Zc(3900) (and X(3872)) on the phenomenological and lattice side

Based on: PhysRevD.110.114029, 2502.05789

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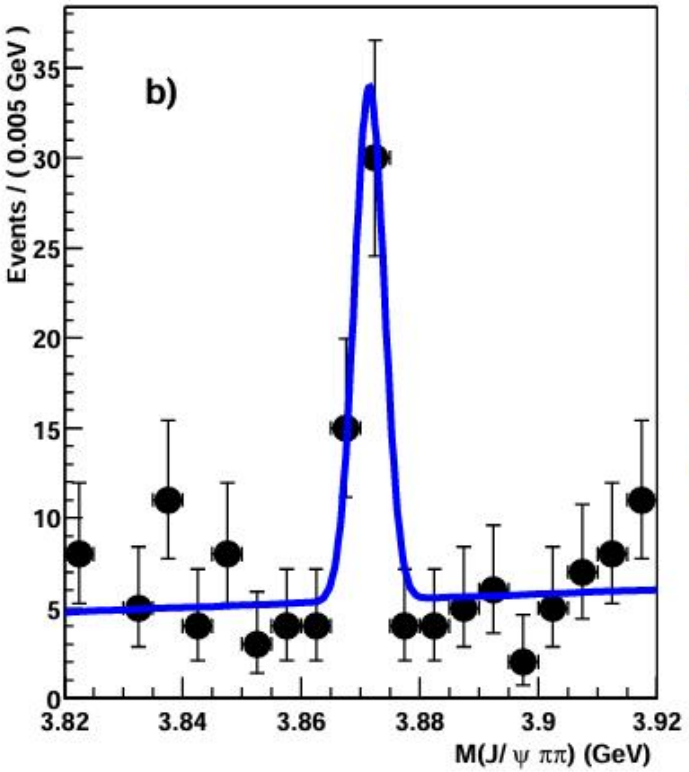
Exp line shapes of the three exotic states

2003
X(3872)



Belle PRL 91 (26): 262001

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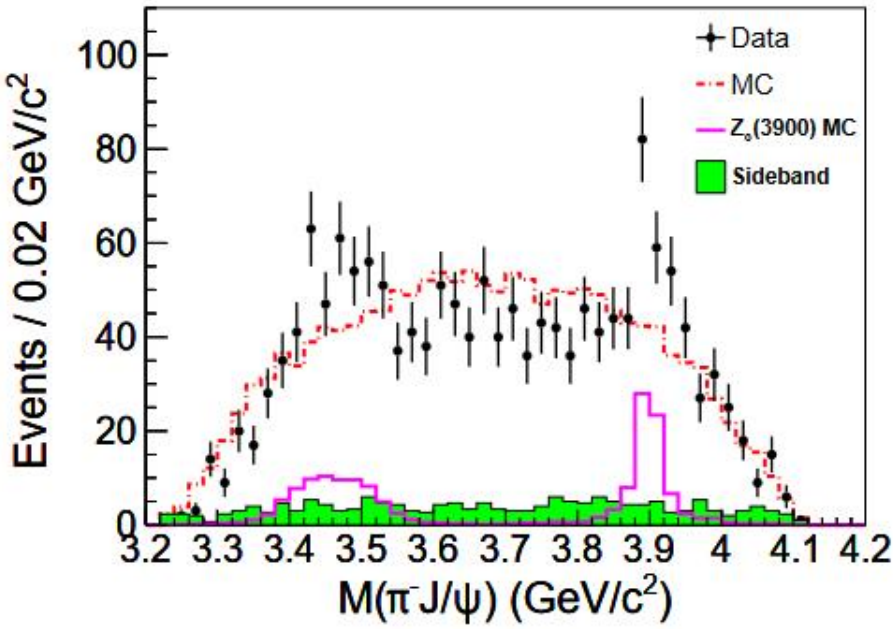
2013
Zc(3900)



BES PRL 110 (25): 252001

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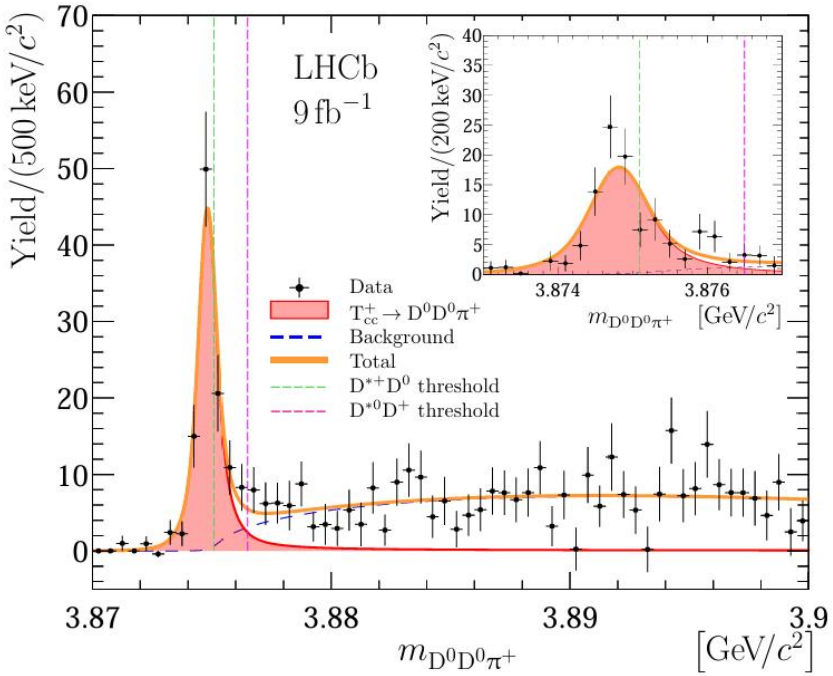
2022
Tcc



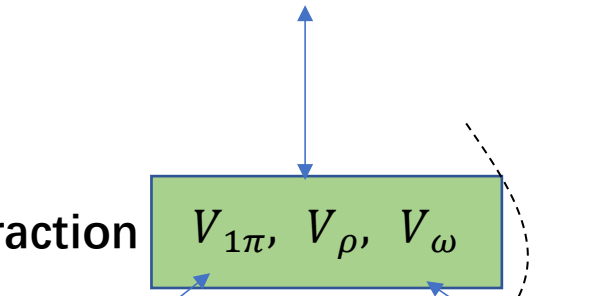
LHCb Nature Physics Vol.18(2022)

ph relationship between the three states

X(3872) : $c\bar{c}$ core ($\chi_{c1}(2P)$) + $D\bar{D}^*$(I=0) FSI

supported by lattice study

S. Prelovsek et.al 1503.03257
G.S. Bali et.al 1110.2381.



Tcc : DD^*(I=0) interaction

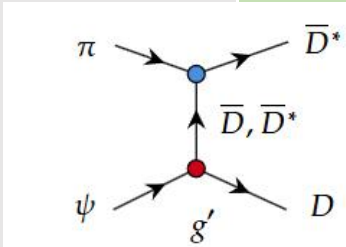
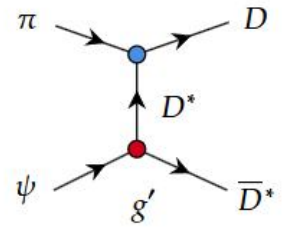
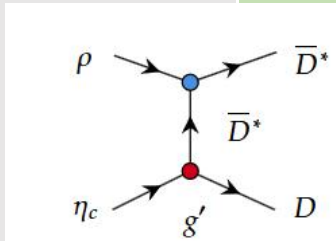
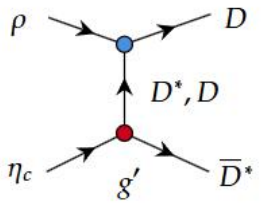
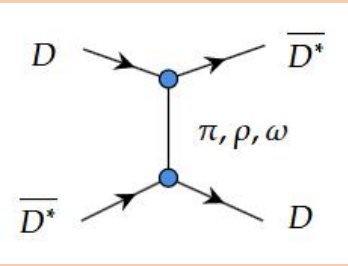
Zc(3900) : $D\bar{D}^*$(I=1) interaction
(also couple with $\pi J/\psi$, $\rho\eta_c$)

established in *Jia-Jun Wu et.al 2306.12406*
(binding energy of X3872 √ line shape of Tcc √)

The inclusion of $\rho\eta_c$ is implied by lattice study and recent experiment result

HALQCD 10.1088/1361-6471/aa9afd

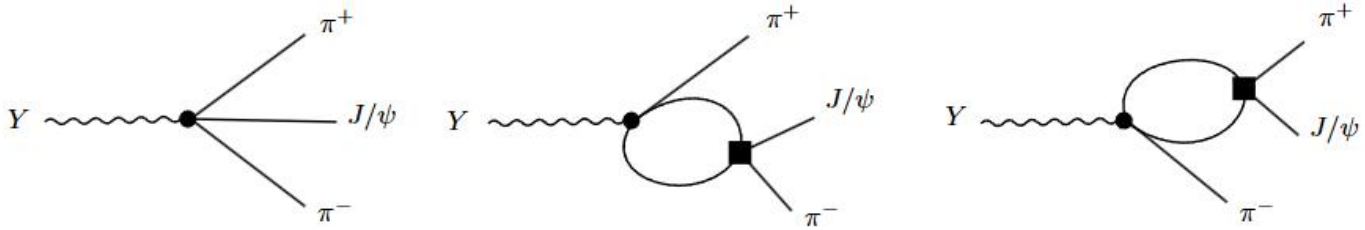
hadron-hadron interactions for Zc(3900)

	$\pi J/\psi$	$\rho\eta_c$	$D\bar{D}^*$
$\pi J/\psi$	OZI-suppression		
$\rho\eta_c$			
$D\bar{D}^*$	$\mathcal{L}_{\psi HH} = g' \mathrm{Tr}\left[\mathcal{J}\bar{H}_2 \overleftrightarrow{\partial}_\mu \gamma^\mu \bar{H}_1\right] + \mathrm{H.c.},$		totally determined 

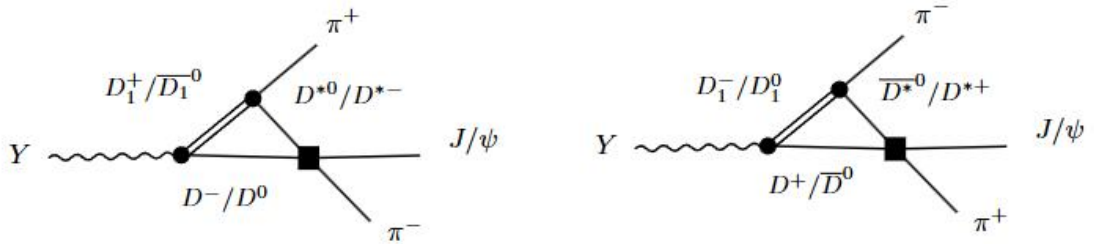
$(J/\psi, \eta_c)$ superfileds

$(D, D^*), (\bar{D}, \bar{D}^*)$,superfileds

Production Amp for Y(4230) decay

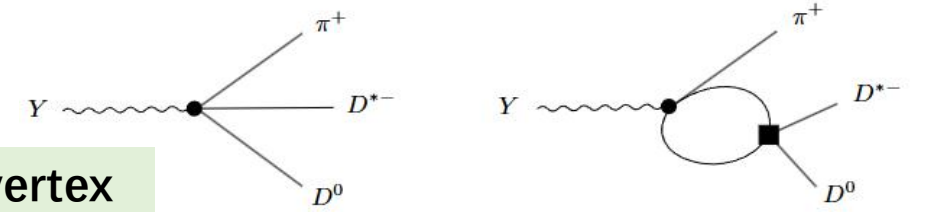


$e^+e^- \to \pi^+\pi^- J/\psi$

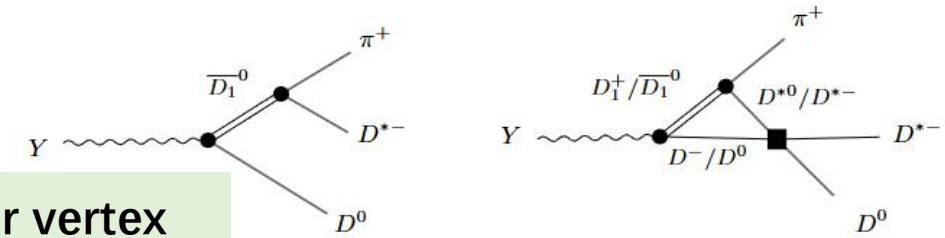


$e^+e^- \to \pi D\overline{D}^*$

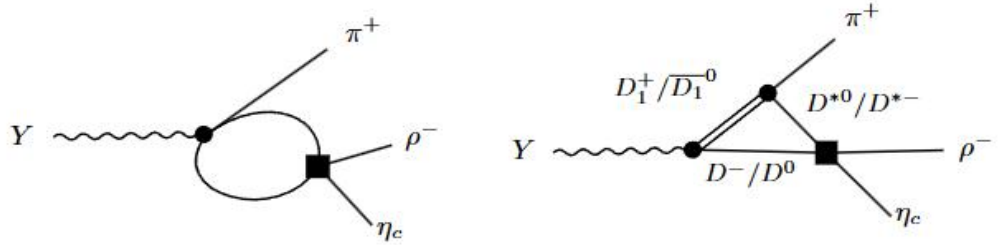
four-point vertex



$\boldsymbol{D_1\overline{D}}$ molecular vertex



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



Fitting formulas for line shape

$$\mathrm{dN} \sim N \int |M|^2 d\Phi + \mathrm{P}$$

scale factor

amplitude squared

phase space

incoherent polynomials

$b_0\left(\sqrt{s_{\pi^- J/\psi}} - m_\pi - m_{J/\psi}\right)^{b_1}\left(\sqrt{s} - m_\pi - \sqrt{s_{\pi^- J/\psi}}\right)^{b_1}$ ⇨ mimic $\pi\pi$ FSI

BES PhysRevLett.112.022001

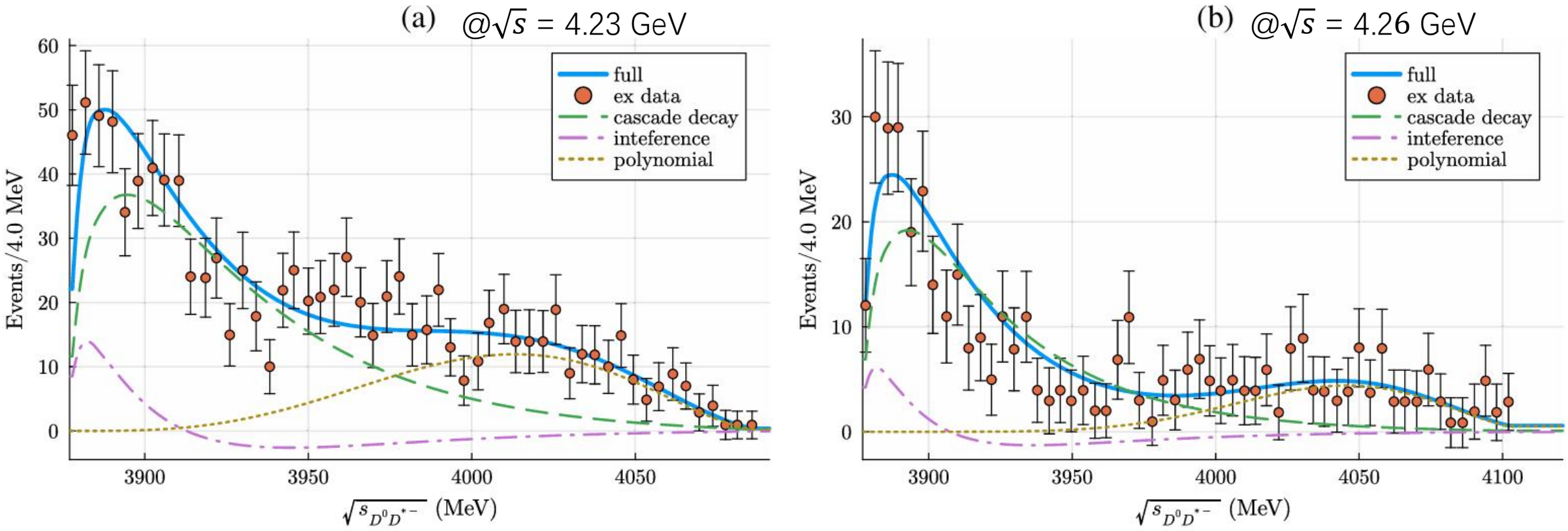
$c_0(\sqrt{s_{D^0 D^{*-}}} - m_D - m_{\bar{D}^*})^{c_1}\left(\sqrt{s} - m_\pi - \sqrt{s_{D^0 D^{*-}}}\right)^{c_2}$ ⇨ mimic possible background contribution

#. par = 2*11+1=23

#. ex data ~ 250 @$\sqrt{s} = 4.23,\ 4.26\ GeV$

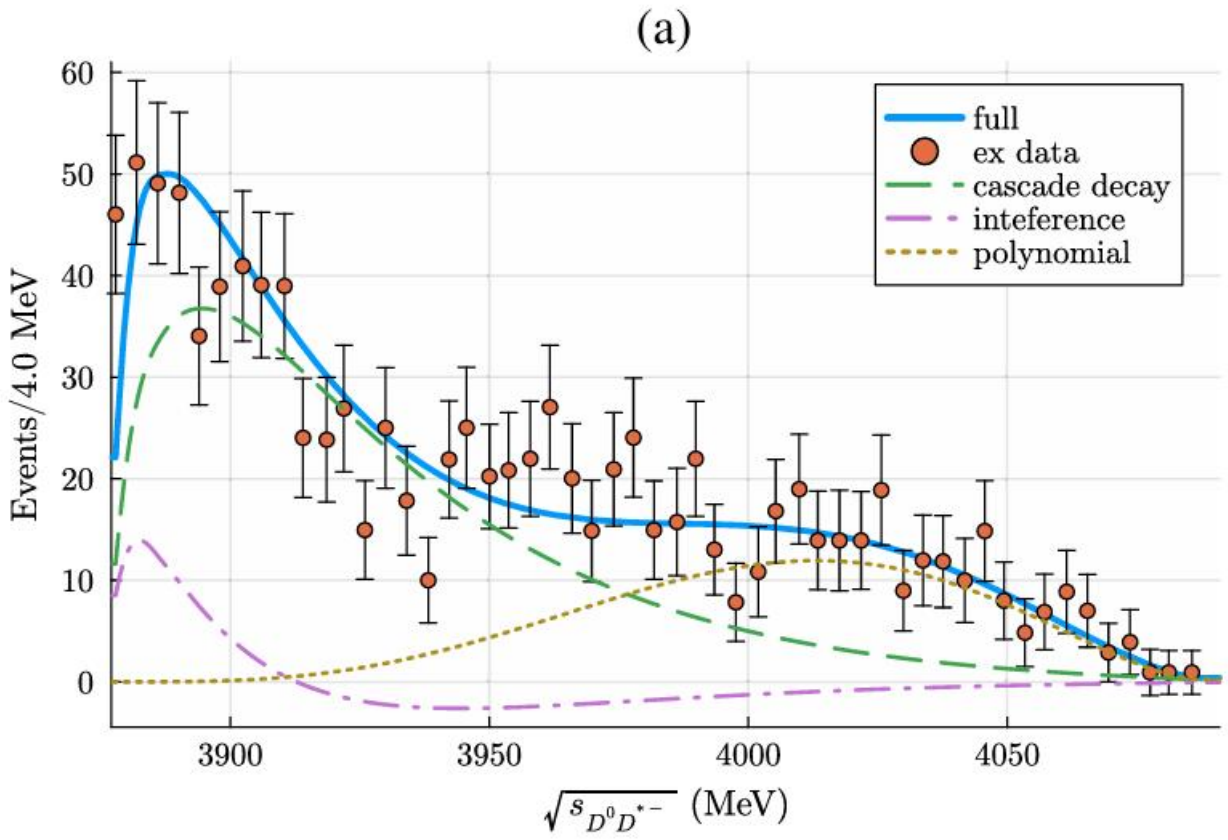
we get a $\hat{\chi}^2 \sim 1.6$ fitting results

Fitted line shape of D^0D^*- distribution



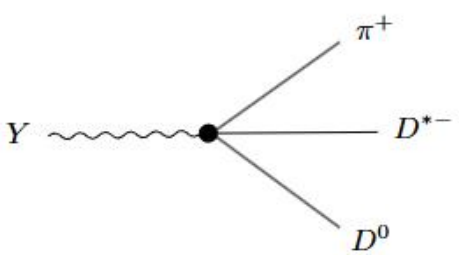
- Tree-level cascade decay $Y \to D_1\bar{D} \to D\bar{D}^*\pi$ contributes most.
- interference between tree-level cascade decay and triangle diagram enhances.
- polynomial only contributes at the tail.

Fitted line shape of D^0D^*- distribution

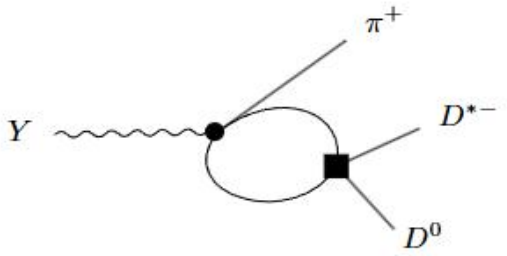


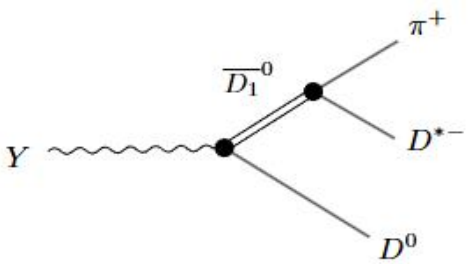
I=1 OBE is relatively weak
→ tree level dominates
→ cascade decay contributes to peak most

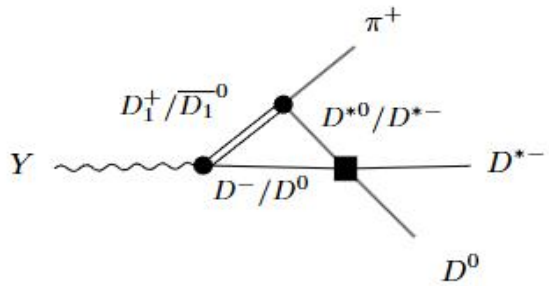
tree-level



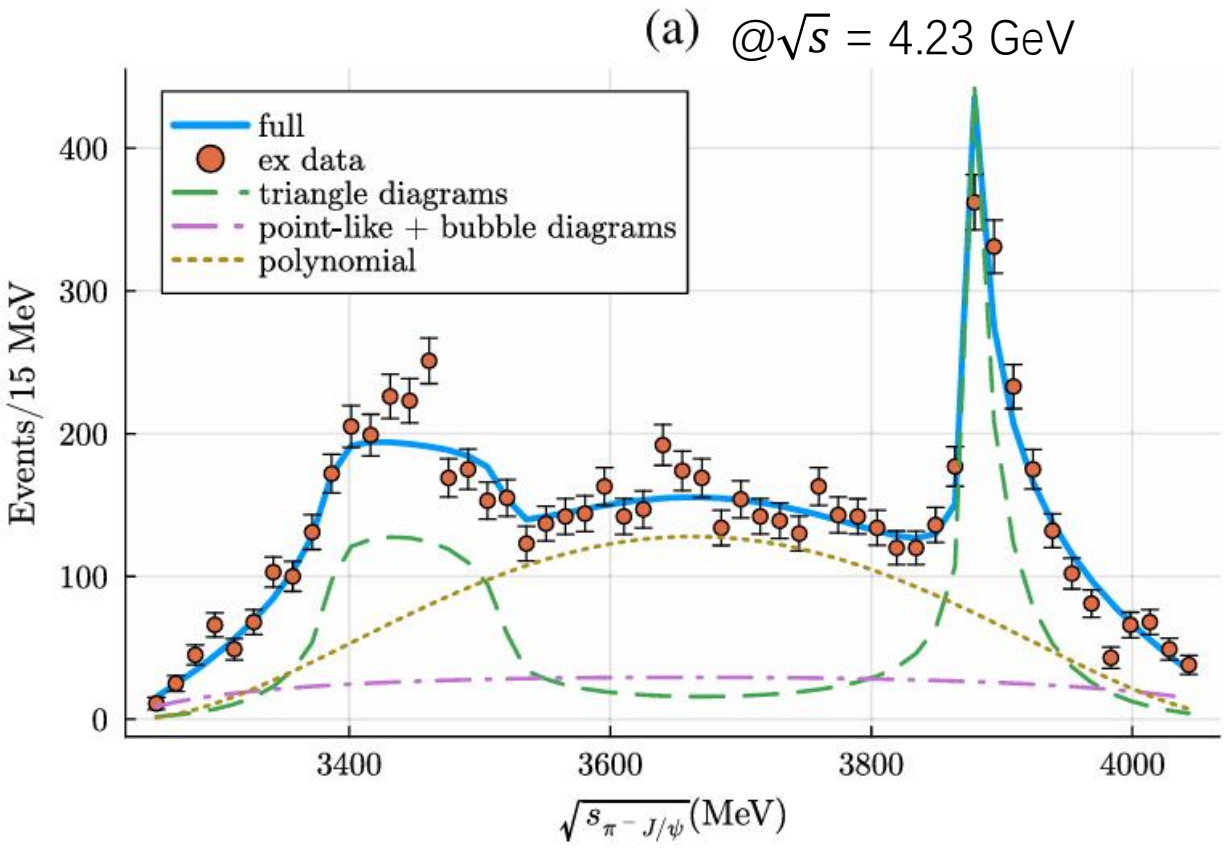
re-scattering

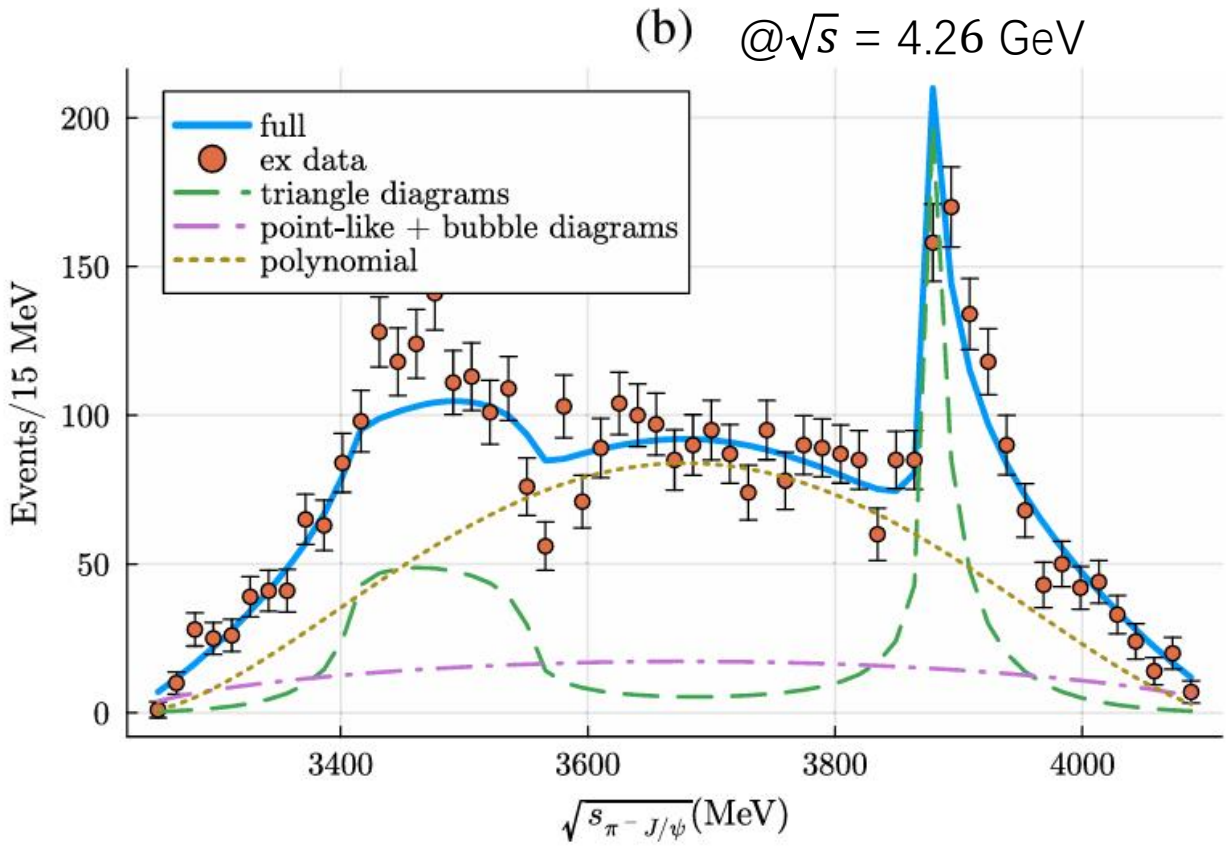






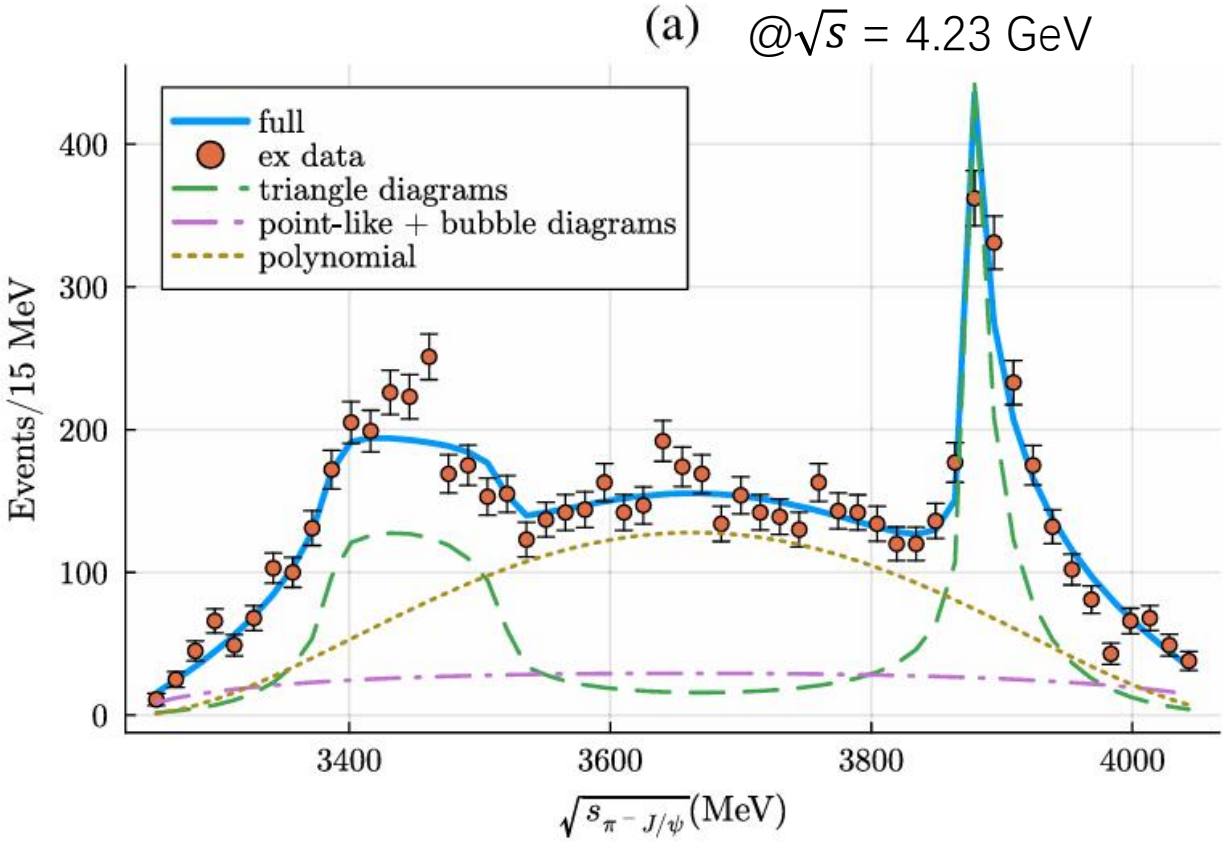
Fitted line shape of piJ/psi distribution

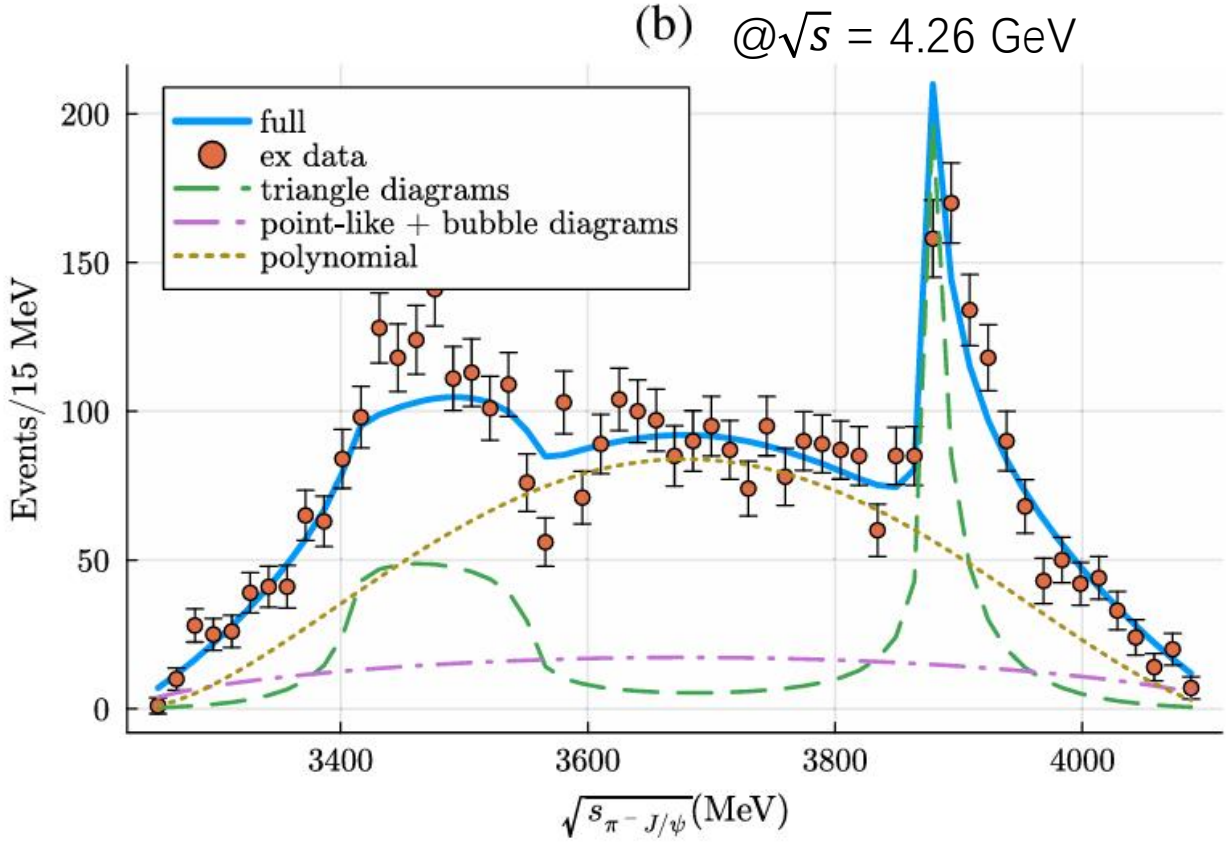


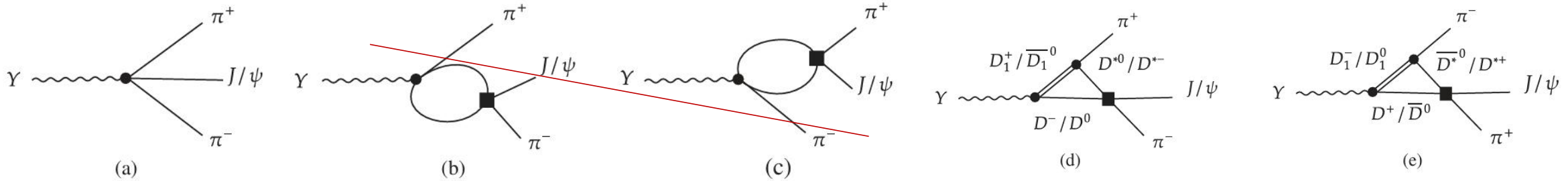


- triangle diagram $Y \to \bar{D}_1 D(\to D\bar{D}^*\pi) \to \pi\pi J/\psi$ produce the peak
- polynomial produce the similar line shape of $\pi\pi$ FSI as in *BES PhysRevLett.112.022001*

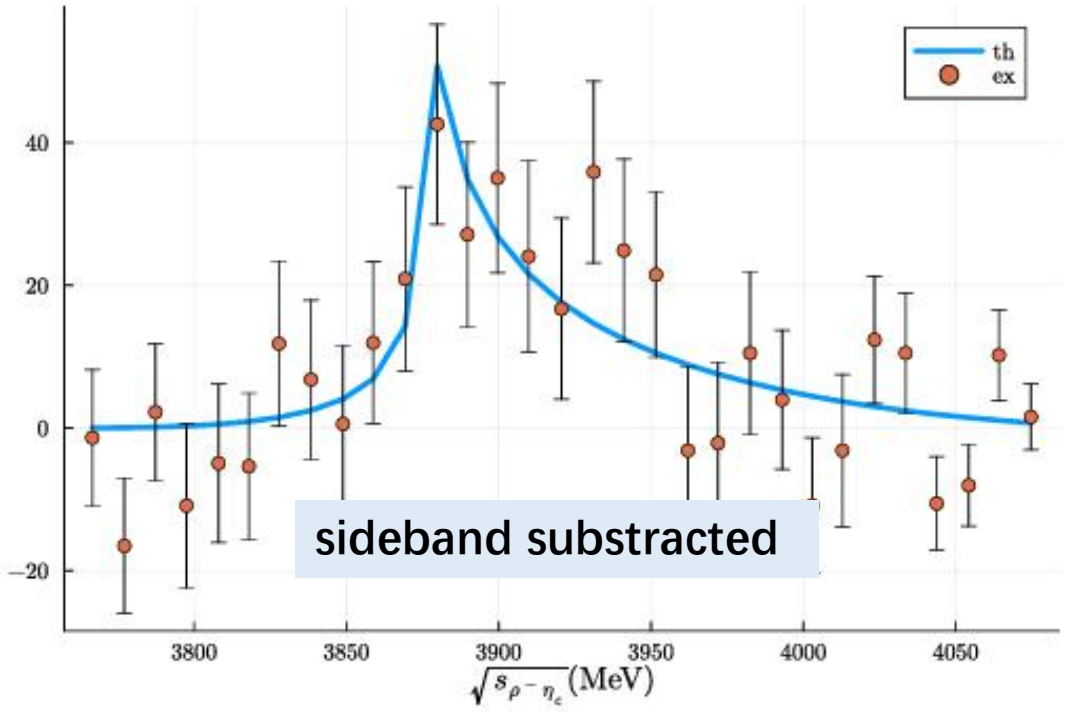
Fitted line shape of piJ/psi distribution







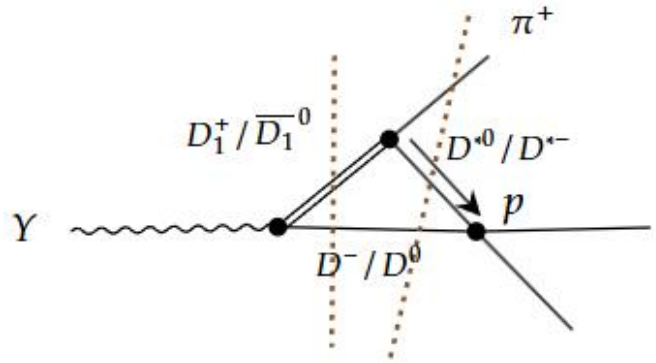
Fitted line shape of rhoEtac distribution



peak contributed by triangle diagram

exp data from: C.Z. Yuan 10.1142/S0217751X18300181

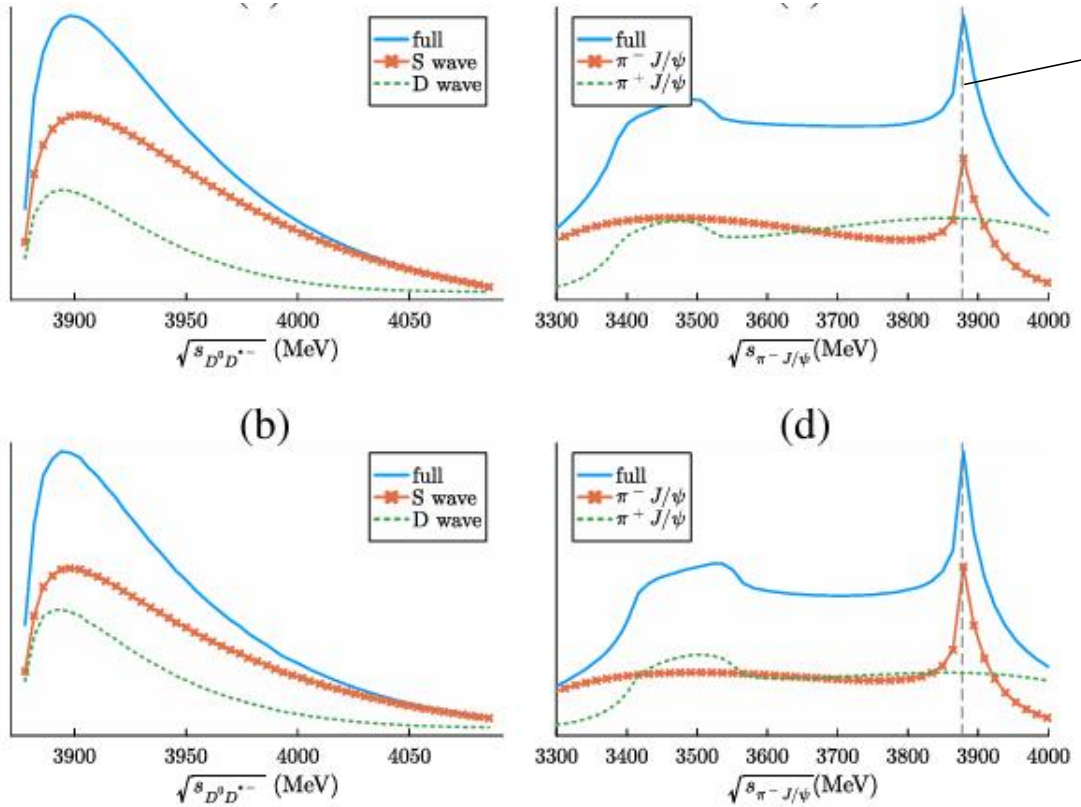
line shape by pure triangle loop



triangle diagram = pure triangle loop + T-matrix (FSI)

$$\sim V_{D_1 D^* \pi} \int \frac{d^3p}{\sqrt{s} - E_D - E_{D_1} + \frac{i\Gamma_{D_1}}{2}} \; \frac{1}{\sqrt{s} - E_\pi - E_{D^*} - E_D + i0^+}$$

width of $D_1(2420)$ is taken into account



Indeed a cusp Exactly at $D\overline{D}^*$ threshold

$\sqrt{s} - E_\pi - E_{D^*} - E_D = 0$ can hold above the $D\overline{D}^*$ threshold

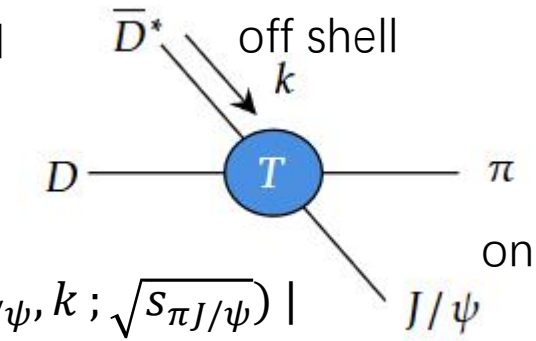
However…

- for $D\overline{D}^*$, peak not close enough
- for $\pi J/\psi$, peak not high enough

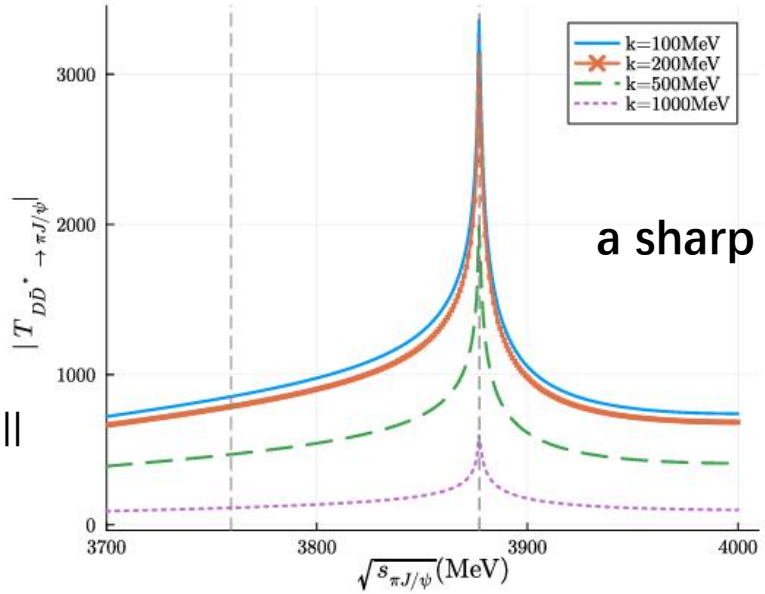
pure triangle loop is not all of the story

cusp from T-matrix

half-on-shell

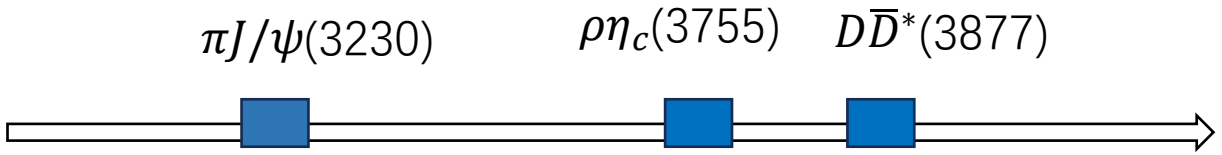


$$|T_{D\bar{D}^*\to\pi J/\psi}(\bar{p}_{\pi J/\psi}, k\,; \sqrt{s_{\pi J/\psi}})|$$



a sharp cusp EXACTLY at $D\bar{D}^*$ threshold (thanks to OPE)

pole of T-matrix



$2^3 = 8$ Riemann sheets

only one pole $\sim$ **3798** MeV is found in RS^{---}

("virtual")

Reference [25]	3798^{+25}_{-31}	Virtual
	$3902(6) - 38(9)i$	Resonance
Reference [19]	3831^{+27}_{-38}	Virtual
	$3894(6) - 30(13)i$	Resonance
Reference [21]	3870	Virtual
Reference [20]	3879	Virtual
Reference [22]	3872	Virtual
Reference [26]	$3880(3) - 13(1)i$	Resonance
Reference [32]	$3884 - 22i$	Resonance
Reference [27]	3840	Virtual
Reference [62]	3839(11)	Virtual

a virtual pole far below $D\bar{D}^*$ threshold in LQCD at larger m_π

PhysRevLett.117.242001

👉**peak from triangle diagram is threshold cusp mainly from T-matrix and enhanced by pure triangle loop**

Finite Volume Hamiltonian method: from ph to lat

workflow of FVH method

phenomenological model

↓

matrix in the discretized momentum space

↓

irreducible representation decomposition

↓

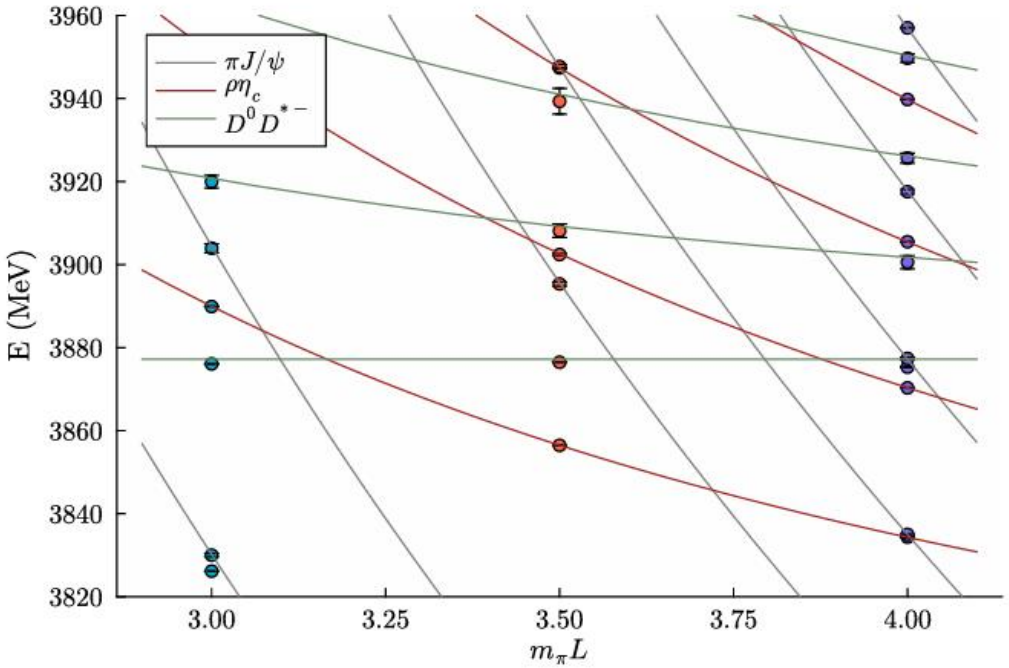
eigenvalues of the matrix
(which can be compared to lat spectra)

2502.05789

provide a systematic calculation procedure

(also address left-hand cut issue)
(generalization to three-body system is in progress)

Finite Volume energy levels: Zc(3900)



all levels are close to the non-interacting levels (I=1 OBE is weak)

Prelovsek et.al PhysRevD.91.014504

"The levels appear near the noninteracting energies of the two-particle states"

HSC 10.1007/JHEP11(2017)033

"the majority of energies lie close to the non-interacting levels."

MILC, http://arxiv.org/abs/1411.1389

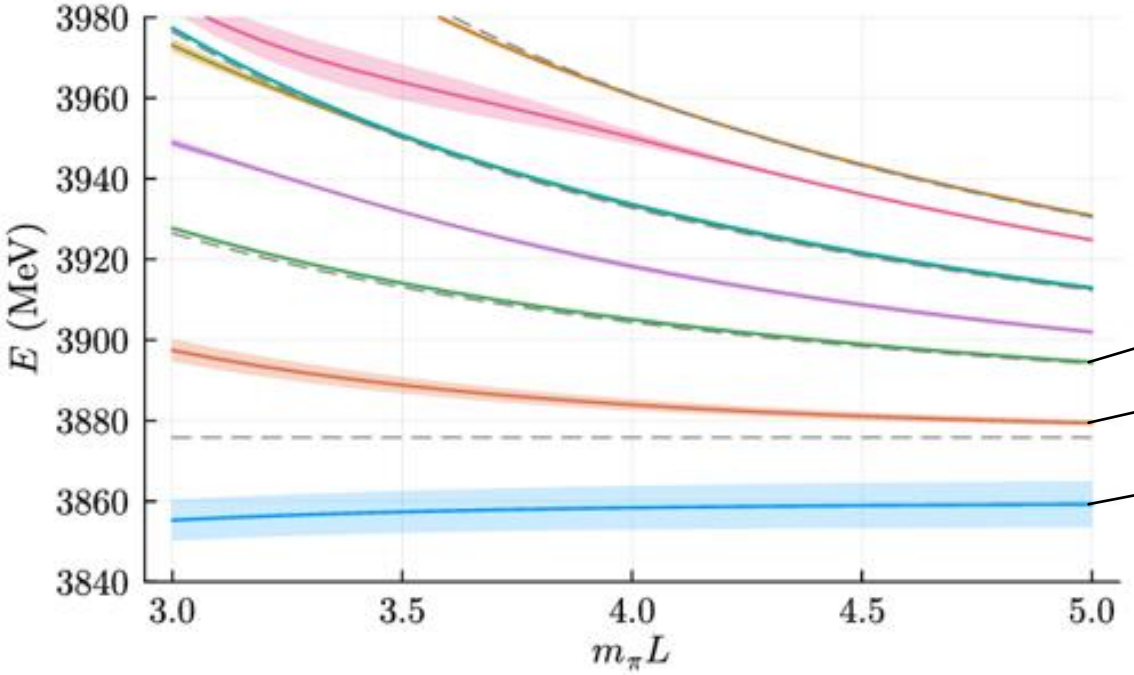
"The mixing is evidently too weak to produce a state distinct from the noninteracting scattering states"

Finite Volume energy levels: X(3872)

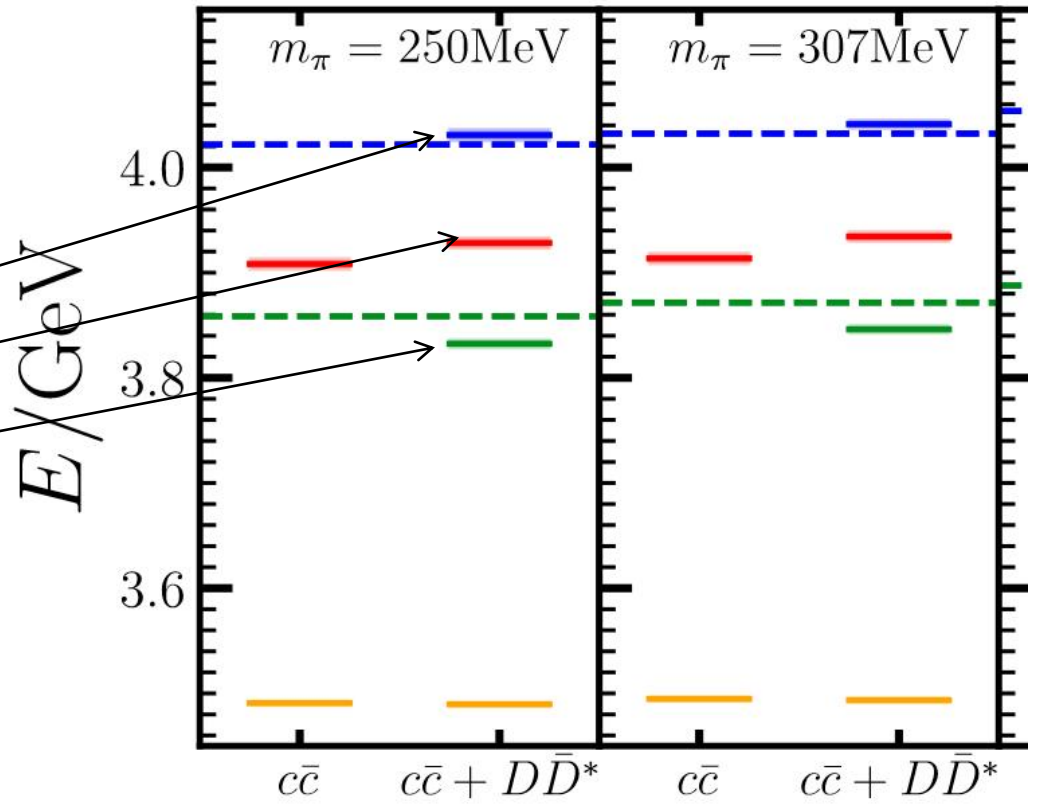
Signal of X(3872) on the lattice is reported by several lattice studies

$c\bar{c}$ core ($\chi_{c1}(2P)$) + $D\bar{D}^*$(I=0)

MILC, http://arxiv.org/abs/1411.1389
Prelovsek et.al PhysRevLett.111.192001
HaoZheng Li 2402.14541
...



(a) full model



2402.14541

Summary

- A OBE model reproducing: the binding energy of X(3872), line shape of Zc(3900) and Tcc
- Based on the current experiment data, Zc(3900) is more likely to be a cusp in our model.
- The finite volume spectra is calculated. The results are qualitatively same as the lattice study