Preliminary results

Exploring the π radiation properties between possible Pc(s) molecules

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Outline

I. **Background and motivation:** a simple review of Pc/Pcs states; puzzles of Pc/Pcs as molecules;

II. **π radiation property in chiral quark model;**

III. **Numerical results:** single-channel and coupled-channel analysis;

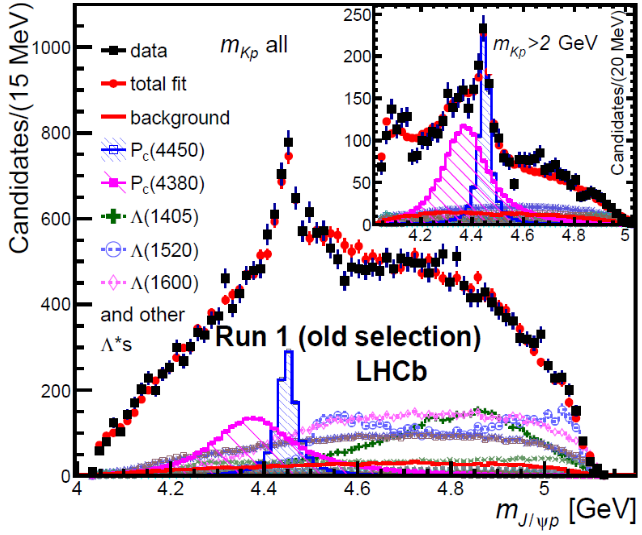
IV. **Summary**

I. Background: A simple review of Pc/Pcs states

1.1 Pc(4380) and Pc(4450) in 2015 @LHCb

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

PRL 115, 072001 (2015)



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)

Theoretical explanations

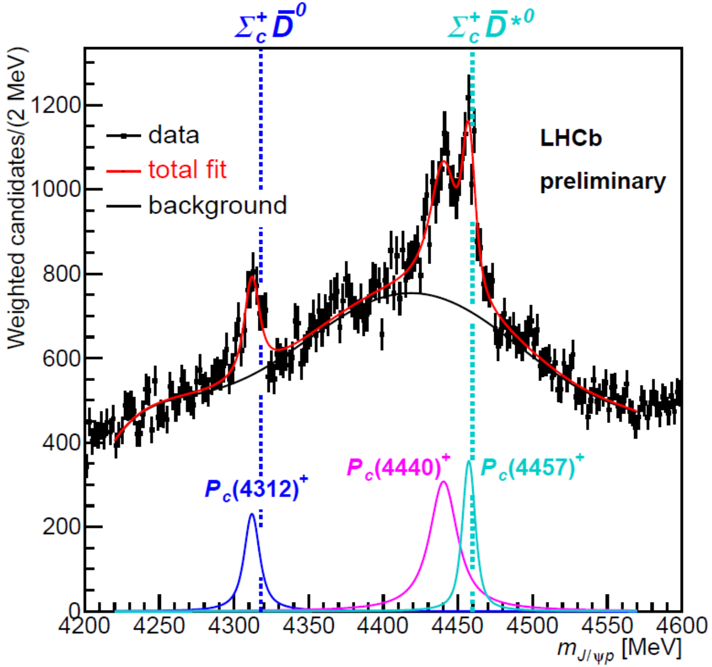
- **Molecular states:** loosely bound states composed of a pair of hadrons, probably bound by the long-range color-singlet pion exchange
- **Compact Pentaquarks:** bound states of five quarks, bound by colored-force between quarks, decay through rearrangement, some are charged or carry strangeness, there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

Molecule: about 28 papers

Others: about 33 papers

1.2 Pc(4312), Pc(4440), and Pc(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 Pc 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

Prog. Part. Nucl. Phys. 107, 237(2019), Phys. Rep.873, 1 (2020) , Phys. Rep.873, 1 (2020), Rept. Prog. Phys. 86,no.2, 026201 (2023)

1.3 Puzzles: the story just begin

- Molecules? Compact pentaquarks? Mixture?

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

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

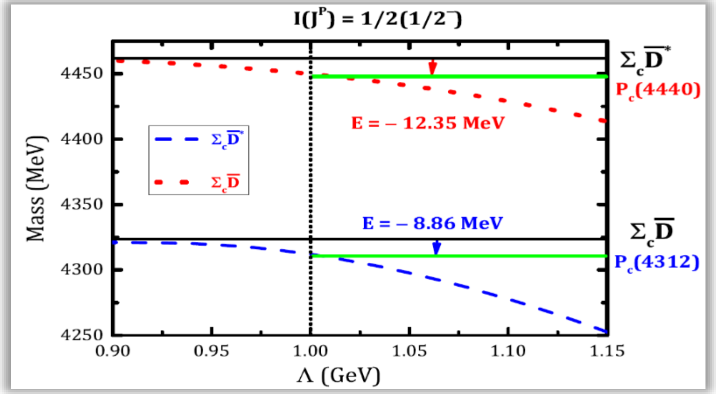
M. Z. Liu et al., Phys.Rev.Lett. 122 (2019) 24, 242001, Jun He, Eur.Phys.J.C 79 (2019) 5, 393

R. Chen et al, PRD 100 (2019) 1, 011502

One-boson-exchange potentials
Coupled channel effects

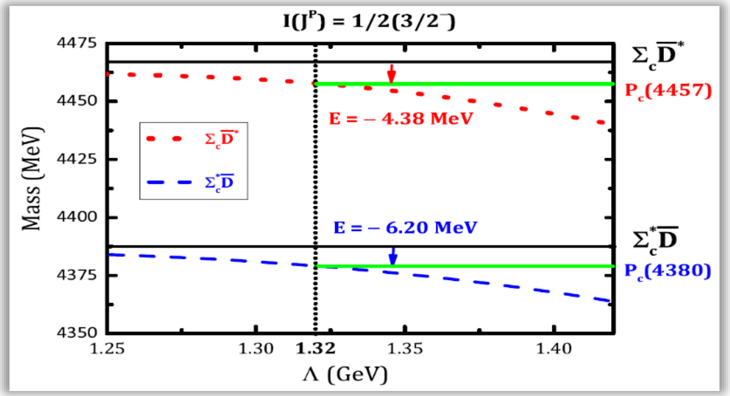
$I(J^P) = 1/2(1/2^-)$ reproduce Pc(4312) and Pc(4440) with $\Lambda = 1.00$ GeV

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



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

- Pc(4457): $\boldsymbol{\Sigma_c \bar{D}^*}: \Sigma_c^* \bar{D}^* = 3:1$, 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



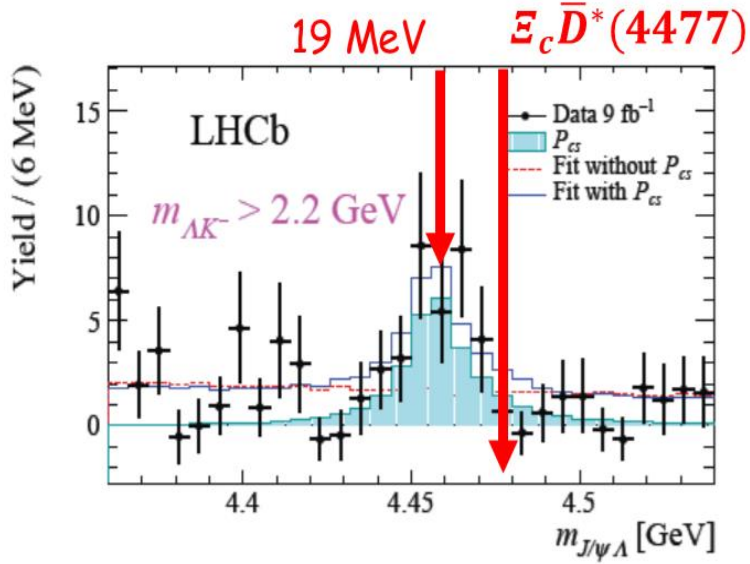
Both theory and experiment need to conduct in-depth research!!!

1.4 Pcs(4459) in 2020 @LHCb

Pcs(4338) in 2023 @LHCb

$\Xi_b^- \to J/\Psi \Lambda K^-$

Sci.Bull. 66 (2021) 1278-1287

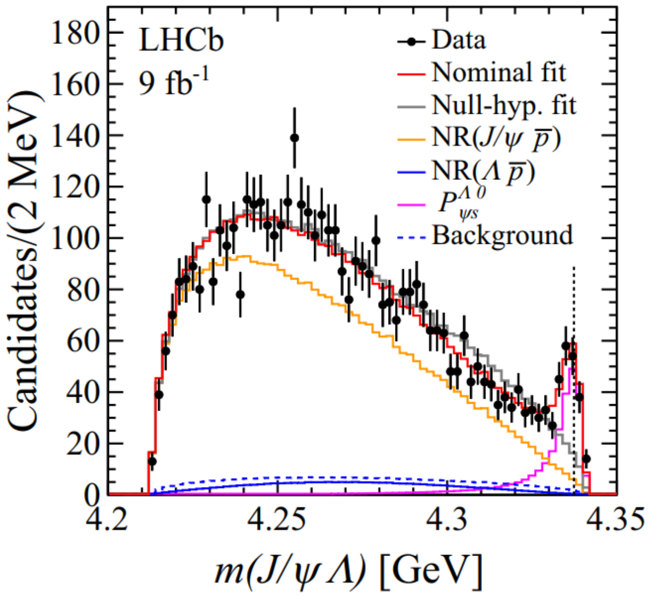


State	M_0 [MeV]	Γ_0 [MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

J^P: Statistics not enough for determination

$B^- \to J/\Psi \Lambda \bar{p}$

PRL 131, 031901 (2023)



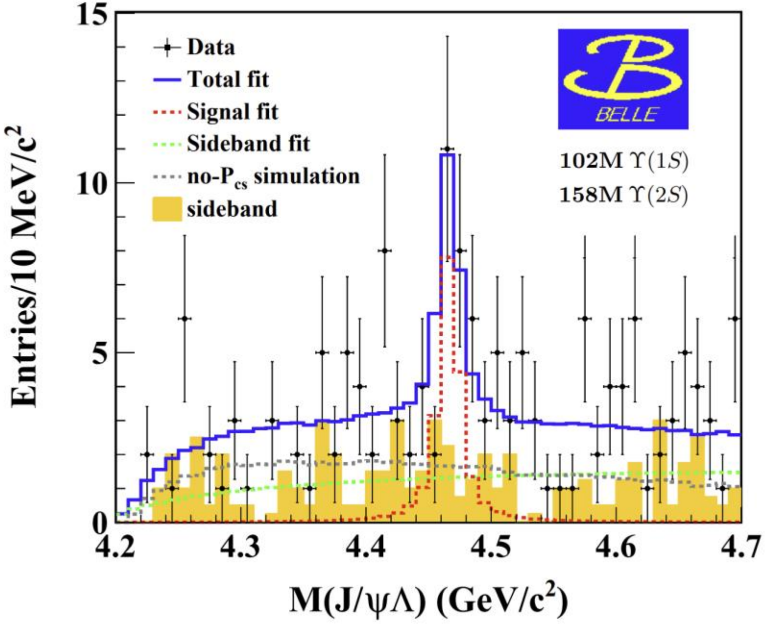
$$M_{P^{\Lambda}_{\psi s}} = 4338.2 \pm 0.7 \text{ MeV}$$

$$\Gamma_{P^{\Lambda}_{\psi s}} = 7.0 \pm 1.2 \text{ MeV}$$

Spin-parity: 1/2- preferred

$\Upsilon(1S,2S)$ **inclusive decays at Belle**

arXiv:2502.09951 [hep-ex]



$M = 4471.7 \pm 4.8 \pm 0.6$ MeV

$\Gamma = 22 \pm 13 \pm 3$ MeV

Molecular scenario

1. arXiv:2507.06991 [hep-ph]
2. arXiv:2506.22723 [hep-ph]
3. arXiv:2504.07693 [hep-ph]
4. Eur. Phys. J. C 85, 492 (2025)
5. Phys. Rev. D 111,7 (2025)
6. Phys. Rev. D 109,094003 (2024)
7. Phys. Rev. D 109, 094027 (2024)
8. Phys. Rev. D 109,074035 (2024)
9. Symmetry 16, 354 (2024)
10. ….

About 38 papers

Compact scenario

1. Phys. Rev. D 111, 074038 (2025)
2. Phys. Rev. D 109, 114037 (2024)
3. Phys. Rev. D 108, 056015 (2023)
4. Phys. Rev. D 105, 116021 (2022)
5. Phys. Rev. D 104, 116007 (2021)
6. Phys. Rev. D 104, 054016 (2021)
7. Eur. Phys. J. A 57, 237 (2021)
8. Eur. Phys. J. C 81, 277 (2021)
9. ……

About 13 papers

A coupled $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ channel analysis

Predictions for $\Xi_c^{(\prime,*)}\bar{D}^*$ molecules Chin. Phys. C 41, 103105 (2017)

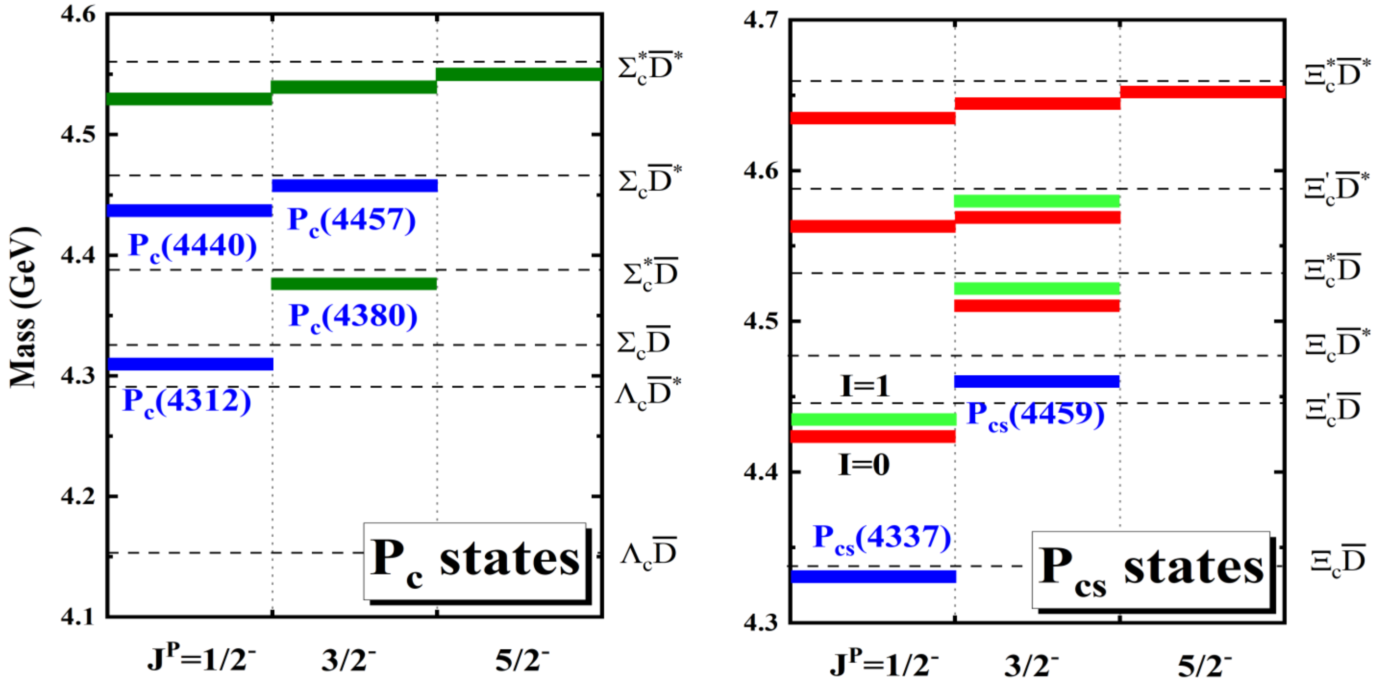
	GeV	MeV	fm	Probabilities			
$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c\bar{D}^*$	$\Xi_c^*\bar{D}$	$\Xi_c'\bar{D}^*$	$\Xi_c^*\bar{D}^*$
$0(1/2^-)$	1.17	−1.63	1.39	30.66	...	**64.13**	5.21
	1.18	−7.52	0.62	15.82	...	**77.10**	7.08
	1.19	−14.29	0.50	11.12	...	**80.82**	8.06
	1.20	−21.62	0.45	8.60	...	**82.62**	8.78
$0(3/2^-)$	0.99	−1.46	2.18	**69.44**	19.46	2.81	8.28
	1.01	−5.73	1.09	**53.70**	28.41	5.52	13.37
	1.03	−11.77	0.79	**44.88**	**32.50**	5.69	16.93
	1.05	−19.28	0.65	**38.95**	**34.58**	6.61	18.86

- Pcs(4459): the coupled $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ state with I(JP) = 0(3/2−), $\Xi_c\bar{D}^*$ and $\Xi_c^*\bar{D}$ channels are dominant
- The coupled channel effect is helpful to form this bound state

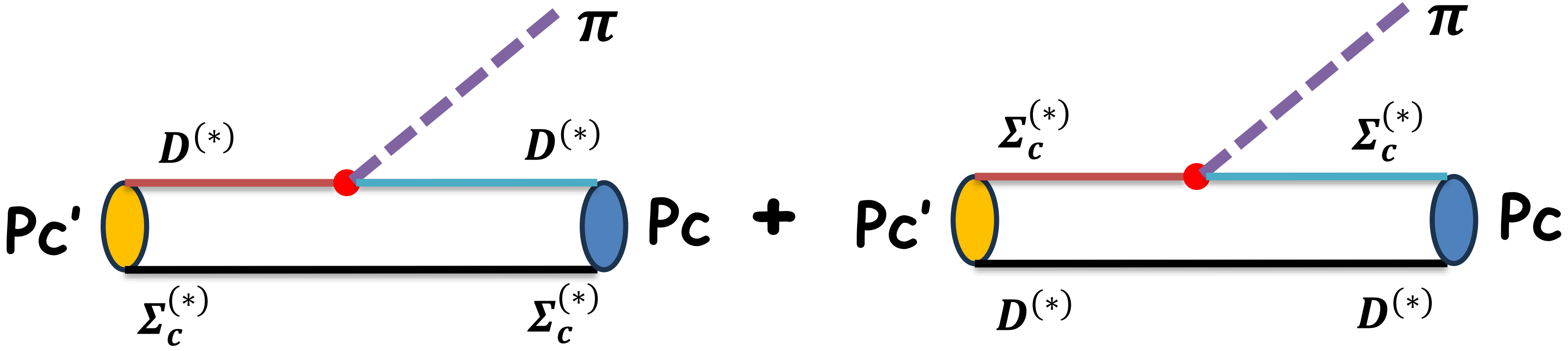
Phys. Rev. D 103, 054007 (2021)

1.4 Pion radiation properties

- Molecular partner: charmed baryon and anti-charm meson;
- Decay properties: more sensitive to the wave function;



1.4 Pion radiation properties



- Pion radiation process: occur at the constituent hadron,
  $\Sigma_c^{(*)} \to \Sigma_c\pi, \quad \Xi_c^{(*)} \to \Xi_c\pi, \quad D^* \to D\pi,$
- 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 order

$$\mathcal{H}^{NR} = g \sum_j \left(\mathcal{G} \boldsymbol{\sigma}_j \cdot \boldsymbol{q} + h \boldsymbol{\sigma}_j \cdot \boldsymbol{p}_j \right) F(\boldsymbol{q}^2) I_j \varphi_m$$

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

X.H. Zhong et al., Phys. Rev. D 78 (2008) 014029; Phys. Rev. D 110 (11) (2024) 116034.

2.2 Decay width

In the rest frame of the molecular state

$$\Gamma = \frac{1}{8\pi}\frac{|\boldsymbol{q}|}{M_i^2}\frac{1}{2J_i+1}\sum_{J_{i_z}J_{f_z}}\left|\mathcal{M}_{J_{i_z}J_{f_z}}\right|^2$$

Amplitude $\boldsymbol{P_c(4457) \to P_c(4312) + \pi}$

$$\mathcal{M} = \langle P_c(4312)|H^{NR}|P_c(4457)\rangle$$

$$\mathcal{H}^{NR} = g\sum_j \left(\mathcal{G}\boldsymbol{\sigma}_j\cdot\boldsymbol{q} + h\boldsymbol{\sigma}_j\cdot\boldsymbol{p}_j\right)F(\boldsymbol{q}^2)I_j\varphi_m$$

2.2 Decay width

$$\mathcal{M} = \langle P_c(4312) | H^{NR} | P_c(4457) \rangle$$

Wave functions

- $\varphi_m = e^{-i\,q.r_j}$: plane wave function of the light meson
- Molecule: $\boldsymbol{\Psi} = \boldsymbol{\phi_D} \times \boldsymbol{\phi_{\Sigma_c}} \times \boldsymbol{\phi}$
- $\boldsymbol{\phi_D}, \boldsymbol{\phi_{\Sigma_c}}$: meson/baryon wave function;

Simple harmonic oscillator wave function

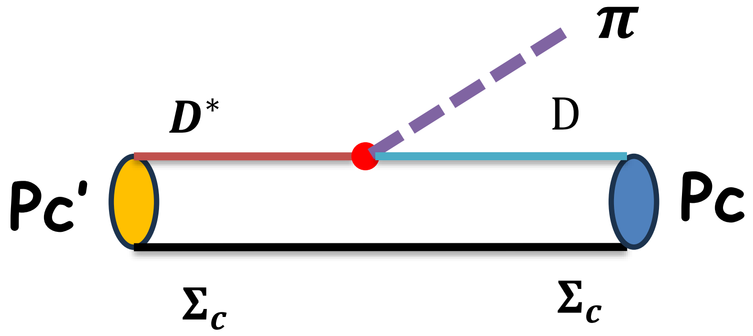
$$\phi_{n,l,m}(\beta, \mathbf{r}) = \sqrt{\frac{2n!}{\Gamma\left(n+l+\frac{3}{2}\right)}} L_n^{l+\frac{1}{2}}\left(\beta^2 r^2\right) \beta^{l+\frac{3}{2}} \mathrm{e}^{-\frac{\beta^2 r^2}{2}} r^l Y_{lm}(\Omega)$$

Phys. Rev. D109, (2024) 054036; Eur.Phys. J. C 85 (5) (2025) 582;
Phys. Rev. D 108 (3) (2023)034006

III. Numerical results

3.1 $P_c(4457) \to P_c(4312) + \pi$

- Single channel $\Psi = \phi_D \phi_{\Sigma_c} \phi$ → S-wave Gaussian function



Oscillating parameter

$$r \sim 1/\sqrt{2\mu(M_A + M_B - M)}$$

$$\beta_{P_c} = \sqrt{3\mu(M_A + M_B - M)}$$

$\Sigma_c \overline{D^*}[I(J^P) = \frac{1}{2}(\frac{1}{2}^-)] \to \Sigma_c \bar{D}[\frac{1}{2}(\frac{1}{2}^-)] + \pi[1(0^-)]$ **0.1 keV**

$\Sigma_c \overline{D^*}[\frac{1}{2}(\frac{3}{2}^-)] \to \Sigma_c \bar{D}[\frac{1}{2}(\frac{1}{2}^-)] + \pi[1(0^-)]$ **3 keV**

3.1 $P_c(4457) \to P_c(4312) + \pi$

- Coupled channel $P_c(4457)[\frac{1}{2}(\frac{3}{2}^-)] \to P_c(4312)[\frac{1}{2}(\frac{1}{2}^-)] + \pi$

Pc(4457): $\Sigma_c\overline{D^*}:\Sigma_c^*\overline{D^*} = 3:1$

Pc(4312): $\Sigma_c\bar{D}:\Sigma_c\overline{D^*}:\Sigma_c^*\overline{D^*}$ =0.66:0.18:0.16

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

$\Psi = \phi_D \phi_{\Sigma_c} \boldsymbol{\phi}$ ⟶ Obtained by solving Schrodinger equations

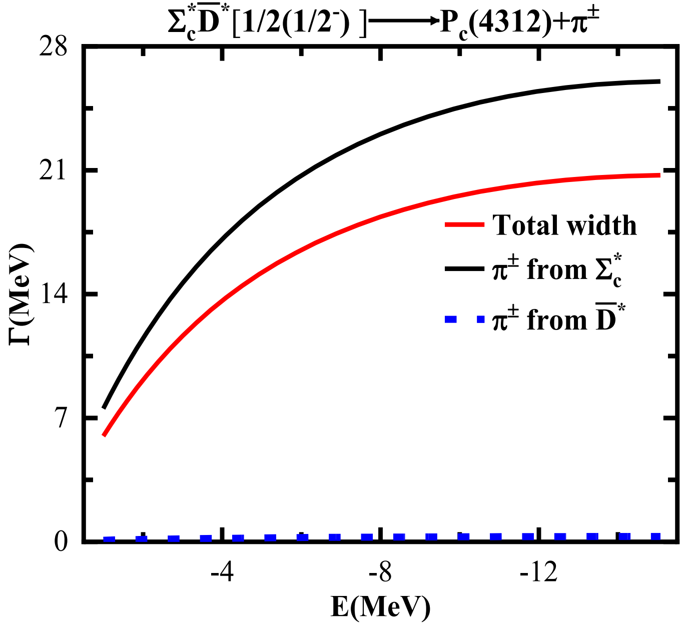
R. Chen et al, PRD 100 (2019) 1, 011502

$\Sigma_c\overline{D^*}[\frac{1}{2}(\frac{3}{2}^-)] \to \Sigma_c\bar{D}[\frac{1}{2}(\frac{1}{2}^-)] + \pi[1(0^-)]$ **100 keV**

Coupled channel effects: much larger than results in single channel

3.2 $\Sigma_c^*\bar{D}^*[I(J^P) = \frac{1}{2}(\frac{1}{2}^-)] \to P_c(4312) + \pi$

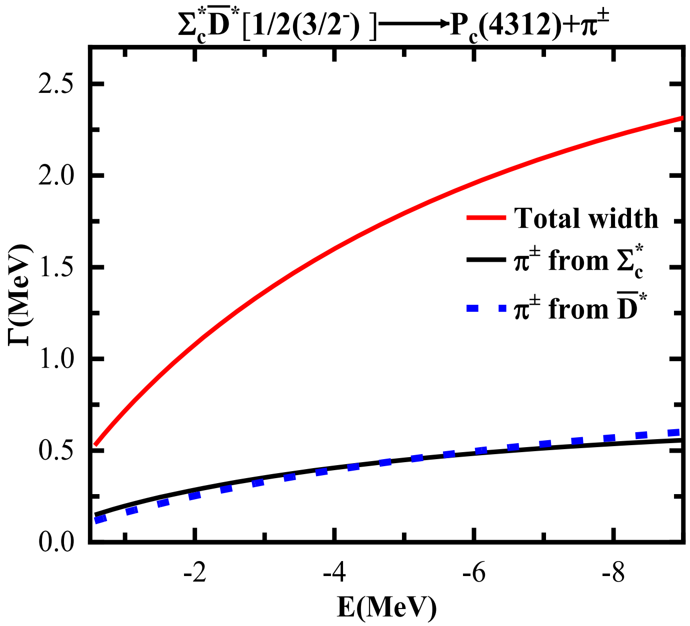
- Single channel: suppressed. $\Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{1}{2}^-)] \nrightarrow \Sigma_c\bar{D}[\frac{1}{2}(\frac{1}{2}^-)]+\pi[1(0^-)]$
- Coupled channel: allowed. Pc(4312): $\Sigma_c\bar{D}:\Sigma_c\overline{D^*}:\Sigma_c^*\overline{D^*}$ =0.66:0.18:0.16



- ☐ Total decay width: around 10 to 20 MeV.
- ☐ Mainly come from $\Sigma_c^{(*)} \to \Sigma_c^{(*)} + \pi$.
- ☐ Coupled channel effects: important, a coherent annihilation.
- ☐ π^0 radiation: 2 times smaller due to the isospin factor

3.3 $\Sigma_c^*\bar{D}^*[I(J^P)=\frac{1}{2}(\frac{3}{2}^-)]\to P_c(4312)+\pi$

- Single channel: suppressed. $\Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{3}{2}^-)]\nrightarrow\Sigma_c\bar{D}[\frac{1}{2}(\frac{1}{2}^-)]+\pi[1(0^-)]$
- Coupled channel: allowed. Pc(4312): $\Sigma_c\bar{D}:\Sigma_c\overline{D^*}:\Sigma_c^*\overline{D^*}$ =0.66:0.18:0.16

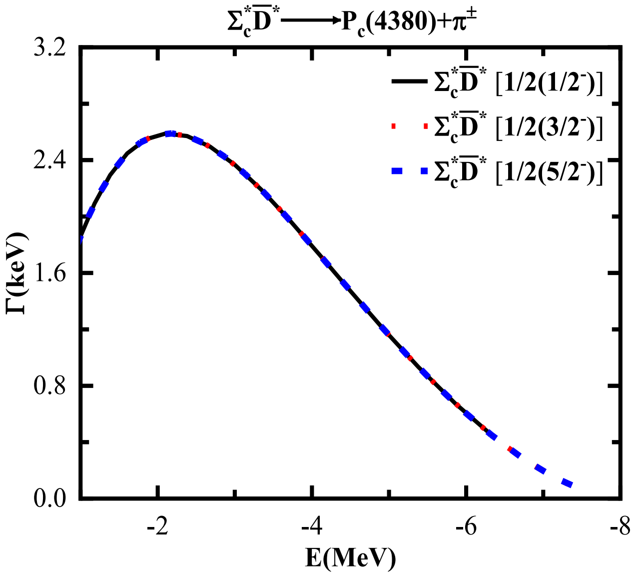


- Total decay width: few MeV.
- Interactions from D* and Σ_c^* are comparable.
- Coupled channel effects: important, a coherent growth.
- π^0 radiation: 2 times smaller due to the isospin factor.

3.4 $\Sigma_c^*\bar{D}^*[I(J^P) = \frac{1}{2}(\frac{5}{2}^-)] \rightarrow P_c(4312) + \pi$ Tiny: F-wave interactions

3.5 $\Sigma_c^*\bar{D}^*[I(J^P) = \frac{1}{2}(\frac{1}{2}^-)] \rightarrow P_c(4380) + \pi$

- Single channel: $\Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{3}{2}^-)] \rightarrow \Sigma_c^*\bar{D}[\frac{1}{2}(\frac{3}{2}^-)] + \pi[1(0^-)]$

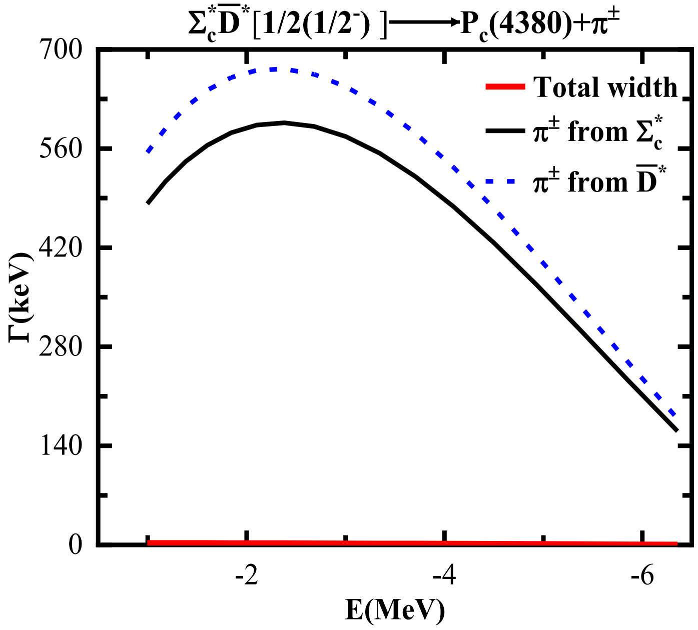


- Interactions from D* decay.
- Don't depend on the total spin of the initial state.
- Width: few keV.
- π^0 radiation: very similar due to the very small phase space

3.6 $\Sigma_c^*\bar{D}^*[I(J^P)=\frac{1}{2}(\frac{1}{2}^-)] \rightarrow P_c(4380)+\pi$

- Coupled channel   P[$\Sigma_c^*\bar{D}$]>87%,

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

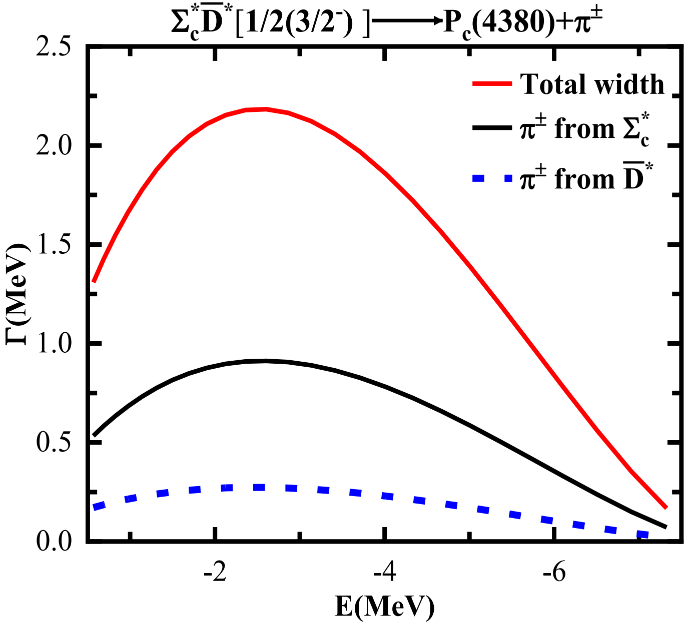


- D* decay and $\Sigma_c^{(*)}$ decay: same order.
- Coupled channel effects: important, a coherent annihilation.
- Width: few keV.
- π^0 radiation: very similar due to the very small phase space

3.6 $\Sigma_c^*\bar{D}^*[I(J^P)=\frac{1}{2}(\frac{3}{2}^-)]\to P_c(4380)+\pi$

- Coupled channel P[$\Sigma_c^*\bar{D}$]>87%,

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

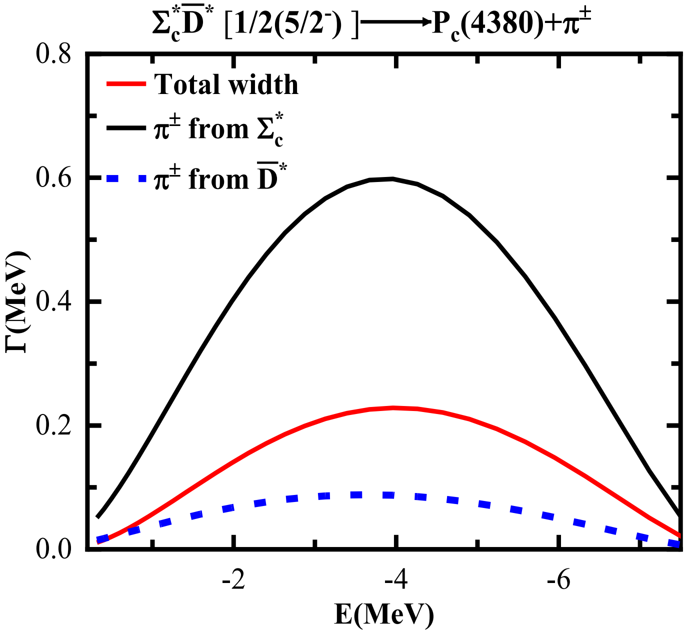


- ☐ Interactions from $\Sigma_c^{(*)}$ decay.
- ☐ Coupled channel effects: important, a coherent growth.
- ☐ Width: few MeV.
- ☐ π^0 radiation: very similar due to the very small phase space

3.7 $\Sigma_c^*\bar{D}^*[I(J^P) = \frac{1}{2}(\frac{5}{2}^-)] \to P_c(4380) + \pi$

- Coupled channel P[$\Sigma_c^*\bar{D}$]>87%,

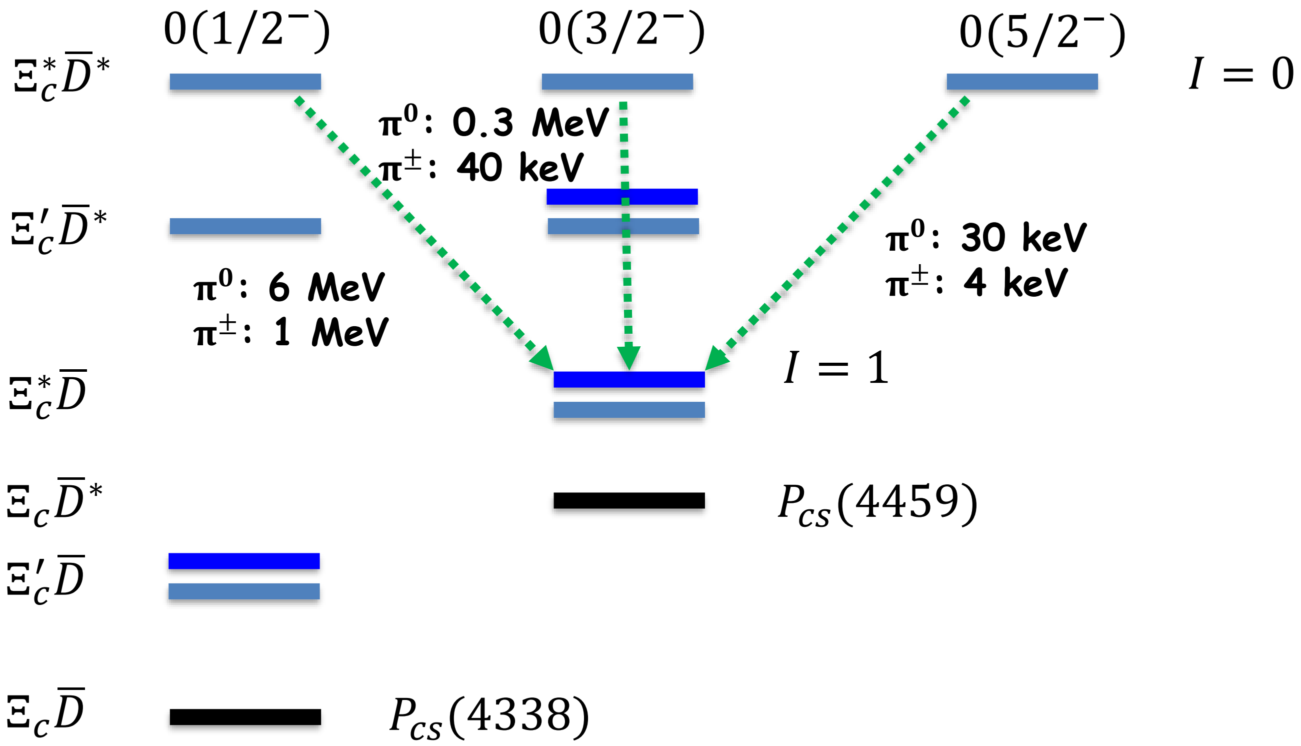
$$\mathcal{M} = \mathcal{M}(\Sigma_c^{(*)} \to \Sigma_c^{(*)} + \pi) + \mathcal{M}(\bar{D}^* \to \bar{D}^{(*)} + \pi)$$



- ☐ Interactions from $\Sigma_c^{(*)}$ decay.
- ☐ Coupled channel effects: important, a coherent annihilation.
- ☐ Width: less than 1 MeV.
- ☐ π^0 radiation: very similar due to the very small phase space

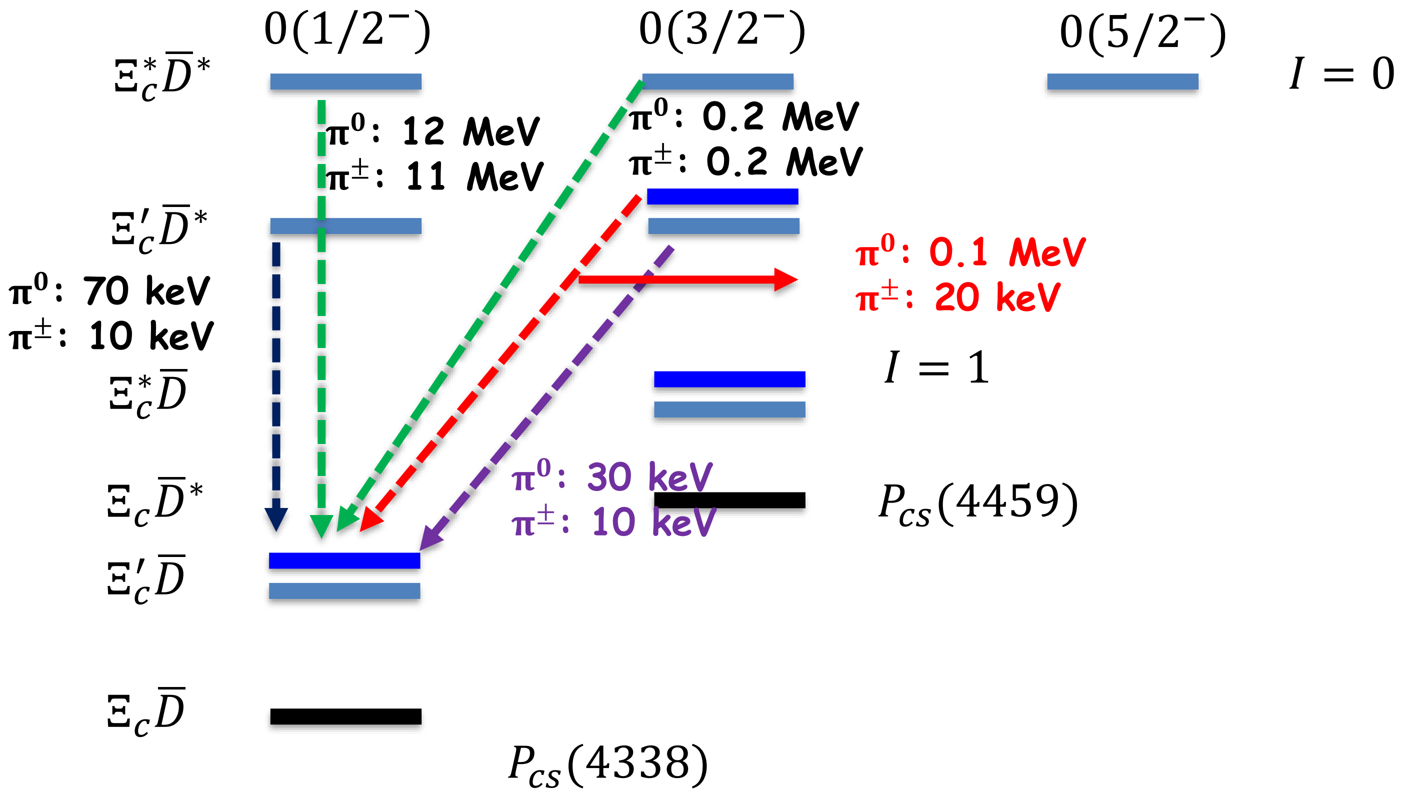
3.8 π radiation from Pcs molecules

$$P_{cs} \to \Xi_c^* \bar{D}[1(3/2^-)] + \pi$$



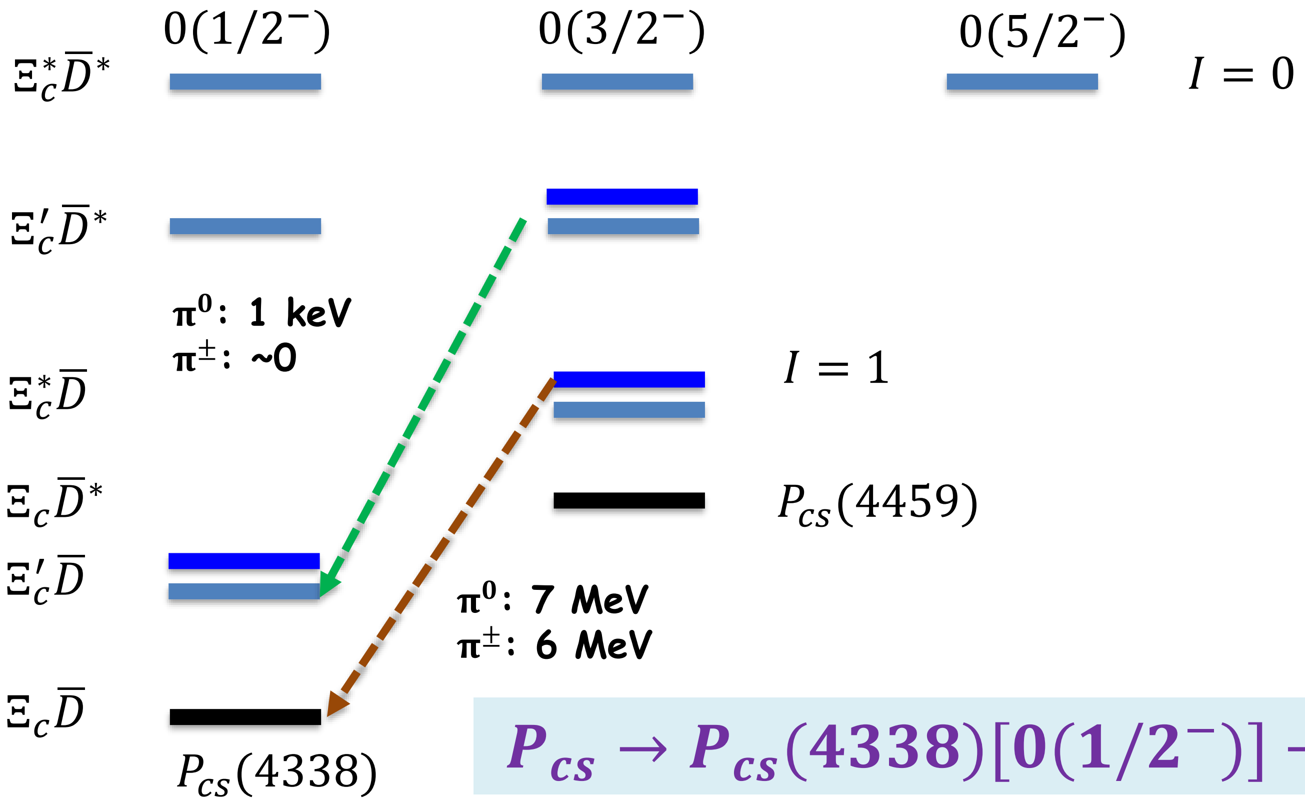
3.8 π radiation from Pcs molecules

$$P_{cs} \to \Xi_c^{'}\bar{D}[1(1/2^-)] + \pi$$



3.8 π radiation from Pcs molecules

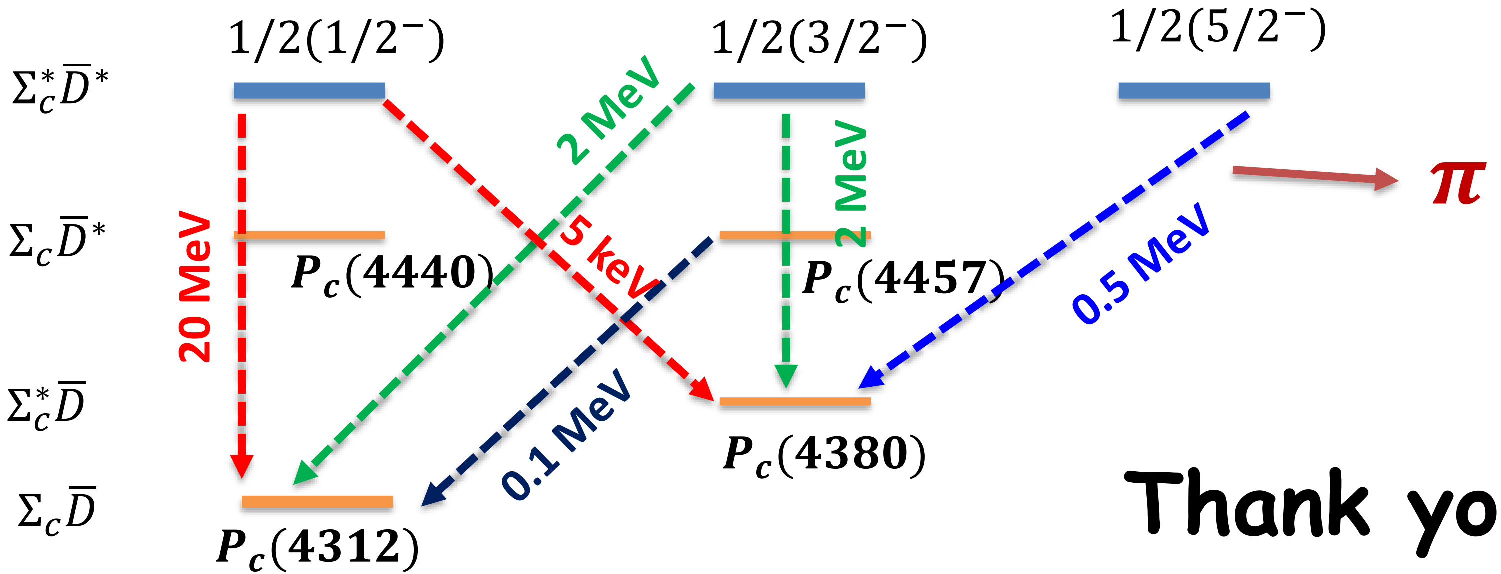
$$P_{cs} \to \Xi_c^{'} \bar{D}[0(1/2^-)] + \pi$$



$$P_{cs} \to P_{cs}(4338)[0(1/2^-)] + \pi$$

IV. Summary

Predicting the pion radiation widths between possible Pc/Pcs molecules using chiral quark model study.



Thank you!

Coupled channel effects are important!