X and Z_{cs} in $B^+ \to J/\psi\phi K^+$ as *s*-wave threshold cusps and alternative spin-parity assignments to $X(4274)$ and $X(4500)$

Phys. Rev. D 107, L011504 (2023)

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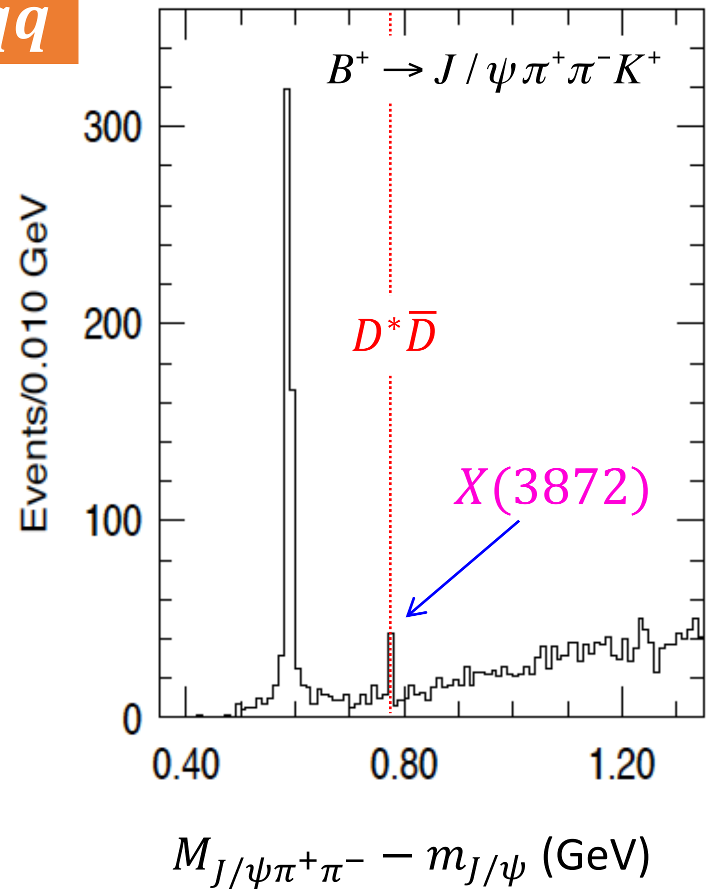
Introduction

Discoveries of many exotic candidates near thresholds

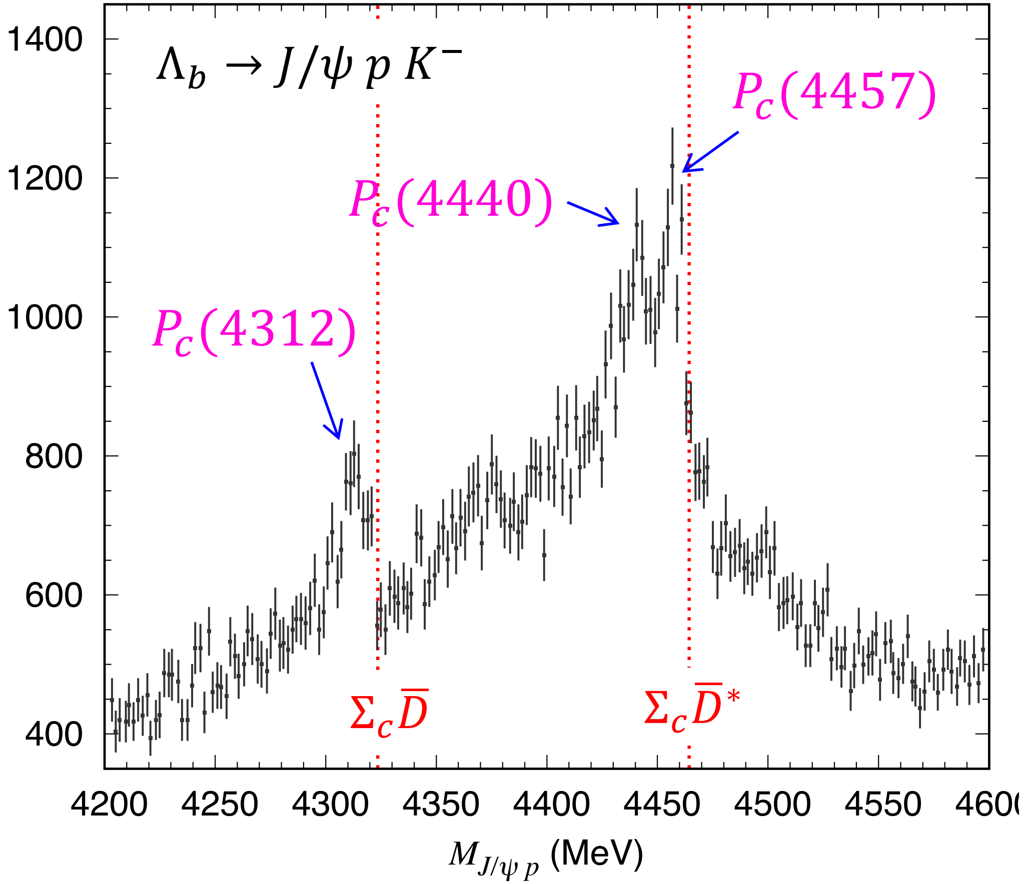
$qq\bar{q}\bar{q}$

Belle, PRL 91 262001 (2003)



$qqqq\bar{q}$

LHCb, PRL 122, 222001 (2019)



Amplitude analysis: First step to understanding exotic hadrons

Data → Mass, width, spin-parity (J^P) of exotic candidates

crucial information to address the nature of exotic hadrons (compact multi-quark, molecule, etc.)

or → Non-exotic explanation such as reflection of other known resonance

and kinematical effect (threshold cusp, triangle singularity)

Common amplitude analysis method: Breit-Wigner fit

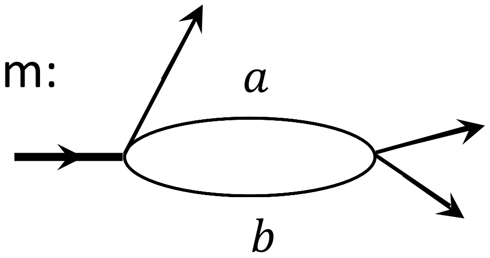
Resonance amplitude in Breit-Wigner form + non-resonant background (usually, experimentalists' first option)

$$\frac{1}{E - M + i\frac{\Gamma}{2}} \quad + \quad (\text{polynomial of } E)$$

Breit-Wigner is good to describe resonances distant from relevant thresholds, but unsuitable near thresholds

Why Breit-Wigner fit may be unsuitable near threshold ?

Ans. Resonance-like structure might be caused by threshold cusp from:

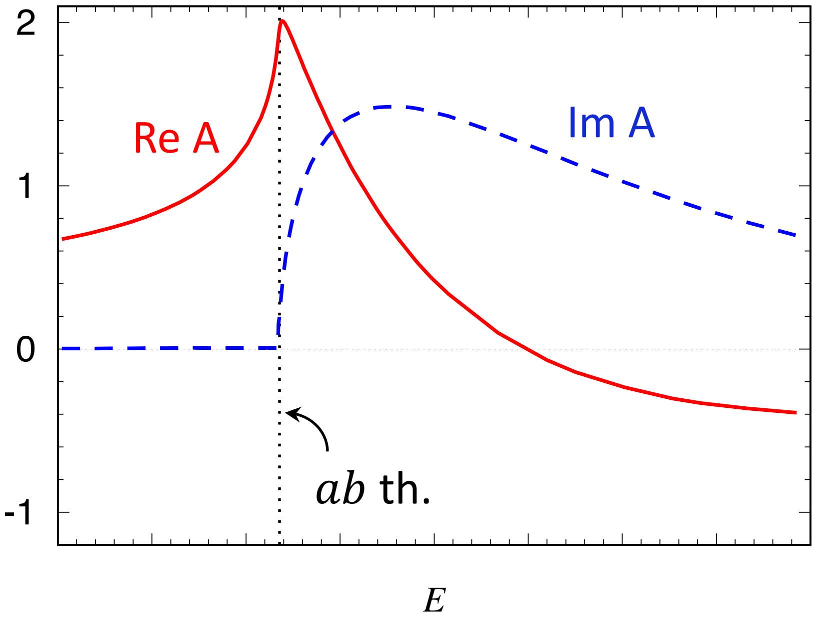


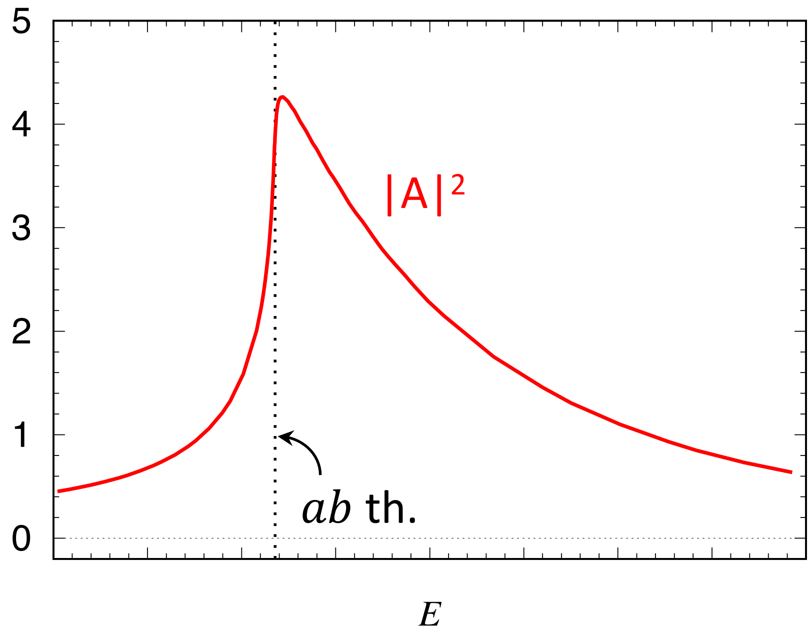
ab s-wave subsystem of energy E

$$A \sim \int d^3q \, \frac{1}{E - E_a(q) - E_b(q) + i\varepsilon} \sim i\pi q_0 \, \rho\theta(E - m_a - m_b) \; + \; \text{principal value (real)}$$

q_0: on-shell momentum of ab

dA/dE is divergent at ab threshold (Square-root singularity)





$|A|^2$ shows resonance-like behavior

Singularity is not from pole (dynamics) but from kinematical effect

Nearby pole due to ab rescattering may sharpen and/or shift the peak

Suppose resonance-like peaks and dips near thresholds in data

Two options for amplitude analysis model:

- Breit-Wigner fits the peaks; dips are from interferences $\leftarrow$ more common
- Threshold cusp mechanisms for the peaks and dips

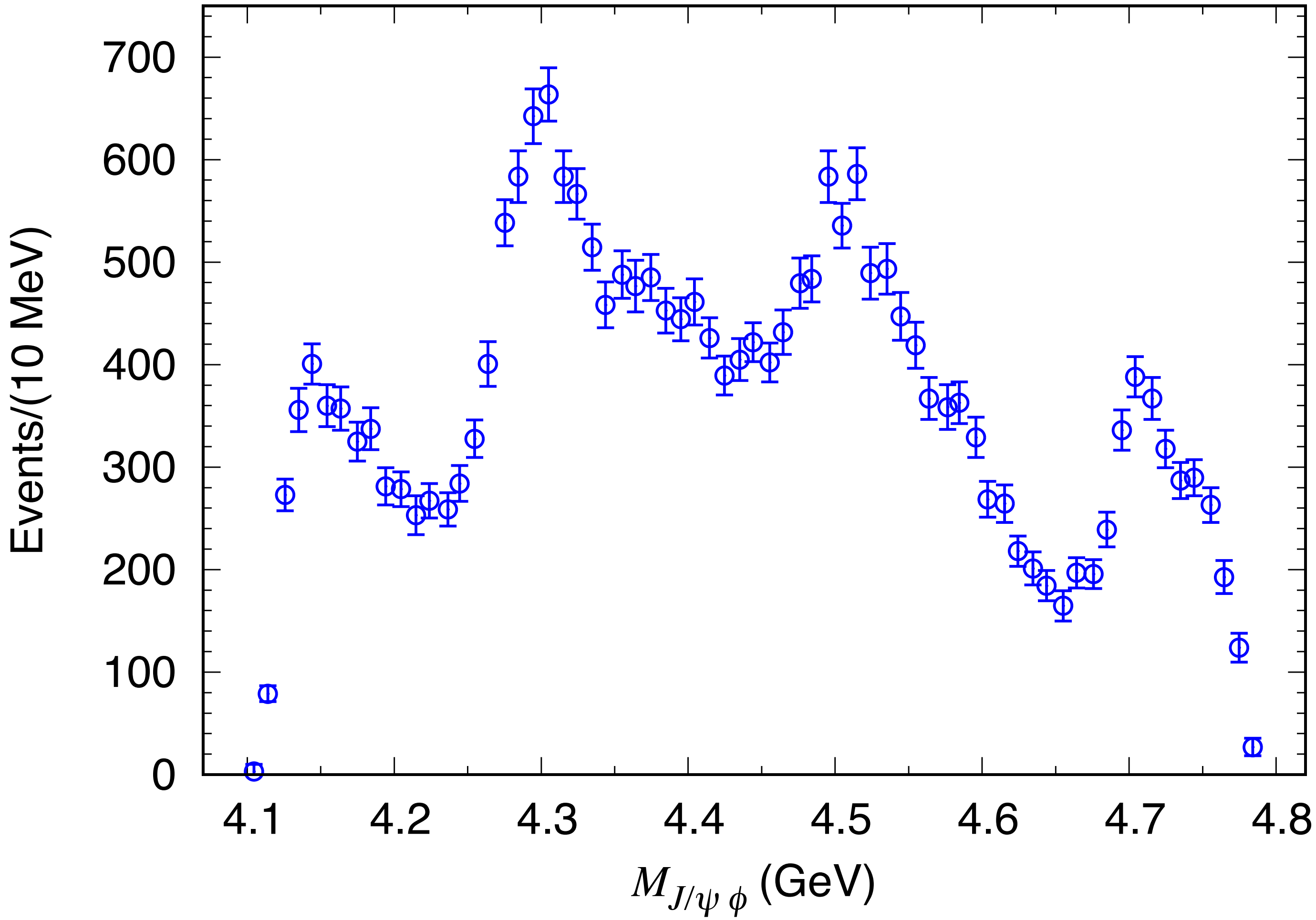
Depending on this choice, amplitude analysis results can be quite different

This talk: an interesting example from our recent analysis on $B^+ \to J/\psi\, \phi\, K^+$

Xuan Luo and SXN, PRD 107, L011504 (2023)

Introduction to $B^+ \to J/\psi\, \phi\, K^+$

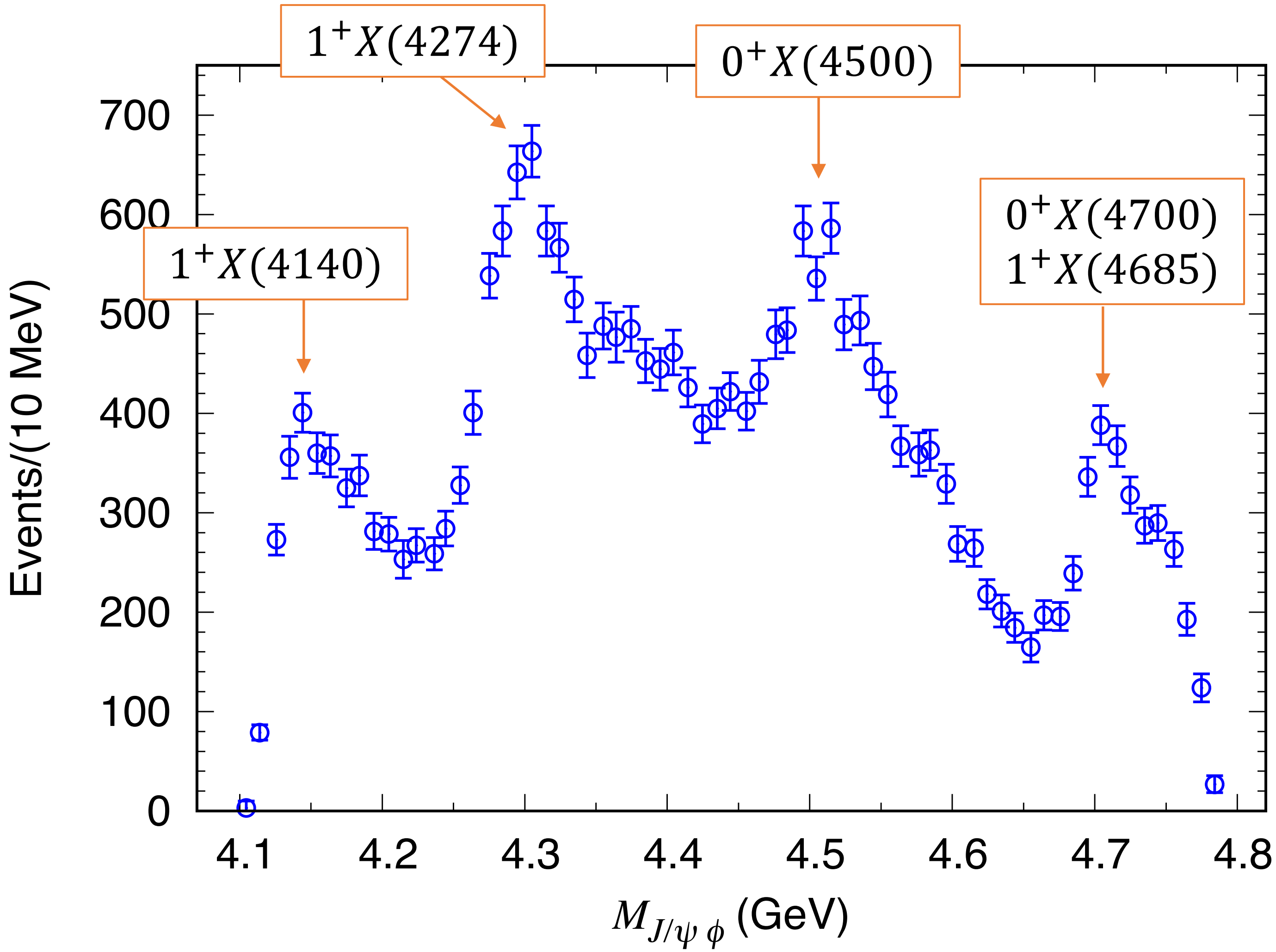
Interesting structures in $M_{J/\psi\phi}$ distribution in $B^+ \to J/\psi\, \phi\, K^+$



LHCb, PRL 127, 082001 (2021)

Clear resonance-like structures

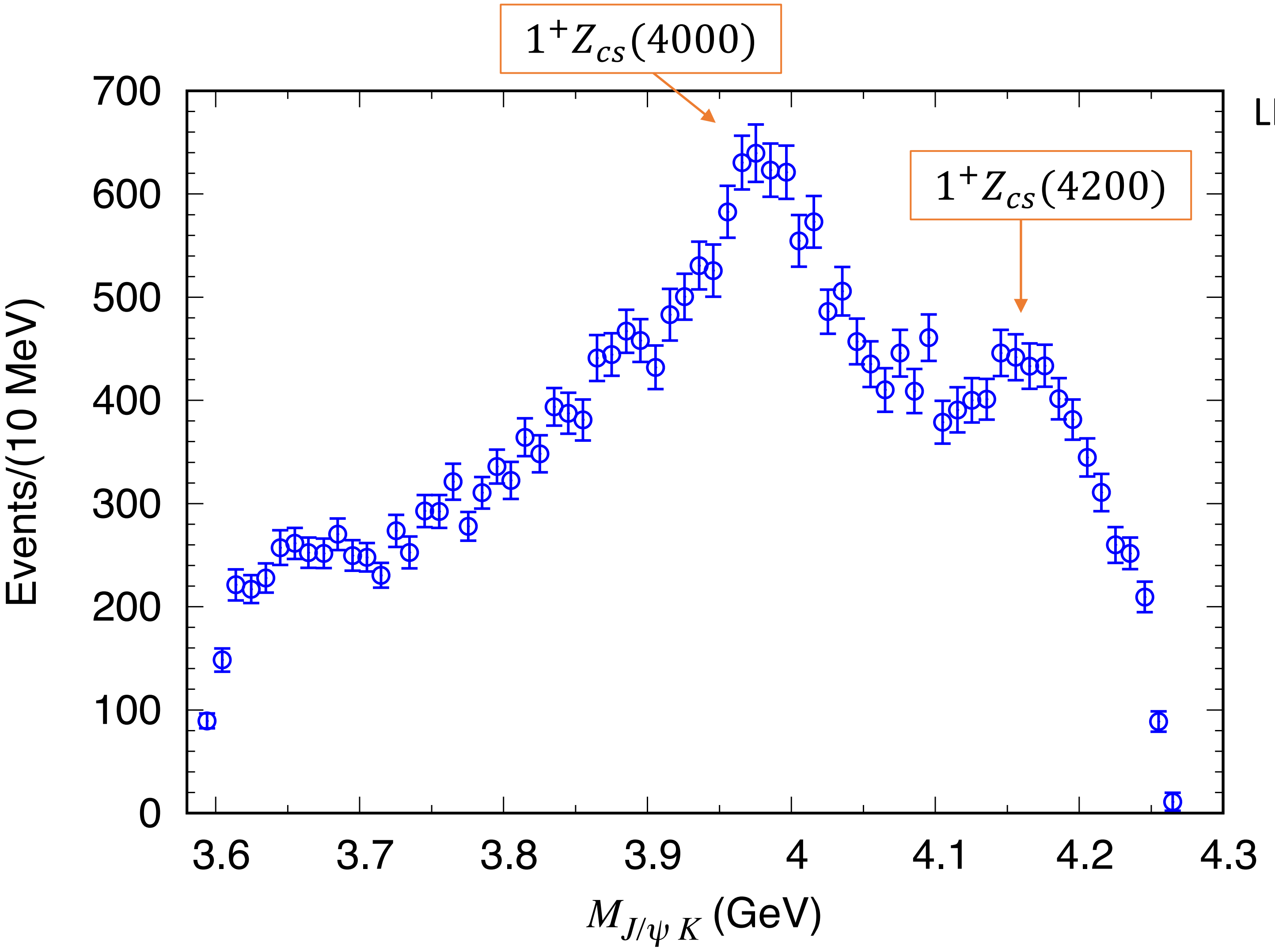
Interesting structures in $M_{J/\psi\phi}$ distribution in $B^+ \to J/\psi\,\phi\,K^+$



LHCb, PRL 127, 082001 (2021)

LHCb's six-dimensional amplitude analysis

Also, structures in $M_{J/\psi K^+}$ distribution in $B^+ \to J/\psi\, \phi\, K^+$



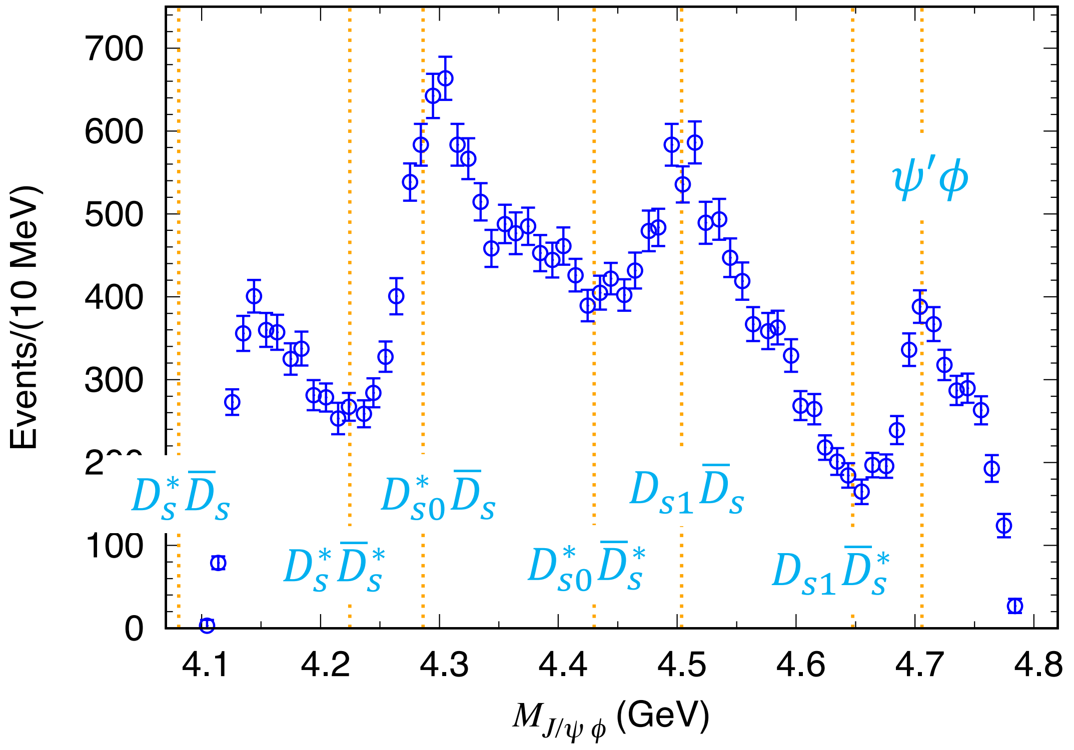
LHCb, PRL 127, 082001 (2021)

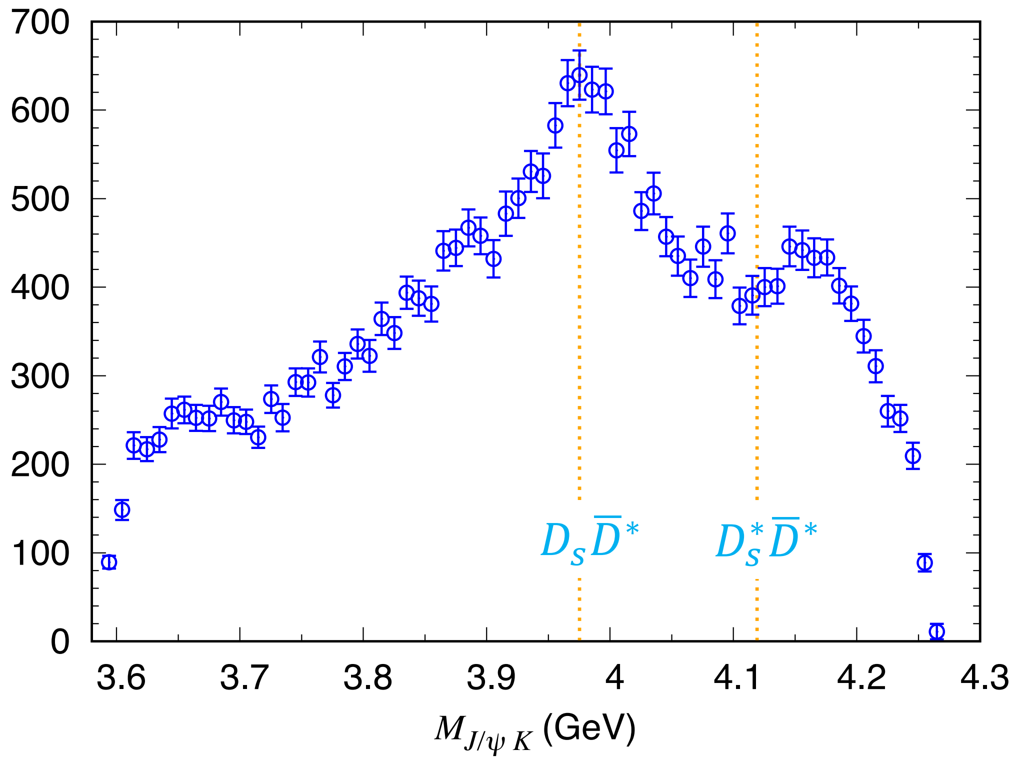
LHCb's six-dimensional amplitude analysis

Interesting coincidences of structures and thresholds

All peaks and dips are located at (near) thresholds !

X.-H. Liu, PLB 766, 117 (2017)
X.-K. Dong et al., Prog. Phys. 41, 65 (2021)





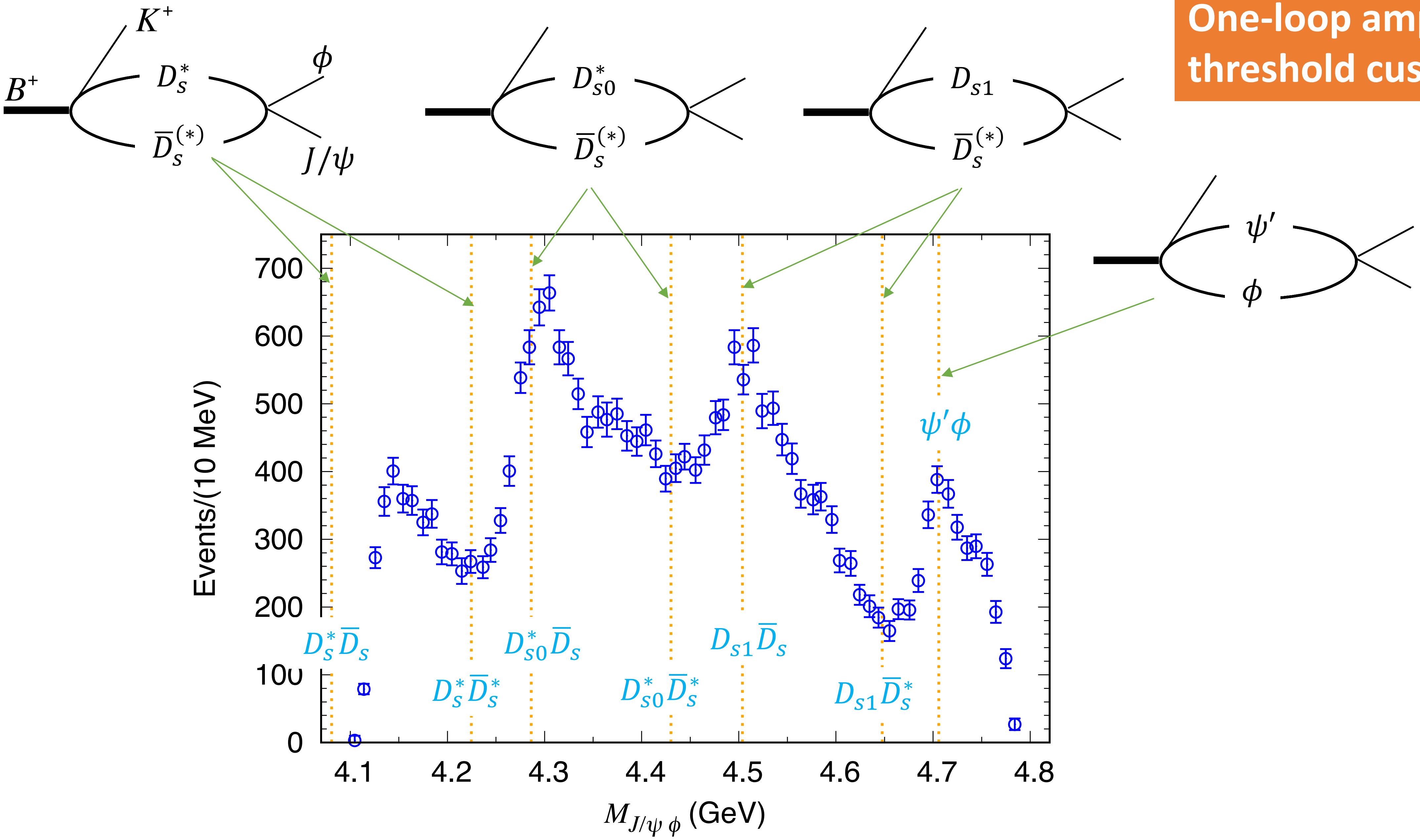
LHCb's assumption: All peaks are from resonances simulated well by Breit-Wigner form

However, threshold cusps might describe well the structures

This work: an independent amplitude analysis with all relevant threshold cusps

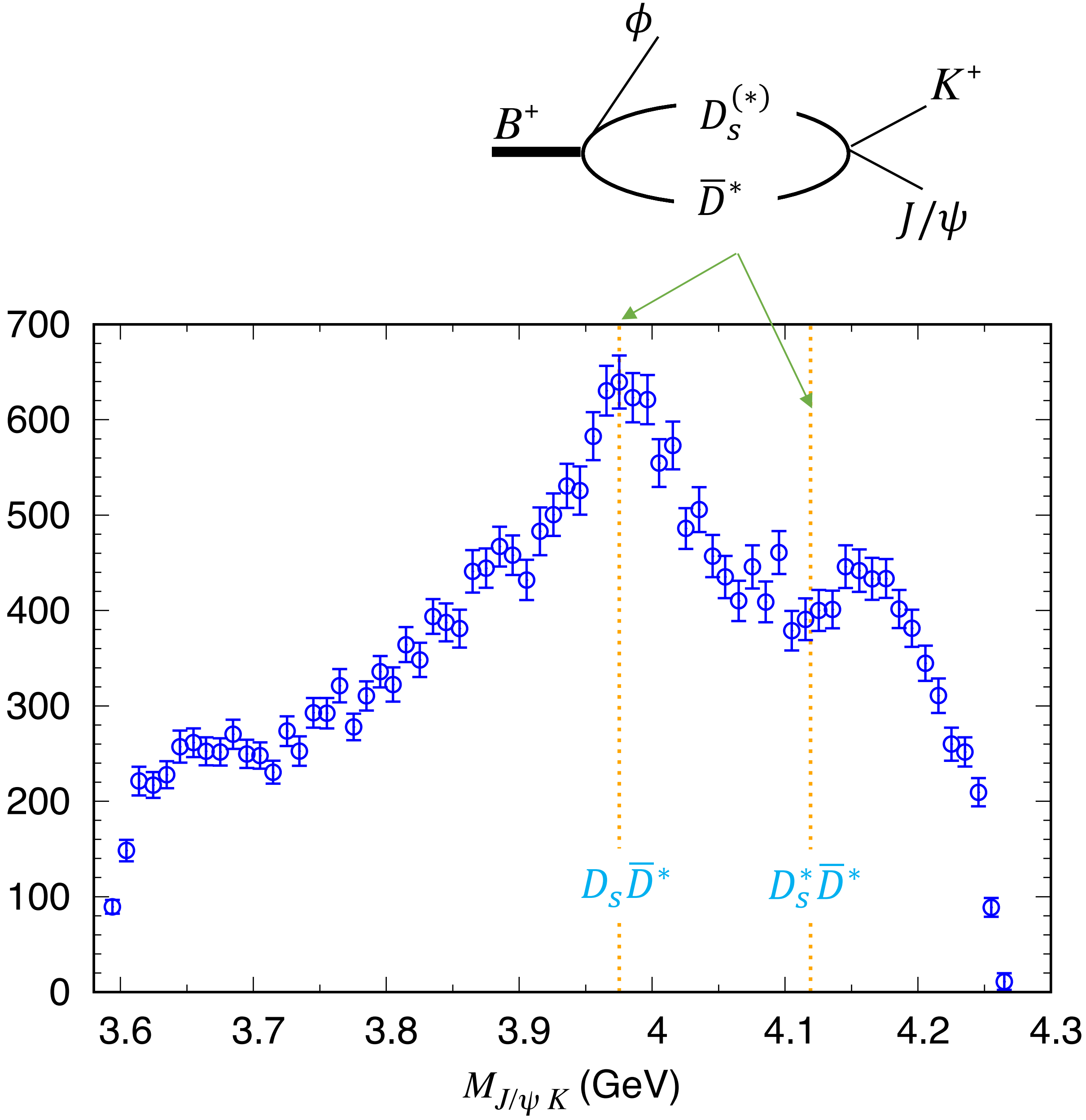
Model for $B^+ \to J/\psi\ \phi\ K^+$

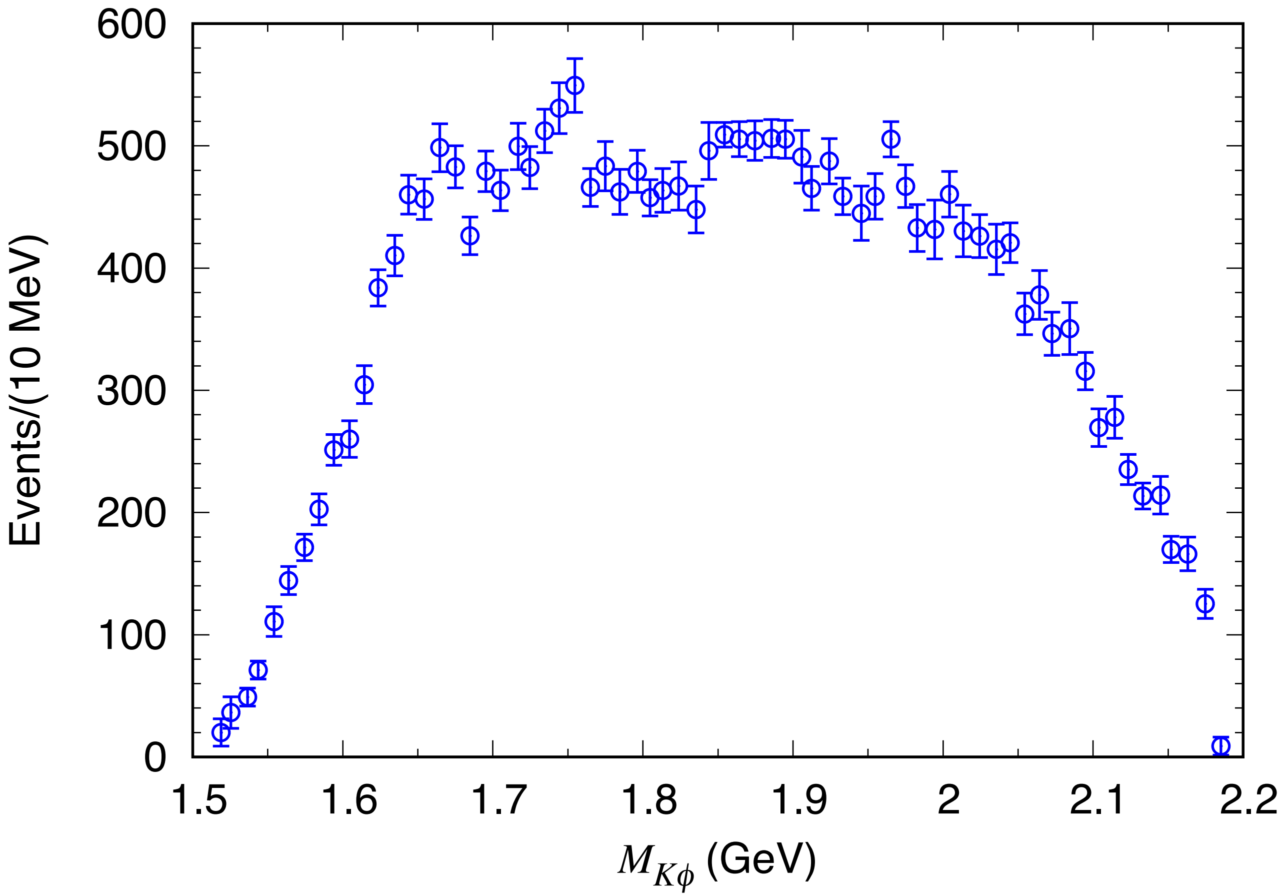
One-loop amplitudes for threshold cusps

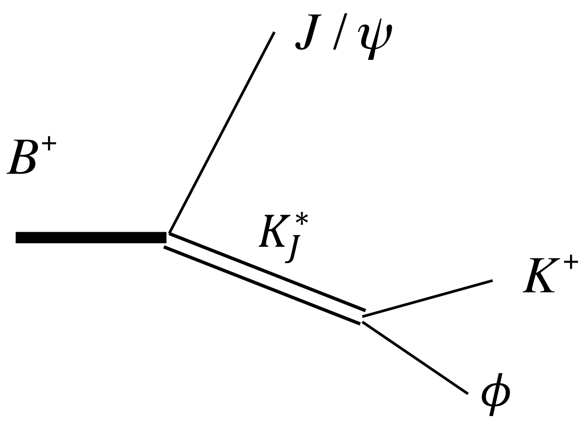


S-wave meson-meson intermediate states are considered (s-wave cusps should dominate)

One-loop amplitudes for threshold cusps







1^- $K^*(1410), K^*(1680)$

1^+ $K_1(1650)$

2^- $K_2(1770), K_2(1820)$

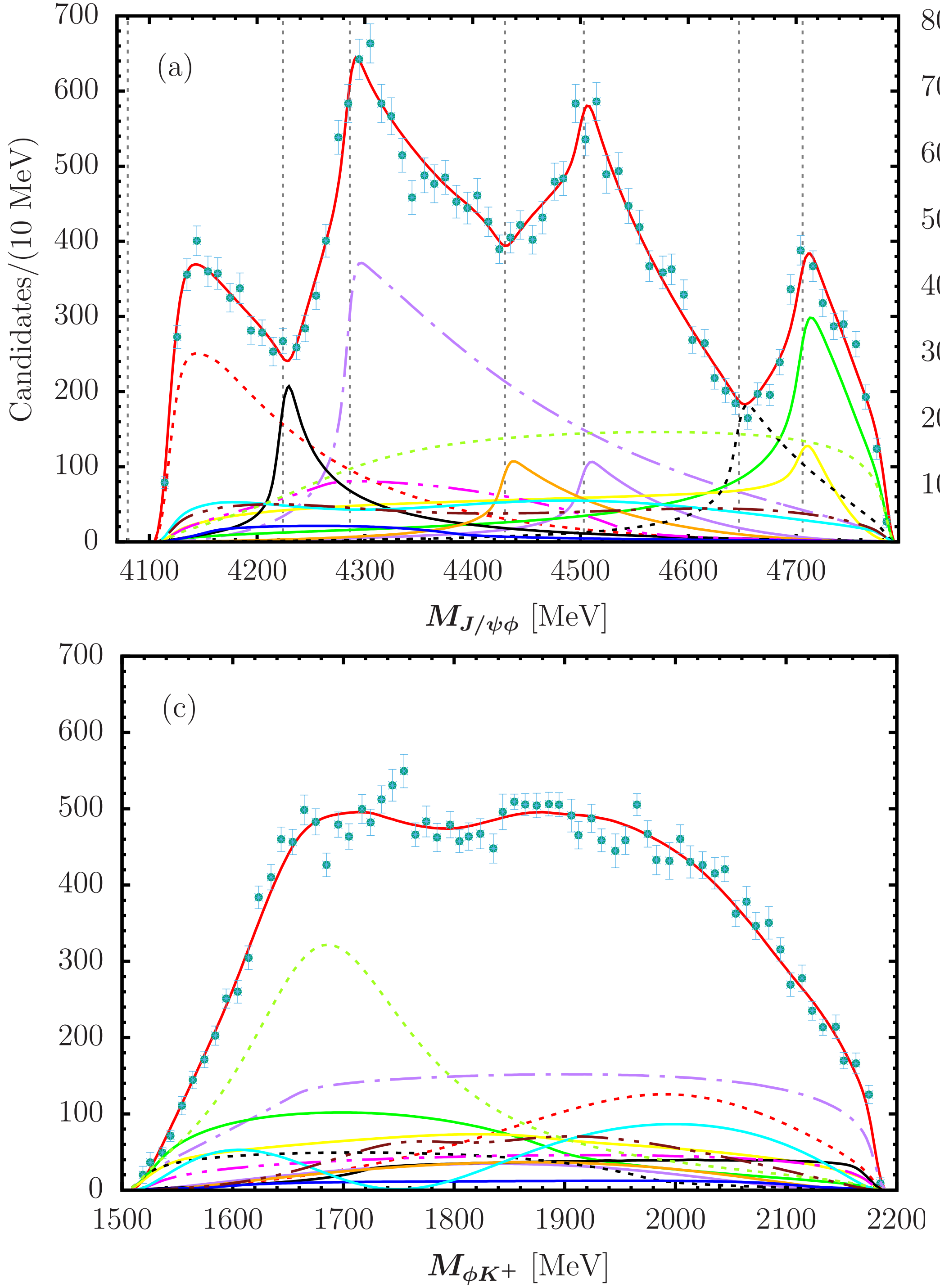
No obvious structures in $M_{K\phi}$ distribution

(broad) K_J^* excitation mechanisms are considered with the LHCb analysis as a reference

We retain only K_J^* that significantly improve fitting the data; interference with others is important

Results

Fitting LHCb data



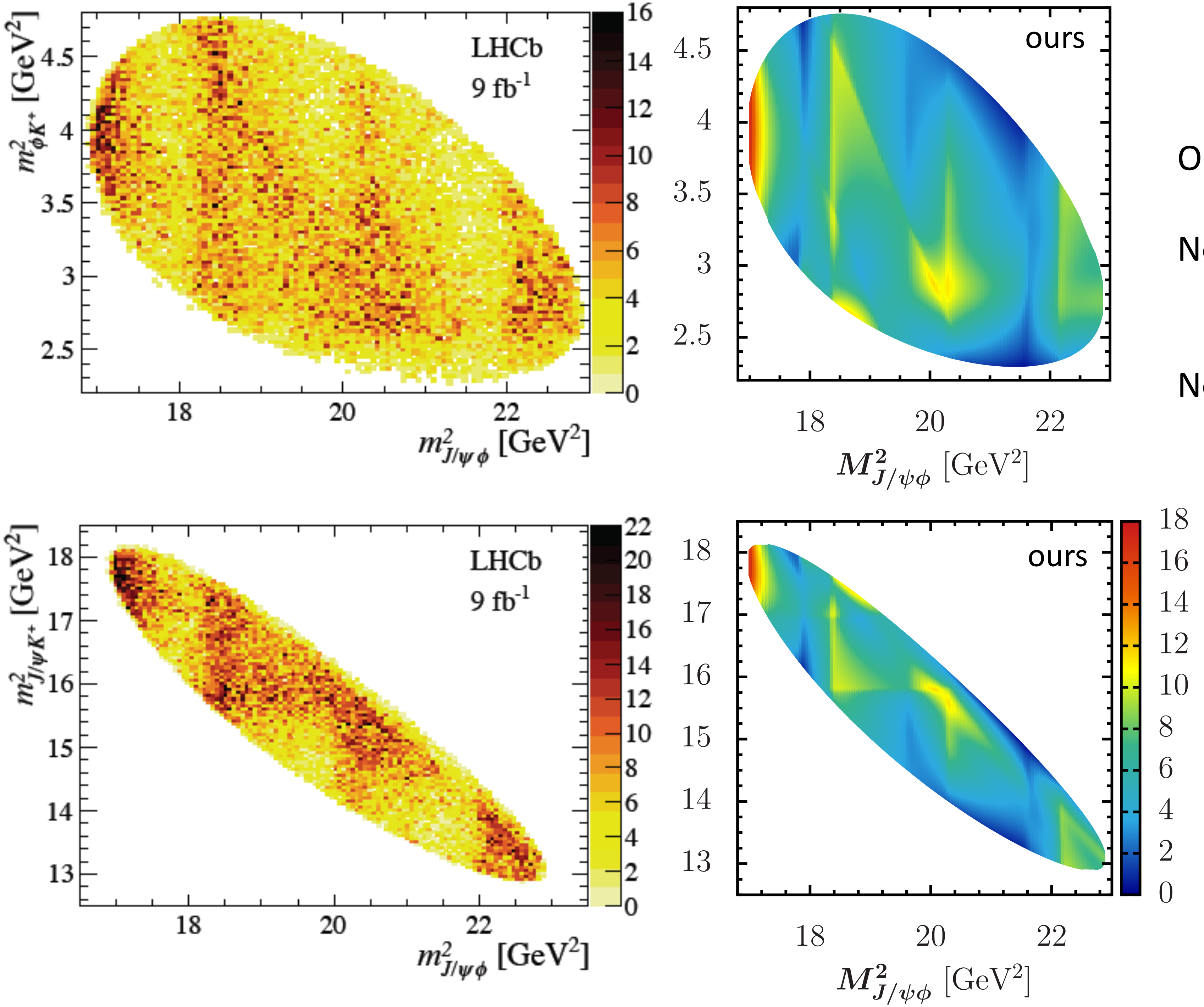
X. Luo and SXN
PRD 107, L011504 (2023)

$M_{J/\psi\phi}$, $M_{J/\psi K^+}$, and $M_{K^+\phi}$ distributions are simultaneous fitted

χ^2/ndf = 1.77

Peak and dip structures are well fitted with threshold cusps through interference; no nearby poles

Dalitz plots



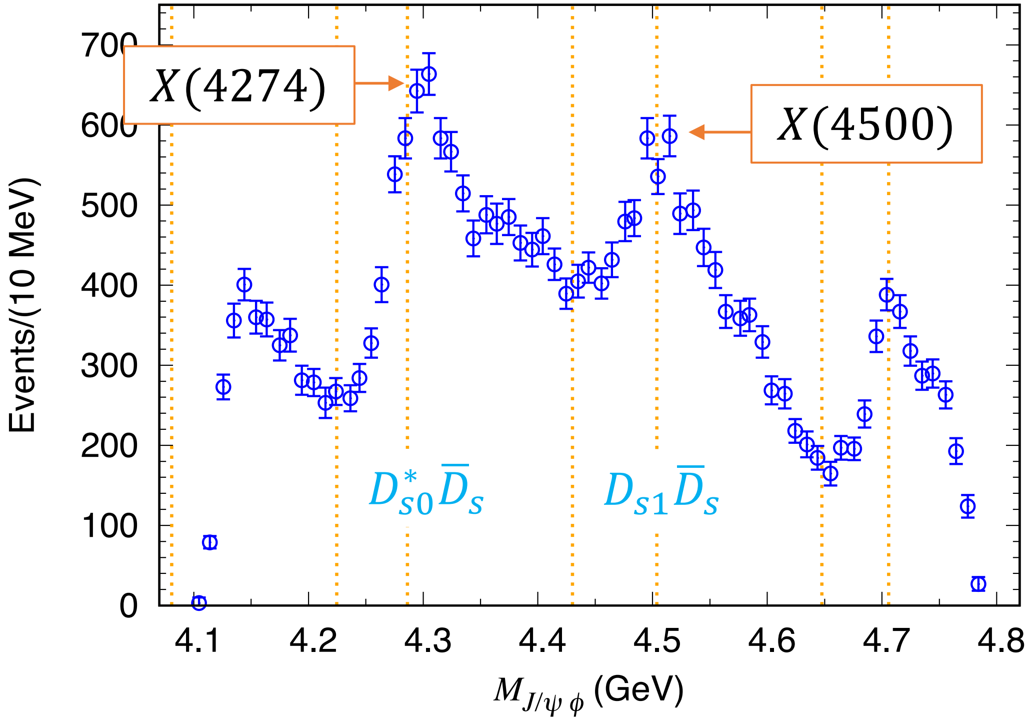
Our model reproduces overall patterns

No smearing applied → sharper peaks than data

No direct fit to Dalitz data

Comparison with LHCb amplitude analysis

	Ours	LHCb
X and Z_{cs} structures (origin)	threshold cusps	resonances (Breit-Wigner)
J^P of $X(4274)$	0^- ($D_{s0}^*\bar{D}_s$ s-wave)	1^+
J^P of $X(4500)$	1^- ($D_{s1}\bar{D}_s$ s-wave)	0^+
dips (origin)	threshold cusps	no resonance nor cusp complicated interference



Why J^P of $X(4274)$ and $X(4500)$ are different between our and LHCb analyses ?

→ Possibly from difference in describing the dips

J^P determination is model-dependent and influenced by assumptions in the analyses

Comparison with LHCb amplitude analysis

	Ours	LHCb
N_p (number of fitting parameters)	29	144
data	3 x one-dimensional distribution	six-dimensional distribution

N_p may tell us whether a model includes essential mechanisms or not

← If essential mechanisms are included, N_p would be small or reasonable

$\boldsymbol{N_p^{\mathrm{LHCb}} \sim 5 \times N_p^{\mathrm{ours}}}$ partly because data is different; data fitted by LHCb include more information

→ unlikely to explain ~5 times more fitting parameters

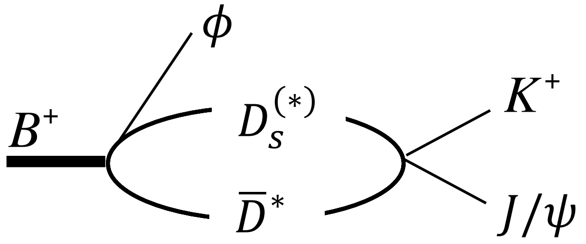
Our model setting (cusp at all peaks and dips) significantly reduces N_p

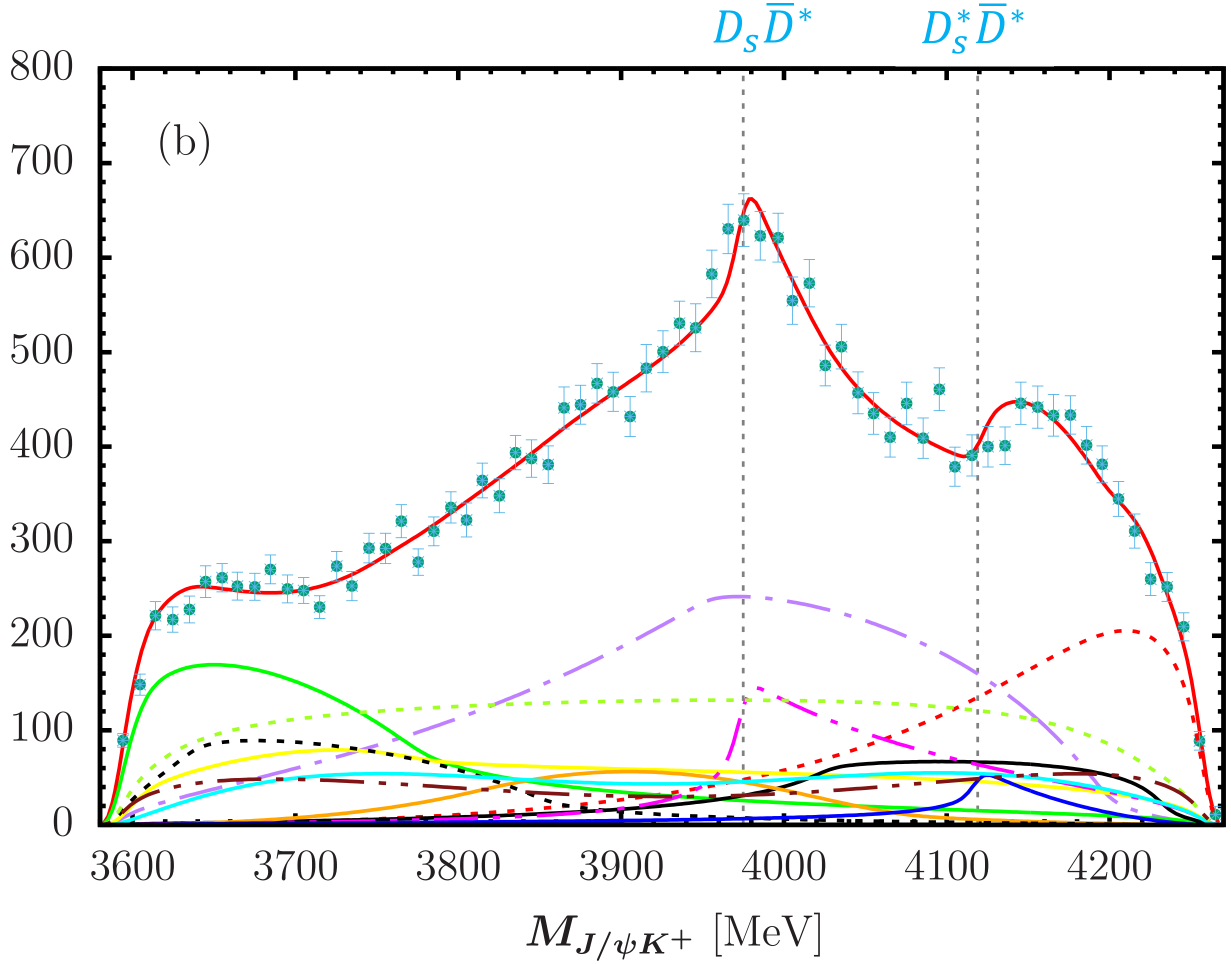
Likely, LHCb model misses relevant mechanisms (cusp) and mimic them with many other mechanisms through complicated interference → many fitting parameters

Z_{cs} as $D_s^{(*)}\bar{D}^*$ molecule ?

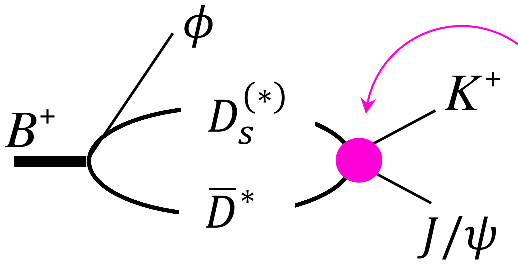
Our default fit describes Z_{cs} structures with $D_s^{(*)}\bar{D}^*$ threshold cusps

(no nearby poles)





Q: To what extent $D_s^{(*)}\bar{D}^*$ molecule scenario for Z_{cs} is allowed by the LHCb data ?



$D_s^{(*)}\bar{D}^*$ elastic scattering followed by a perturbative transition to $J/\psi K^+$

$D_s^{(*)}\bar{D}^*$ s-wave interaction strength is fitted to LHCb data

→ Virtual poles at ∼100 MeV below $D_s^{(*)}\bar{D}^*$ threshold or deeper

LHCb data disfavors hadron molecule scenario for Z_{cs}

Consistency with lattice QCD result related to Z_{cs}

Previous LQCD analyses on $Z_c(3900)$ in:

Prelovsek et al. PLB 727, 172 (2013), PRD 91, 014504 (2015)
Chen et al. PRD 89 , 094506 (2014)
Ikeda et al. (HAL QCD) PRL 117, 242001 (2016)
Cheung et al. (Hadron spectrum Collab.) JHEP 11, 033 (2017)

LQCD conclusion : $I = 1,\ J^{PC} = 1^{+-}\ D^*\overline{D}$ s-wave interaction is very weak,

disfavoring narrow $Z_c(3900)$ pole near $D^*\overline{D}$ threshold

SU(3) relation ↓

disfavoring narrow Z_{cs} pole near $D_s\overline{D}^*$ threshold

Our analysis result is consistent with LQCD-based expectation on Z_{cs}

To reach this consistency, considering threshold cusps is must

Summary

Resonance-like structures at thresholds should be suspected to be kinematical cusps

→ Message to ongoing and future experimental analyses

$B^+ \to J/\psi\ \phi\ K^+$ as an interesting case study

- We developed a model accounting for all relevant threshold cusps
- $M_{J/\psi\phi}$, $M_{J/\psi K^+}$, and $M_{K^+\phi}$ distributions are simultaneously well fitted without nearby poles

  All peaks and dips in the spectra are generated by the threshold cusps
- Results from our analysis (threshold cusps) and LHCb's analysis (Breit-Wigner resonances) are quite different

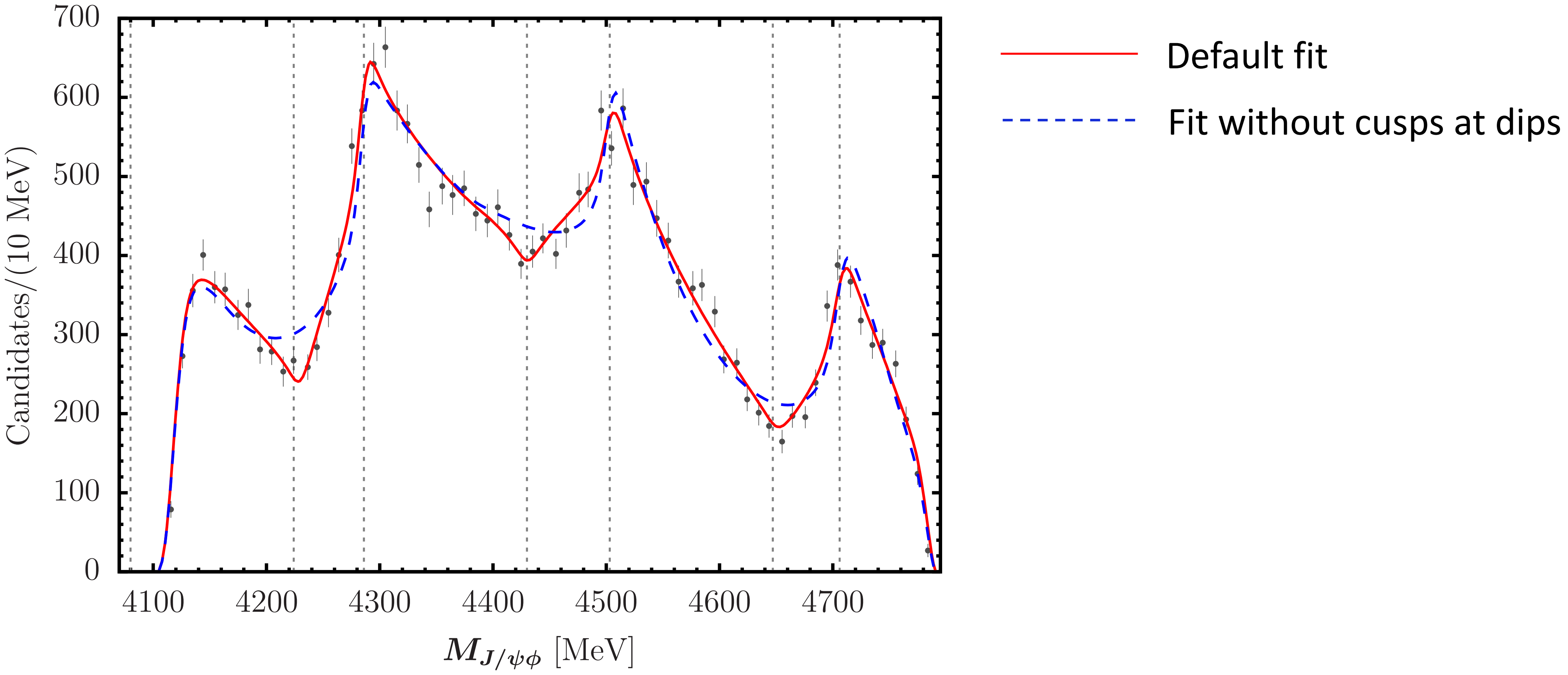
  -- J^P of $X(4274)$ and $X(4500)$: 0^- and 1^- (Ours) 1^+ and 0^+ (LHCb)

  -- $N_p^{\mathrm{LHCb}} \sim 5 \times N_p^{\mathrm{ours}}$ suggests threshold cusps at peaks and dips are essential mechanisms

  -- With $D_s^{(*)}\bar{D}^*$ threshold cusps taken into account, LHCb data disfavors molecule scenario for Z_{cs}, being consistent with LQCD result via SU(3) relation

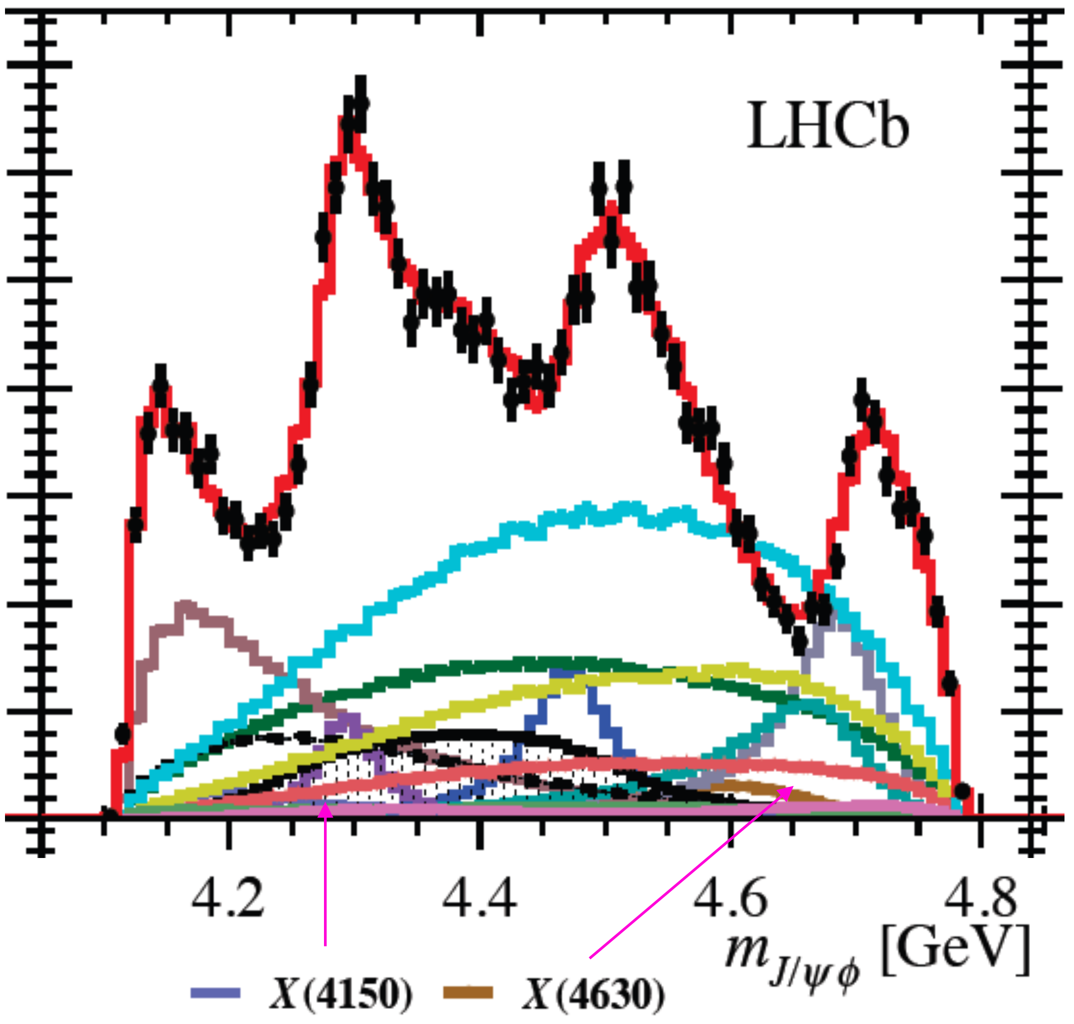
Backup

Fit without cusps at dip locations



Within our model, the dip regions are not well fitted without the threshold cusps

$2^{-}X(4150)$ and $1^{-}X(4630)$ claimed by LHCb



$2^{-}X(4150)$ and $1^{-}X(4630)$ do not create visible peaks,

but improve the fit through interference in LHCb analysis

$2^{-}X(4150)$ and $1^{-}X(4630)$ are added to our default model

→ No significant improvement

Our conclusion: their importance is model-dependent

Cutoff dependence