HUNAN NORMAL UNIVERSITY

物理与电子科学学院

π radiation properties from charmed baryon-excited anticharmed meson molecules to Pc states

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Outline

I. Background and motivation: baryon-meson molecular explanations to Pc states; excited Pc states?

II. π radiation property in chiral quark model;

III. Numerical results

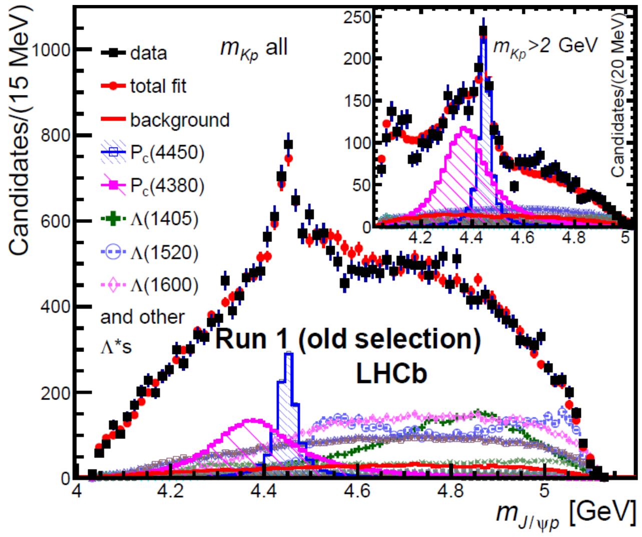
IV. Summary

I. Background

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

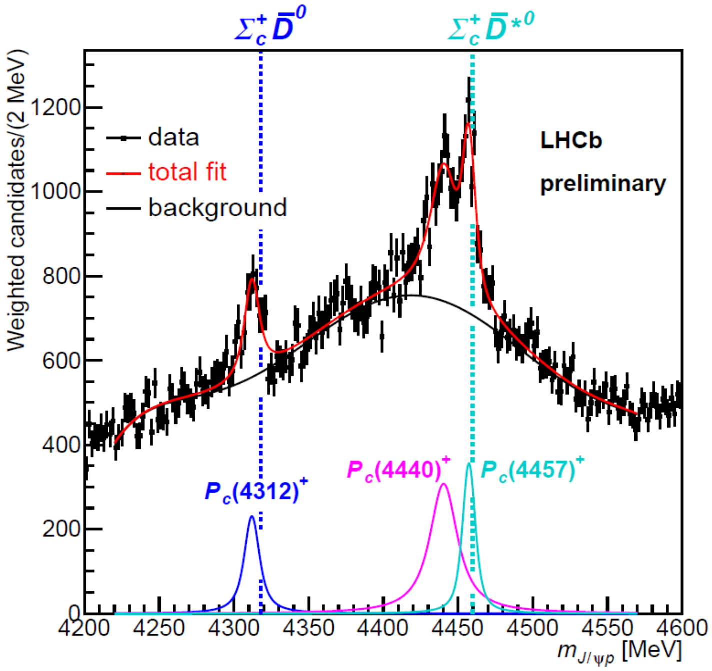
- **Molecular states:** loosely bound states composed of a pair of hadrons, probably bound by the long-range color-singlet pion exchange
- **Compact Pentaquarks:** bound states of five quarks, bound by colored-force between quarks, decay through rearrangement, some are charged or carry strangeness, there 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

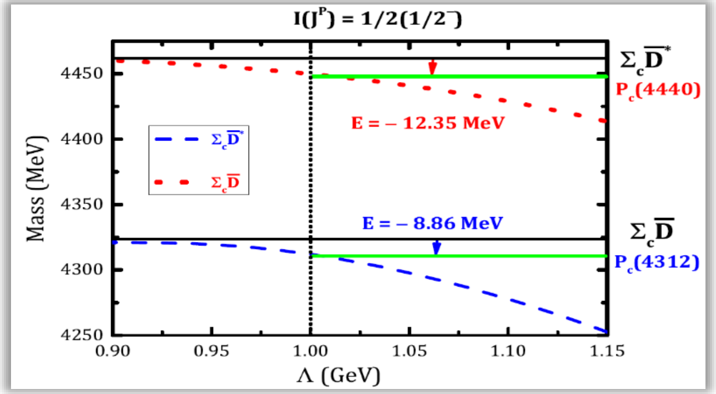
Prog. Part. Nucl. Phys. 107, 237(2019), Phys. Rep.873, 1 (2020) , Phys. Rep.873, 1 (2020), Rept. Prog. Phys. 86,no.2, 026201 (2023)

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

One-boson-exchange potentials
Coupled channel effects

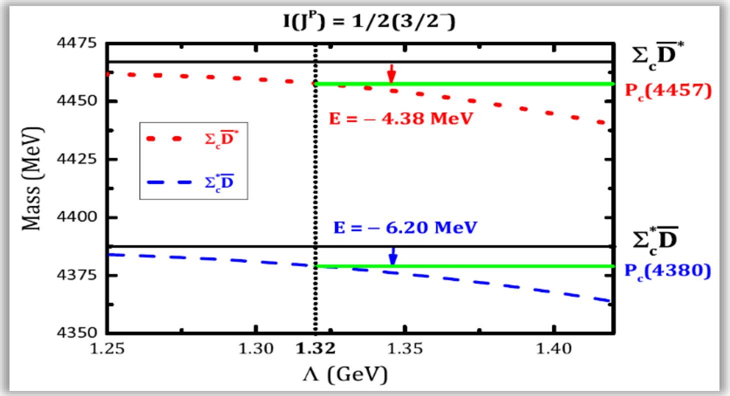
$I(J^P) = 1/2(1/2^-)$ reproduce Pc(4312) and Pc(4440) with $\Lambda = 1.00$ GeV

- 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

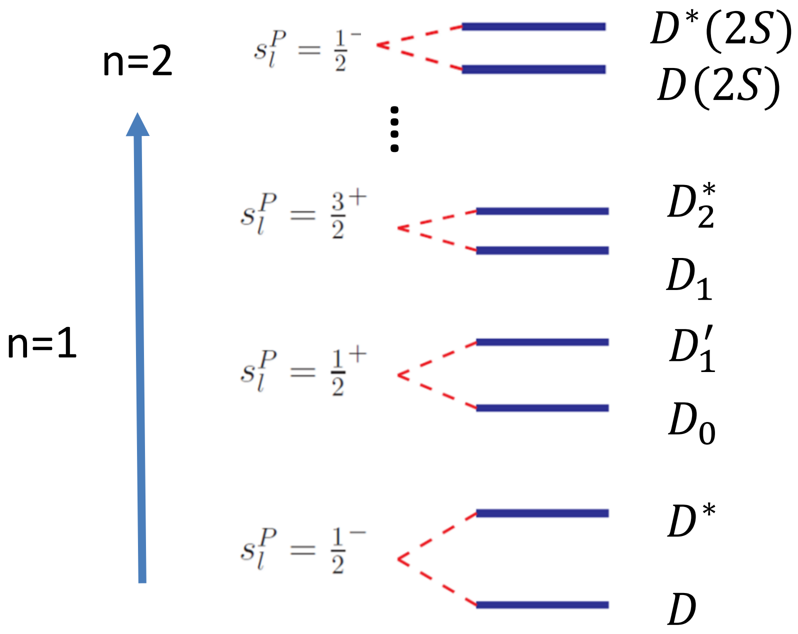
- Pc(4457): $\boldsymbol{\Sigma_c \bar{D}^*}: \Sigma_c^* \bar{D}^* = 3:1$, root-mean-square radius: R=1.61 fm, loosely bound molecular state, coupled-channel effect: **very important**
- One more molecular pentaquark: Pc(4380) M=4379 MeV, **P[$\Sigma_c^* \bar{D}$]>87%,** R=1.40 fm



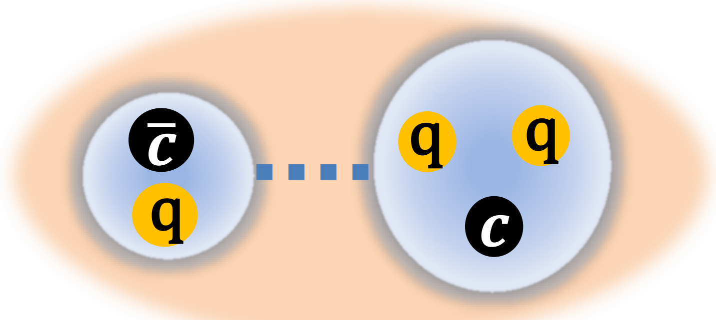
1.3 Questions: excited Pc states exist or not?

Charmed mesons

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



Molecular pentaquarks



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

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

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

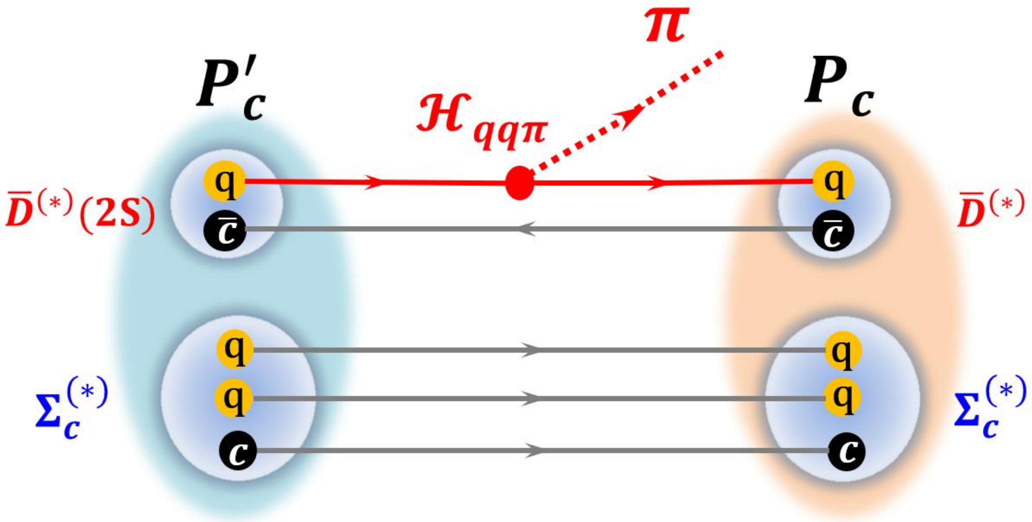
PHYSICAL REVIEW C **101**, 025201 (2020)

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,[1,2,‡] and Xiang Liu[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 $\Lambda_b^0 \to \psi(2S)p\pi^-$. 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.

1.3 Questions: excited Pc states exist or not? How to find?



- Pion radiation process: occur at the constituent hadron $D^* \to D\pi$;
- 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/m2 order

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

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

- σ_j, p_j: the j-th light quark; ω, q, mp: 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: 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

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

Amplitude

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

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

Wave functions

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

Simple harmonic oscillator wave function

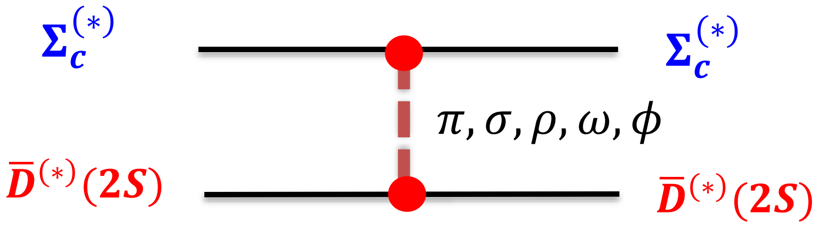
$$\phi_{n,l,m}(\beta,\mathbf{r}) = \sqrt{\frac{2n!}{\Gamma\left(n+l+\frac{3}{2}\right)}}L_n^{l+\frac{1}{2}}\left(\beta^2 r^2\right)\beta^{l+\frac{3}{2}}\mathrm{e}^{-\frac{\beta^2 r^2}{2}} r^l Y_{lm}(\Omega)$$

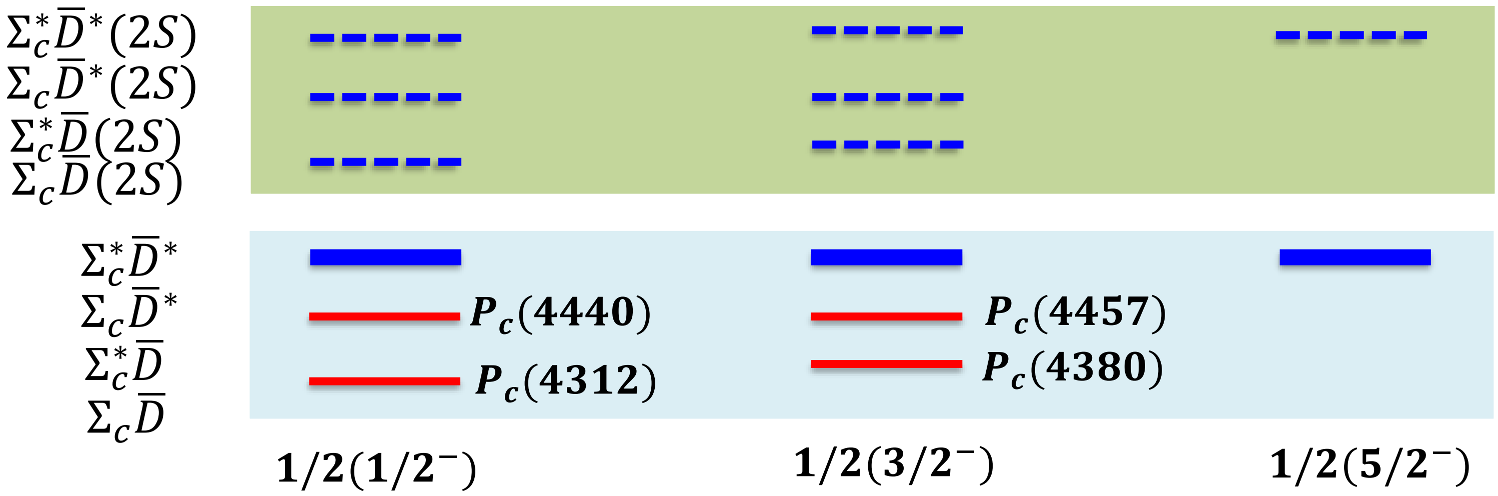
Phys. Rev. D109, (2024) 054036; Eur.Phys. J. C 85 (5) (2025) 582; Phys. Rev. D 108 (3) (2023)034006

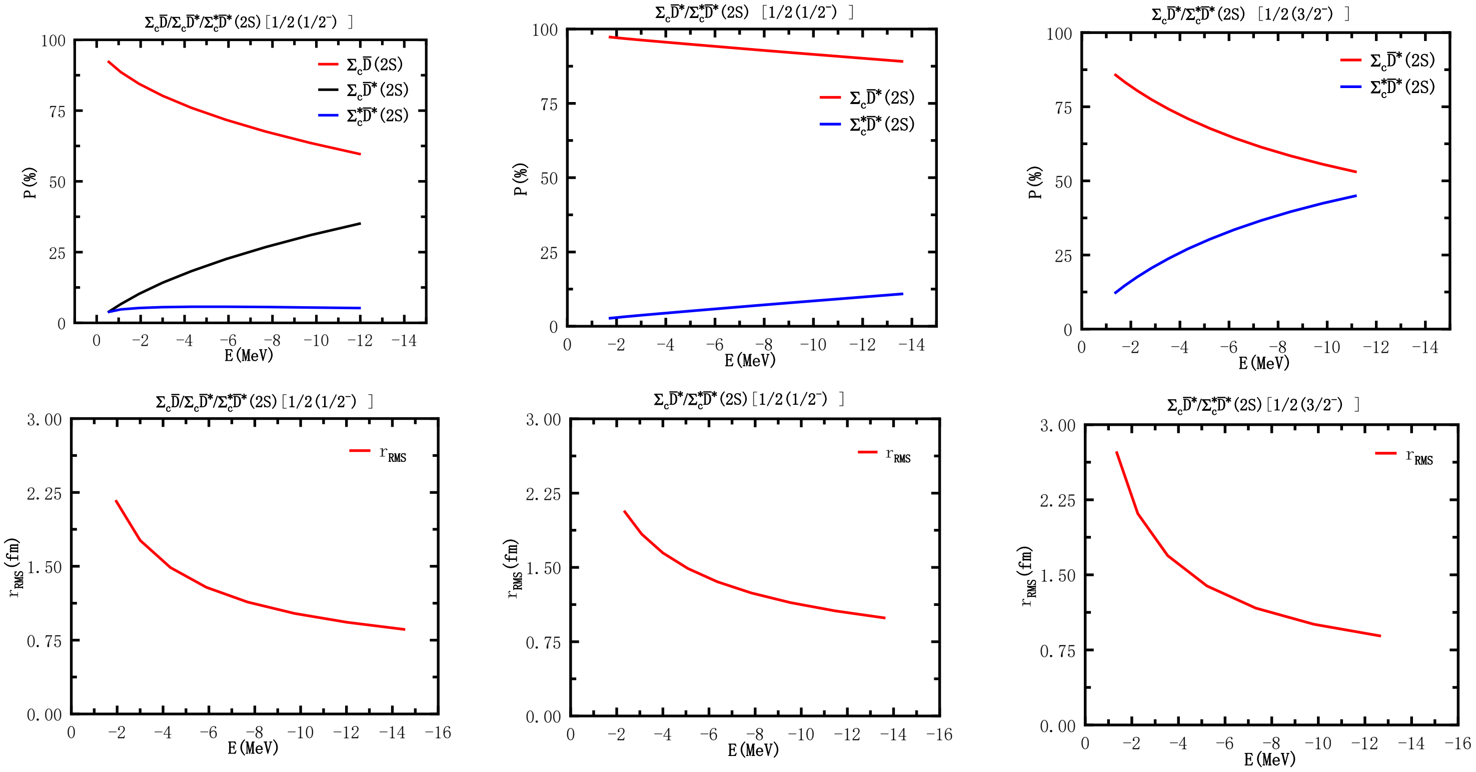
III. Numerical results

3.1 $\Sigma_c\bar{D}/\Sigma_c\bar{D}^*/\Sigma_c^*\bar{D}^*(2S)$ molecular candidates

OBE effective potentials

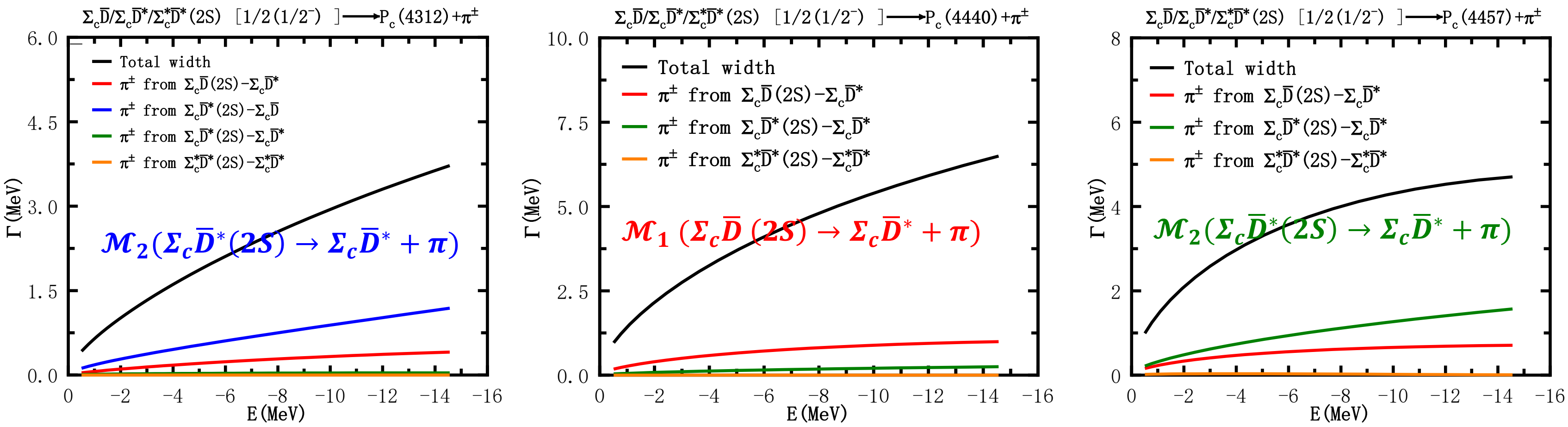






- **Reasonable loosely bound molecular candidates: binding energies and reasonable RMS radii.**
- **Coupled channel effects: important.**

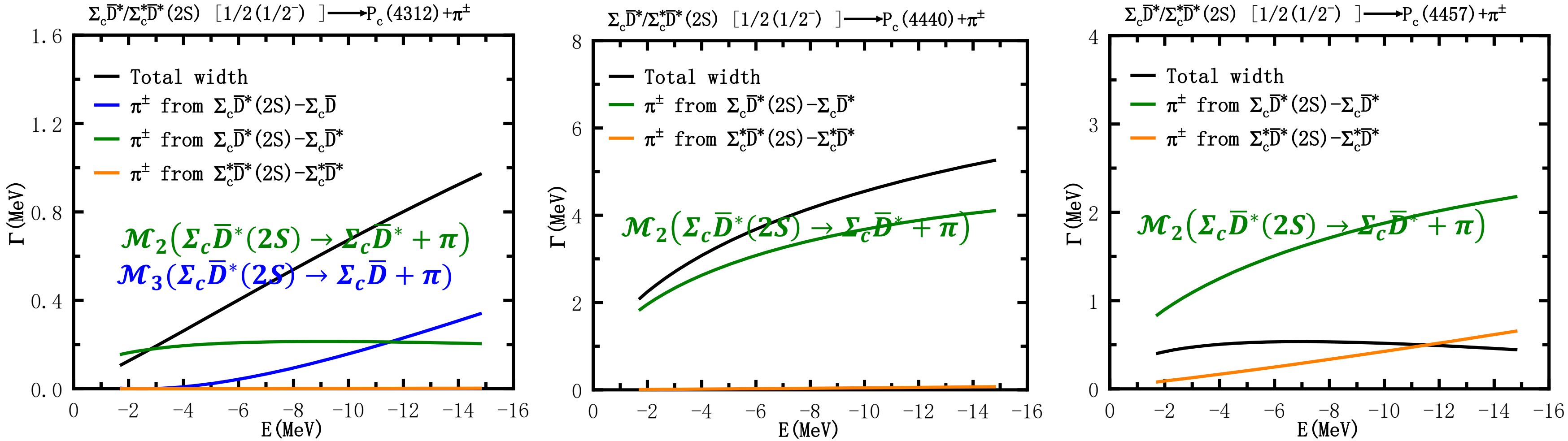
3.2 $\Sigma_c\bar{D}/\Sigma_c\bar{D}^*/\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{1}{2}^-)] \to P_c(4312)/P_c(4440)/P_c(4457)+\pi$



$$\mathcal{M} = \mathcal{M}_1(\Sigma_c\bar{D}(2S) \to \Sigma_c\bar{D}^* + \pi) + \mathcal{M}_2(\Sigma_c\bar{D}^*(2S) \to \Sigma_c\bar{D}^* + \pi) + \mathcal{M}_3(\Sigma_c\bar{D}^*(2S) \to \Sigma_c\bar{D} + \pi) + \mathcal{M}_4(\Sigma_c^*\bar{D}^*(2S) \to \Sigma_c^*\bar{D}^* + \pi)$$

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

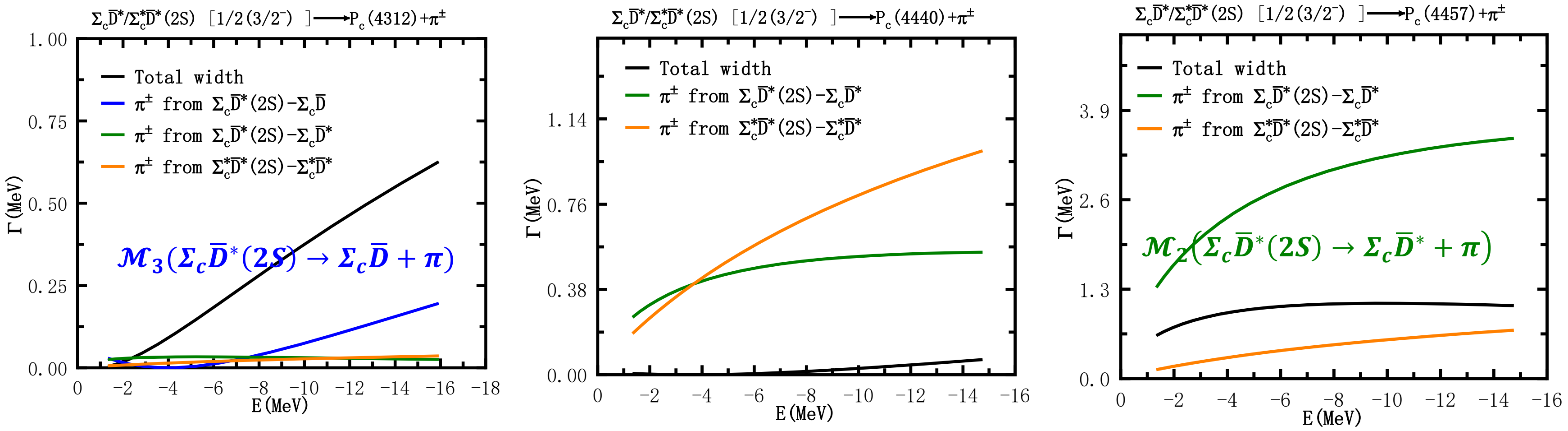
3.3 $\Sigma_c\bar{D}^*/\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{1}{2}^-)] \to P_c(4312)/P_c(4440)/P_c(4457)+\pi$



$$\mathcal{M}=\mathcal{M}_2(\Sigma_c\bar{D}^*(2S)\to\Sigma_c\bar{D}^*+\pi)+\mathcal{M}_3(\Sigma_c\bar{D}^*(2S)\to\Sigma_c\bar{D}+\pi)+\mathcal{M}_4(\Sigma_c^*\bar{D}^*(2S)\to\Sigma_c^*\bar{D}^*+\pi)$$

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

3.4 $\Sigma_c\bar{D}^*/\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{3}{2}^-)] \to P_c(4312)/P_c(4440)/P_c(4457) + \pi$



$$\mathcal{M} = \mathcal{M}_2(\Sigma_c\bar{D}^*(2S) \to \Sigma_c\bar{D}^* + \pi) + \mathcal{M}_3(\Sigma_c\bar{D}^*(2S) \to \Sigma_c\bar{D} + \pi) + \mathcal{M}_4(\Sigma_c^*\bar{D}^*(2S) \to \Sigma_c^*\bar{D}^* + \pi)$$

- ☐ 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.

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{1}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{1}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0.3 MeV. ($\pi^{\pm}$)

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{1}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{3}{2}^-)]+\pi[1(0^-)]$ Total decay width: 1.6 MeV.

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{1}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{5}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0 MeV. (spin=0)

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{3}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{1}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0.9 MeV.

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{3}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{3}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0.1 MeV.

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{3}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{5}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0.14 MeV.

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{5}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{1}{2}^-)]+\pi[1(0^-)]$ Total decay width:0 MeV. (spin=0)

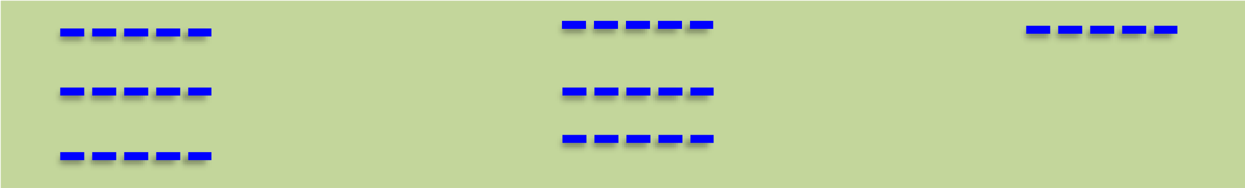
$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{5}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{3}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0.8 MeV.

$\Sigma_c^*\bar{D}^*(2S)[\frac{1}{2}(\frac{5}{2}^-)] \rightarrow \Sigma_c^*\bar{D}^*[\frac{1}{2}(\frac{5}{2}^-)]+\pi[1(0^-)]$ Total decay width: 0.06MeV.

IV. Summary

1. Predicting possible excited Pc molecular candidates

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



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!