$P_c(4312)$, $P_c(4380)$, and $P_c(4457)$ as double triangle cusps

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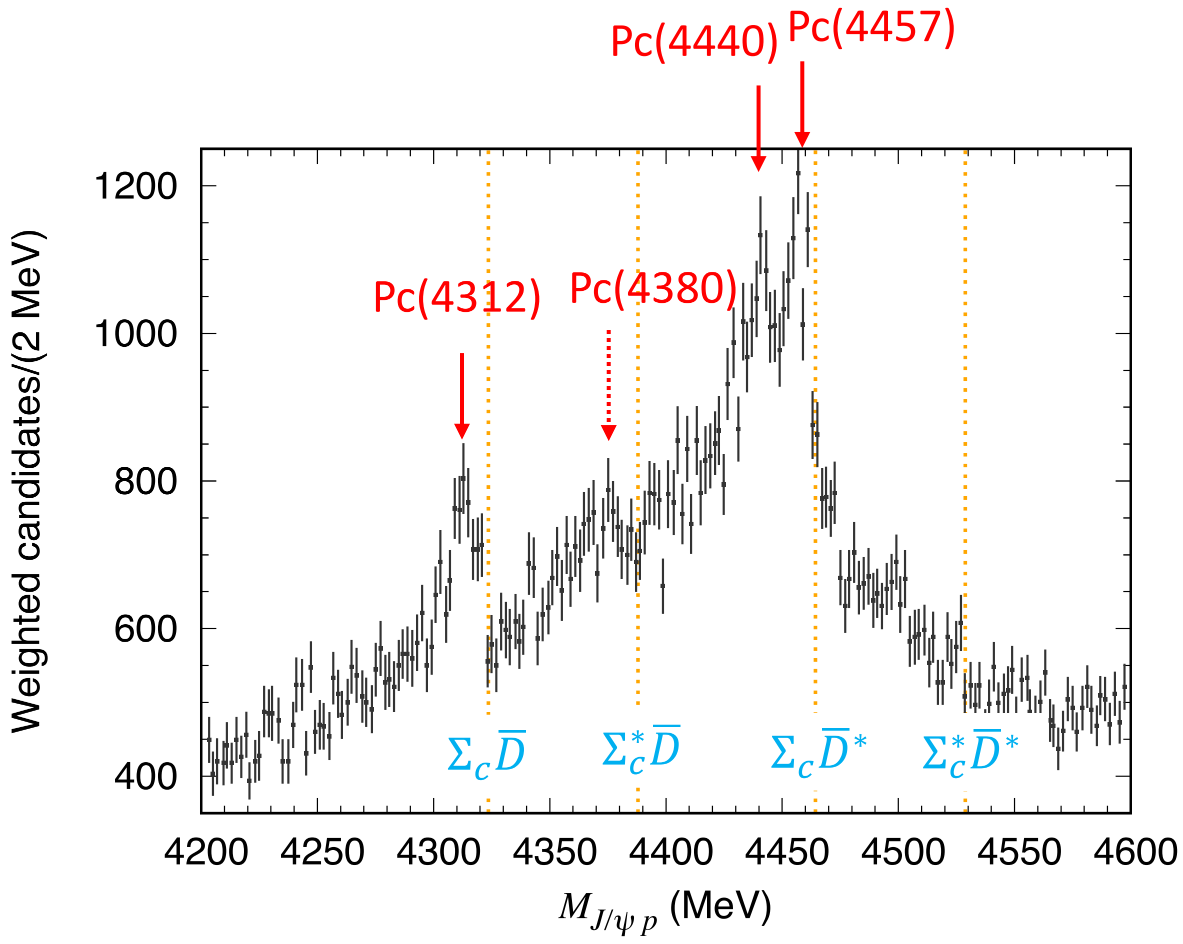
Introduction

P_c signals in $\Lambda_b^0 \to J/\psi\, p\, K^-$ data



LHCb, PRL 122, 222001 (2019)

Spectrum bumps suggest:

resonance
bound state
virtual state
(poles)

} decay → $J/\psi\, p$

$c\bar{c}\ \ uud$ ← pentaquark

Peaks at slightly below $\Sigma_c^{(*)}\bar{D}^{(*)}$ thresholds

$\Sigma_c : \Sigma_c(2455)$
$\Sigma_c^* : \Sigma_c(2520)$

→ $\Sigma_c^{(*)}\bar{D}^{(*)}$ bound states (hadron molecule) ?

Other possibilities also proposed:

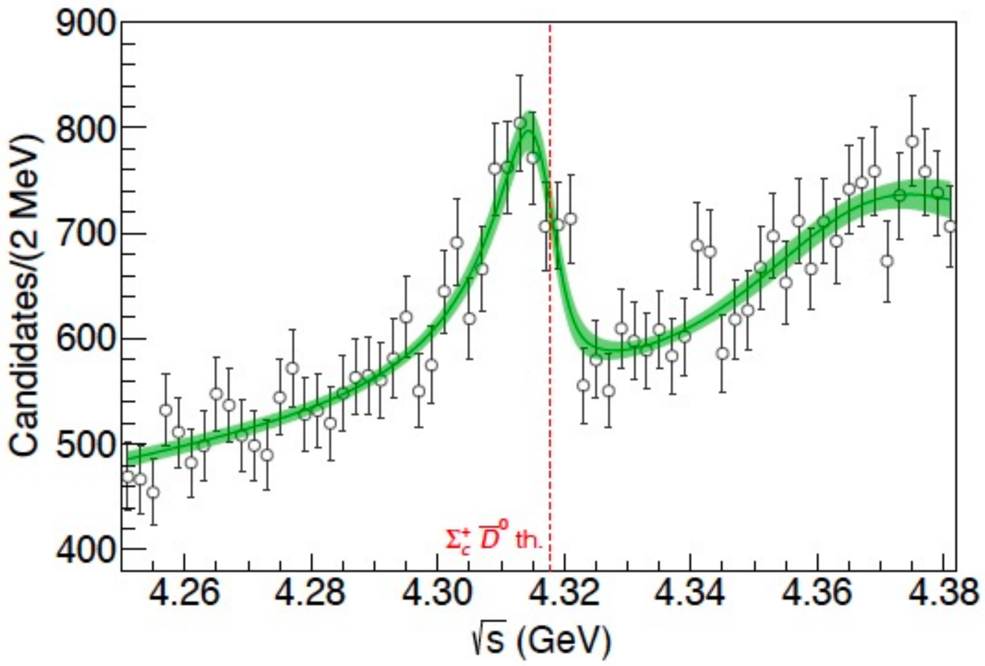
Compact constituent pentaquark, hadrocharmonium

Many papers and discussions !

Previous analysis of LHCb data ($M_{J/\psi\, p}$ distribution)

Fernandez-Ramirez et al. (JPAC), PRL 123, 092001 (2019)

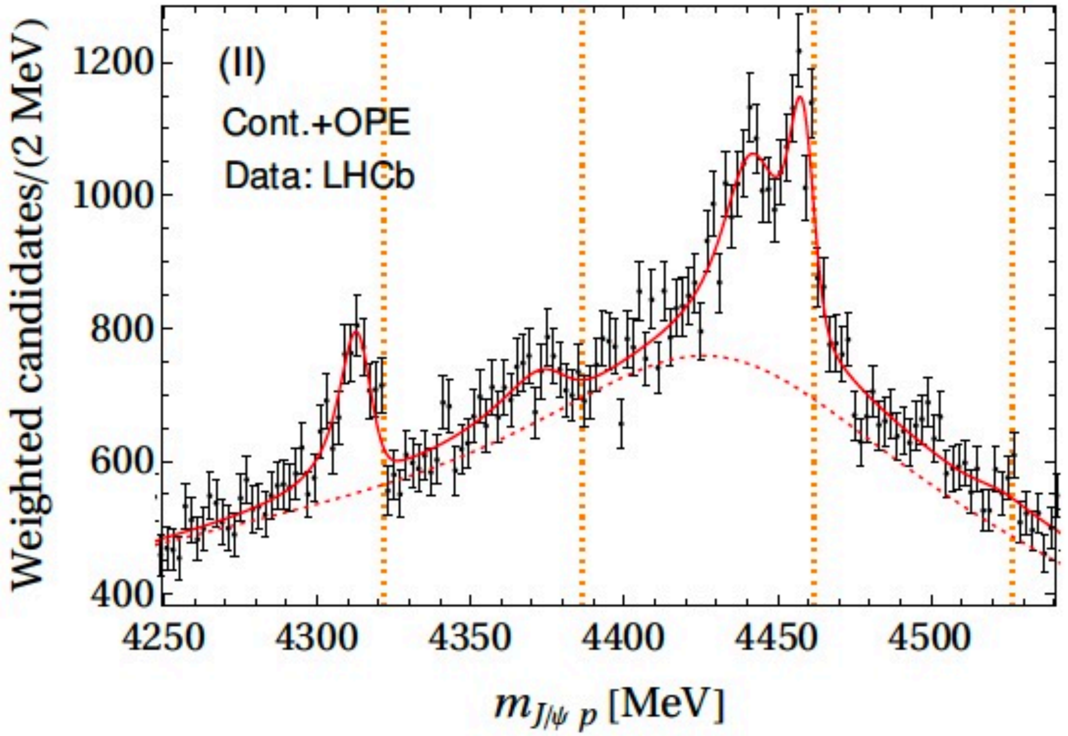
Two-channel ($\Sigma_c\bar{D}$-$J/\psi\, p$) K-matrix model for Pc(4312)



Pc(4312) is interpreted as a virtual state pole

Du et al. (Germany-China group), PRL 124, 072001 (2020)

$\Sigma_c^{(*)}\bar{D}^{(*)}$ coupled-channel model
heavy quark spin symmetry + one-pion-exchange

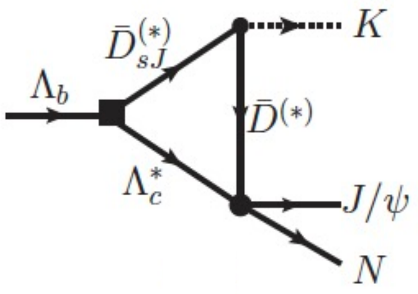


Pc(4312), Pc(4440), Pc(4380), Pc(4457) as $\Sigma_c^{(*)}\bar{D}^{(*)}$ bound states

P_c as kinematical effect

Triangle singularities (TS) explored to interpret Run I data

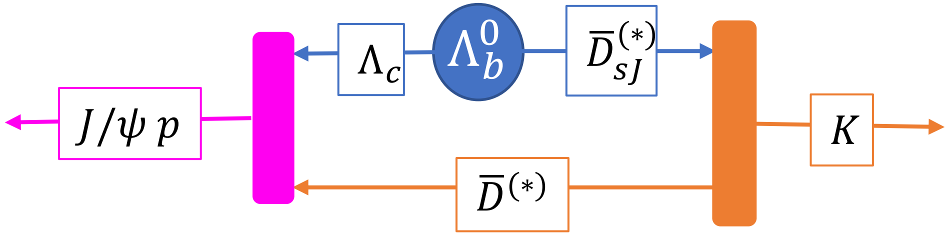
Guo et al., PRD 92, 071502(R) (2015); Liu et al., PLB 757, 231 (2016)



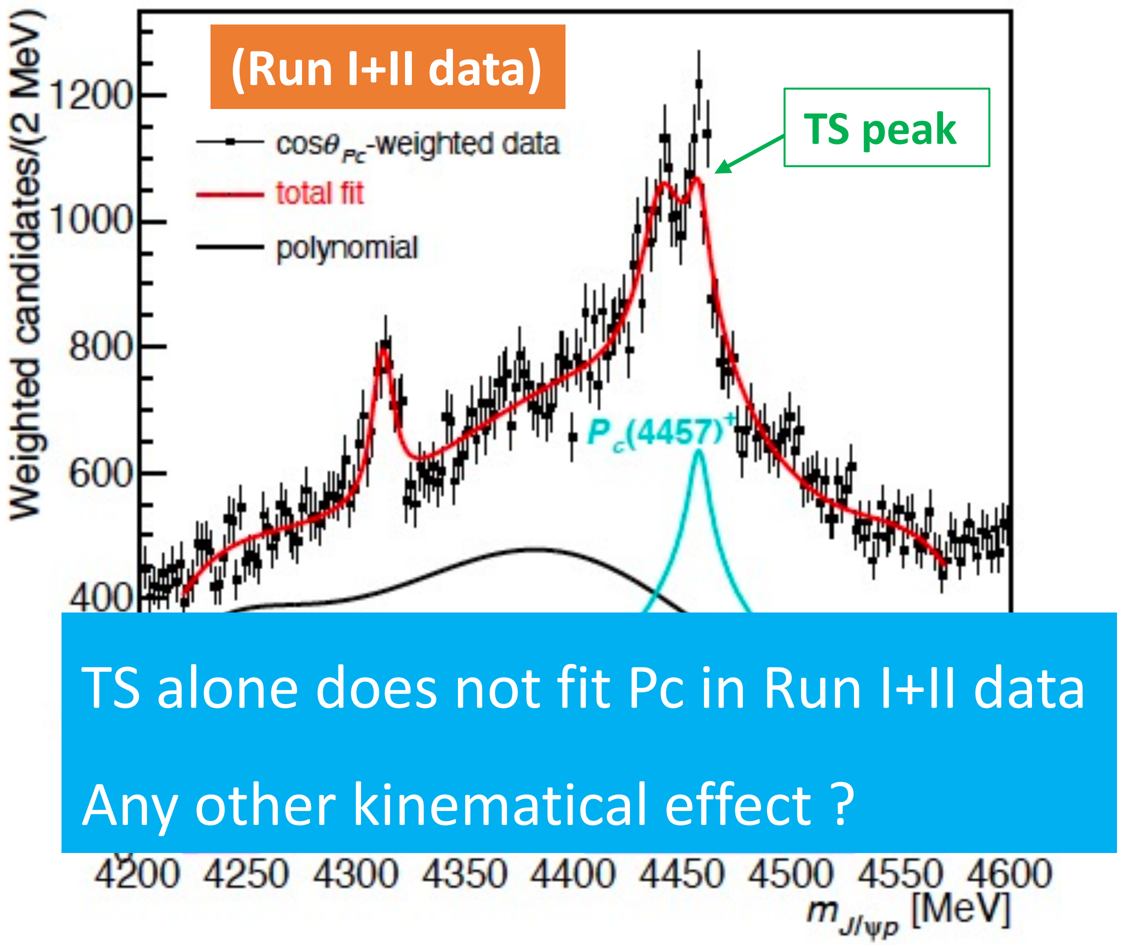
TS conditions : process is kinematically allowed at classical level

(i) on-shell intermediate states (ii) collinear internal momenta

(iii) $v_{\bar{D}^{(*)}} \geq v_{\Lambda_c^*}$



LHCb, PRL 122, 222001 (2019)

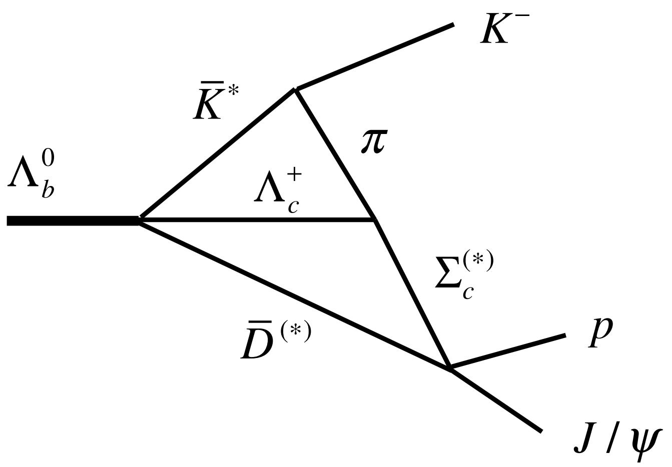


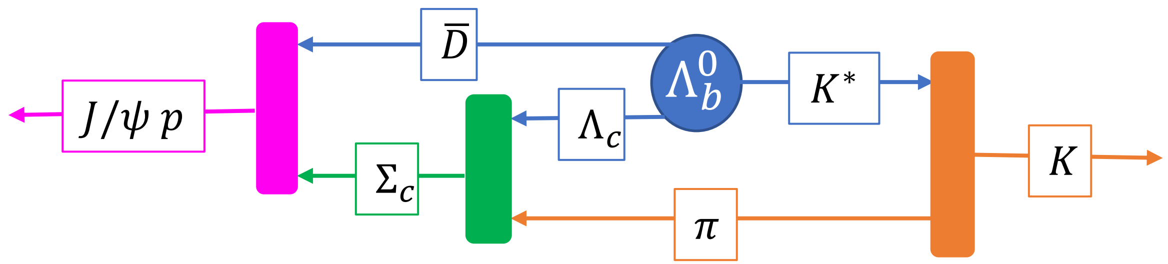
TS alone does not fit Pc in Run I+II data

Any other kinematical effect ?

Double triangle singularity (DTS)

Kinematical condition for DTS : kinematically classical process is allowed (Coleman-Norton theorem)





All intermediate states can be on-shell simultaneously (Σ_c case) → leading singularity

One (or more) state is necessarily off-shell (Σ_c^* case) → lower-order singularity

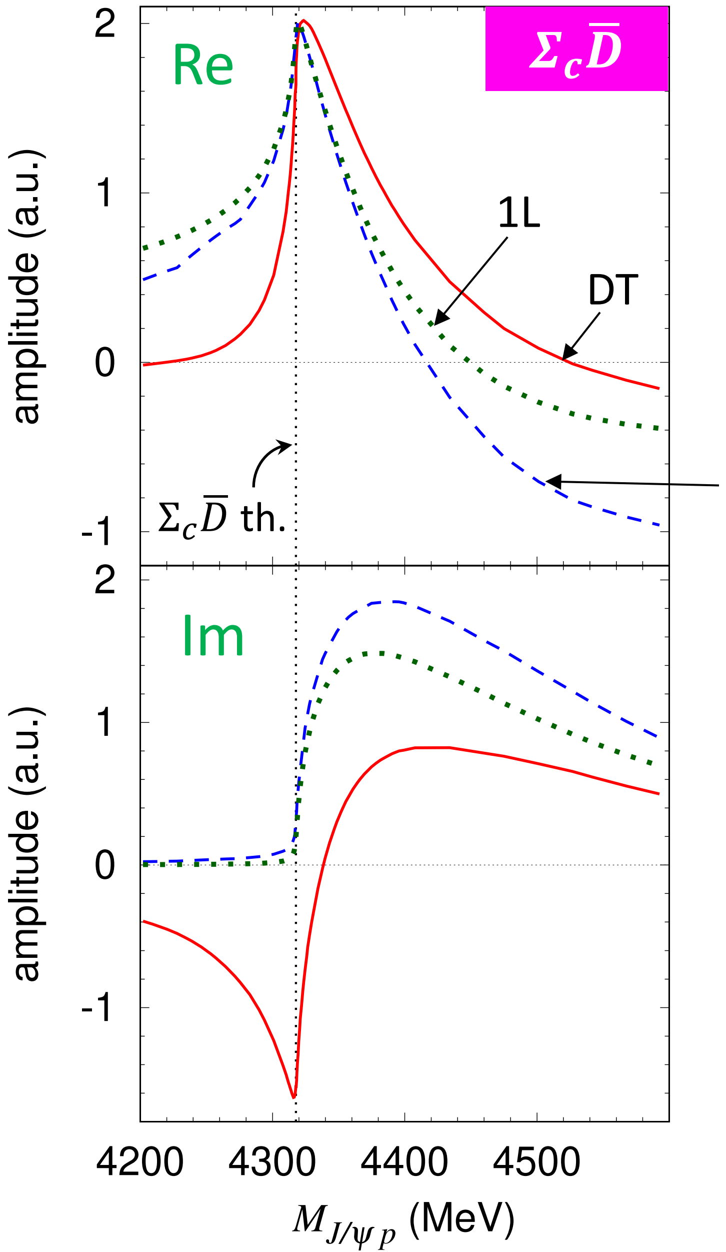
This work

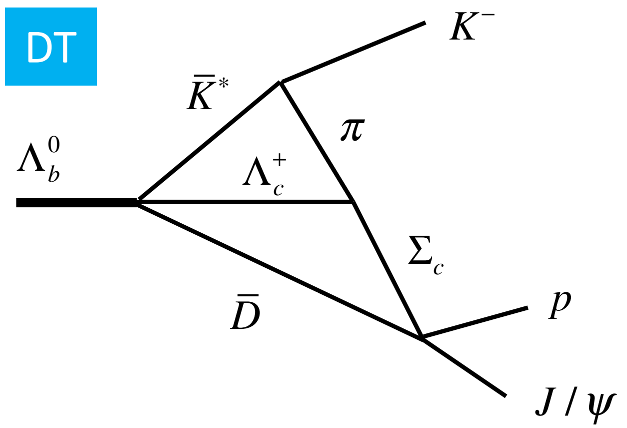
- DTS causes anomalous threshold cusp significantly more singular than ordinary threshold cusp
- DT amplitudes reproduce Pc signals of LHCb data through interference with common (one-loop, tree) mechanisms
- Only Pc(4440) is required as a resonance, with width and strength significantly smaller than LHCb analysis result

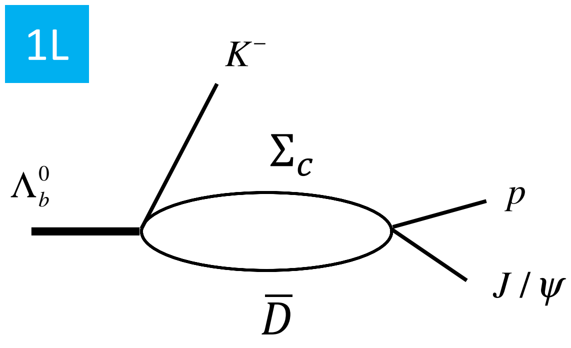
New interpretation of Pc signals in LHCb data

Singular behavior of double triangle amplitude

Singular behavior of double triangle amplitude

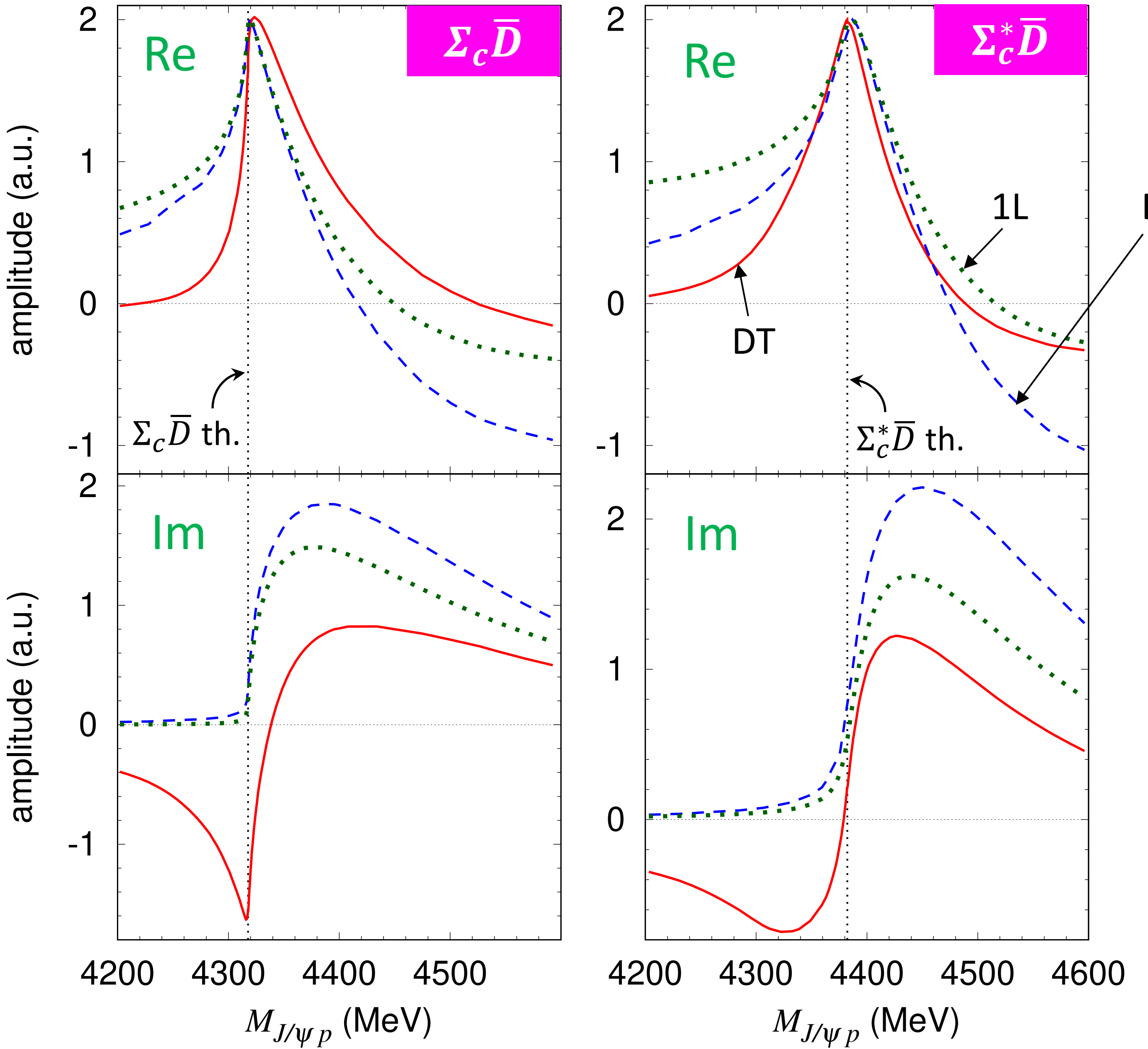






- DT amplitude (leading DTS) are significantly more singular than ordinary threshold cusp (square root singularity)
- For $m_{\Lambda_c} = 3$ GeV, DT amplitude has ordinary threshold cusp
- With attractive $\Sigma_c\bar{D}$ interaction, the amplitudes become more singular (In figures, perturbative $\Sigma_c\bar{D} \rightarrow J/\psi\, p$ interaction is used)

Singular behavior of double triangle amplitude



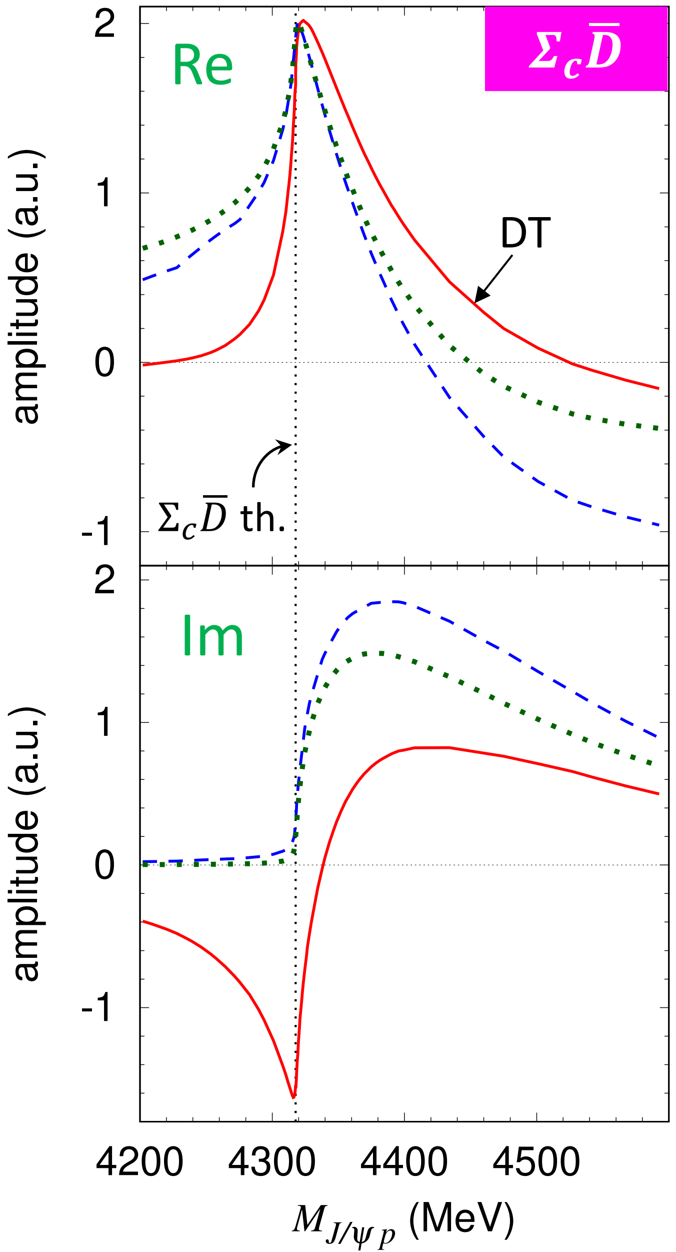
DT ($m_{\Lambda_c} = 3$ GeV)

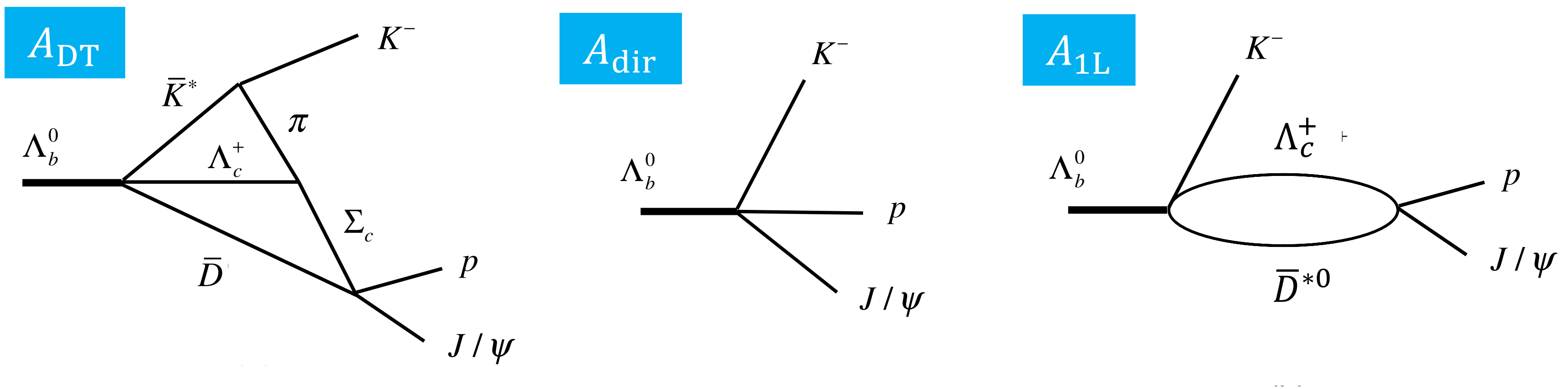
$\Sigma_c\bar{D}$ DT amplitude (leading singularity) is more singular than $\Sigma_c^*\bar{D}$ DT amplitude (lower-order singularity)

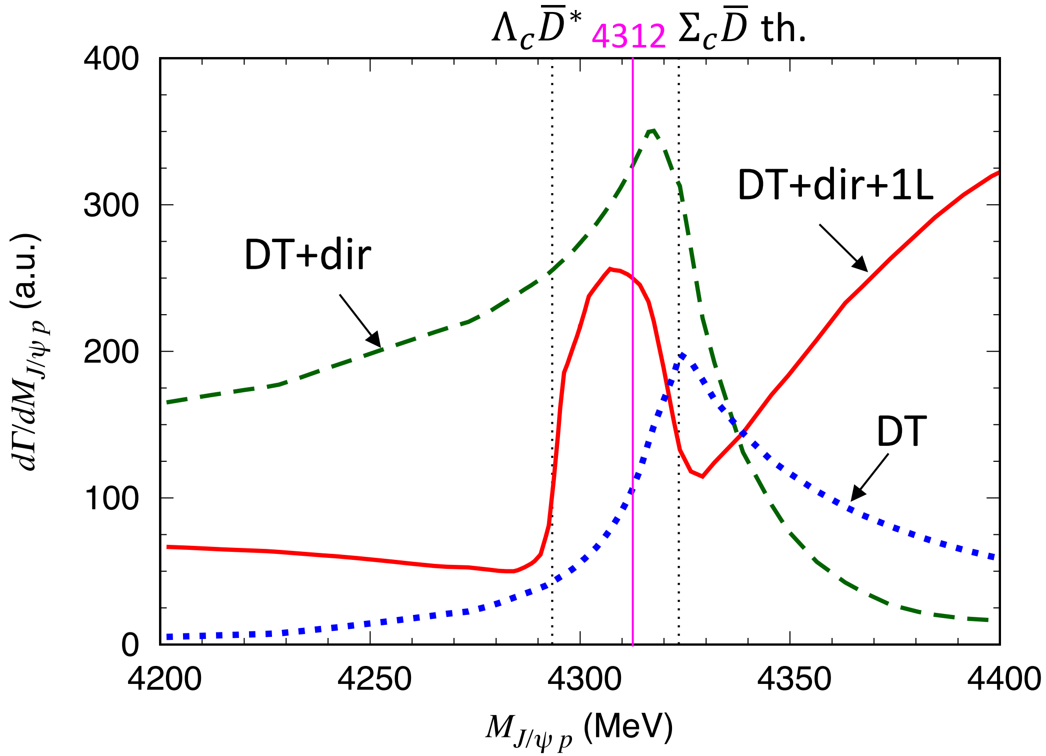
More analytic approach to examine singular behavior

→ Analysis of Landau equation

How double triangle amplitude appears as Pc ?





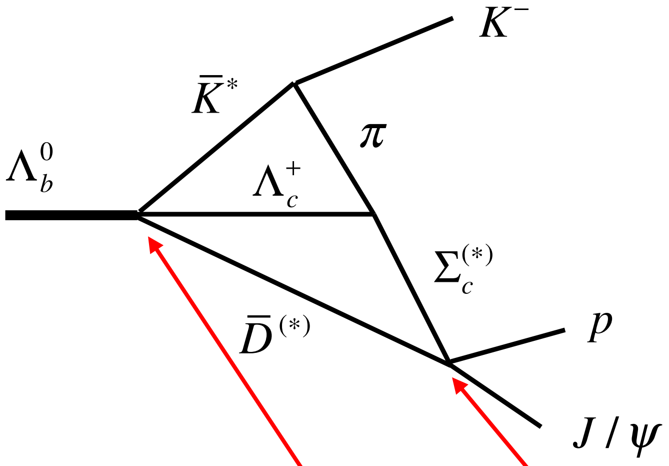


DT amplitude alone creates a peak at $\Sigma_c\bar{D}$ threshold ← not Pc

Interference among DT, one-loop, direct amplitudes play major role to create Pc peak

Analysis of LHCb data

Setup



$\Sigma_c^{(*)}\bar{D}^{(*)}(J^P)$
$\Sigma_c(2455)\bar{D}\ (1/2^-)$
$\Sigma_c(2520)\bar{D}\ (3/2^-)$
$\Sigma_c(2455)\bar{D}^*\ (1/2^-)$
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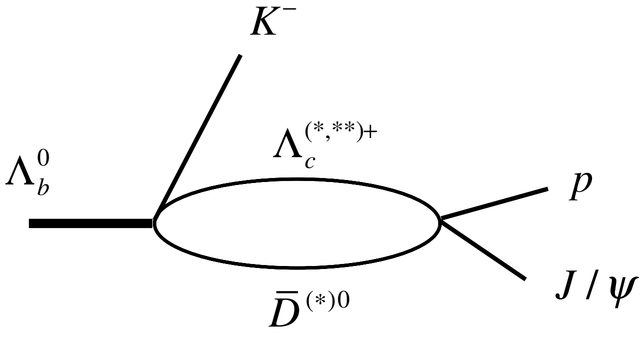


$\Lambda_c^{(*,**)}\bar{D}^{(*)}\ (J^P)$
$\Lambda_c\bar{D}^*\ (1/2^-)$
$\Lambda_c(2593)\bar{D}\ (1/2^+)$
$\Lambda_c(2625)\bar{D}\ (3/2^+)$

2×6 fitting parameters : $c_{\Lambda_c\bar{D}^{(*)}\bar{K}^*,\Lambda_b} \times c^{J^P}_{\psi p,\Sigma_c^{(*)}\bar{D}^{(*)}}$

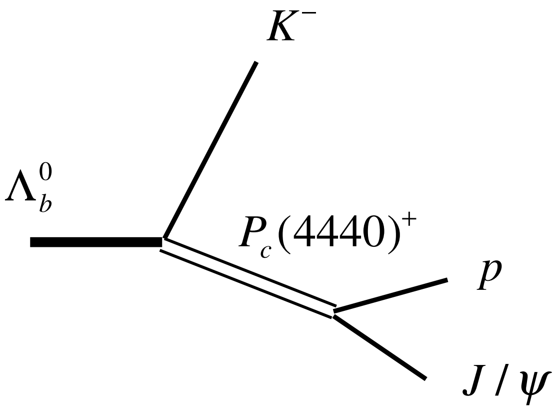
(complex couplings)

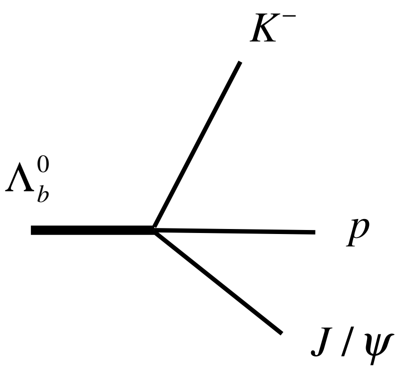
2×3 fitting parameters : $c_{\Lambda_c^{(*)}\bar{D}^{(*)}\bar{K},\Lambda_b} \times c^{J^P}_{\psi p,\Lambda_c^{(*)}\bar{D}^{(*)}}$

Only color-favored weak vertices are used ↔ color-suppressed $\Lambda_b^0 \to \Sigma_c^{(*)}\bar{D}^{(*)}K^-$ are often used in previous models

→ Cannot explain Pc production rates ? Burns and Swanson, PRD 100, 114033 (2019)

Setup





$P_c(4440)$ of $J^P = 1/2^{\pm}, 3/2^{\pm}$ are examined

One direct-decay amplitude in each of

$J^P = 1/2^{\pm}, 3/2^{\pm}$ partial waves

J^P : spin-parity of $J/\psi\, p$ pair

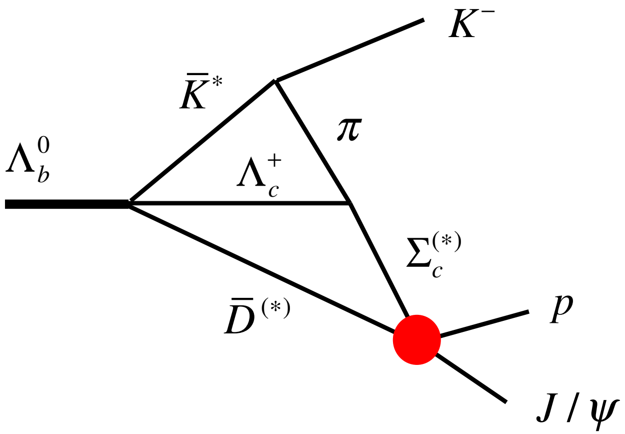
4 fitting parameters : m_{P_c} , Γ_{P_c} , $c_{P_c \bar{K},\Lambda_b} \times c^{J^P}_{\psi p, P_c}$

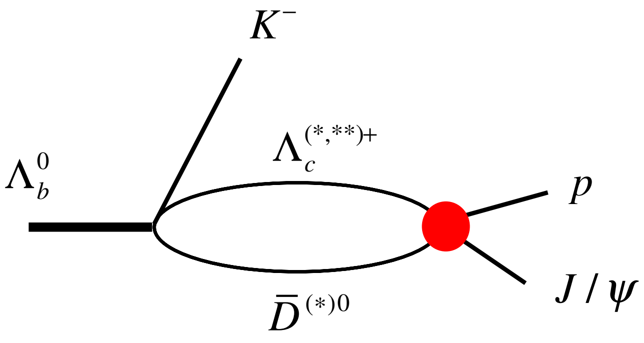
4 fitting parameters : $c^{J^P}_{J/\psi\, p\, \bar{K},\Lambda_b}$ (real) for each J^P

Totally 26 fitting parameters in the full model

$Y_c\bar{D}^{(*)}$ final state interactions

$Y_c = \Lambda_c^{(*,**)}, \Sigma_c^{(*)}$





Our model :

- $Y_c\bar{D}^{(*)}$ single-channel scattering (elastic unitarity)
- other possible coupled-channel effect

  → absorbed by couplings fitted to data
- Examine if fit favors attraction or repulsion

  for each channel of $Y_c\bar{D}^{(*)}$ (J^P)

Attraction : $\Sigma_c\bar{D}(1/2^-)$, $\Sigma_c^*\bar{D}(3/2^-)$, $\Sigma_c\bar{D}^*(1/2^-)$, $\Sigma_c\bar{D}^*(3/2^-)$, $\Lambda_c(2593)\bar{D}$ $(1/2^+)$, $\Lambda_c(2625)\bar{D}$ $(3/2^+)$

All interaction strengths are fixed so that $a \approx 0.5$ fm ; $p\cot\delta \sim 1/a + \mathcal{O}(p^2)$

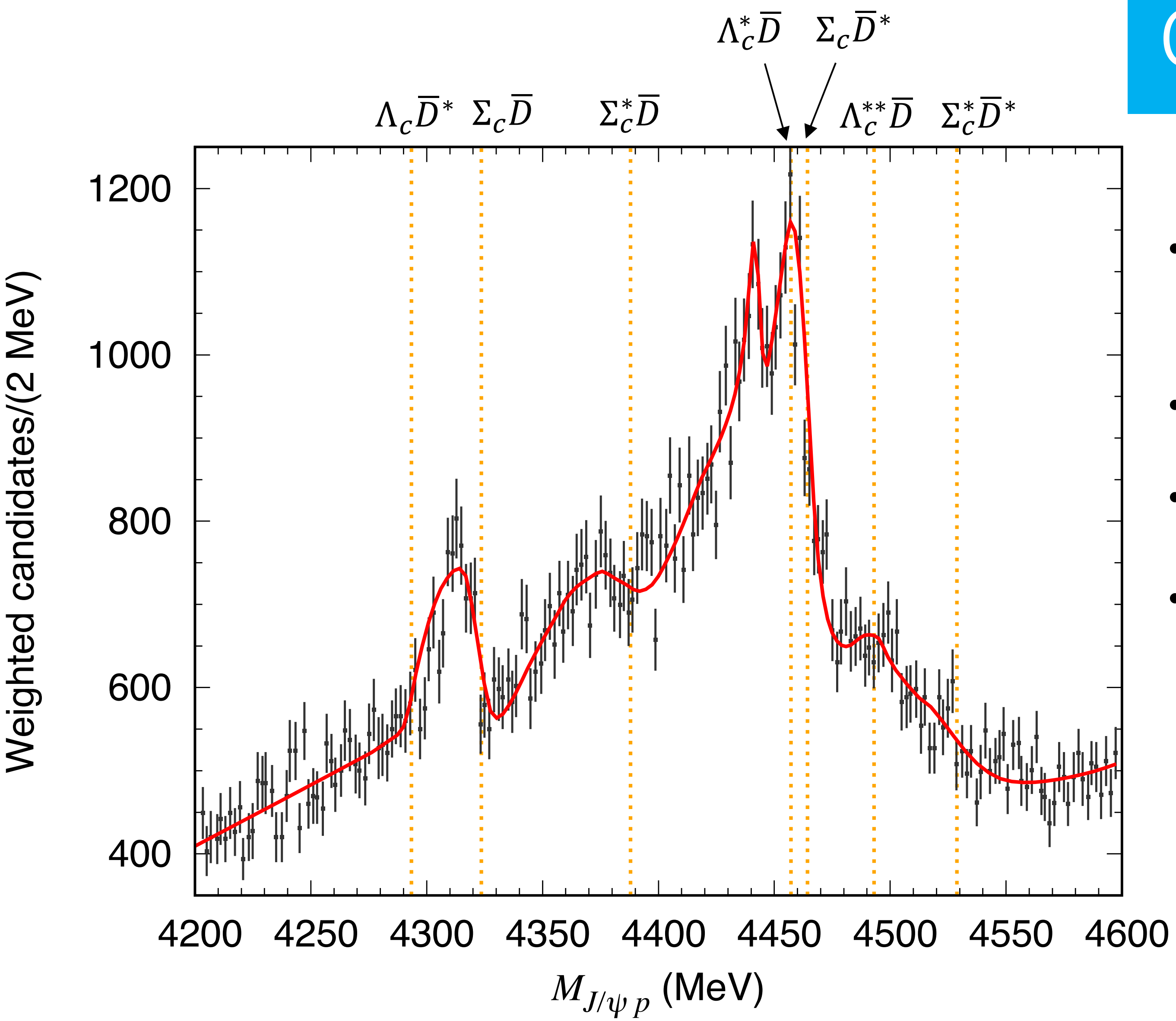
Repulsion : $\Lambda_c\bar{D}^*$ $(1/2^-)$, $\Sigma_c^*\bar{D}^*(1/2^-)$, $\Sigma_c^*\bar{D}^*(3/2^-)$ ← common interaction strength is used

$\Lambda_c\bar{D}^*$ $(1/2^-)$ interaction strength is fitted to LHCb data → $a = -0.4 \sim -0.05$ fm for $\Lambda = 0.8 \sim 2$ GeV

(Λ: cutoff in form factors)

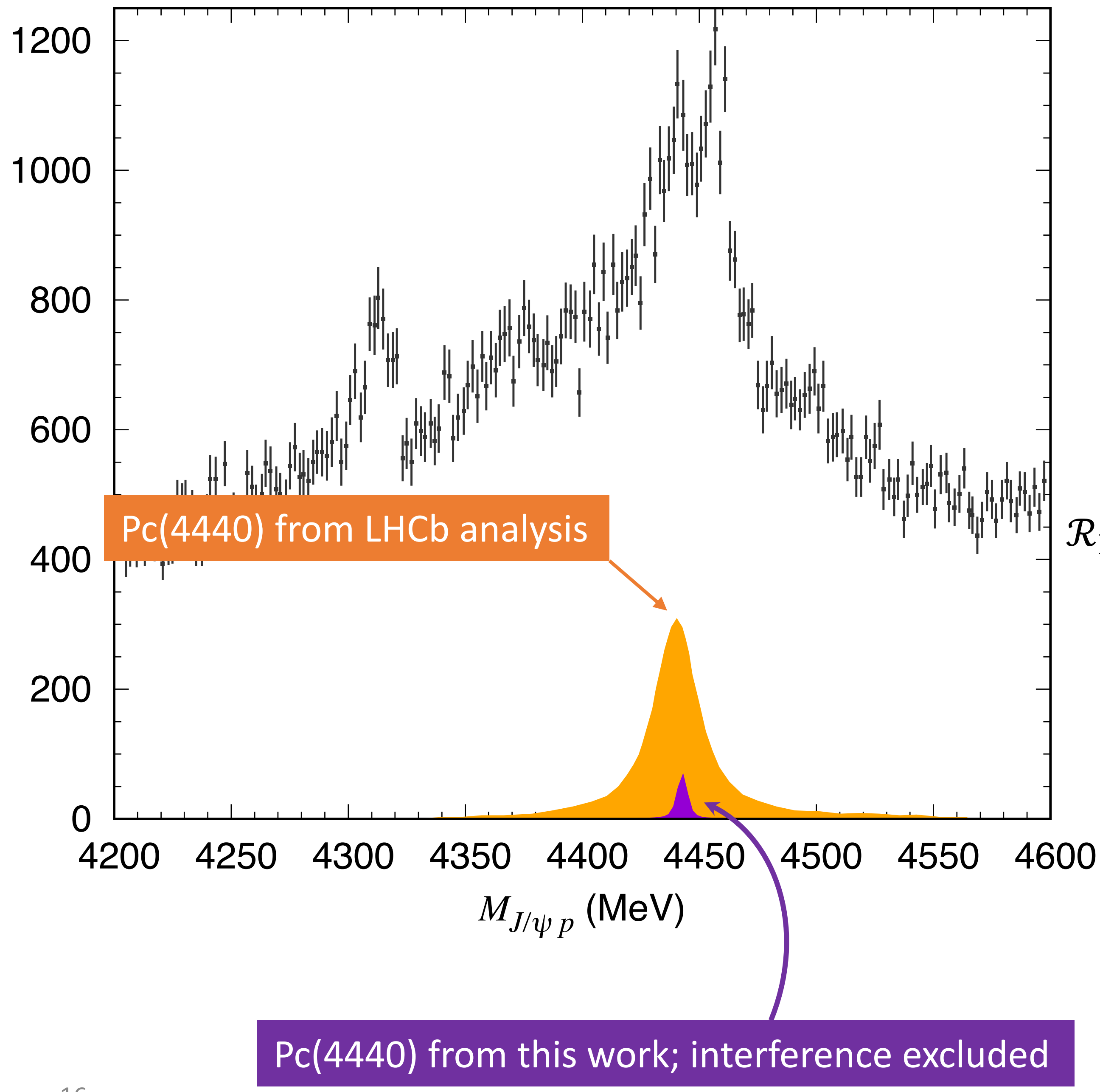
Note: Pc-like peak positions are NOT sensitive to a values

Comparison with LHCb data



: full model (smeared by exp. resolution)

- Pc(4312), Pc(4380), Pc(4457) peaks are well described by kinematical effects; not by poles
- $\Lambda_c\bar{D}^*$ and $\Lambda_c(2625)\bar{D}$ threshold cusps fit the data
- Pc(4440) requires a resonance pole ($J^P = 3/2^-$ in figure)
- Similar fit quality when changing cutoff over $0.8 - 2$ GeV and changing $J^P = 1/2^{\pm}, 3/2^{\pm}$ for Pc(4440)



Pc(4440)

	Mass (MeV)	Width (MeV)
This work	4443.1 ± 1.4	2.7 ± 2.4
LHCb	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$

Pc(4440) contribution

$$\mathcal{R}_{\rm LHCb} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\,\mathcal{B}(P_c^+ \to J/\psi\, p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\, K^-)} = 1.11 \pm 0.33^{+0.22}_{-0.10}\ \%$$

$$\approx 22 \times \mathcal{R}_{\rm This\ work}$$

Pc(4440) from this work has significantly narrower width and weaker coupling strength than LHCb analysis

← Different strategies to fit large structure at ~ 4450 MeV

LHCb : fit with incoherent Pc(4440) and Pc(4457)

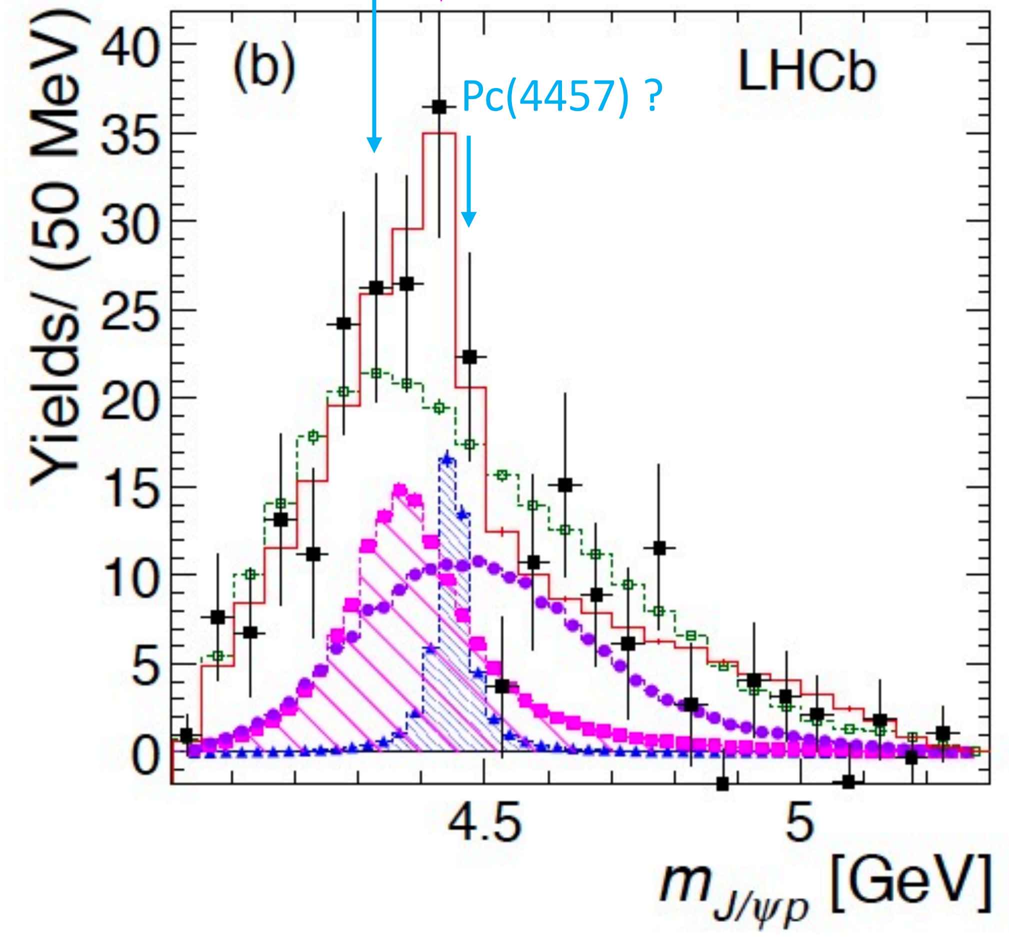
This work : mostly kinematical effect, Pc(4440) is small spike

P_c signal in $\Lambda_b^0 \to J/\psi\, p\, \pi^-$ data

Pc(4440) !

Pc(4312) ?

LHCb, PRL 117, 082003 (2016)



LHCb data

- $M_{J/\psi\, p}$ bin for Pc(4440) is enhanced
- No enhancement for other Pc's bins

This observation is consistent with our model because:

- $\Lambda_b^0 \to J/\psi\, p\, \pi^-$ cannot have DTS of $\Lambda_b^0 \to J/\psi\, p\, K^-$

  → no Pc(4312), Pc(4380), Pc(4457) in $\Lambda_b^0 \to J/\psi\, p\, \pi^-$

- $\Lambda_b^0 \to J/\psi\, p\, \pi^-$ can have $\Lambda_b^0 \to P_c(4440)\, \pi^-$ mechanism

  → Pc(4440) signal is possible in $\Lambda_b^0 \to J/\psi\, p\, \pi^-$

However, this data may conflict with some other Pc models

Pc signals in $\Lambda_b^0 \to J/\psi\, p\, \pi^-$ are inconclusive due to limited statistics

→ Higher statistics $\Lambda_b^0 \to J/\psi\, p\, \pi^-$ data can seriously test Pc models !

Summary

Summary

- LHCb data of $\Lambda_b^0 \to J/\psi\, p\, K^-$ with Pc structures is analyzed
- Pc(4312), Pc(4380), and Pc(4457) peaks are well described by double triangle cusps

  and their interference with common mechanisms
- Only Pc(4440) is interpreted as a resonance

  Its width and coupling strength are significantly smaller than the LHCb analysis
- The proposed interpretation of Pc structures in $\Lambda_b^0 \to J/\psi\, p\, K^-$ is completely different

  from hadron molecule and compact pentaquark models
- In future, understand other resonance-like structures near thresholds with DTS

  DTS should now be a possible option