



π radiation decays of excited hidden- charm pentaquark molecules --from ground to excited

arXiv: 2606.15619

Eur. Phys. J. C (2026) 86:889

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Outline

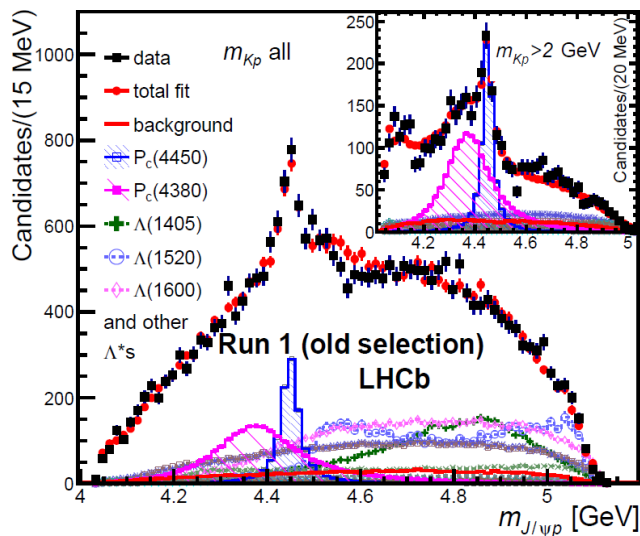
- I. Background and motivation: baryon-meson
molecular explanations to P_c states; excited P_c
states? Why pion radiation?
- II. π radiation property in chiral quark model;
- III. Numerical results
- IV. Summary

I. Background

1.1 $P_c(4380)$ and $P_c(4450)$ in 2015 @LHCb

$$\Lambda_b^0 \rightarrow J/\psi p K^-$$

PRL 115, 072001 (2015)



Theoretical explanations

- **Molecular states:** loosely bound states composed of a pair of hadrons, probably bound by the long-range color-singlet pion exchange
- **Compact Pentaquarks:** bound states of five quarks, bound by colored-force between quarks, decay through rearrangement, some are charged or carry strangeness, there are many states within the same multiplet
- **No-resonant:** Kinematical artifact? Cusp effect? Final state interaction? Triangle singularity due to the special kinematics?

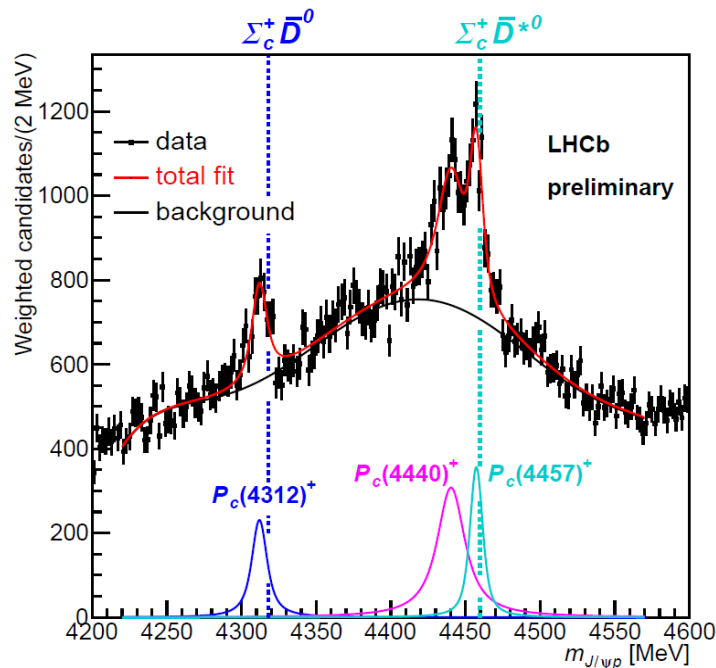
Prog. Part. Nucl. Phys. 107, 237 (2019), Phys. Rep. 639, 1 (2016), Few Body Syst. 57, 1185-1212 (2016), Prog. Part. Nucl. Phys. 93, 143-194 (2017), Rev. Mod. Phys. 90, 015004(2018)

Molecule: about 28 papers

Others: about 33 papers

1.2 $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ in 2019 @LHCb

PRL122, 222001



State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)

Loosely bound meson-baryon molecular explanations for these three P_c states after 2019

1. M. Z. Liu, et al, Phys. Rev. Lett. 122, 242001 (2019).
2. J. He, Eur. Phys. J. C 79, 393 (2019).
3. C. W. Xiao, J. Nieves, and E. Oset, Phys. Rev. D 100, 014021 (2019).
4. L. Meng, B. Wang, G. J. Wang, and S. L. Zhu, Phys. Rev. D 100, 014031 (2019).
5. J. J. Wu, T.-S. H. Lee, and B. S. Zou, Phys. Rev. C 100, 035206 (2019).
6. S. Sakai, H. J. Jing, and F. K. Guo, Phys. Rev. D 100, 074007 (2019).
7. Z. H. Guo and J. A. Oller, Phys. Lett. B 793, 144 (2019).
8. H. X. Chen, W. Chen, and S. L. Zhu, Phys. Rev. D 100, 051501 (2019).
9.

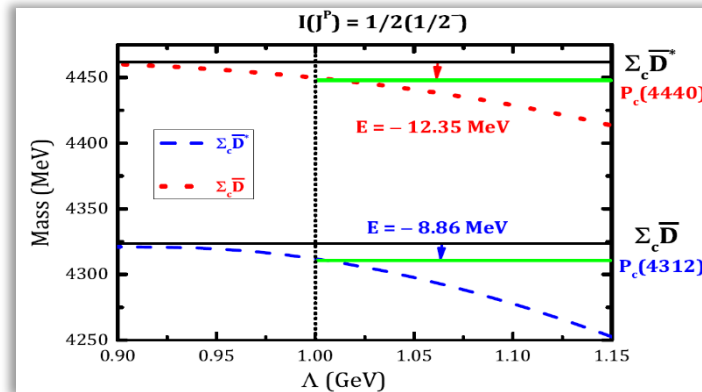
Molecule: about 43 papers
Others: about 5 papers

One-boson-exchange potentials

Coupled channel effects

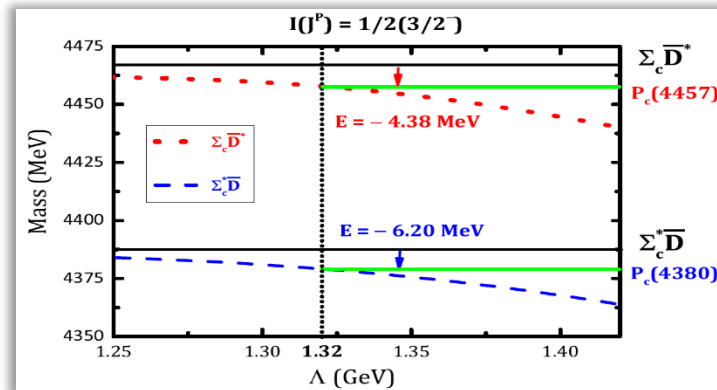
$I(J^P) = 1/2(1/2^-)$ reproduce Pc(4312) and Pc(4440) with $\Lambda = 1.00$ GeV

- Pc(4312): $\Sigma_c \bar{D}^* : \Sigma_c^* \bar{D}^* : \Sigma_c^* \bar{D} = 0.66 : 0.18 : 0.16$,
root-mean-square radius: $R=1.03$ fm
- Pc(4440): $P[\Sigma_c \bar{D}^*] > 92\%$,
 $R=0.83$ fm



$I(J^P) = 1/2(3/2^-)$ reproduce Pc(4457) with $\Lambda = 1.32$ GeV

- Pc(4457): $\Sigma_c \bar{D}^* : \Sigma_c^* \bar{D}^* = 3 : 1$,
root-mean-square radius: $R=1.61$ fm,
loosely bound molecular state,
coupled-channel effect: **very important**
- One more molecular pentaquark: Pc(4380)
 $M=4379$ MeV, $P[\Sigma_c^* \bar{D}] > 87\%$, $R=1.40$ fm



1.3 Question 1: the story just begin

- Molecules? Compact pentaquarks? Mixture?

Ahmed Ali et al. Phys.Lett.B 793 (2019) 365-371

$P_c(4312)^+ = \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 0, J^P = 3/2^-\}$, the S -wave state, and the other two as P -wave states, with $P_c(4440)^+ = \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 1, J^P = 3/2^+\}$ and $P_c(4457)^+ = \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 1, J^P = 5/2^+\}$. The

- Molecules: Constituents? Role of coupled channel effects? Spin-parities?

H. X. Chen et al, Phys.Rev.D 100 (2019) 5, 051501

LHCb. Our results suggest that the $P_c(4312)$ can be well interpreted as the $[\Sigma_c^{++}\bar{D}^-]$ bound state with $J^P = 1/2^-$, and the $P_c(4440)$ and $P_c(4457)$ as the $[\Sigma_c^{*++}\bar{D}^-]$ and $[\Sigma_c^+\bar{D}^{*0}]$ bound states with $J^P = 3/2^-$, respectively. Our results also suggest that one of the $P_c(4440)$ and $P_c(4457)$ may be interpreted as the $[\Sigma_c^+\bar{D}^{*0}]$ bound state with $J^P = 1/2^-$ or the $[\Sigma_c^{*+}\bar{D}^{*0}]$ bound state with $J^P = 5/2^-$. We propose to measure their spin-parity quantum numbers to verify these assignments.

H. X. Huang et al, Phys.Rev.D 99 (2019) 1, 014010

taquarks $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ can be identified as the hidden-charm molecular states $\Sigma_c D$ with $J^P = \frac{1}{2}^-$, $\Sigma_c D^*$ with $J^P = \frac{3}{2}^-$, and $\Sigma_c D^*$ with $J^P = \frac{1}{2}^-$, in the baryon-meson scattering process, respectively. Besides, the $\Sigma_c^* D^*$ of both $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ are also possible molecular

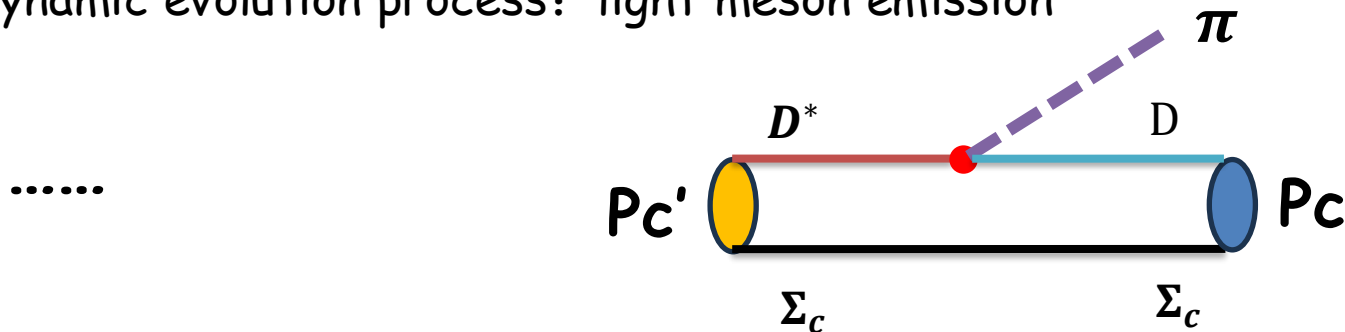
M. Z. Liu et al., Phys.Rev.Lett. 122 (2019) 24, 242001, Jun He, Eur.Phys.J.C 79 (2019) 5, 393

Ways to determine the internal structure of P_c

Mass spectrum: reproduce the experimental data,
partners (heavy quark symmetry (P_b , P_{bc}),
SU(3) flavor symmetry (P_{cs}))

Decay properties: two or three body strong decay behavior (P_c , P_{cs} , $\Omega(2012)$),
special decay processes ($X(3872)$, $D_s(2317, 2460)$...)

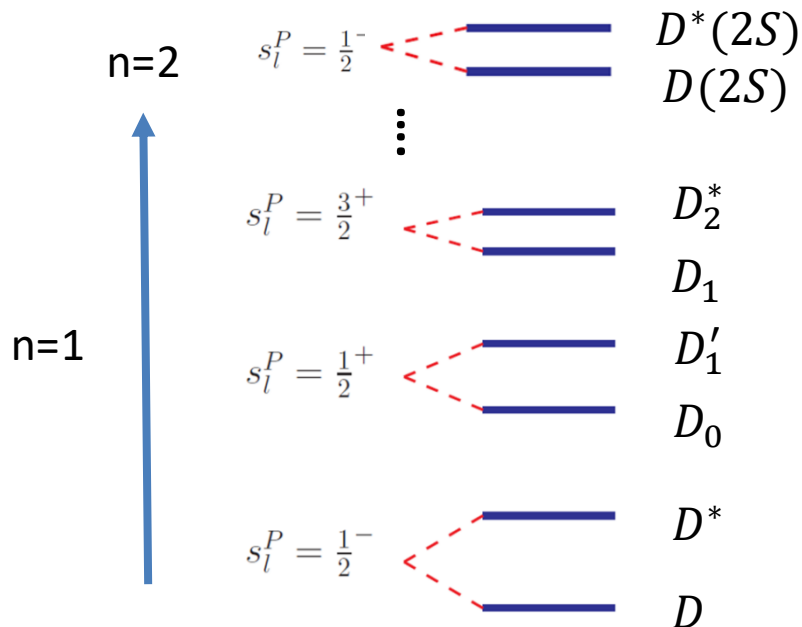
Dynamic evolution process: light meson emission



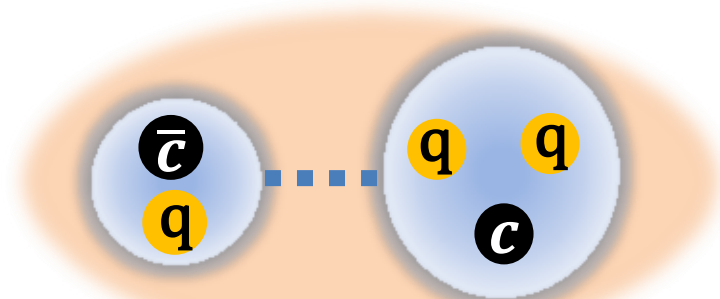
1.3 Question 2: excited Pc states exist or not?

Charmed mesons

$$J = s_Q + s_l = s_Q + s_q + l.$$



Molecular pentaquarks



$$\bar{D}^{(*)} + \Sigma_c^{(*)} = P_c$$

$$\bar{D}_{1,2}^{(*)} + \Sigma_c^{(*)}$$

$$\bar{D}^{(*)}(2S) + \Sigma_c^{(*)}$$

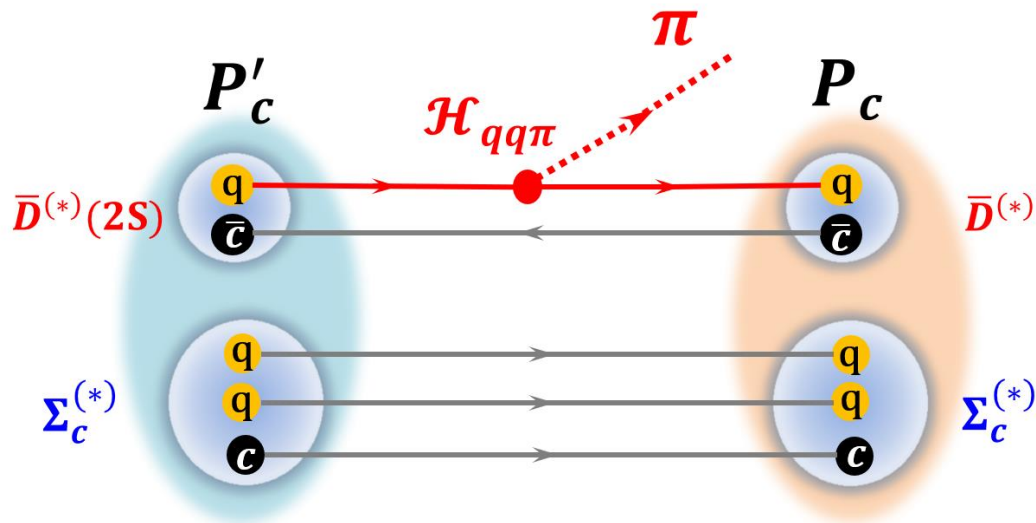


Probing new types of P_c states inspired by the interaction between an S -wave charmed baryon and an anticharmed meson in a $\bar{T}$ doublet state

Fu-Lai Wang,^{1,2,*} Rui Chen,^{1,2,3,4,†} Zhan-Wei Liu^{db, 1,2,‡} and Xiang Liu^{db, 1,2,§}

Inspired by the observations of three P_c states, we systematically investigate interactions between an S -wave charmed baryon $\mathcal{B}_c^{(*)} = \Lambda_c/\Sigma_c/\Sigma_c^*$ and an anticharmed meson $\bar{T} = \bar{D}_1/\bar{D}_2^*$ with the one-pion-exchange potential model and the one-boson-exchange potential model, and search for possible new types of P_c states with the structures of $\mathcal{B}_c^{(*)}\bar{T}$. Both S - D wave mixing and coupled channel effects are considered. Our results suggest that in some $\mathcal{B}_c^{(*)}\bar{T}$ systems there are ideal candidates of new types of P_c states—i.e., the $\Sigma_c\bar{D}_1$ state with $I(J^P) = 1/2(1/2^+)$, the $\Sigma_c\bar{D}_2^*$ state with $I(J^P) = 1/2(3/2^+)$, the $\Sigma_c^*\bar{D}_1$ state with $I(J^P) = 1/2(1/2^+)$, and the $\Sigma_c^*\bar{D}_2^*$ states with $I(J^P) = 1/2(1/2^+, 3/2^+)$ —and we suggest that these predicted new types of P_c states can be detected in the process $\Lambda_b^0 \rightarrow \psi(2S)p\pi^-$. Meanwhile, we also extend our study to the interactions between an S -wave charmed baryon and a charmed meson in a T doublet, and we predict a series of double-charm molecular pentaquarks.

1.4 Proposals: excited Pc states exist or not? How to find?



- ❑ Pion radiation process: occur at the constituent hadron $D^* \rightarrow D\pi$;
- ❑ Coupled channel effects: interference;
- ❑ Determine spin-parities: spin-related interactions;
- ❑ Testing molecular explanations;
- ❑ Searching for new molecular partners.

II. π radiation property in chiral quark model

2.1 Interactions: chiral quark model

$$\mathcal{L}_{ps} = \sum_j \frac{\delta}{\sqrt{2}f_M} \bar{\psi}_j \gamma_\mu \gamma_5 \psi_j \vec{I} \cdot \vec{\partial}^\mu \vec{\phi}_M$$

Non-relativistic reduction, keep to $1/m^2$ order

$$\mathcal{H}_{qq\pi} = g \sum_j \left(\mathcal{G} \sigma_j \cdot \mathbf{q} + \frac{\omega_m}{2\mu_q} \sigma_j \cdot \mathbf{p}_j \right) F(q^2) I_j \varphi_m - \frac{g}{32\mu_q^2} \sum_j \left[m_{\mathbb{P}}^2 (\sigma_j \cdot \mathbf{q}) + 2\sigma_j \cdot (\mathbf{q} - 2\mathbf{p}_j) \times (\mathbf{q} \times \mathbf{p}_j) \right] F(q^2) I_j \varphi_m$$

$$g = \delta \sqrt{(E_f + M_f) / (\sqrt{2} f_m)} \quad \mathcal{G} = - \left(\frac{\omega_m}{E_f + M_f} + 1 + \frac{\omega_m}{2m'_j} \right) \quad \mu_q = \frac{m_j m'_j}{m_j + m'_j}$$

- σ_j, p_j : the j -th light quark; ω, q, m_p : emitted meson
- $F(q^2) = \sqrt{\frac{\Lambda^2}{\Lambda^2 + q^2}}$: suppress the unphysical contributions in the high momentum region;
- Coupling constants and Λ : estimated by fitting mass and decay width

2.2 Decay width

In the rest frame of the molecular state

$$\Gamma = \frac{1}{8\pi} \frac{|q|}{M_i^2} \frac{1}{2J_i + 1} \sum_{J_{iz} J_{fz}} |\mathcal{M}_{J_{iz} J_{fz}}|^2$$

Amplitude

$$P'_c \rightarrow P_c(4312) + \pi$$

$$\mathcal{M} = \langle P_c(4312) + \pi | H | P'_c \rangle$$

Wave
functions

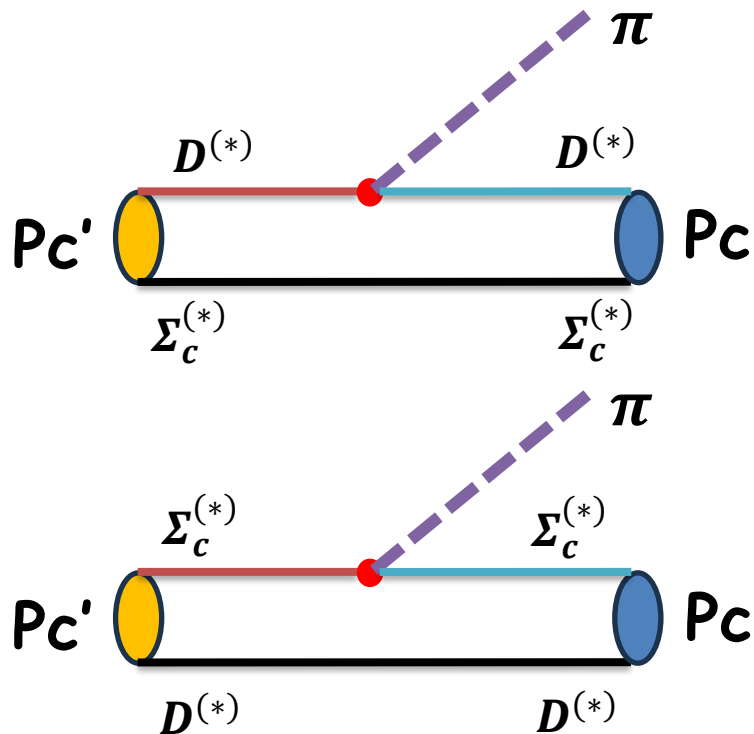
- $\varphi_m = e^{-i q \cdot r_j}$: plane wave function of the light meson
- Molecule: $\Psi = \phi_D \times \phi_{\Sigma_c} \times \phi \longrightarrow$ Obtained by solving Schrodinger equations
R. Chen et al, PRD 100 (2019) 1, 011502
- ϕ_D, ϕ_{Σ_c} : meson/baryon wave function;

Simple harmonic oscillator wave function

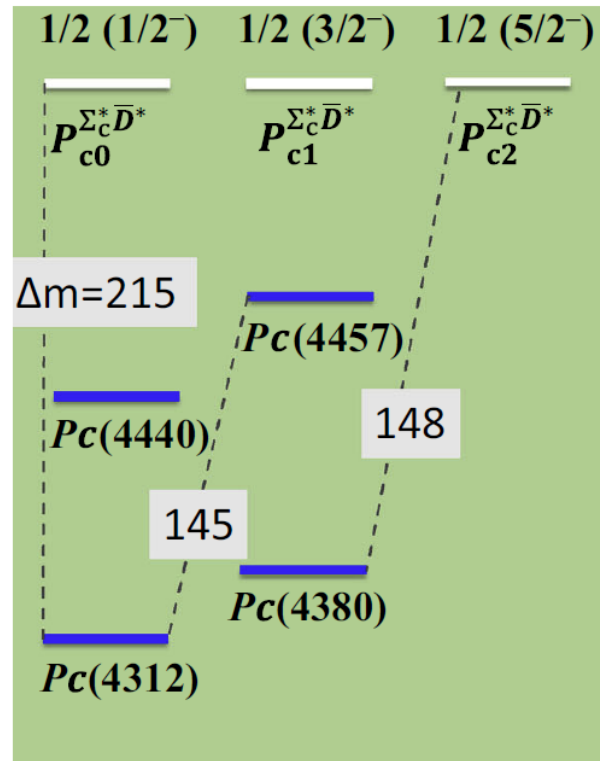
$$\phi_{n,l,m}(\beta, \mathbf{r}) = \sqrt{\frac{2n!}{\Gamma(n + l + \frac{3}{2})}} L_n^{l+\frac{1}{2}}(\beta^2 r^2) \beta^{l+\frac{3}{2}} e^{-\frac{\beta^2 r^2}{2}} r^l Y_{lm}(\Omega)$$

III. Numerical results

3.1 Pion radiation properties



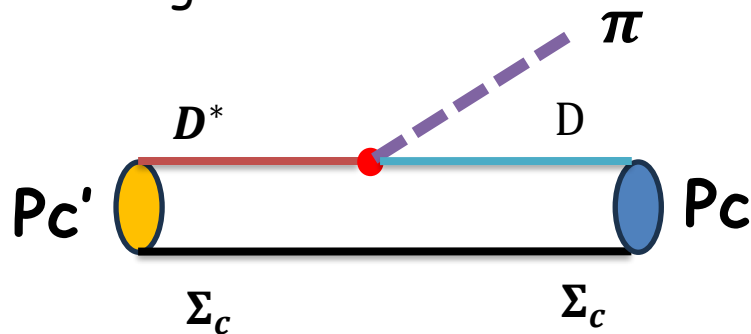
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Coupled channel effects are very important!

Example $P_c(4457)[\frac{1}{2}(\frac{3}{2}^-)] \rightarrow P_c(4312)[\frac{1}{2}(\frac{1}{2}^-)] + \pi$

- Single channel



3 keV

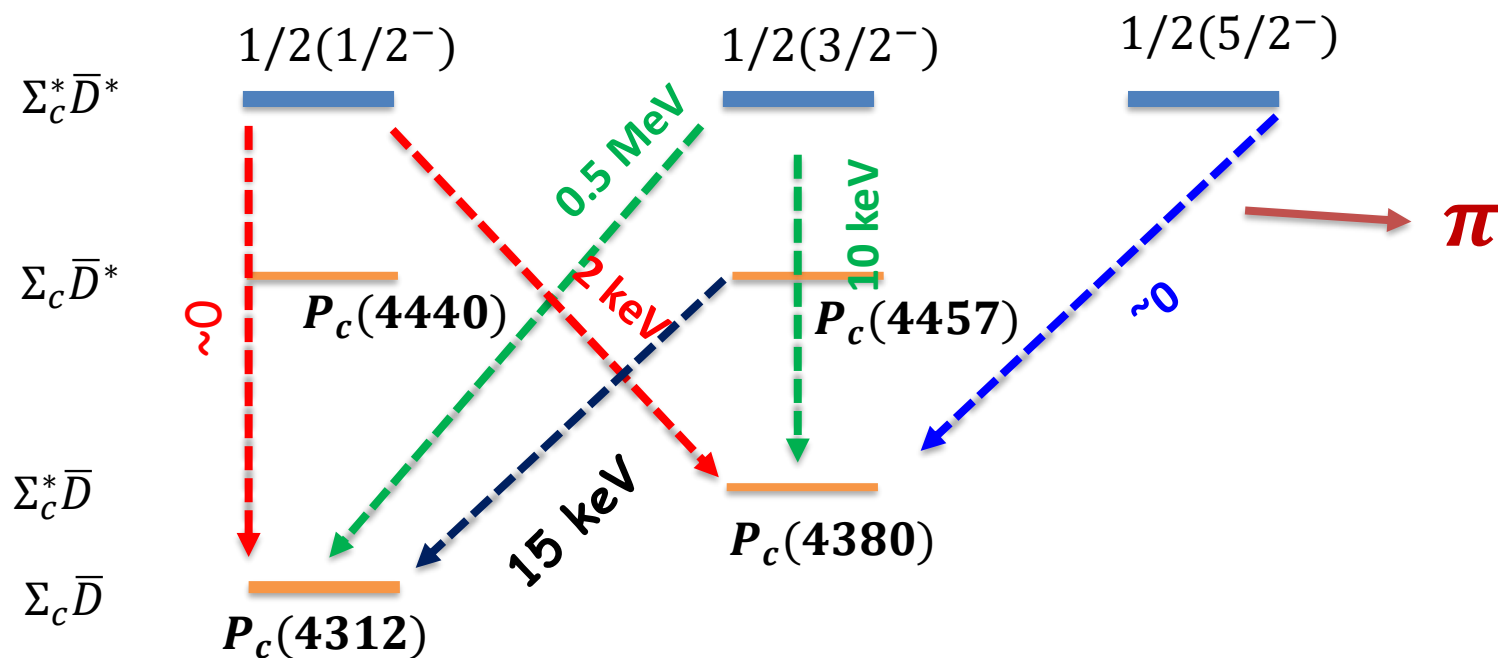
- Coupled channel

$$\mathcal{M} = \mathcal{M}(\Sigma_c^{(*)} \rightarrow \Sigma_c^{(*)} + \pi) + \mathcal{M}(\bar{D}^* \rightarrow \bar{D}^{(*)} + \pi)$$

15 keV

Much larger than results in single channel

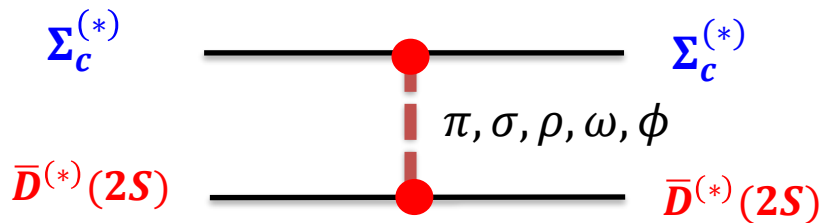
A summary of pion emission widths between Pc states



Spin-related interactions, phase space

3.2 $\Sigma_c \bar{D} / \Sigma_c \bar{D}^* / \Sigma_c^* \bar{D}^* (2S)$ molecular candidates

OBE effective
potentials

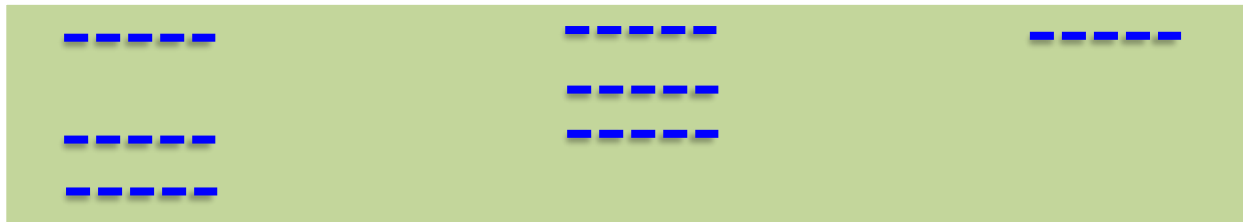


$\Sigma_c^* \bar{D}^* (2S)$

$\Sigma_c^* \bar{D} (2S)$

$\Sigma_c \bar{D}^* (2S)$

$\Sigma_c \bar{D} (2S)$



$\Sigma_c^* \bar{D}^*$

$\Sigma_c \bar{D}^*$

$\Sigma_c^* \bar{D}$

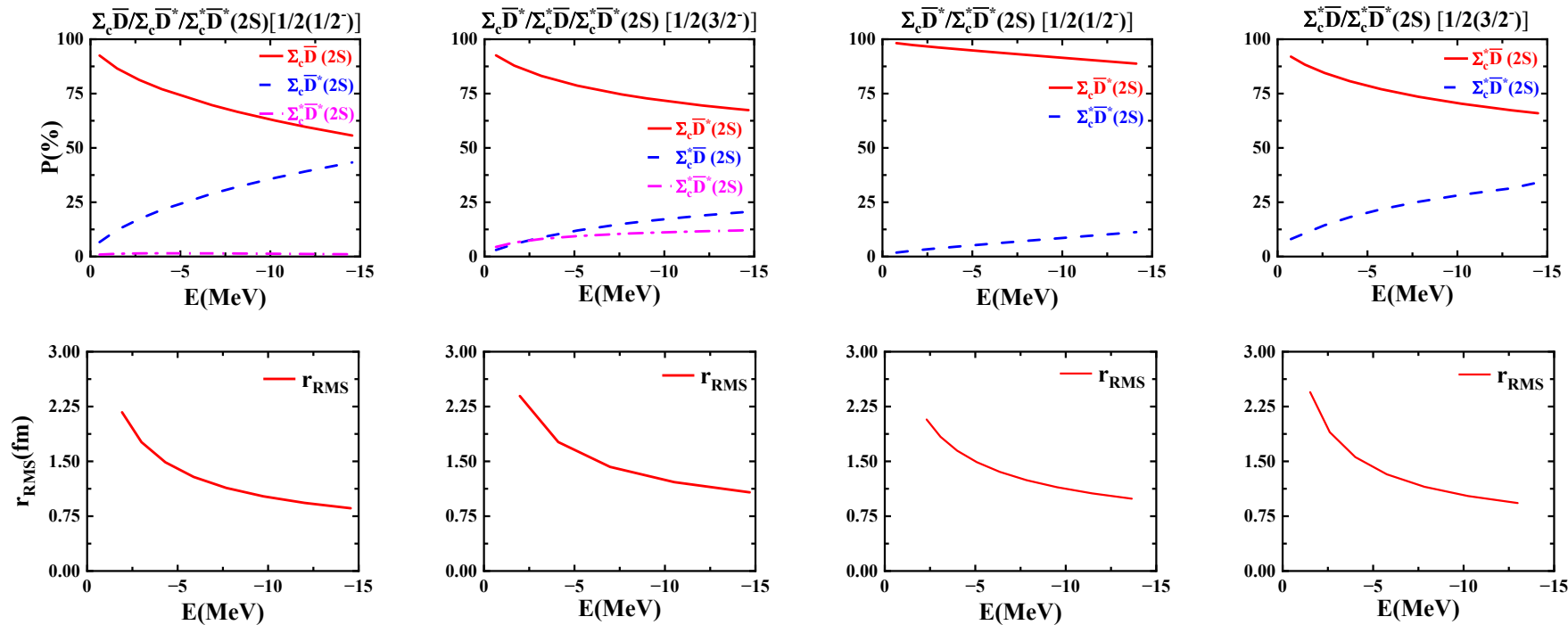
$\Sigma_c \bar{D}$



$1/2(1/2^-)$

$1/2(3/2^-)$

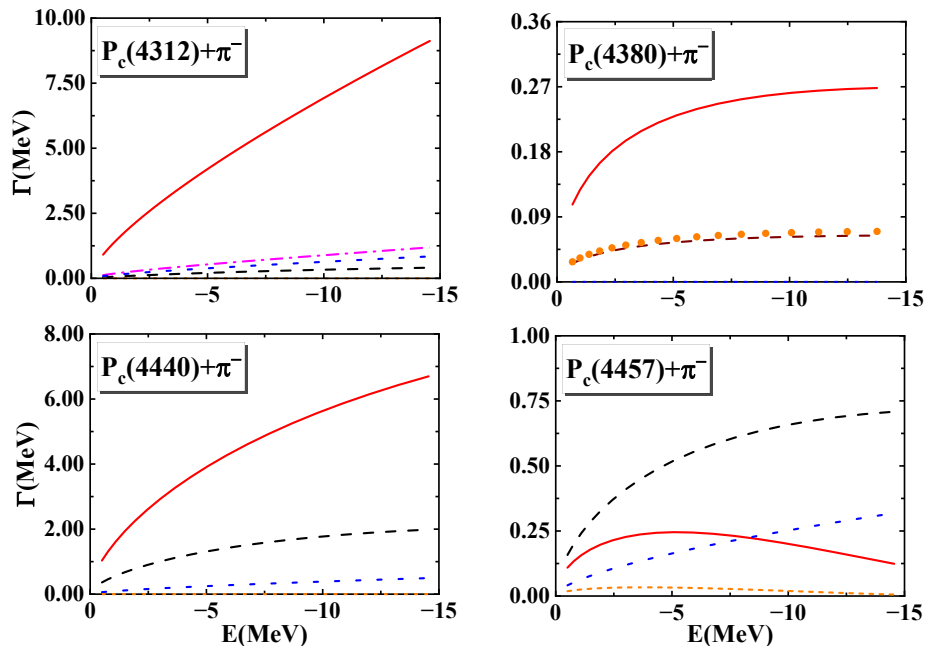
$1/2(5/2^-)$



- Reasonable loosely bound molecular candidates: binding energies and reasonable RMS radii.
- Coupled channel effects: **important**.

3.3 $\Sigma_c \bar{D} / \Sigma_c \bar{D}^* / \Sigma_c^* \bar{D}^* (2S) [\frac{1}{2} (\frac{1}{2}^-)] \rightarrow P_c(4312) / P_c(4380) / P_c(4440) / P_c(4457) + \pi$

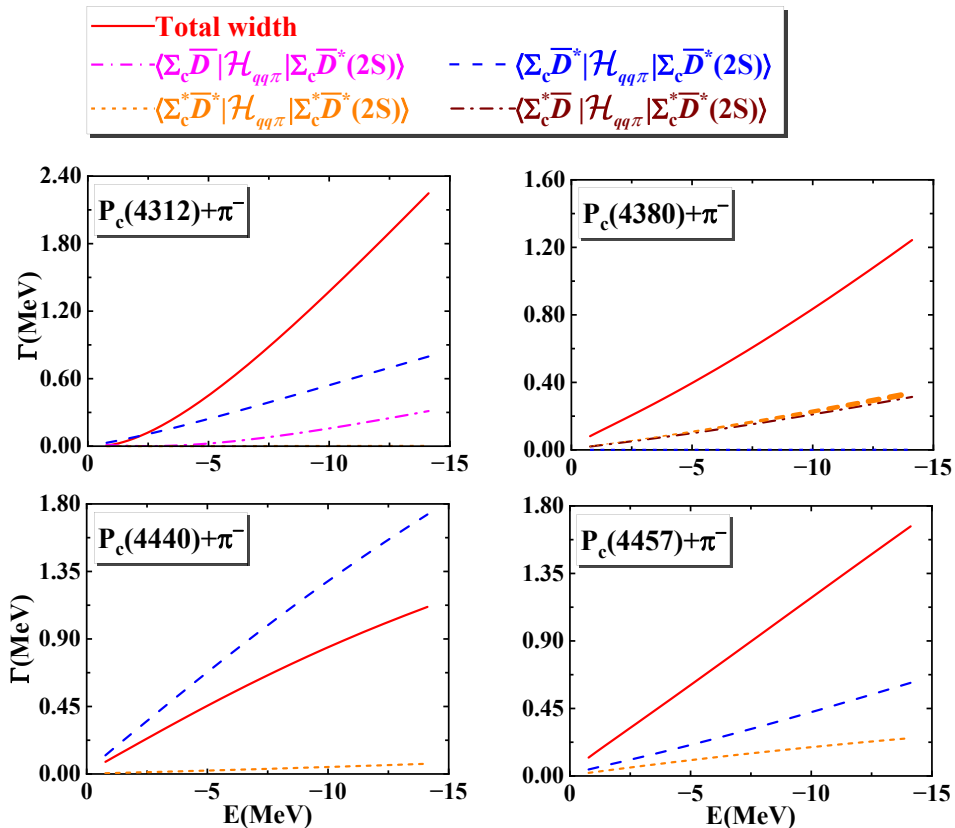
$$\begin{aligned}
 &-- \langle \Sigma_c \bar{D}^* | \mathcal{H}_{qq\pi} | \Sigma_c \bar{D}(2S) \rangle \quad \text{---} \langle \Sigma_c^* \bar{D}^* | \mathcal{H}_{qq\pi} | \Sigma_c^* \bar{D}(2S) \rangle \quad \text{---} \text{Total width} \\
 &\text{---} \langle \Sigma_c \bar{D} | \mathcal{H}_{qq\pi} | \Sigma_c \bar{D}^*(2S) \rangle \quad \text{---} \langle \Sigma_c \bar{D}^* | \mathcal{H}_{qq\pi} | \Sigma_c \bar{D}(2S) \rangle \\
 &\text{---} \langle \Sigma_c^* \bar{D}^* | \mathcal{H}_{qq\pi} | \Sigma_c^* \bar{D}^*(2S) \rangle \quad \text{---} \langle \Sigma_c^* \bar{D} | \mathcal{H}_{qq\pi} | \Sigma_c^* \bar{D}^*(2S) \rangle
 \end{aligned}$$



$$\begin{aligned}
 \mathcal{M} = & \mathcal{M}_1 (\Sigma_c \bar{D} (2S) \rightarrow \Sigma_c \bar{D}^* + \pi) \\
 & + \mathcal{M}_2 (\Sigma_c \bar{D}^* (2S) \rightarrow \Sigma_c \bar{D}^* + \pi) \\
 & + \mathcal{M}_3 (\Sigma_c \bar{D}^* (2S) \rightarrow \Sigma_c \bar{D} + \pi) \\
 & + \mathcal{M}_4 (\Sigma_c^* \bar{D}^* (2S) \rightarrow \Sigma_c^* \bar{D}^* + \pi) \\
 & + \mathcal{M}_5 (\Sigma_c^* \bar{D}^* (2S) \rightarrow \Sigma_c^* \bar{D} + \pi)
 \end{aligned}$$

- Total decay width: **several MeV or less;**
different decay mechanisms;
- Coupled channel effects: **important**, **coherent**
constructive / destructive interference.
- π^0 radiation: 2 times smaller due to the isospin factor.

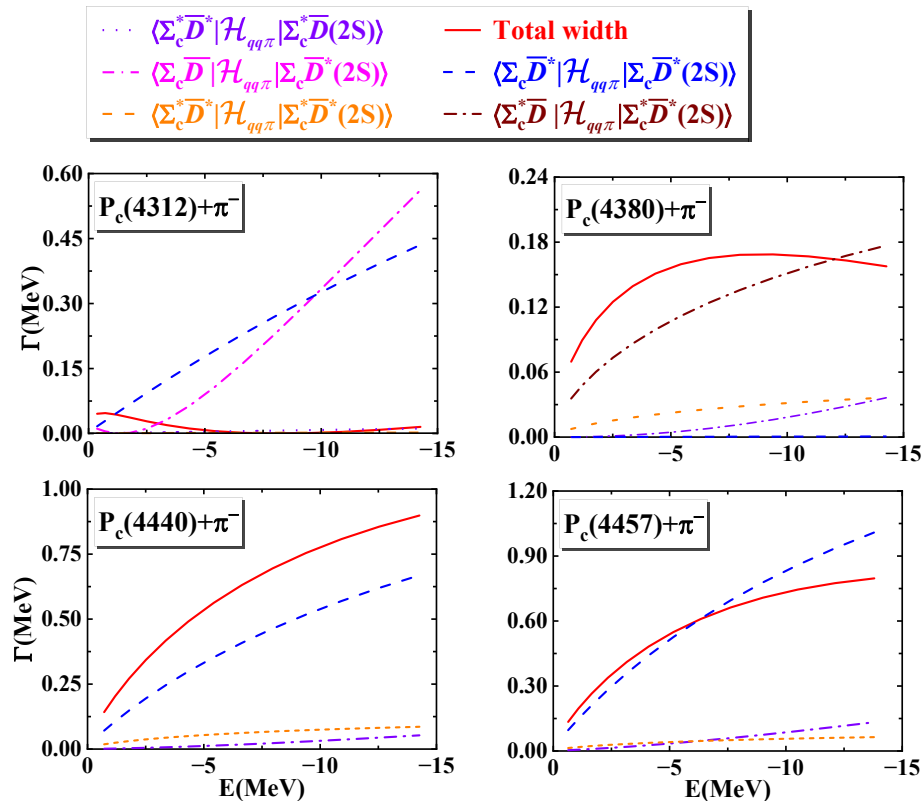
3.4 $\Sigma_c \bar{D}^* / \Sigma_c^* \bar{D}^* (2S) [\frac{1}{2}(\frac{1}{2}^-)] \rightarrow P_c(4312)/P_c(4380)/P_c(4440)/P_c(4457) + \pi$



$$\begin{aligned} \mathcal{M} = & \mathcal{M}_2(\Sigma_c \bar{D}^* (2S) \rightarrow \Sigma_c \bar{D}^* + \pi) \\ & + \mathcal{M}_3(\Sigma_c \bar{D}^* (2S) \rightarrow \Sigma_c \bar{D} + \pi) \\ & + \mathcal{M}_4(\Sigma_c^* \bar{D}^* (2S) \rightarrow \Sigma_c^* \bar{D}^* + \pi) \end{aligned}$$

- Total decay width: **several MeV**; **similar** decay mechanisms;
- Coupled channel effects: **important**, **coherent constructive/ destructive** interference;
- π^0 radiation: 2 times smaller due to the isospin factor.

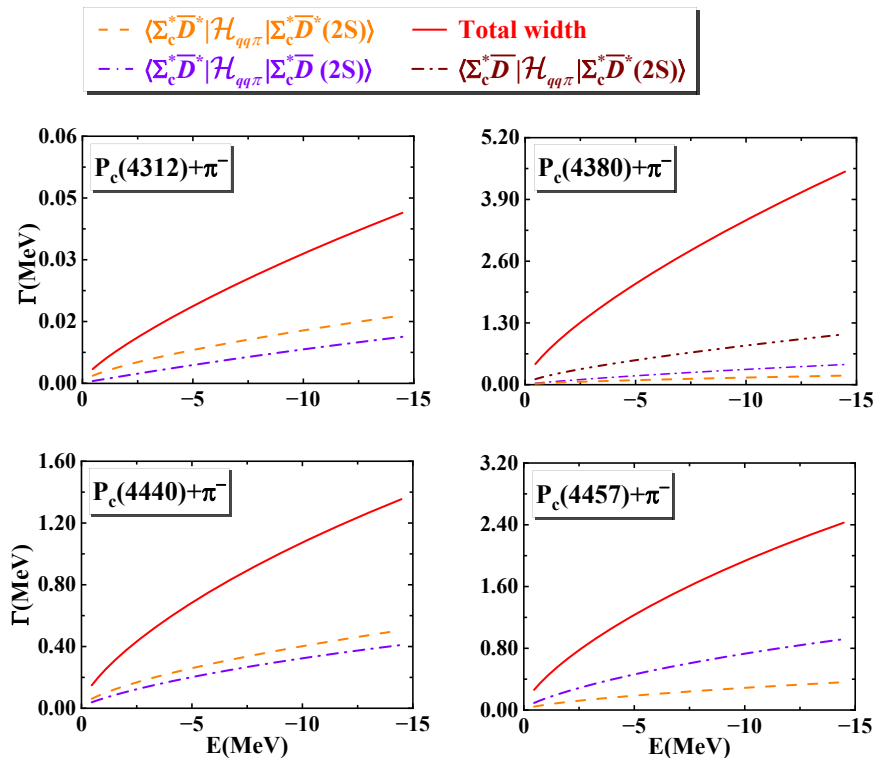
3.5 $\Sigma_c \bar{D}^* / \Sigma_c^* \bar{D} / \Sigma_c^* \bar{D}^* (2S) [\frac{1}{2} (\frac{3}{2}^-)] \rightarrow P_c(4312)/P_c(4380)/P_c(4440)/P_c(4457) + \pi$



$$\begin{aligned} \mathcal{M} = & \mathcal{M}_2(\Sigma_c \bar{D}^*(2S) \rightarrow \Sigma_c \bar{D}^* + \pi) \\ & + \mathcal{M}_3(\Sigma_c \bar{D}^*(2S) \rightarrow \Sigma_c \bar{D} + \pi) \\ & + \mathcal{M}_4(\Sigma_c^* \bar{D}^*(2S) \rightarrow \Sigma_c^* \bar{D}^* + \pi) \end{aligned}$$

- Total decay width: **less than 1 MeV**; different decay mechanisms;
- Coupled channel effects: **important**, coherent constructive/ destructive interference;
- π^0 radiation: 2 times smaller due to the isospin factor.

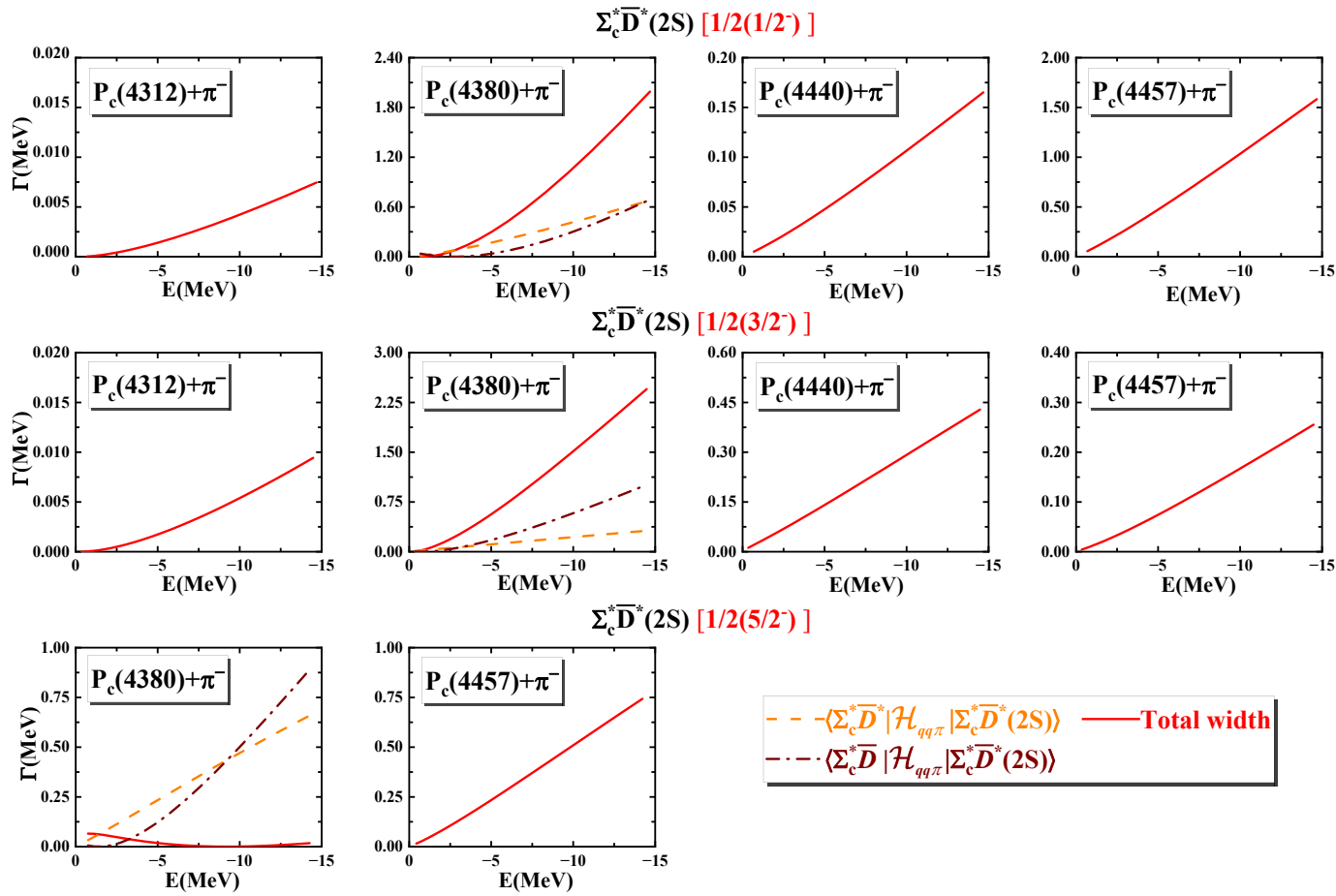
3.6 $\Sigma_c^* \bar{D} / \Sigma_c^* \bar{D}^* (2S) [\frac{1}{2} (\frac{3}{2}^-)] \rightarrow P_c(4312) / P_c(4380) / P_c(4440) / P_c(4457) + \pi$



$$\begin{aligned} \mathcal{M} = & \mathcal{M}_2(\Sigma_c \bar{D}^* (2S) \rightarrow \Sigma_c \bar{D}^* + \pi) \\ & + \mathcal{M}_3(\Sigma_c \bar{D}^* (2S) \rightarrow \Sigma_c \bar{D} + \pi) \\ & + \mathcal{M}_4(\Sigma_c^* \bar{D}^* (2S) \rightarrow \Sigma_c^* \bar{D}^* + \pi) \end{aligned}$$

- Total decay width: **several MeV**; different decay mechanisms;
- Coupled channel effects: **important**, **coherent constructive interference**;
- π^0 radiation: 2 times smaller due to the isospin factor.

3.7 $\Sigma_c^* \bar{D}^* (2S) [\frac{1}{2}(\frac{1}{2}^-)/(\frac{3}{2}^-)/(\frac{5}{2}^-)] \rightarrow P_c(4312)/P_c(4440)/P_c(4380)/P_c(4457) + \pi$



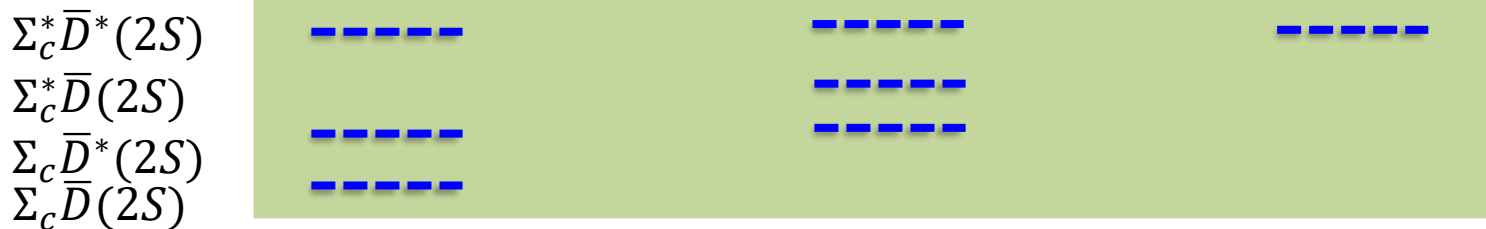
$$\Sigma_c^* \bar{D}^*(2S) \left[\frac{1}{2} \left(\frac{1}{2}^- \right) / \frac{1}{2} \left(\frac{3}{2}^- \right) / \frac{1}{2} \left(\frac{5}{2}^- \right) \right] \rightarrow \Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{1}{2}^- \right) / \frac{1}{2} \left(\frac{3}{2}^- \right) / \frac{1}{2} \left(\frac{5}{2}^- \right) \right] + \pi$$

$$\mathcal{M} = \mathcal{M}_4(\Sigma_c^* \bar{D}^*(2S) \rightarrow \Sigma_c^* \bar{D}^* + \pi)$$

Initial State($\Sigma_c^* \bar{D}^*(2S)$)	Final State($\Sigma_c^* \bar{D}^*$)	Total decay width(MeV)	
$\Sigma_c^* \bar{D}^*(2S) \left[\frac{1}{2} \left(\frac{1}{2}^- \right) \right]$ 	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{1}{2}^- \right) \right]$	0.006~0.60	
	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{3}{2}^- \right) \right]$	0.030~2.40	
	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{5}{2}^- \right) \right]$	x	spin=0
$\Sigma_c^* \bar{D}^*(2S) \left[\frac{1}{2} \left(\frac{3}{2}^- \right) \right]$ 	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{1}{2}^- \right) \right]$	0.014~1.12	
	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{3}{2}^- \right) \right]$	0.002~0.15	
	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{5}{2}^- \right) \right]$	0.003~0.18	
$\Sigma_c^* \bar{D}^*(2S) \left[\frac{1}{2} \left(\frac{5}{2}^- \right) \right]$ 	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{1}{2}^- \right) \right]$	x	spin=0
	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{3}{2}^- \right) \right]$	0.001~0.80	
	$\Sigma_c^* \bar{D}^* \left[\frac{1}{2} \left(\frac{5}{2}^- \right) \right]$	0.001~0.09	

IV. Summary

1. Predicting possible excited Pc molecular candidates



2. Predicting π radiation properties of possible excited Pc molecules in chiral quark model

- Decay widths on the order of MeV.
- π radiation properties depend on the structures of molecular states
(isospin-related, spin-related, coupled channel effects).

Thank you!