambda_C\,|S\delta\rangle r^L B_L'(r,r_0,d)$$

- The fit fraction (FF) of each intermediate resonance is calculated by:

$$\mathrm{FF}_i = \frac{\int|A_i|^2 d\Phi}{\int|\sum_k A_k|^2 d\Phi} \propto \frac{\sum_{j\in\mathrm{PHSP}}|A_i(x_j)|^2}{\sum_{j\in\mathrm{PHSP}}|\sum_k A_k(x_j)|^2},\ \mathrm{FF}_{i,j} = \frac{\int|A_i+A_j|^2 d\Phi'}{\int|\sum_k A_k|^2 d\Phi'} - \mathrm{FF}_i - \mathrm{FF}_j$$

Baseline Solution

- Test baseline solution based on the significance.

$$\begin{cases} D^{*0}D^{*-}\pi^{+} = T_{c\bar{c}}(4020)^{-}\pi^{+}, D^{*}\bar{D}_1(2420),\ NRD^{*0} \\ \pi^{+}\pi^{-}J/\psi = T_{c\bar{c}}(4020)^{\mp}\pi^{\pm}, T_{c\bar{c}1}(3900)^{\mp}\pi^{\pm},\ \underline{\sigma J/\psi, f_0(980)J/\psi, f_0(1370)J/\psi}, f_2(1270)J/\psi \\ \pi^{+}\pi^{-}h_c = T_{c\bar{c}}(4020)^{\mp}\pi^{\pm}, \underline{\sigma h_c, f_0(980)h_c} \end{cases}$$

$(\pi^{+}\pi^{-})_{S\,wave} = \sigma + f_0(980) + f_0(1370)$

$(\pi^{+}\pi^{-})_{S\,wave} = \sigma + f_0(980)$

- Simultaneously fit on $\sqrt{s} = 4.395, 4.416$ GeV.
- The shared parameters between two energy points are decaying g_{LS}.

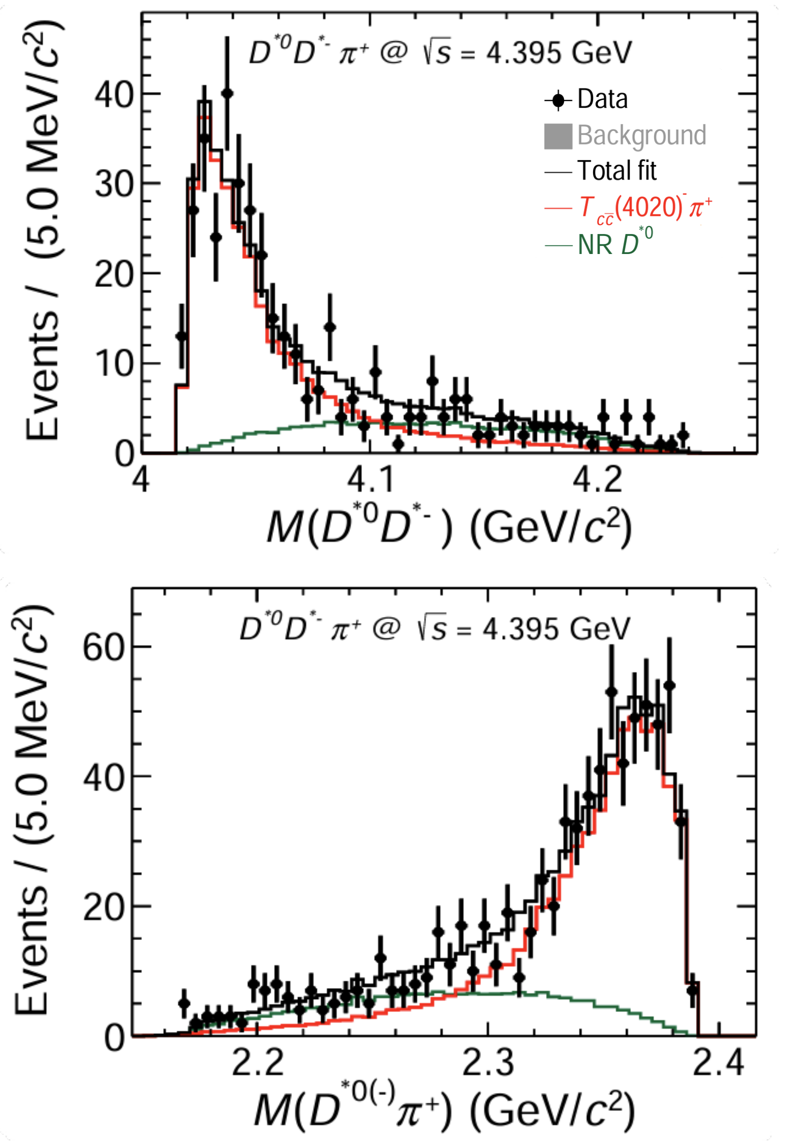
$$A = A_{e^{+}e^{-}\to T_{c\bar{c}}^{-}\pi^{+}} \cdot R(T_{c\bar{c}}^{-}) \cdot A_{T_{c\bar{c}}^{-}\to X}$$

- The insignificant processes will be considered in studying of the systematic uncertainty.

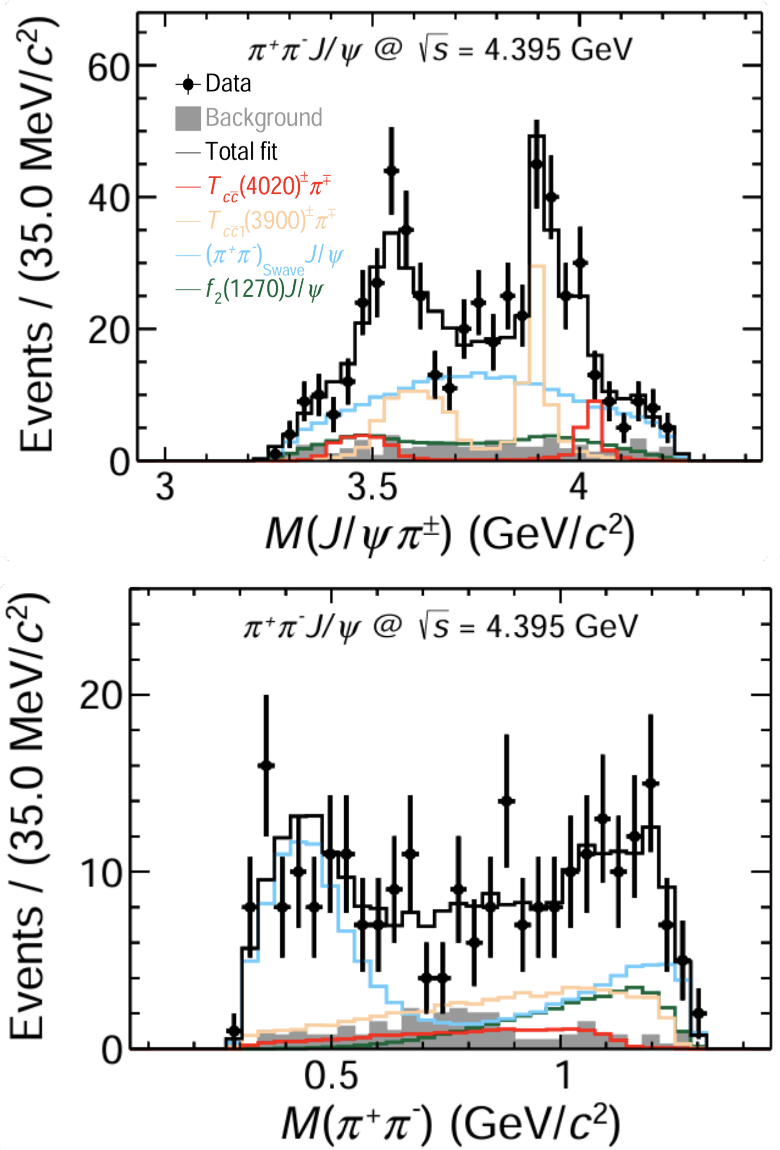
Fit Result at $\sqrt{s} = 4.395$ GeV

BESIII

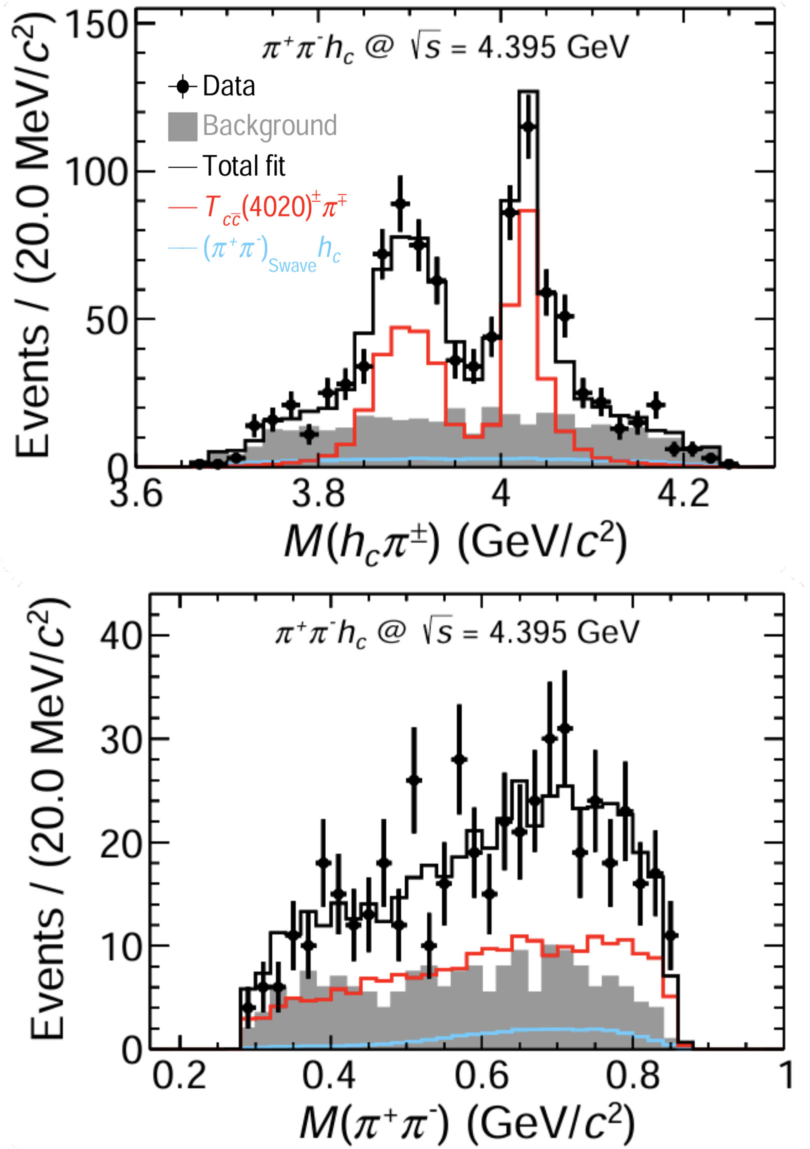
$D^{*0}D^{*-}\pi^+$



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

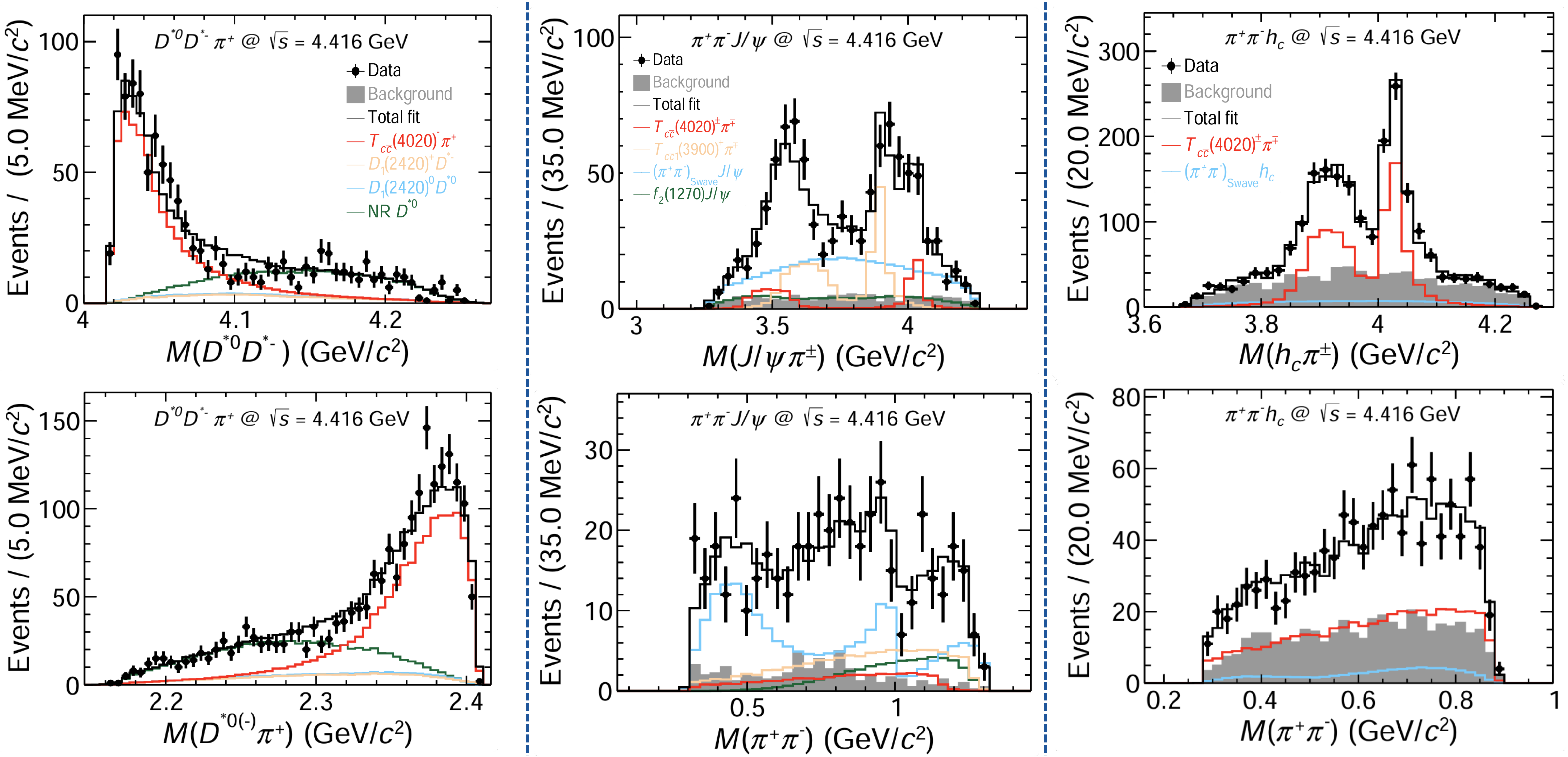


$\pi^+\pi^-h_c$



Fit Result at $\sqrt{s} = 4.416$ GeV

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



Fit Result

- Statistic uncertainty only

$$\sigma^B_{e^+e^-\to T_{c\bar{c}}(4020)^-\pi^+ + c.c.} \cdot Br[T_{c\bar{c}}(4020)^\pm \to D^{*0}D^{*-}(c.c)] = FF(T^-_{c\bar{c}}\pi^+) \text{ in } D^{*0}D^{*-}\pi^+ \cdot \sigma^B_{e^+e^-\to D^{*0}D^{*-}\pi^+ + c.c.}$$

(From PRL 130, 121901)

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

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

$$Br[T_{c\bar{c}}(4020)^\pm \to D^{*0}D^{*-}(c.c.)]: Br[T_{c\bar{c}}(4020)^\pm \to \pi^\pm J/\psi]: Br[T_{c\bar{c}}(4020)^\pm \to \pi^\pm h_c] = 1.000(48) : 0.004(1) : 0.090(8)$$

Pole solution

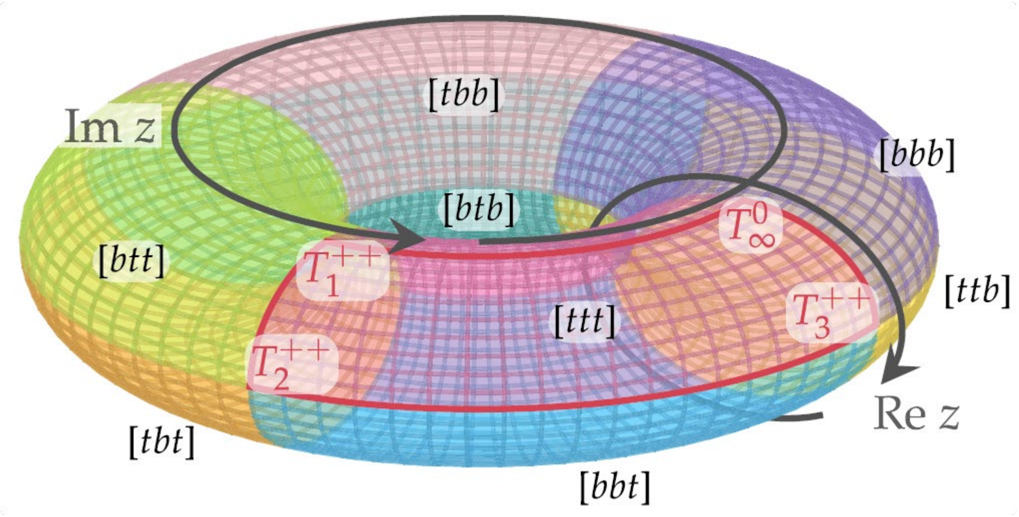
- Eight poles on Riemann-sheets:

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

$$\Gamma(m) = \frac{1}{8\pi}\overline{\sum_{\lambda_B,\lambda_C}}\left|H^J_{\lambda_B,\lambda_C}\right|^2\frac{|\mathbf{p}|}{m^2}$$

$$\text{Imag.}(p) = (J/\psi, h_c, D^*)$$

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



PRL 129, 192001 (2022)

J^P Hypothesis Test

- Conservation of spin and parity: $\begin{cases} \gamma^* \to \pi T_{c\bar{c}}(1^- \to 0^- J^P) : J^P \neq 0^+ \\ T_{c\bar{c}} \to \pi h_c \ (J^P \to 0^- 1^+) : J^P \neq 0^- \end{cases}$
- Only : $J^P = 1^+, 1^-, 2^+, 2^-$.

Two hypotheses:

- H_0 stands the $T_{c\bar{c}}(4020)^-$ component in data only includes $J^P = 1^- / 2^+ / 2^-$.
- H_1 stands the $T_{c\bar{c}}(4020)^-$component in data includes $J^P = 1^- / 2^+ / 2^-$ but adding a more component with $J^P = 1^+$.

Using two hypotheses to fit data.

Checking the significance for $J^P = 1^+$ over the $J^P = 1^- / 2^+ / 2^-$.

Table 1. Significance to distinguish the $T_{c\bar{c}}(4020)^-$quantum number 1^+over other quantum numbers.

H_0	H_1	$\Delta(-2\ln\mathcal{L})$	Δ(ndof)	Statistical significance
only 1^-	1^- with additional 1^+	409.2	23	18.0σ
only 2^+	2^+ with additional 1^+	435.4	23	18.7σ
only 2^-	2^- with additional 1^+	329.4	23	15.8σ
only 1^+	1^+ with additional 1^-	27.8	21	1.5σ
only 1^+	1^+ with additional 2^+	30.2	23	1.5σ
only 1^+	1^+ with additional 2^-	56.4	25	3.6σ

Systematic Uncertainty

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Part 1. Uncertainties from input cross section

Part 1 is used in the cross section measurement for two body process.

Part 2. Uncertainties from PWA Fit

Table 1. The relative systematic uncertainties (%) of FFs in different $T_{c\bar{c}}(4020)^-$ decay channels.

Data set	4.395 GeV			4.416 GeV		
Decay mode	$D^{*0}D^{*-}$	π^-J/ψ	π^-h_c	$D^{*0}D^{*-}$	π^-J/ψ	π^-h_c
$\pi\pi$ S-wave	1.0	19.0	0.4	0.8	12.3	2.0
Background	0.7	8.0	6.6	0.4	6.8	6.3
Fit model	7.0	20.0	12.3	3.5	16.5	3.5
$T_{c\bar{c}1}(3900)$ propagator	0.1	13.4	2.5	0.9	12.0	3.7
Other BW parameters	1.2	29.9	12.3	1.9	28.0	11.8
Fit strategy	2.5	8.2	2.5	1.3	10.7	0.2
Total	7.6	44.3	19.0	4.4	38.9	14.4

Table 2. The absolute systematic uncertainties of the pole mass (m_{pole}, in MeV/c^2) and width (Γ_{pole}, in MeV) for the $T_{c\bar{c}}(4020)^-$ state.

	Pole 1		Pole 2		Pole 3		Pole 4	
Source	m_{pole}	Γ_{pole}	m_{pole}	Γ_{pole}	m_{pole}	Γ_{pole}	m_{pole}	Γ_{pole}
$\pi\pi$ S-wave	0.38	0.77	0.29	0.51	0.08	1.95	0.00	1.83
Background	0.05	0.17	0.06	0.21	0.10	0.08	0.09	0.05
Fit model	0.40	1.09	0.18	1.60	0.79	7.04	0.55	1.07
$T_{c\bar{c}}(3900)$ propagator	0.03	1.08	0.14	0.52	0.38	5.57	0.53	5.16
Other BW parameters	0.36	1.43	0.28	1.23	0.70	10.98	0.70	9.15
Fit strategy	1.07	1.33	0.86	0.80	0.09	9.07	0.14	8.49
Mass resolution	-	1.37	-	1.37	-	1.37	-	1.37
Total	1.26	2.95	0.98	2.68	1.13	17.00	1.05	13.74

J^P Hypothesis Test

- **Considering the systematic uncertainties from PWA Fit.**

Two hypotheses:

- H_0 stands the $T_{c\bar{c}}(4020)^-$ component in data only includes $J^P = 1^-/\ 2^+/\ 2^-$.
- H_1 stands the $T_{c\bar{c}}(4020)^-$ component in data includes $J^P = 1^-/\ 2^+/\ 2^-$ but adding a more component with $J^P = 1^+$.

Using two hypotheses to fit data.

Checking the significance for $J^P = 1^+$ over the $J^P = 1^-/\ 2^+/\ 2^-$.

Table 1. Confidence levels of H_1 hypothesis versus H_0 hypothesis for the $T_{c\bar{c}}(4020)^-$ spin-parity assignments.

Source	1^+over 1^-	1^+over 2^+	1^+over 2^-	1^-over 1^+	2^+over 1^+	2^-over 1^+
Default	18.0σ	18.7σ	15.8σ	1.5σ	1.5σ	3.6σ
$\pi^+\pi^-$ S-wave	18.7σ	19.2σ	18.3σ	0.5σ	0.0σ	3.9σ
Background	17.2σ	17.8σ	15.7σ	1.6σ	1.4σ	3.8σ
Fit model	17.2σ	18.5σ	14.1σ	3.1σ	0.5σ	3.9σ
$T_{c\bar{c}1}(3900)$ BW	17.8σ	18.8σ	15.4σ	1.9σ	2.0σ	3.2σ
Others BW parameters	17.5σ	18.7σ	15.4σ	1.1σ	1.6σ	3.7σ

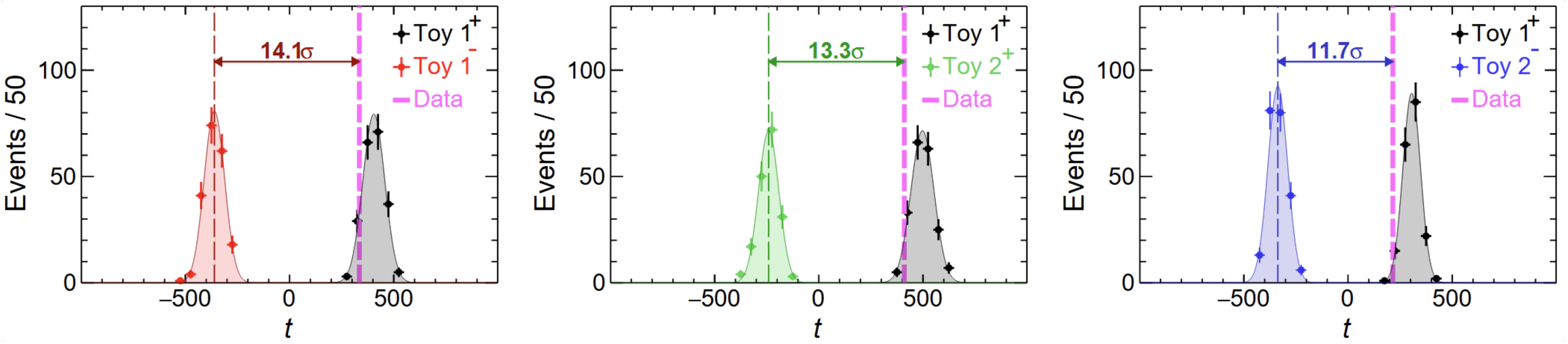
Perform Toy MC test when consider this.

Toy MC test

- Generate two Toy MC samples, repeating 500 times (Poisson sampling).
  a. MC is based on fit result with 1^+model.
  b. MC is based on fit result with 1^-model.

- Fit the same MC sample, repeating 1000 times.
  a. MC is fitted with 1^+model.
  b. MC is fitted with 1^-model.

$$t \equiv \Delta(-2\ln L) = -2\,[-\ln L^{1^+} - (-\ln L^{J^P})]$$



Summary

- Multi-channel joint analysis of the exotic charmonium-like state $T_{c\bar{c}}(4020)$ at $\sqrt{s} = 4.395$ and 4.416 GeV.
  - Determine spin-parity of $T_{c\bar{c}1}(4020)$, $J^P = 1^+$ with $> 11.7\sigma$
  - Relative decay BF of $T_{c\bar{c}1}(4020)^-$

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

    $Br[T_{c\bar{c}1}(4020)^- \to \pi^- h_c]/Br[T_{c\bar{c}1}(4020)^- \to D^{*0}D^{*-}] = (8.9 \pm 1.3 \pm 2.3) \times 10^{-2}$
  - Pole mass and width

Thanks for your attention!

Backup

Data Samples

Data samples	$\sqrt{s}$ (GeV)	Integrated luminosity (pb^{-1})
4400	4.395	508.18
4420	4.416	1090.70

For signal MC samples

3-body processes --- PHSP model --- Cross section lineshapes measured in previous works.

For background MC samples

Hadrons productions, bhabha productions, continuum process $e^+e^- \to \gamma\gamma, \mu\mu$ and $\tau\tau\ldots$

Determine Baseline Solution

- We first consider all possible processes into the fitting for each channel.

Round1		Round2		Round3		Round4	
(Physical)							
$Z_c(4020)^-\pi^+$	$(35.1\ \sigma)$	$Z_c(4020)^-\pi^+$		$Z_c(4020)^-\pi^+$		$Z_c(4020)^-\pi^+$	
$D^*D_1(2420)$	$(9.3\ \sigma)$	$D^*D_1(2420)$		$D^*D_1(2420)$		$D^*D_1(2420)$	
$Z_c(3900)^{\pm}_{J/\psi}\pi^{\mp}$	$(9.9\ \sigma)$	$Z_c(3900)^{\pm}_{J/\psi}\pi^{\mp}$		$Z_c(3900)^{\pm}_{J/\psi}\pi^{\mp}$		$Z_c(3900)^{\pm}_{J/\psi}\pi^{\mp}$	
$(\pi^+\pi^-)_{\text{S-wave}}J/\psi$	$(14.3\ \sigma)$	$(\pi^+\pi^-)_{\text{S-wave}}J/\psi$		$(\pi^+\pi^-)_{\text{S-wave}}J/\psi$		$(\pi^+\pi^-)_{\text{S-wave}}J/\psi$	
f_2J/ψ	$(4.5\ \sigma)$	f_2J/ψ		f_2J/ψ		f_2J/ψ	
~~$Z_c(3900)^{\pm}_{h_c}\pi^{\mp}$~~	~~$(2.4\ \sigma)$~~	$(\pi^+\pi^-)_{\text{S-wave}}h_c$		$(\pi^+\pi^-)_{\text{S-wave}}h_c$		$(\pi^+\pi^-)_{\text{S-wave}}h_c$	
$(\pi^+\pi^-)_{\text{S-wave}}h_c$	$(4.7\ \sigma)$	$NR2^-D^{*0}$		$NR2^-D^{*0}$		$NR2^-D^{*0}$	
				$NR0^-D^{*0}$		$NR0^-D^{*0}$	
						$NR1^-D^{*0}$	
(NR)							
$NR0^-D^{*0}$	(6.6σ)	$NR0^-D^{*0}$	(6.6σ)		-		
$NR1^-D^{*0}$	(6.5σ)	$NR1^-D^{*0}$	(6.5σ)	$NR1^-D^{*0}$	(5.6σ)		
$NR2^-D^{*0}$	(9.3σ)		-		-		
$NR2^+D^{*0}$	(4.5σ)	$NR2^+D^{*0}$	(4.5σ)	$NR2^+D^{*0}$	(3.6σ)	$NR2^+D^{*0}$	(1.5σ)

- The spin and parity of $Z_c(3900)$ and $Z_c(4020)$ are assigned at $J^P = 1^+$.
- The baseline solutions for other spin-parity $i.e.\ J^P = 1^-, 2^+, 2^-$ are also checked.
  - ➢ All of them can reach the same conclusion: data sets favor $1^+Z_c(4020)$.

$(\pi^+\pi^-)$ *Swave*

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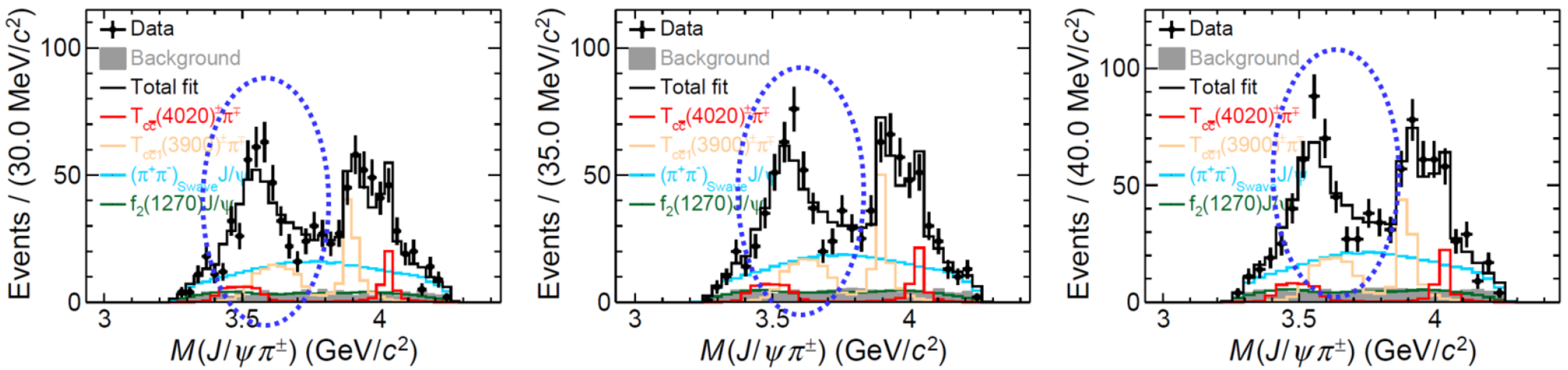
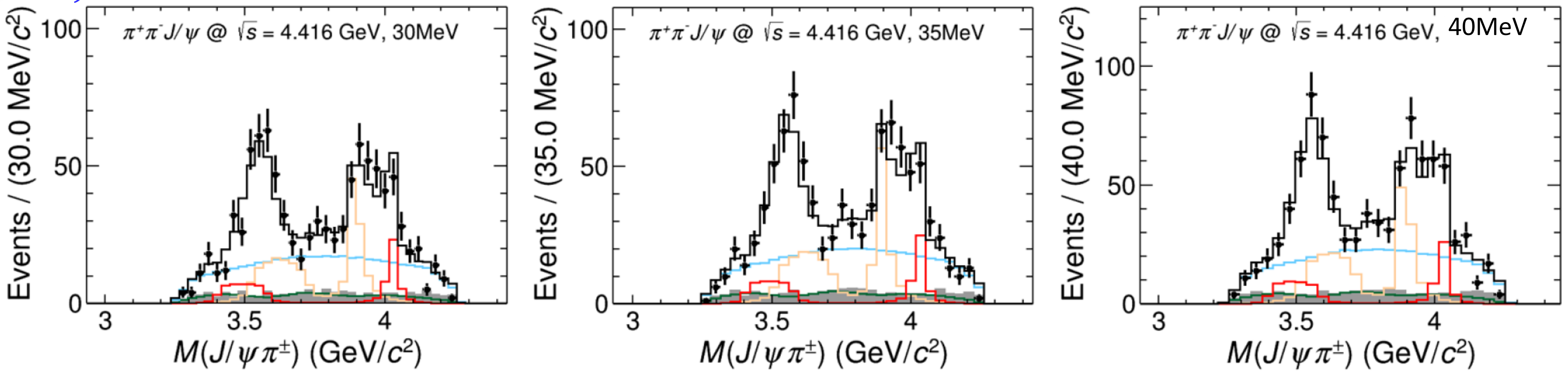
Nominal result

30MeV 35MeV 40MeV



$(\pi^+\pi^-)$ *Swave*



Integrated Partial Width

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

$$\Gamma(m) = \frac{1}{8\pi}\overline{\sum_{\lambda_B,\lambda_C}}\left|H^J_{\lambda_B,\lambda_C}\right|^2\frac{|\mathbf{p}|}{m^2}$$

$$\begin{aligned} I_i &= \int_\Omega |A_{e^+e^-\to Z_c^-\pi^+}|^2\cdot|BW|^2\cdot|A_{Z_c^-\to X_i}|^2 d\Omega \\ &= \int_{threshold_i}^{E_{cms}-m_{\pi^+}} |A_{e^+e^-\to Z_c^-\pi^+}|^2\cdot|BW(m)|^2\cdot|A_{Z_c^-\to X_i}|^2\cdot|q||p|dm \\ &= \int_{threshold_i}^{E_{cms}-m_{\pi^+}} |A_{e^+e^-\to Z_c^-\pi^+}|^2\cdot|BW(m)|^2\cdot C_0|\Gamma_i(m)|\cdot m^2\cdot|q|dm \end{aligned}$$

$$I_i = \int_{threshold_i}^{E_{cms}-m_{\pi^+}} |A_{e^+e^-\to Z_c^-\pi^+}|^2|BW(m)|^2C_0|\Gamma_i(m)|\cdot m^2\cdot|q|dm$$

$$\frac{I_1}{I_1+I_2+I_3+I_X} = 0.4097 \pm 0.2050$$

$$\frac{I_2}{I_1+I_2+I_3+I_X} = 0.0022 \pm 0.0011$$

$$\frac{I_3}{I_1+I_2+I_3+I_X} = 0.0433 \pm 0.0179$$

$$\frac{I_X}{I_1+I_2+I_3+I_X} = 0.5447 \pm 0.2164$$

$$I_1 : I_2 : I_3 = 1.000(500) : 0.005(4) : 0.106(68)$$

Momentum dependence

$$\Gamma_{X_i}(m) = \frac{1}{8\pi}\overline{\sum}_{\lambda_1,\lambda_2}\left|H^{T^-_{c\bar{c}}\to X_i}_{\lambda_1,\lambda_2}\right|^2 \frac{|\mathbf{p}|}{m^2},$$

TABLE I: Comparison of the different momentum assumptions on the missing decay.

Momentum dependence	Momentum $|\mathbf{p}|$(GeV/c)	Fitting ($\sum|H_x|^2$)	$|\mathbf{p}|\cdot(\sum|H_x|^2)$	$Br(X)$
$\pi^- J/\psi$	0.815	9.5 ± 3.7	7.7 ± 3.0	0.530 ± 0.222
$\pi^- h_c$	0.453	17.3 ± 6.7	7.8 ± 3.0	0.536 ± 0.224
$\pi^- \psi(3686)$	0.300	26.5 ± 10.4	8.0 ± 3.1	0.538 ± 0.226
$(D\bar{D}^*)^-$	0.552	14.2 ± 5.5	7.9 ± 3.1	0.528 ± 0.223
Non (set $|\mathbf{p}| = 1$)	1.000	7.6 ± 2.9	7.6 ± 2.9	0.542 ± 0.210