Pole determination of first discovered pentaquark with strangeness

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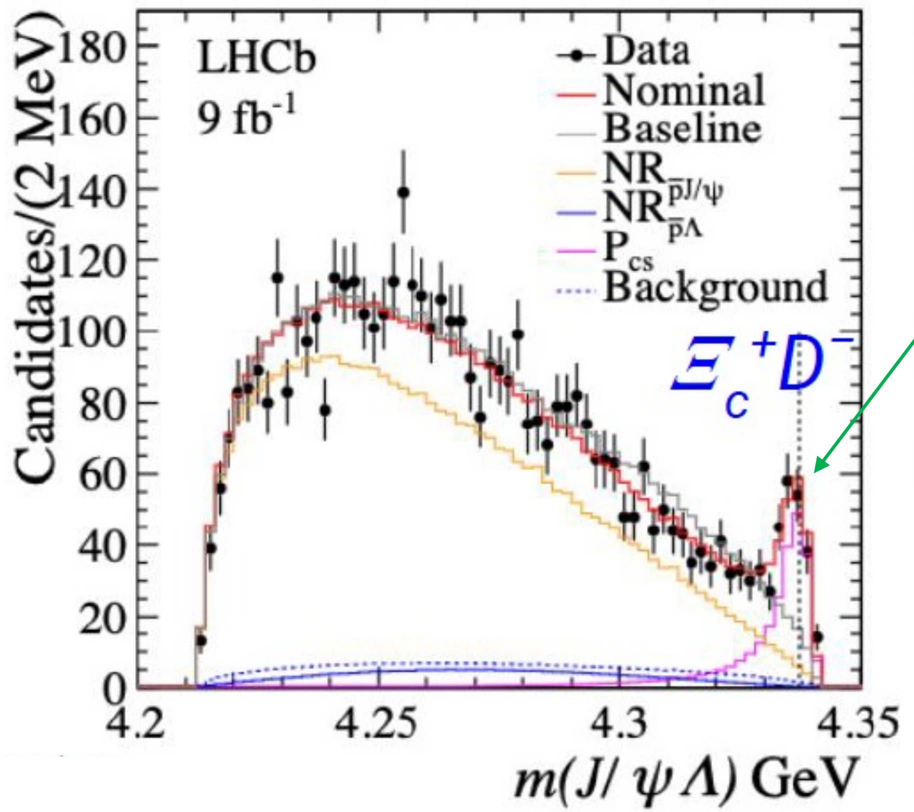
Introduction

New LHCb data on $B^- \to J/\psi\Lambda\bar{p}$

arXiv:2210.10346



Discovery (>10σ) of first pentaquark candidates with strangeness ($c\bar{c}uds$)

$P_{\psi s}^{\Lambda}(4338)$ propertiers:

$M = 4338.2 \pm 0.7 \pm 0.4$ MeV (mass)

$\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV (width)

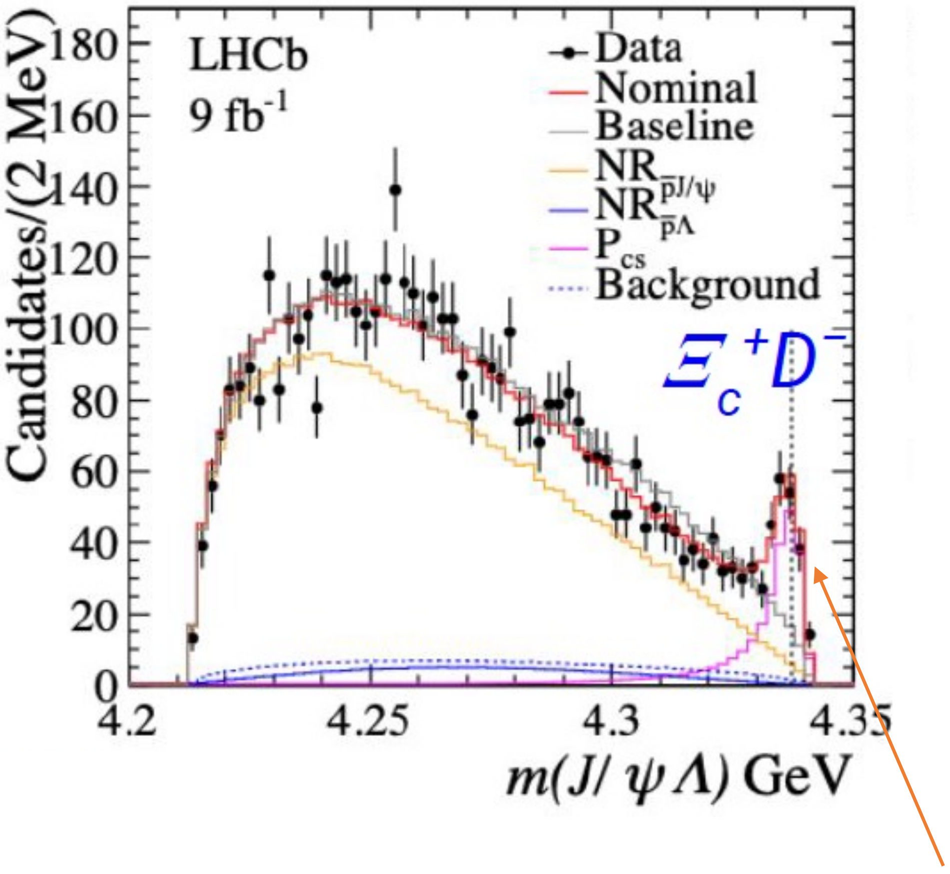
$J^P = 1/2^-$ (spin parity)

M, Γ, and J^P are crucial information to understand

the nature (hadron molecule, compact pentaquark, etc.) of $P_{\psi s}^{\Lambda}(4338)$

Q: M and Γ determined by LHCb are reliable ?

Basic assumption in LHCb amplitude analysis : Breit-Wigner (BW) amplitude well simulates $P_{\psi s}^{\Lambda}(4338)$



BW fit

Resonance-like peak is right on the $\Xi_c \bar{D}$ threshold

→ BW fit (no unitarity) ignores important physics

- Resonance-like $\Xi_c \bar{D}$ threshold cusp appears (kinematical effect) even without a pole

In the presence of a pole

- Distortion of peak shape due to $\Xi_c \bar{D}$ branch point and cut
- Rapid increase of width just above $\Xi_c \bar{D}$ threshold

M and Γ from BW fit are quetionable

What needs to be done ?

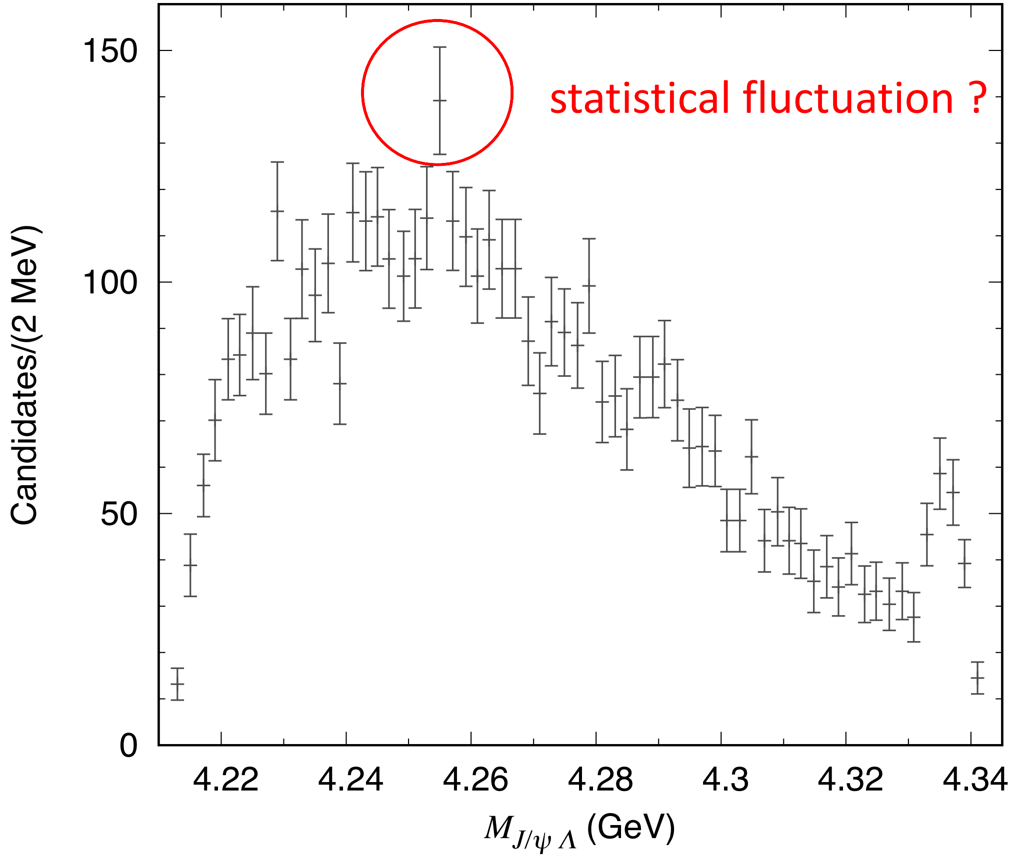
Ans. Replace BW fit with the proper pole extraction method ← The main task of this work

- Unitary coupled-channel amplitude is fitted to data
- Poles on relevant Riemann sheets are searched by analytic continuation of the amplitude

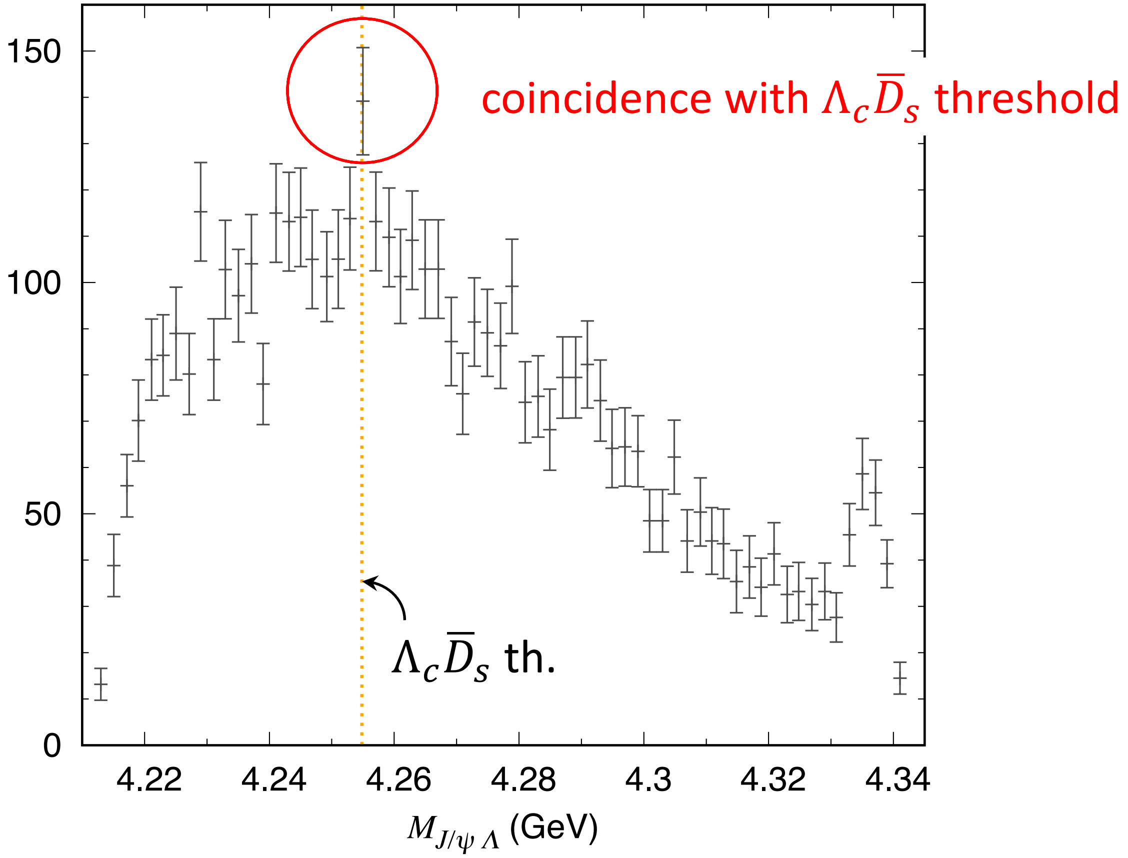
The pole value is:

- Important knowledge reflecting QCD dynamics
- Primary basis to study the nature of the pentaquark

Possible $P_{\psi s}^{\Lambda}(4255)$?



statistical fluctuation ?



coincidence with $\Lambda_c\bar{D}_s$ threshold

Possibility : $\Lambda_c\bar{D}_s$ threshold cusp is enhanced by a nearby pole $P_{\psi s}^{\Lambda}(4255)$ → to be examined

In this work

Conduct amplitude analysis on the LHCb data for $B^- \to J/\psi \Lambda \bar{p}$

$M_{J/\psi\Lambda}$, $M_{J/\psi\bar{p}}$, $M_{\Lambda\bar{p}}$, and $\cos\theta_{K^*}$ distribution data are simultaneously fitted with a model in which $\Xi_c \overline{D} - \Lambda_c \overline{D}_s$ coupled-channel amplitude is implemented

Based on the $\Xi_c \overline{D} - \Lambda_c \overline{D}_s$ amplitude, we address:

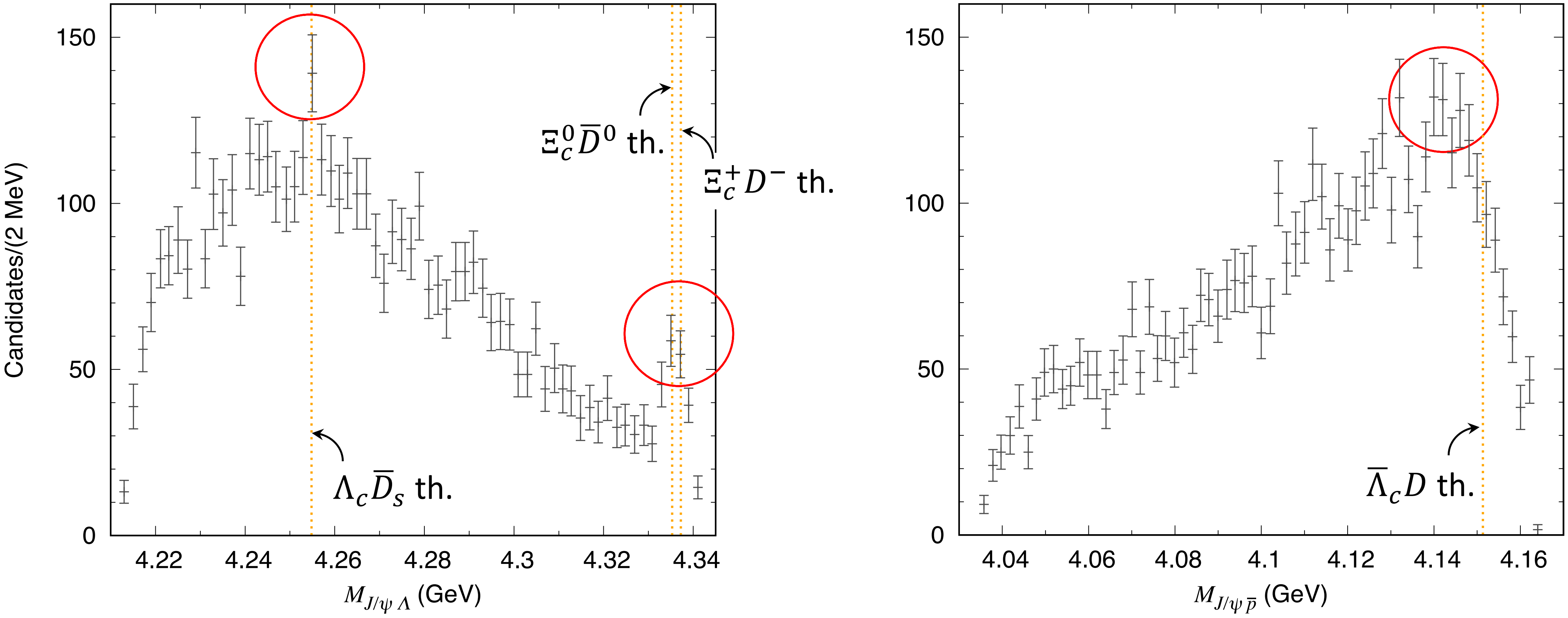
(i) Pole position of $P_{\psi s}^{\Lambda}(4338)$

(ii) Possibility that $P_{\psi s}^{\Lambda}(4338)$ is merely a threshold cusp (no pole)

(iii) Implication of large fluctuation at $\Lambda_c \overline{D}_s$ threshold

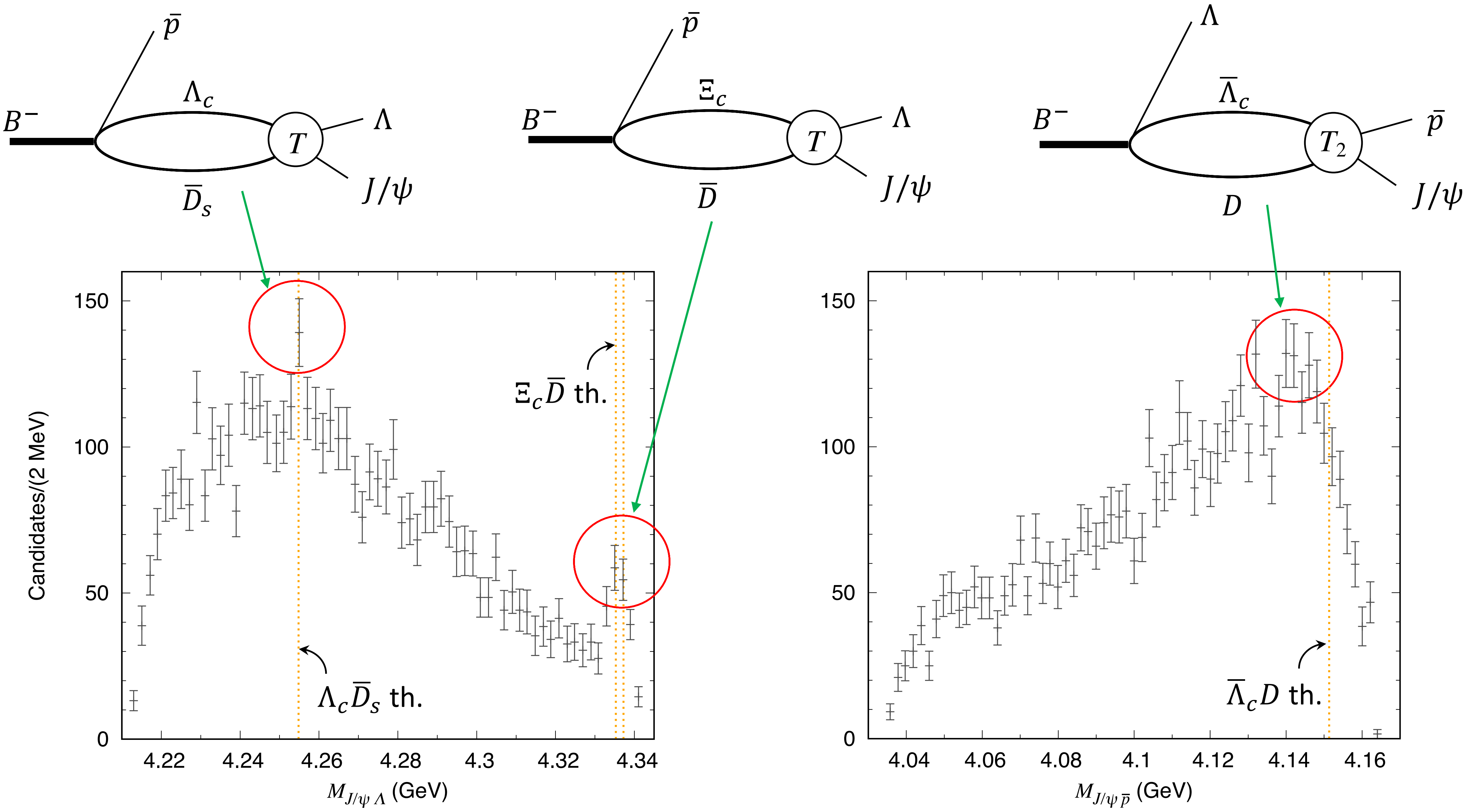
Model

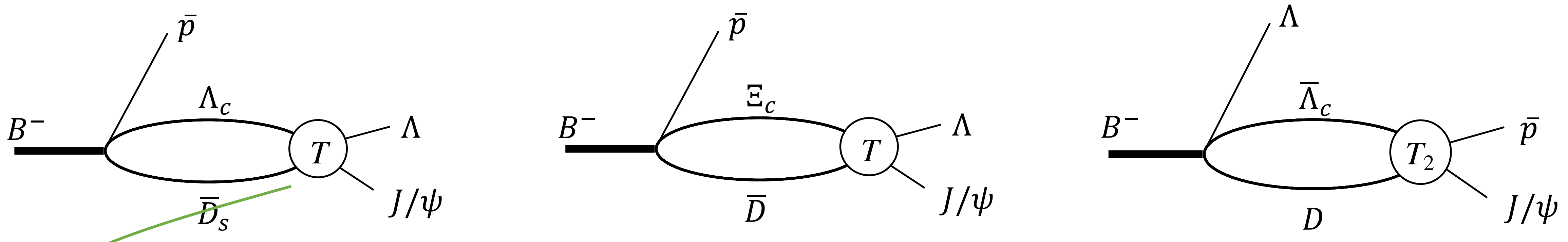
Model for $B^- \to J/\psi \Lambda \bar{p}$



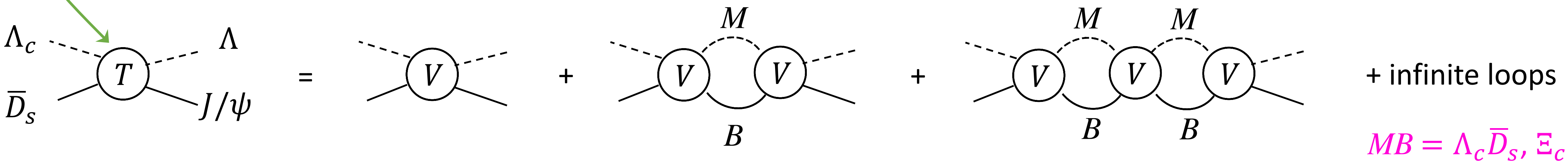
All visible structures are at thresholds

→ threshold cusps enhanced or suppressed by hadron scattering and pole (reasonable assumption)


B^-
$\bar{p}$
Λ_c
T
Λ
J/ψ
$\bar{D}_s$
B^-
$\bar{p}$
Ξ_c
T
Λ
J/ψ
$\bar{D}$
B^-
Λ
$\bar{\Lambda}_c$
T_2
$\bar{p}$
J/ψ
D
Candidates/(2 MeV)
150
100
50
0
4.22
4.24
4.26
4.28
4.3
4.32
4.34
$M_{J/\psi\,\Lambda}$ (GeV)
$\Xi_c\bar{D}$ th.
$\Lambda_c\bar{D}_s$ th.
150
100
50
0
4.04
4.06
4.08
4.1
4.12
4.14
4.16
$M_{J/\psi\,\bar{p}}$ (GeV)
$\bar{\Lambda}_c D$ th.



$\Lambda_c\bar{D}_s - \Xi_c\bar{D} - J/\psi\Lambda$ (T) and $\bar{\Lambda}_c D - J/\psi\bar{p}$ (T_2) coupled-channel s-wave amplitudes are implemented

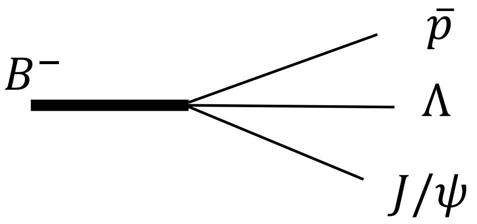


$MB = \Lambda_c\bar{D}_s, \Xi_c\bar{D}$

Data-driven MB contact interactions (V) and coupled-channel unitarity : idea similar to K-matrix approach

Transitions to $J/\psi\Lambda$ and $J/\psi\bar{p}$ channels are treated perturbatively; heavy-quark exchange is expected to be weak

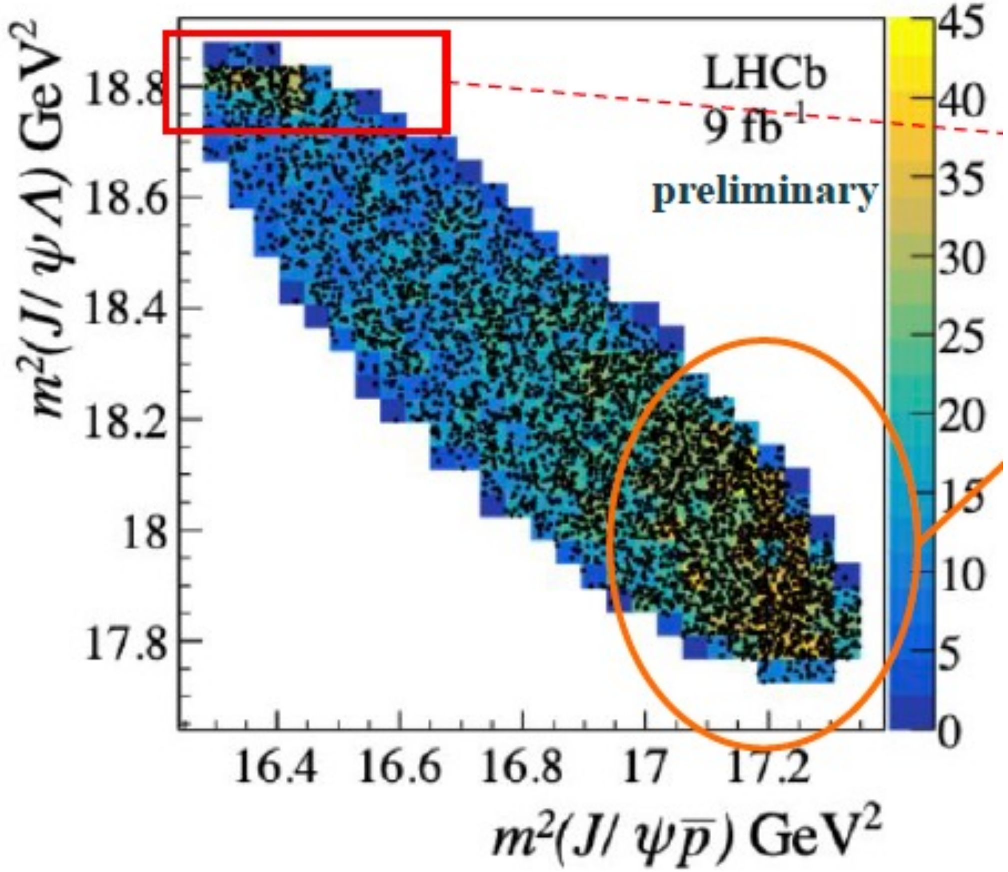
Other mechanisms are assumed to be absorbed in →

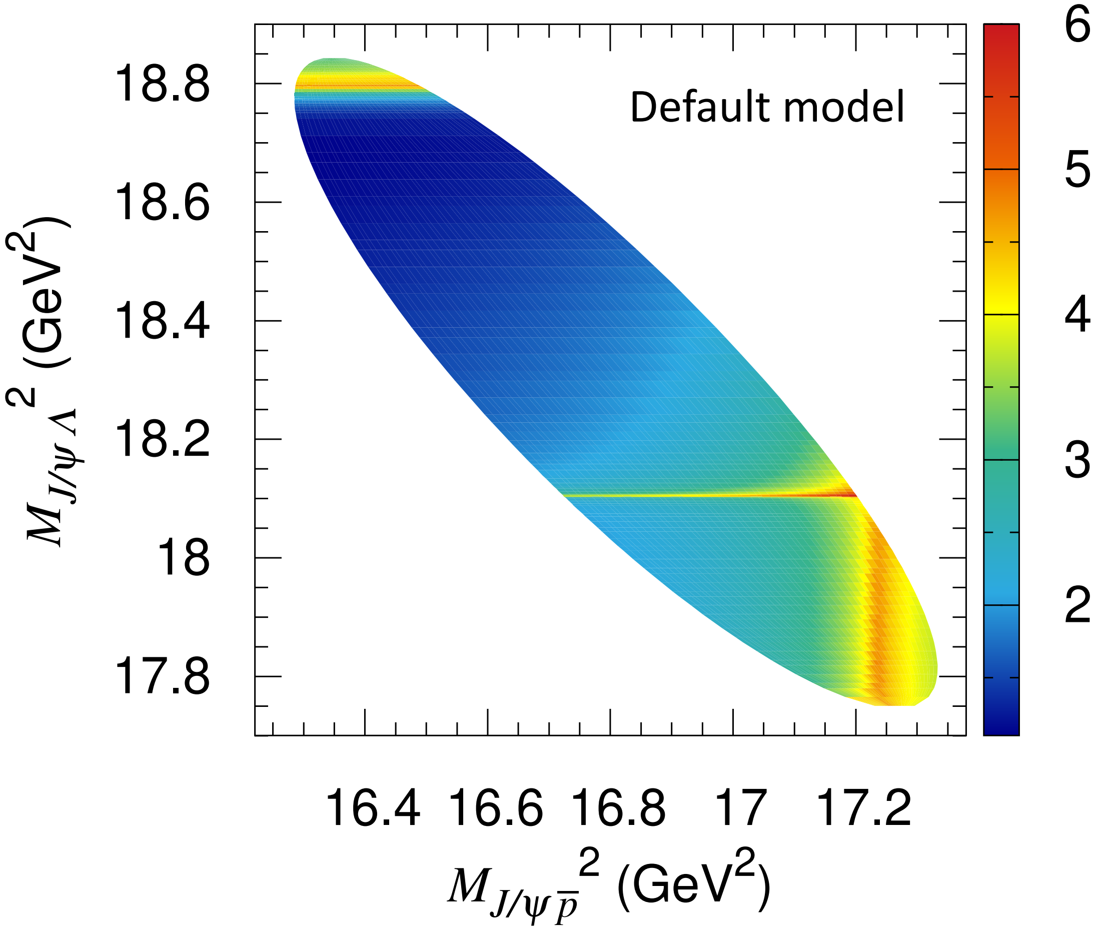


Results

Dalitz plot for $B^- \to J/\psi\Lambda\bar{p}$

LHCb seminar
07/05/2022

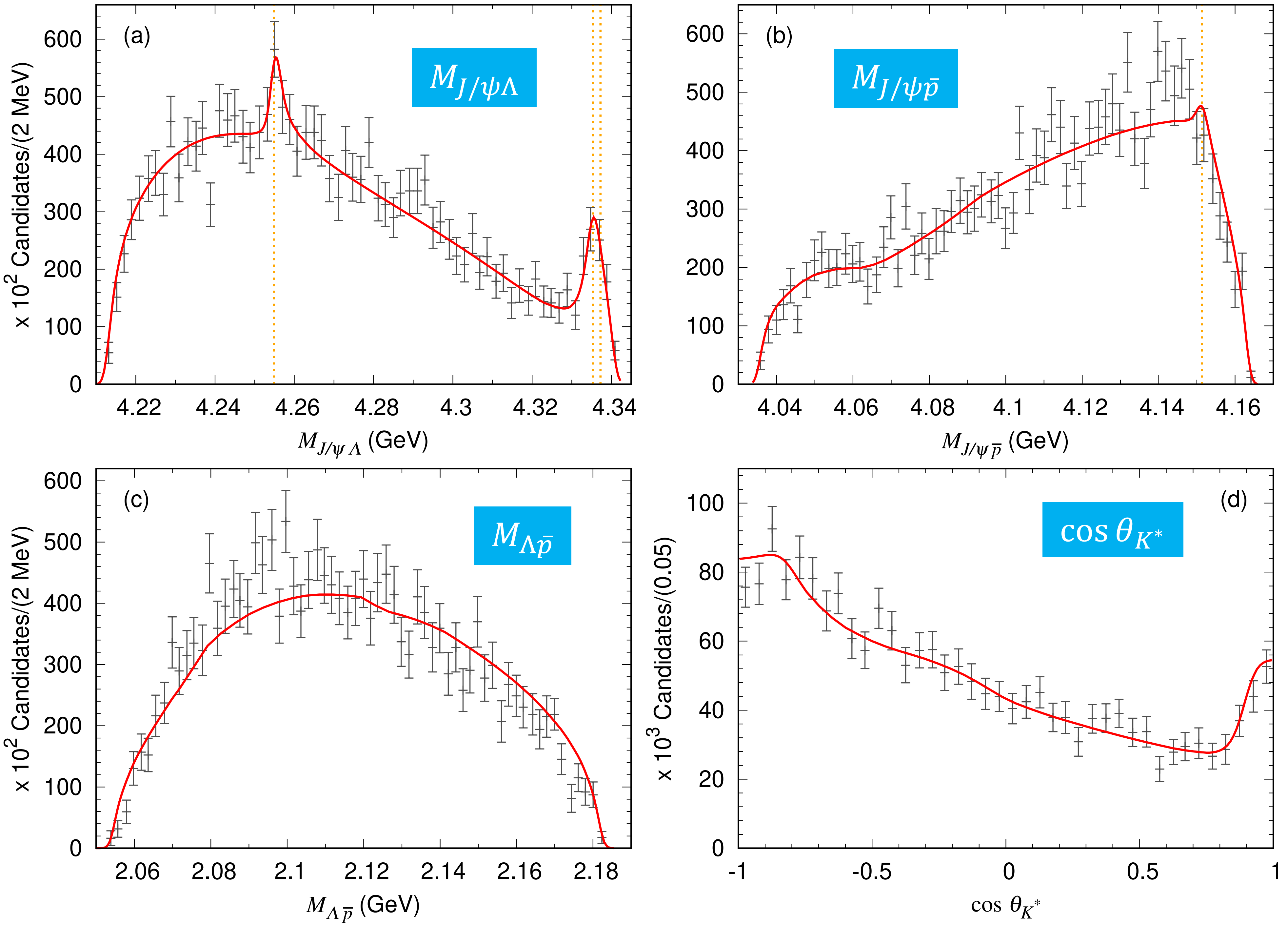




Note: No smearing due to experimental resolution is applied

→ Peak structures seem sharper than data

Fit to LHCb data for $B^- \to J/\psi \Lambda \bar{p}$



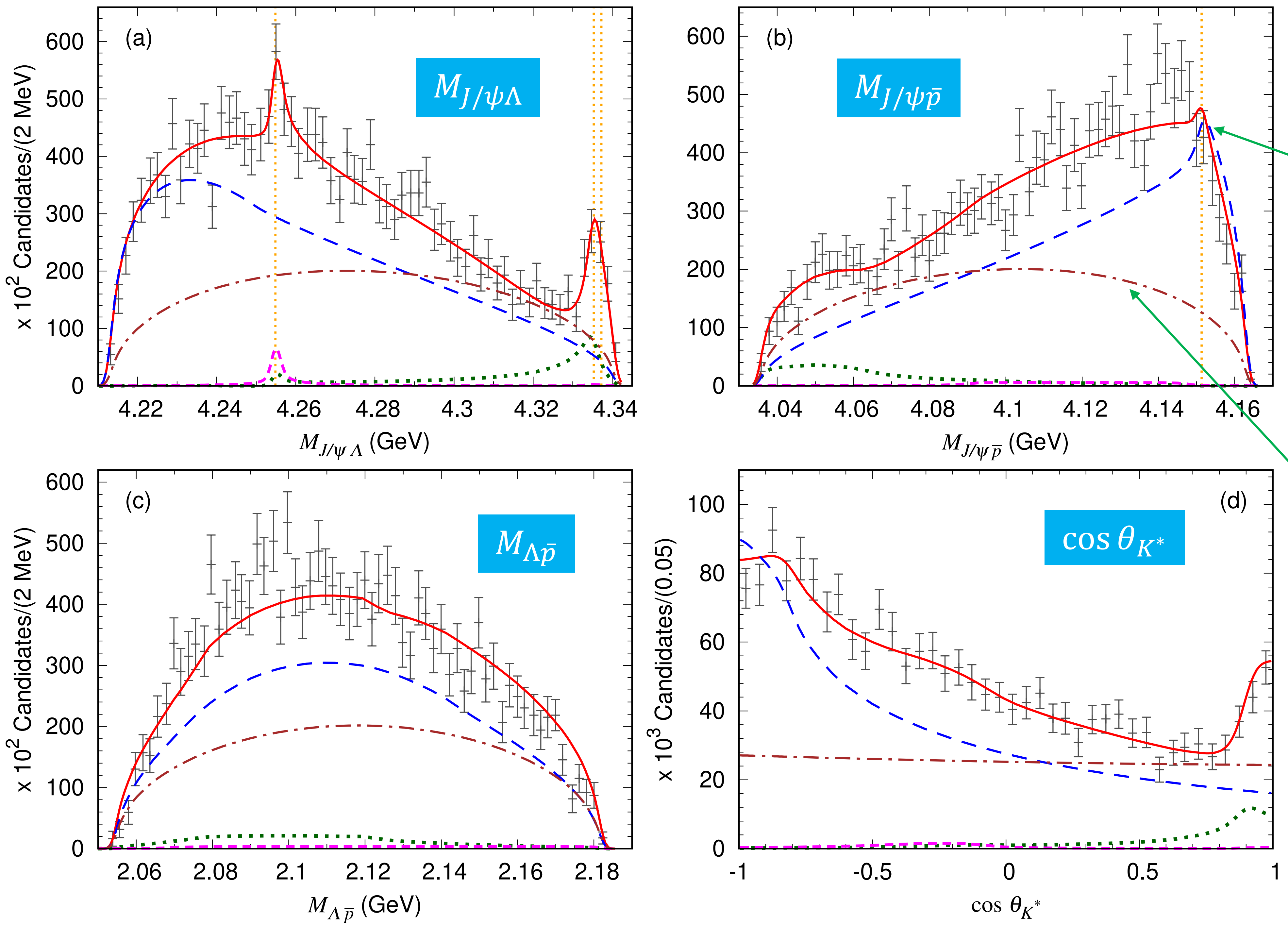
Four distribution data are simultaneously fitted

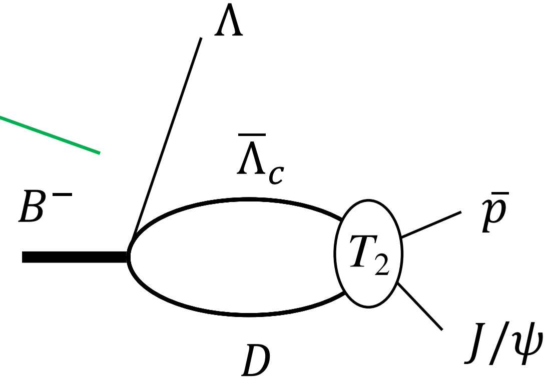
Smearing with bin width applied

$\cos\theta_{K^*} \equiv \hat{p}_\Lambda \cdot \hat{p}_{J/\psi}$ in $\Lambda\bar{p}$ CM frame

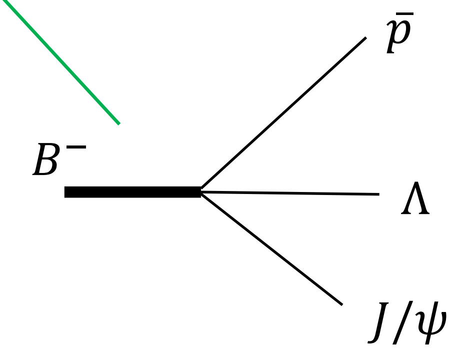
χ^2/ndf ~ 1.20
9 parameters

Fit to LHCb data



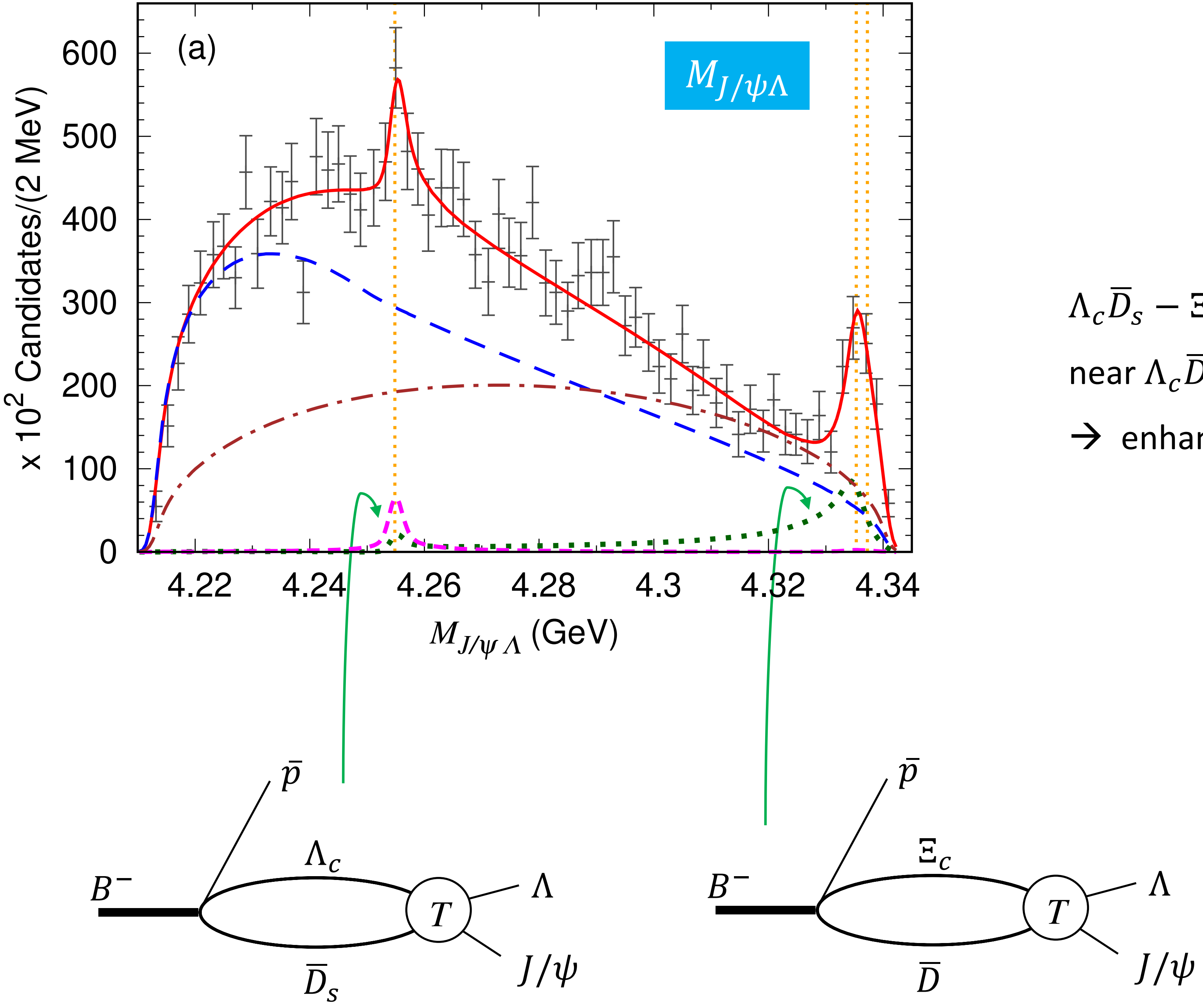


Repulsive $\bar{\Lambda}_c D$ interaction causes suppressed cusp, increasing $M_{J/\psi\bar{p}}$ lineshape



Contribution of phase-space-like shape

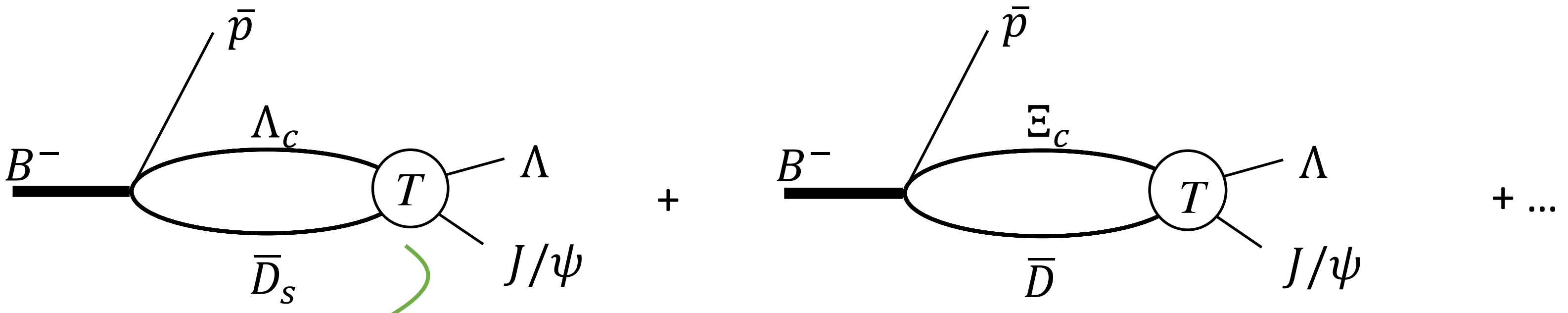
Fit to LHCb data



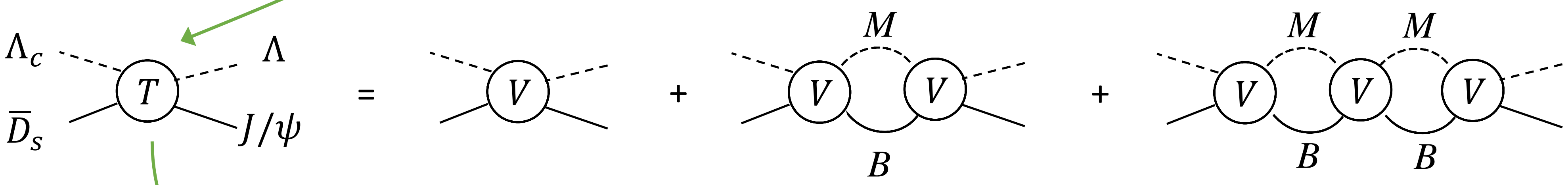
$\Lambda_c\bar{D}_s - \Xi_c\bar{D}$ coupled-channel scattering causes poles near $\Lambda_c\bar{D}_s$ and $\Xi_c\bar{D}$ thresholds

→ enhanced threshold cusps

Pole locations



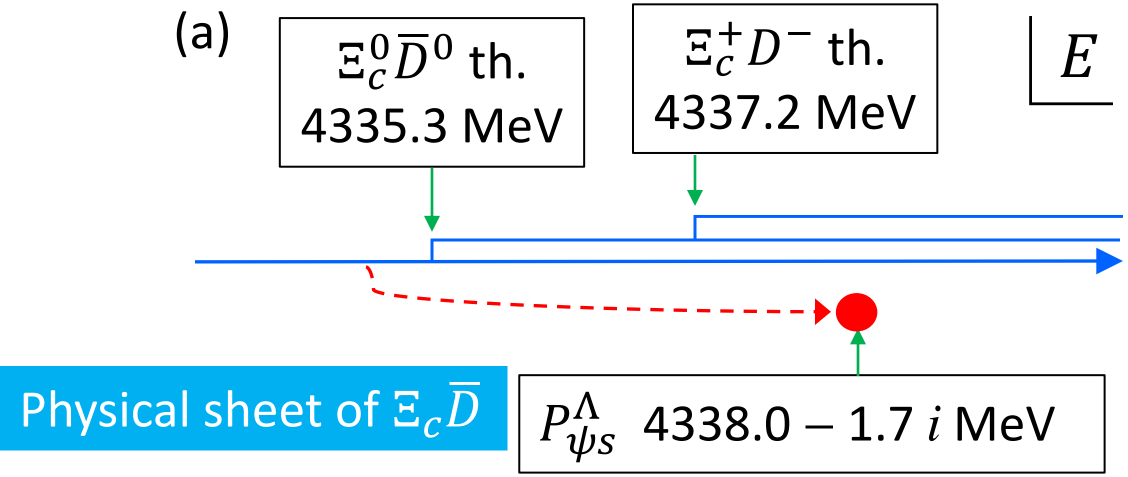
← Fitted to LHCb data



+ infinite loops

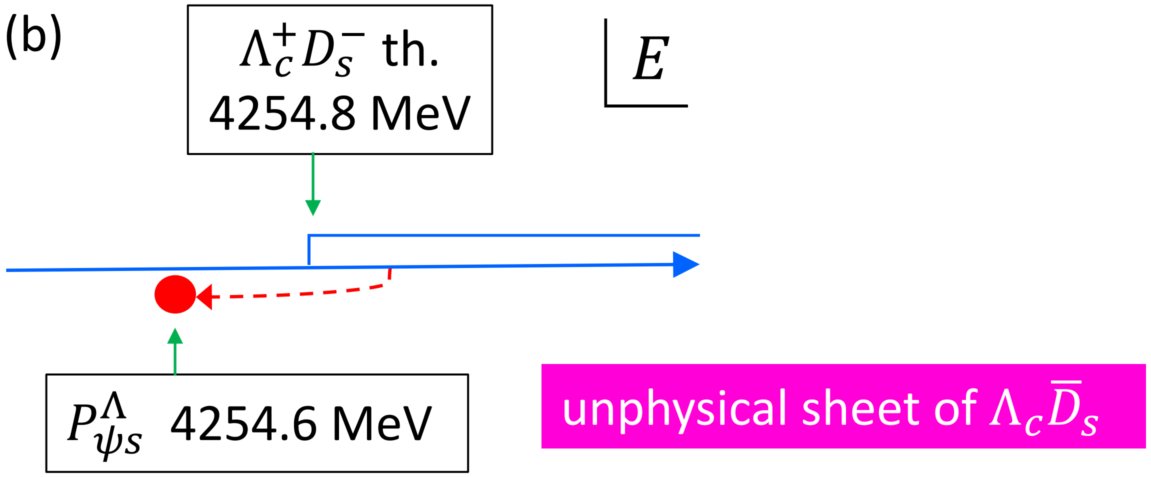
$MB = \Lambda_c \bar{D}_s, \Xi_c \bar{D}$

Analytically continued to complex E where $T(E) \sim 1/(E - E_{\text{pole}})$



$P_{\psi s}^{\Lambda}$ 4338.0 – 1.7 i MeV

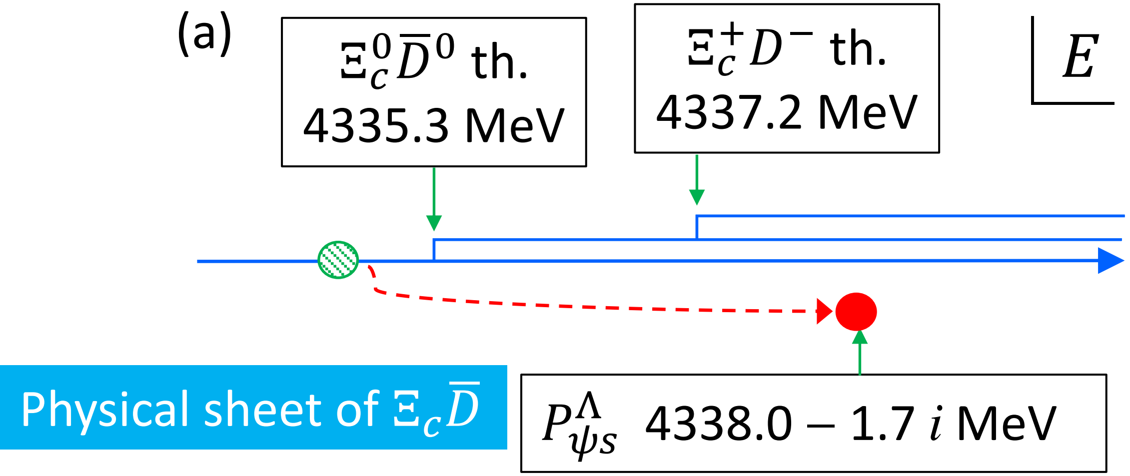
Physical sheet of $\Xi_c \bar{D}$



$P_{\psi s}^{\Lambda}$ 4254.6 MeV

unphysical sheet of $\Lambda_c \bar{D}_s$

Pole locations



(a)

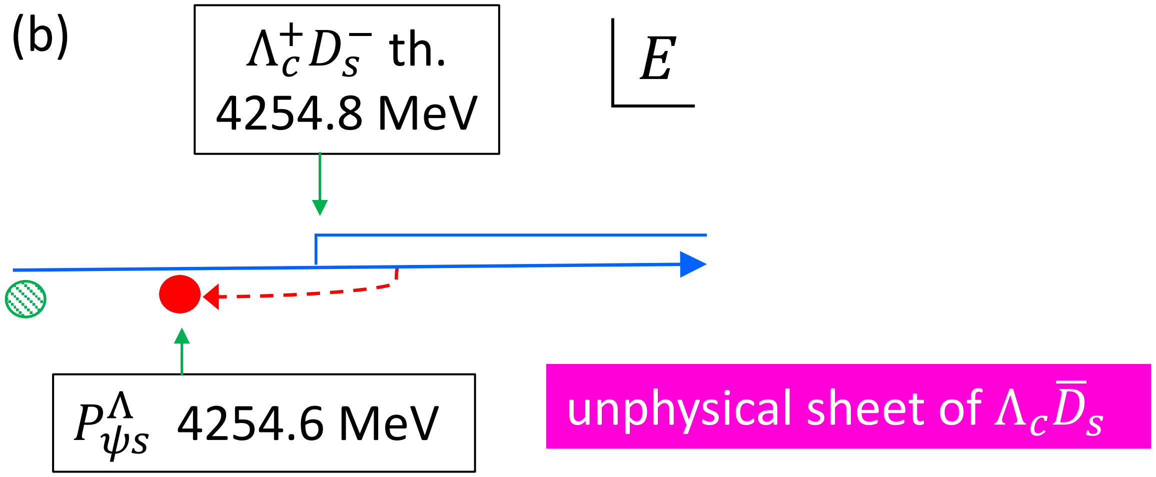
$\Xi_c^0 \bar{D}^0$ th.
4335.3 MeV

$\Xi_c^+ D^-$ th.
4337.2 MeV

E

Physical sheet of $\Xi_c \bar{D}$

$P_{\psi s}^{\Lambda}$ 4338.0 – 1.7 i MeV



(b)

$\Lambda_c^+ D_s^-$ th.
4254.8 MeV

E

$P_{\psi s}^{\Lambda}$ 4254.6 MeV

unphysical sheet of $\Lambda_c \bar{D}_s$

Pole effects on the physical energy region (spectrum lineshape) are significantly screened by branch cut

Resonance-like lineshapes are caused by kinematical threshold cusps, and poles moderately enhance them

Poles are from $\Xi_c \bar{D} - \Lambda_c \bar{D}_s$ s-wave amplitude → $J^P = 1/2^-$ poles; consistent with LHCb analysis result

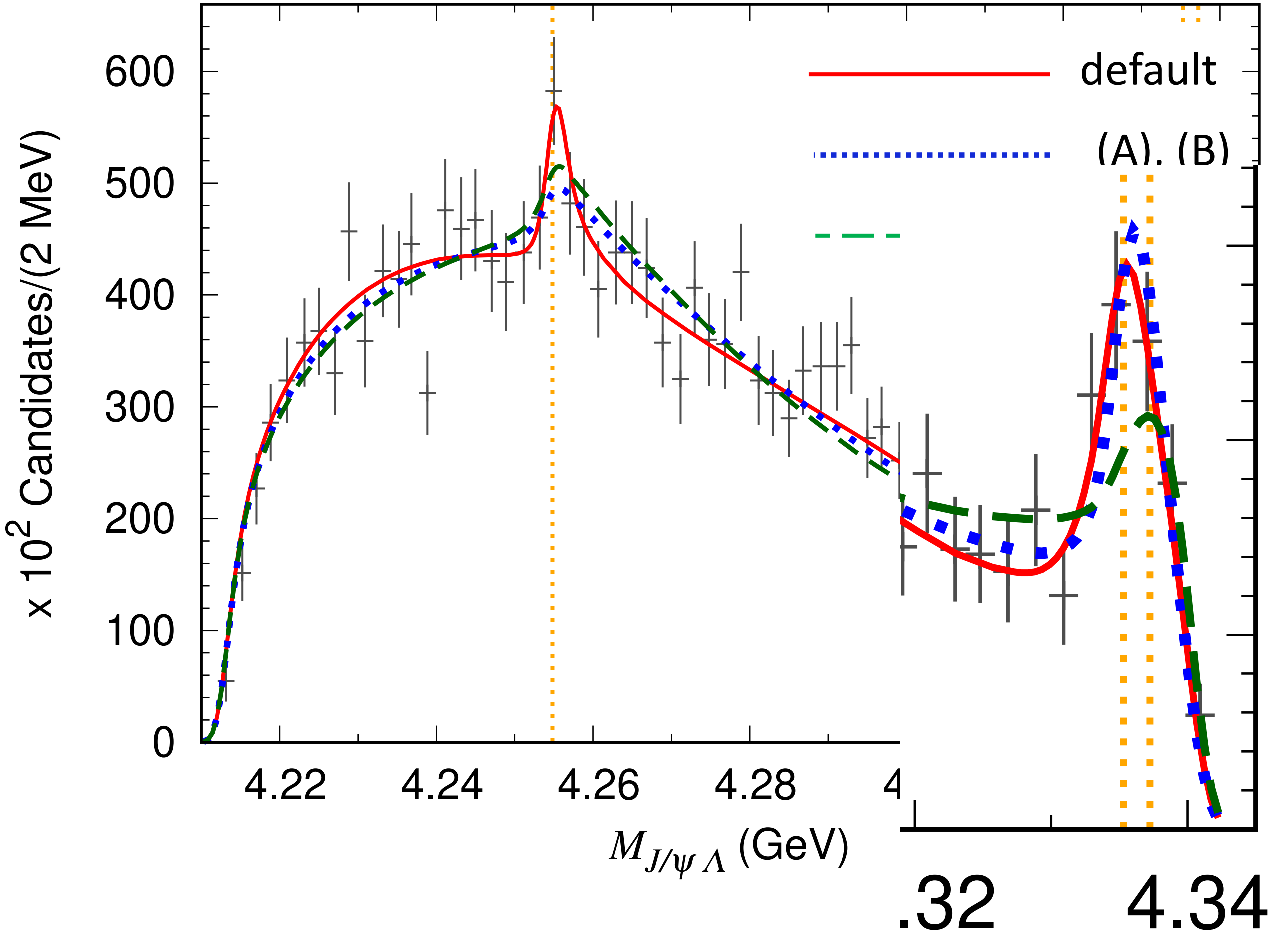
Without coupled-channel effects	$\Xi_c \bar{D} \to \Xi_c \bar{D}$ interaction only	$\Lambda_c \bar{D}_s \to \Lambda_c \bar{D}_s$ interaction only
	$\Xi_c \bar{D}$ bound state → ▨	$\Lambda_c^+ D_s^-$ virtual state → ▨

Other solutions

(A) $P_{\psi s}^{\Lambda}(4255)$ pole doesn't exist; the fluctuation is just statistical

(B) $\Xi_c\overline{D} \to \Xi_c\overline{D}$ interaction has energy dependence (default result is from energy-independent interaction)

(C) Nearby poles do not exist; peak structures in data are solely from threshold cusps



(A) and (B) have fit quality comparable to default fit

$\Lambda_c\overline{D}_s$ threshold cusp w/o pole

(C) fit in $P_{\psi s}^{\Lambda}(4338)$ peak region is visibly worse

→ $P_{\psi s}^{\Lambda}(4338)$ is not merely a threshold cusp

a nearby pole exists

Pole locations for other solutions

$P_{\psi s}^{\Lambda}(4338)$

Solution	E_{pole} (MeV)	sheet $(s_{\Lambda_c \bar{D}_s}\, s_{\Xi_c^0 \bar{D}^0}\, s_{\Xi_c^+ D^-})$		w/o coupled-channel
(default)	$(4338.0 \pm 1.1) - (1.7 \pm 0.4)i$	(upp)		$\Xi_c \bar{D}$ bound pole
(A)	$(4330.7 \pm 4.0) + (3.9 \pm 5.4)i$	(pup)	+ (ppu), (upu) poles	$\Xi_c \bar{D}$ virtual pole
(B)	$(4337.3 \pm 1.3) - (5.1 \pm 2.5)i$	(uuu)	+ (upp), (uup) poles	$\Xi_c \bar{D}$ resonance pole

$P_{\psi s}^{\Lambda}(4255)$

(default)	4254.6 ± 0.5	(upp)	$\Lambda_c \bar{D}_s$ virtual pole

Depending on the solutions, $P_{\psi s}^{\Lambda}(4338)$ pole is located on different Riemann-sheet → More data needed

- Higher statistics $B^- \to J/\psi \Lambda \bar{p}$ not only pin down existence of $P_{\psi s}^{\Lambda}(4255)$ but constrain $P_{\psi s}^{\Lambda}(4338)$ pole sheet
- $\Xi_b^- \to J/\psi \Lambda K^-$ should show pole effect more clearly, since no shrinking phase-space near kinematical end

→ favor or disfavor resonance pole (larger width)

Summary

Summary

- Amplitude analysis of new LHCb data of $B^- \to J/\psi \mathit{\Lambda} \bar{p}$
- $M_{J/\psi\Lambda}$, $M_{J/\psi\bar{p}}$, $M_{\Lambda\bar{p}}$, and $\cos\theta_{K^*}$ distributions are fitted simultaneously; $\chi^2/\mathrm{ndf} \sim 1.20$
- First pole determination of first discovered pentaquark candidate with strangeness $P_{\psi s}^{\Lambda}(4338)$

    -- important in its own right, knowledge of QCD dynamics

    -- primary basis to study the nature of $P_{\psi s}^{\Lambda}(4338)$

- Data disfavors hypothesis that the $P_{\psi s}^{\Lambda}(4338)$ peak is just a kinematical effect
- $P_{\psi s}^{\Lambda}(4255)$ might exist, and its pole is determined
- Alternative solutions have $P_{\psi s}^{\Lambda}(4338)$ poles on different Riemann sheets

    → future data needed to discriminate them

Comment

Recent theoretical papers identified their $\Xi_c\bar{D}$ bound states with $P^{\Lambda}_{\psi s}(4338)$

Common argument : their $\Xi_c\bar{D}$ bound state energy is consistent with M and Γ from LHCb analysis

$M = \underline{4338.2 \pm 0.7 \pm 0.4\ \text{MeV}}$ $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV

1.0 (2.9) MeV above $\Xi_c^+ D^-$ ($\Xi_c^0 \bar{D}^0$) threshold, indicating resonance not bound state, even considering error

→ The LHCb result rules out (or disfavors) the bound state solutions

Good news for $\Xi_c\bar{D}$ bound state model

BW fit employed in the LHCb analysis is unsuitable to describe $P^{\Lambda}_{\psi s}(4338)$

Our proper pole extraction (default model) supports $\Xi_c\bar{D}$ bound state solution for $P^{\Lambda}_{\psi s}(4338)$

Theoretical calculations of $P^{\Lambda}_{\psi s}(4338)$ should be compared with our pole values; not BW values

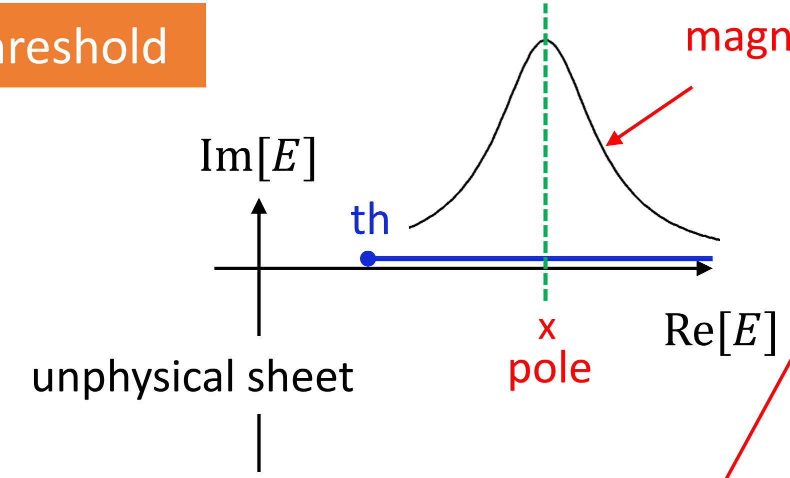
Backup

Pole locations for other solutions

Solution		E_{pole} (MeV)	sheet $(s_{\Lambda_c \bar{D}_s}\ s_{\Xi_c^0 \bar{D}^0}\ s_{\Xi_c^+ D^-})$	
default	$P_{\psi s}^{\Lambda}(4338)$	$(4338.0 \pm 1.1) - (1.7 \pm 0.4)\, i$	(upp)	$\Xi_c \bar{D}$ bound pole
	$P_{\psi s}^{\Lambda}(4255)$	4254.6 ± 0.5	(upp)	$\Lambda_c \bar{D}_s$ virtual pole
(A)	$P_{\psi s}^{\Lambda}(4338)$	$(4334.2 \pm 3.6) + (5.3 \pm 5.7)\, i$	(ppu)	
		$(4330.7 \pm 4.0) + (3.9 \pm 5.4)\, i$	(pup)	
		$(4336.4 \pm 1.4) - (0.1 \pm 1.3)\, i$	(upu)	
(B)	$P_{\psi s}^{\Lambda}(4338)$	$(4338.9 \pm 1.7) - (2.2 \pm 0.7)\, i$	(upp)	
		$(4338.8 \pm 1.9) - (4.3 \pm 2.1)\, i$	(uup)	
		$(4337.3 \pm 1.3) - (5.1 \pm 2.5)\, i$	(uuu)	$\Xi_c \bar{D}$ resonance pole

Impact of pole on amplitude on the physical energy axis (data)

- Pole far from threshold

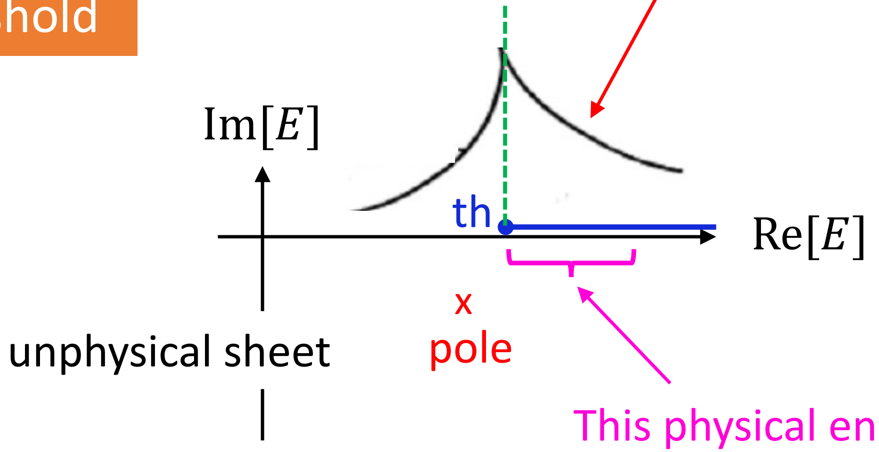


magnitude of amplitude on physical real energy

Breit-Wigner form is

good approximation

- Pole near threshold



- The existence of branch point (threshold) distorts the spectrum shape (data)
- Breit-Wigner ignores branch point (no unitarity)

→ not suitable for pole near threshold

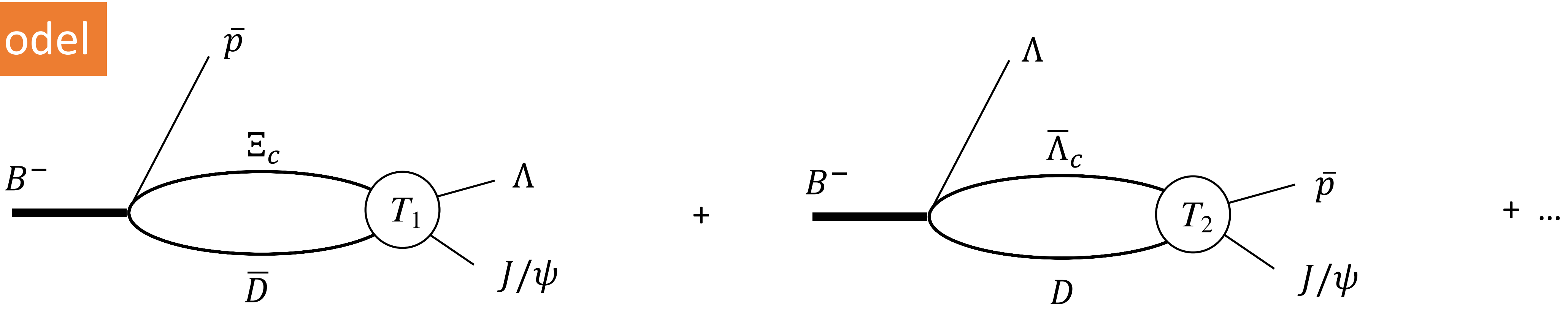
This physical energy region is most affected by pole

1^{st} step : Obtain partial wave amplitudes from data

2^{nd} step : Fit partial wave amplitudes with a model

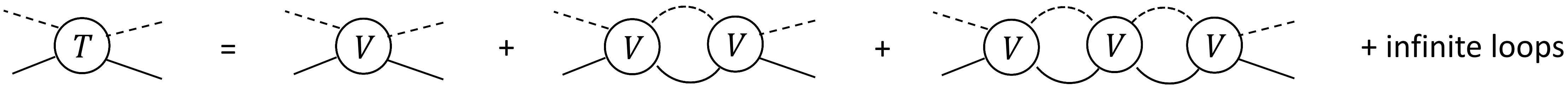
→ In most three-body decay analysis we directly fit data with model

Model



Two-body scattering amplitude T is implemented in three-body decay amplitude

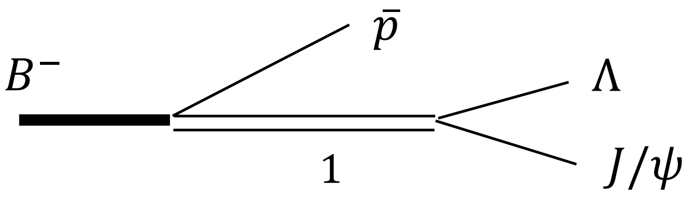
Dynamical model



K-matrix model

$$T\,(E) = \frac{K}{1 - i\rho K}$$

Breit-Wigner model



$$\frac{1}{M_{J/\psi\Lambda} - M_{BW} + i\Gamma_{BW}/2}$$