Hidden-charm pentaquarks

Meng-Lin Du (杜孟林)

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University of Electronic Science and Technology of China (UESTC)

电子科技大学

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Collaborators: V. Baru, X.-H. Dai, F.-K. Guo, Z.-H. Guo, C. Hanhart, P. Ling, U.-G. Meißner, A. Nefediev, I. Strakovsky, J. Oller, Q. Wang, W.-J. Wang, B. Wu

Interpretation of the LHCb Pc states as Hadronic Molecules and Hints of a Narrow Pc(4380)
Revisting the nature of the Pc states
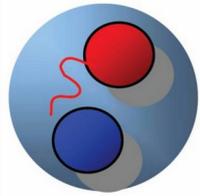Prompt production of the hidden charm pentaquarks in the LHC
Insights into the nature of the Pcs(4459)
Deciphering the mechanism of near-threshold J/ψ photoproduction
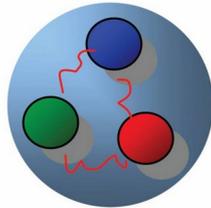In preparation

Conventional hadrons vs. Exotic hadrons

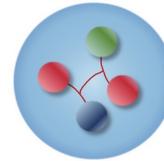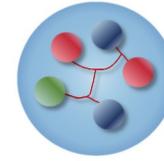## Conv. Hadrons

meson   baryon

Hundreds of hadrons can be described as $q\bar{q}$ and qqq states

Exotic Hadrons
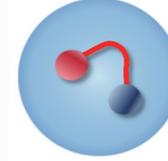

Tetraquark   Pentaquark   Hybrid   Glueball
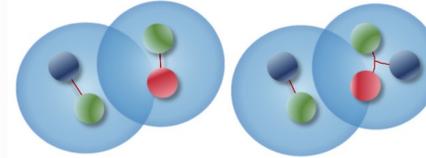
Hadronic molecule

Volume 8, number 3   PHYSICS LETTERS   1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations 1, 8, and 10 that have been observed, while

21 February 1964

AN SU₃ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig

CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\overline{AAAAA}$, $\overline{AAAAAA}$, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\overline{A}$, $\overline{AAAA}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\overline{A}$ and AAA, that is, "deuces and treys".

The multiquark states were predicted at the birth of Quark Model.

The experimental and theoretical study of such states is a key to understand QCD

Light-flavor Pentaquarks

- ## $\Lambda(1405)$ $[ud\bar{s}]$

  - 1959: $\overline{K}N$ molecule predicted by Dalitz-Tuan, PRL2,425

  - 1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

  - 1995: $\overline{K}N$ dynamically generated, by Kaiser et al., NPA954, 325

  - 2001: two-pole structure by $\overline{K}N - \Sigma\pi$ by Oller et al., PLB500, 263

  ......
           ... on two-pole structure, eg. Meißner, Symmetry12,981(2020),
                             Xie et al., PRD108, L111502...

- ## $\theta^+(1540)$ $[uudd\bar{s}]$

  - 1997: predicted w/ chiral soliton model by Diakonov et al., ZPA359, 305

  - 2003: $\theta^+(1540) \rightarrow K^+n$ by LEPS, PRL91, 012002

  - 2004: appear on Review of Particle Physics (RPP) by PDG, supported by many exp.

  - 2005: not supported by many high stats exp.

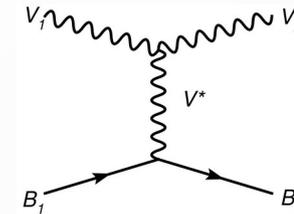 - 2006: removed from RPP by PDG

Hidden-charm Pentaquarks: Predictions

2006: SU(4)+unitarity, by Hofmann et al., NPA776,17-51

(I, S)	State	M_R [MeV] Γ_R [MeV]	$|g_R|$
$(\frac{1}{2}, 0)$	$\pi\Delta$	3430	0.05
	$K\Sigma$	0.50	0.04
	$\bar{D}\Sigma_c$		5.6
$(0, -1)$	$\pi\Sigma$	3538	0.04
	$K\Xi$	0.63	0.05
	$\bar{D}\Xi_c$		5.6

2010: local hidden gauge + unitarity, by J.J. Wu et al., PRL105, 232001

(I, S)	M	Γ			Γ_i		
$(1/2, 0)$			πN	ηN	$\eta' N$	$K\Sigma$	$\eta_c N$
$\bar{D}\Sigma_c$	4261	56.9	3.8	8.1	3.9	17.0	23.4
$(1/2, 0)$			ρN	ωN	$K^*\Sigma$		$J/\psi N$
$\bar{D}^*\Sigma_c$	4412	47.3	3.2	10.4	13.7		19.2

$$T = [1 - VG]^{-1}V$$

2012: One-boson-exchange model $(\pi, \eta, \rho, \omega, \sigma)$ + Schrödinger Eq., by Z.C. Yang et al., CPC36, 6

$\hookrightarrow \bar{D}\Sigma_c(1/2^-), \bar{D}^*\Sigma_c(1/2^-, 3/2^-): 0 \sim 50$ MeV

2013: HQSS + local hidden gauge + unitarity, by C.W. Xiao et al., PRD88, 56012

$\hookrightarrow \bar{D}\Sigma_c(1/2^-), \bar{D}\Sigma_c^*(3/2^-), \bar{D}^*\Sigma_c(1/2^-, 3/2^-),$
$\bar{D}^*\Sigma_c^*(1/2^-, 3/2^-, 5/2^-):$ binding energy ~ 50 MeV

Chiral quark model, W.L. Wang et al., PRC84, 015203 (2011)
Hyperfine interaction, S.G. Yuan et al., EPJA48, 61 (2012)
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Review papers:
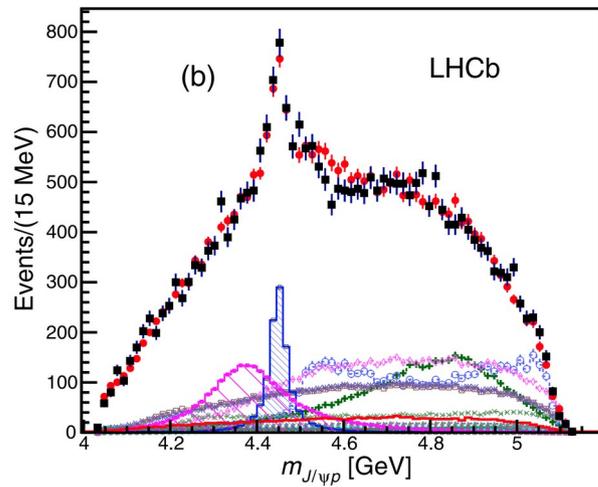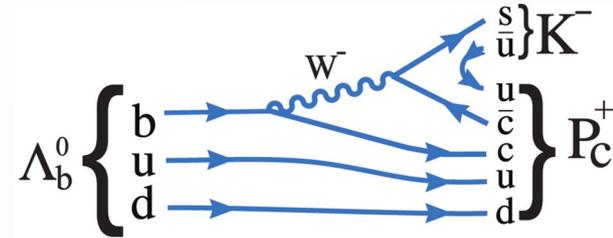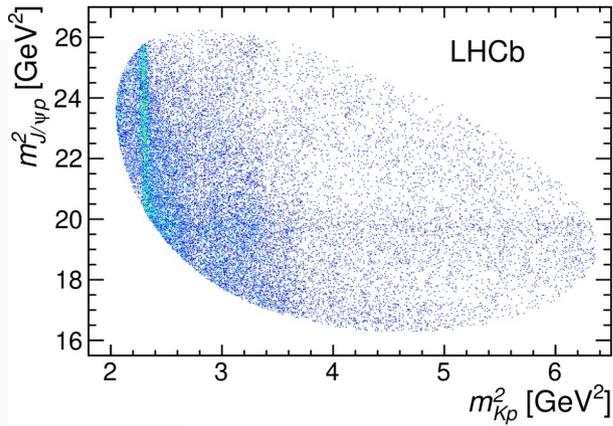H.X. Chen, et al., Phys. Rept. 639, 1 (2016)
F.K. Guo, et al., Rev.Mod.Phys.90,015004(2018)
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Observation of exotic structures (P_c) in $\Lambda_b^0 \to J/\psi p K^-$

LHCb, PRL 115, 072001 (2015)

$P_c(4380)^+ : M = 4380 \pm 8 \pm 29$ MeV

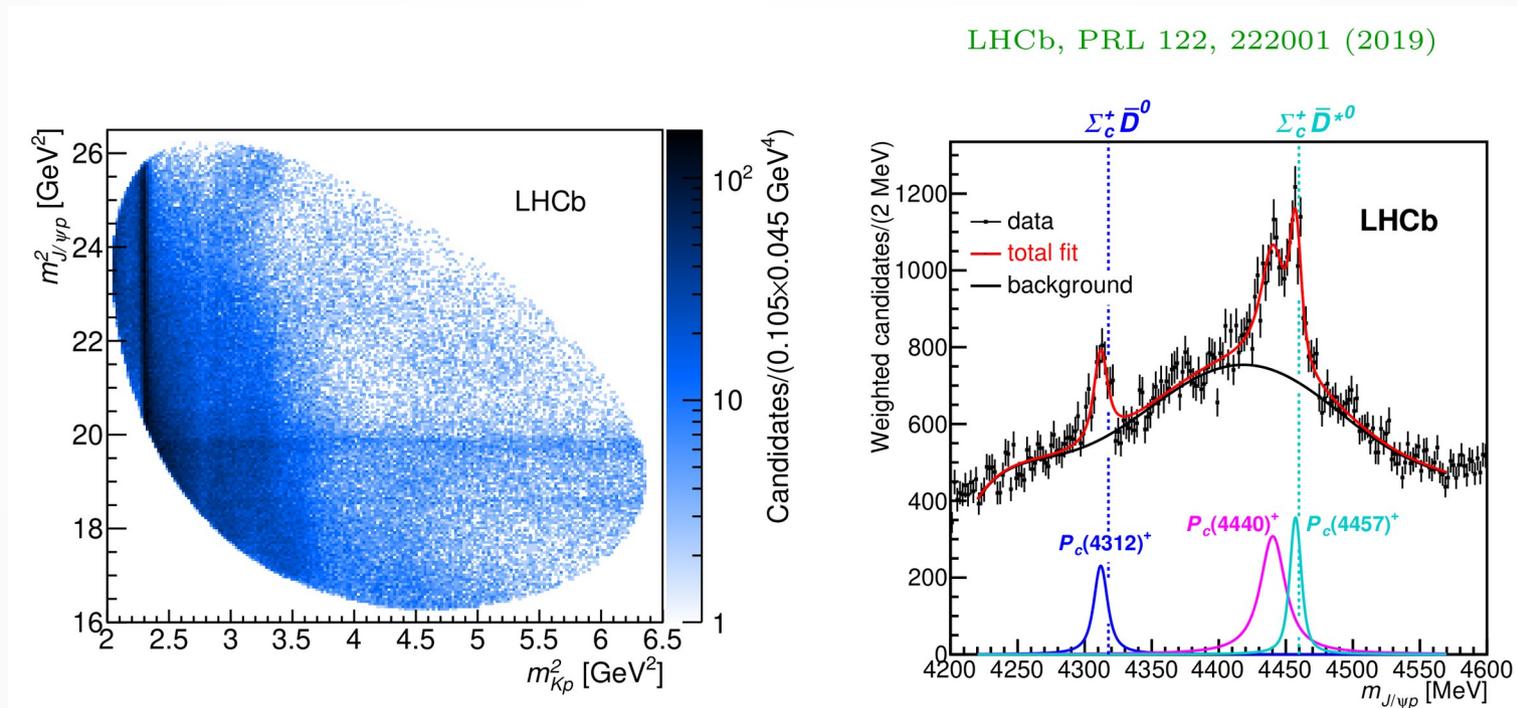$\Gamma = 205 \pm 18 \pm 86$ MeV

$P_c(4450)^+ : M = 4449.8 \pm 1.7 \pm 2.5$ MeV

$\Gamma = 39 \pm 5 \pm 19$ MeV

Preferred Parity: Opposite

LHCb, PRL 122, 222001 (2019)

the $P_c(4440)^+$ and $P_c(4457)^+$ states. The six-dimensional amplitude analysis reported in Ref. [9], which provided evidence for the $P_c(4380)^+$ state, is also obsolete since it used the single $P_c(4450)^+$ state and it lacked the $P_c(4312)^+$ state. Therefore, the results presented in the Letter weaken the previously reported evidence for the $P_c(4380)^+$ state, but do not contradict its existence, since the present one-dimensional analysis is not sensitive to wide P_c^+ states. Only a future six-dimensional amplitude analysis of $\Lambda_b^0 \to J/\psi\, p K^-$ decays that includes the $P_c(4440)^+$, $P_c(4457)^+$, and $P_c(4312)^+$ states will be able to determine if there is still evidence for the $P_c(4380)^+$ state or any other wide P_c^+ states.

$P_c(4450)^+$

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

Proposals [after 2019]
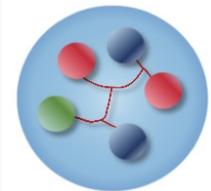
Compact Pentaquark

Chromomagnetic model, JB Cheng and YR Liu, PRD100, 054002 (2019)

$$P_c(4312),\ P_c(4440),\ P_c(4457):\ J^P = 3/2^-,\ 1/2^-,\ 3/2^-$$

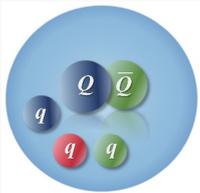$P_c(4380)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ is $\frac{3}{2}^-$ R. Deng, PRD105, 116021 (2022)

Compact diquark model,   Ali et al., JHEP10, 256 (2019)

$3/2^-$	4240 ± 29
$3/2^+$	4440 ± 35
$5/2^+$	4457 ± 35

R. Zhu et al., PLB797, 134869(2019)
Giron et al., JHEP05, 061 (2019)
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Hadron-Charmonium   Compact $(\bar{Q}Q)$ surrounded by light quarks

Eides et al., Mod. Phys. Lett. A 35, 2050151 (2020) $J^P = 1/2^+,\ 1/2^-,\ 3/2^-$

Hadronic Molecule   Extended object

H.X. Chen et al., PRD100, 051501 (2019)
R. Chen et al., PRD100, 011502 (2019)
F.K. Guo et al., PRD99, 091501 (2019)
M.Z. Liu et al., PRL122, 242001 (2019)
Z.H. Guo et al., PLB793, 144 (2019)
L. Meng et al., PRD100, 014031(2019)
J.J. Wu et al., PRC100, 035026 (2019)
J.-Z. Wu et al., CPL41,091201(2024)

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Kinematic effect

Kuang et al., EPJC80,433 (2020)
Nakamura, PRD103, L111503(2021)
Burns et al., PRD106,054029(2022)
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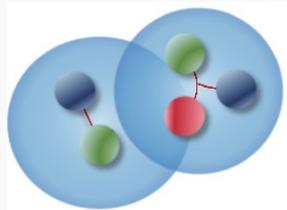
- For a heavy-quark Q ($c$harm, $b$ottom) with $m_Q \gg \Lambda_{\text{QCD}}$

  ☞ chromomag. interaction $\propto \dfrac{\sigma \cdot \mathbf{B}}{m_Q} \to 0$: independent of heavy-quark spin

- For a hadron containing a heavy-quark Q: $J = s_Q + j_\ell$

S-wave baryon-meson system
(ground states)

$$s_Q = \tfrac{1}{2} \otimes \tfrac{1}{2} = 0 \oplus 1$$

$$j_\ell = \tfrac{1}{2} \oplus \tfrac{3}{2}$$

➡ LO Contact Interaction: Only 2 LECs

	Molecule	J^P	M (MeV)		Molecule	J^P	M (MeV)
A	$\bar{D}\Sigma_c$	$\tfrac{1}{2}^-$	$4311.8 - 4313.0$	B	$\bar{D}\Sigma_c$	$\tfrac{1}{2}^-$	$4306.3 - 4307.7$
A	$\bar{D}\Sigma_c^*$	$\tfrac{3}{2}^-$	$4376.1 - 4377.0$	B	$\bar{D}\Sigma_c^*$	$\tfrac{3}{2}^-$	$4370.5 - 4371.7$
A	$\bar{D}^*\Sigma_c$	$\tfrac{1}{2}^-$	4440.3^*	B	$\bar{D}^*\Sigma_c$	$\tfrac{1}{2}^-$	4457.3^*
A	$\bar{D}^*\Sigma_c$	$\tfrac{3}{2}^-$	4457.3^*	B	$\bar{D}^*\Sigma_c$	$\tfrac{3}{2}^-$	4440.3^*
A	$\bar{D}^*\Sigma_c^*$	$\tfrac{1}{2}^-$	$4500.2 - 4501.0$	B	$\bar{D}^*\Sigma_c^*$	$\tfrac{1}{2}^-$	$4523.2 - 4523.6$
A	$\bar{D}^*\Sigma_c^*$	$\tfrac{3}{2}^-$	$4510.6 - 4510.8$	B	$\bar{D}^*\Sigma_c^*$	$\tfrac{3}{2}^-$	$4516.5 - 4516.6$
A	$\bar{D}^*\Sigma_c^*$	$\tfrac{5}{2}^-$	$4523.3 - 4523.6$	B	$\bar{D}^*\Sigma_c^*$	$\tfrac{5}{2}^-$	$4500.2 - 4501.0$

7 Pc states!

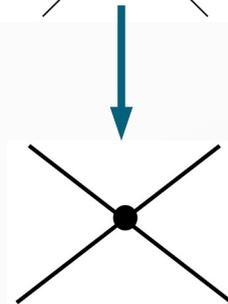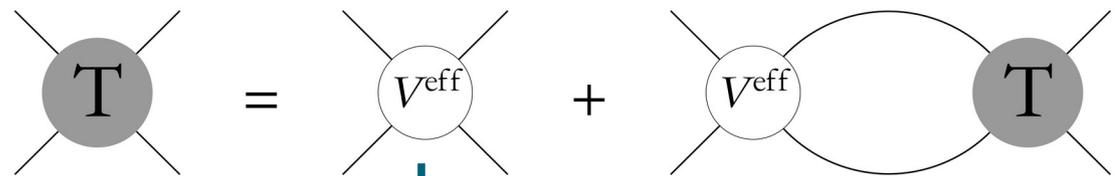Xiao et al., PRD88, 56012 (2013)

Liu et al., PRL122,242001 (2019)

- A coupled-channel analysis of the LHCb spectra using an EFT approach
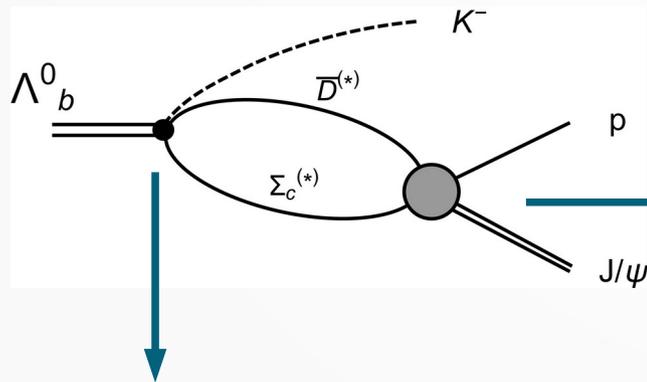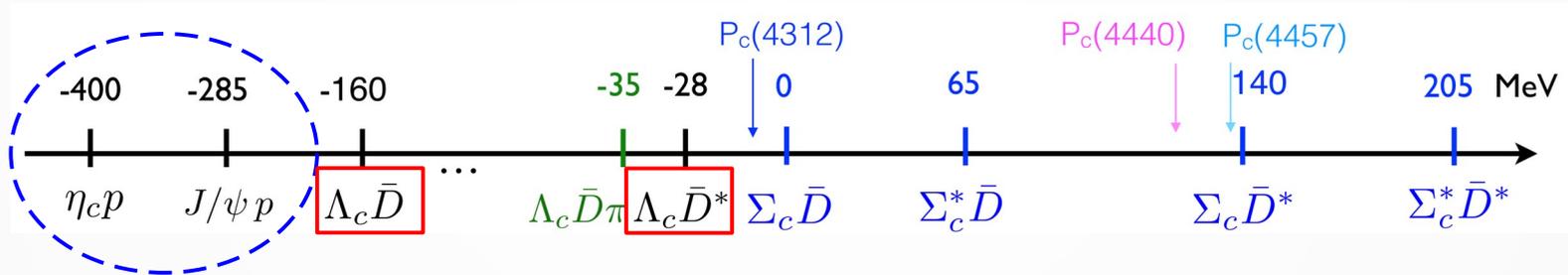
7 LECs for contact Production

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

$\bar{D}^{(*)}\Sigma_c^{(*)}(S) \to J/\Psi p(S),\ J/\Psi p(D)$

2 LECs
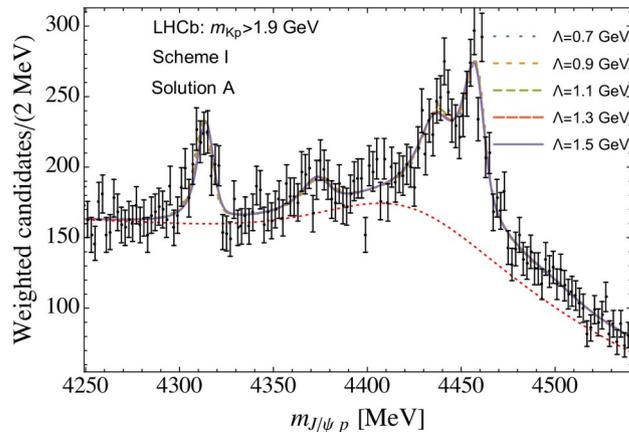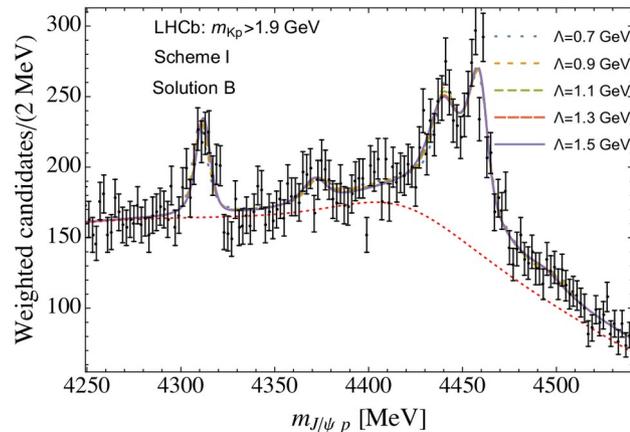
☞ $\Lambda > \Lambda_{\rm soft} \sim \sqrt{2\mu\delta} \sim 0.7$ GeV

☞ Cutoff-independent for both solution A and B

	$\Sigma_c \bar{D}^*$	$P_c(4440)$	$P_c(4457)$
Fit A	$\frac{1}{2}^-$		$\frac{3}{2}^-$
Fit B	$\frac{3}{2}^-$		$\frac{1}{2}^-$

If $\Sigma_c^{(*)} \bar{D}^{(*)} \to \Lambda_c \bar{D}^{(*)}$ is included, one more LEC

☞ No need for $\Lambda_c \bar{D}^{(*)}$ overdetermined

ΣcD Σc*D ΣcD* Σc*D*

Scheme I: Contact
LHCb: m_{Kp} > 1.9 GeV

Solution A: χ^2/dof = 0.91
Solution B: χ^2/dof = 0.91
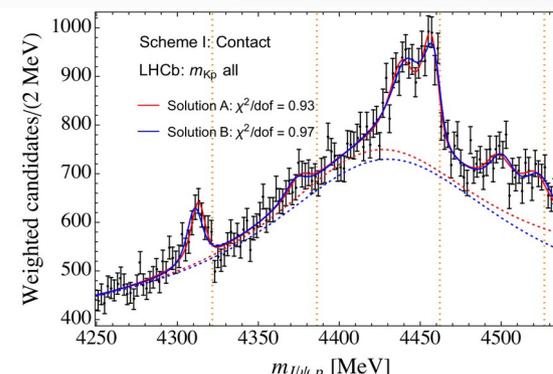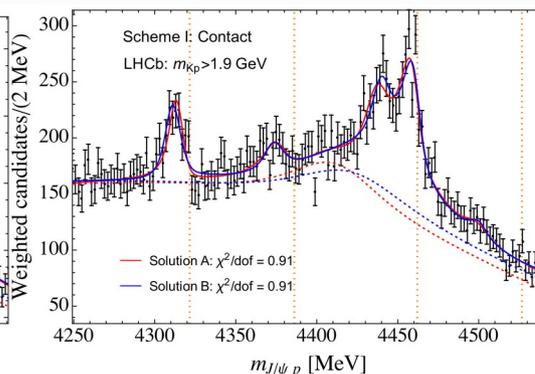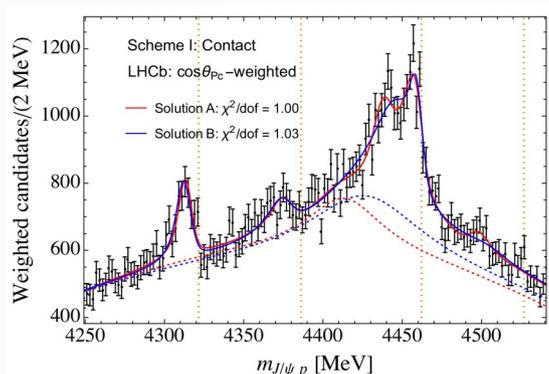
MLD et al., PRL124,072001(2020)
MLD et al., JHEP08,157 (2021)
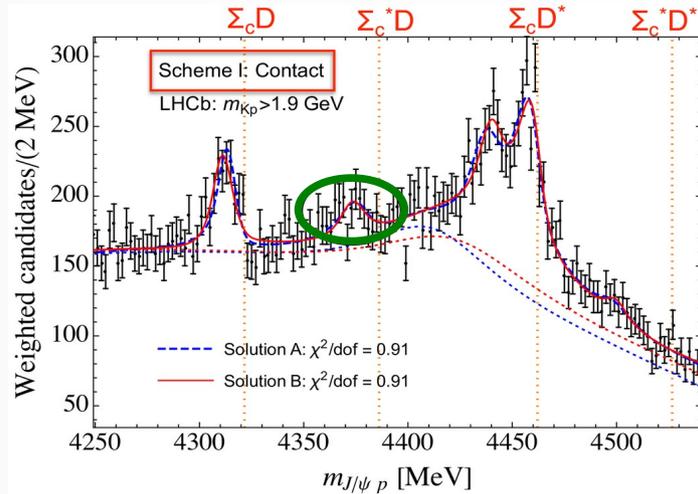
☛ $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ are well understood as $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c D^*$ quasi-bound states, respectively

☛ A narrow Pc(4380) state predicted as a $\Sigma_c^* D$ $3/2^-$ molecule is seen in data

NOT the broad Pc(4380)

reported by LHCb in 2015

☛ $\Sigma_c^* D^*$ states are not seen yet, their production rate is suppressed ?

$\hookrightarrow$ prompt production in the pp collision in the LHC

Poles and quantum numbers:

	thr. ([MeV])	J^P	solution A Pole [MeV]	J^P	solution B Pole [MeV]
$P_c(4312)$	$\Sigma_c \bar{D}$ (4321.6)	$\frac{1}{2}^-$	$4314(1) - 4(1)i$	$\frac{1}{2}^-$	$4312(2) - 4(2)i$
$P_c(4380)$	$\Sigma_c^* \bar{D}$ (4386.2)	$\frac{3}{2}^-$	$4377(1) - 7(1)i$	$\frac{3}{2}^-$	$4375(2) - 6(1)i$
$P_c(4440)$	$\Sigma_c \bar{D}^*$ (4462.1)	$\frac{1}{2}^-$	$4440(1) - 9(2)i$	$\frac{3}{2}^-$	$4441(3) - 5(2)i$
$P_c(4457)$	$\Sigma_c \bar{D}^*$ (4462.1)	$\frac{3}{2}^-$	$4458(2) - 3(1)i$	$\frac{1}{2}^-$	$4462(4) - 5(3)i$
P_c	$\Sigma_c^* \bar{D}^*$ (4526.7)	$\frac{1}{2}^-$	$4498(2) - 9(3)i$	$\frac{1}{2}^-$	$4526(3) - 9(2)i$
P_c	$\Sigma_c^* \bar{D}^*$ (4526.7)	$\frac{3}{2}^-$	$4510(2) - 14(3)i$	$\frac{3}{2}^-$	$4521(2) - 12(3)i$
P_c	$\Sigma_c^* \bar{D}^*$ (4526.7)	$\frac{5}{2}^-$	$4525(2) - 9(3)i$	$\frac{5}{2}^-$	$4501(3) - 6(4)i$

P. Ling et al., EPJC81,819 (2021)

Scheme I: Contact
LHCb: m_{Kp} all
Solution A: χ^2/dof = 0.93
Solution B: χ^2/dof = 0.97

contact + OPE

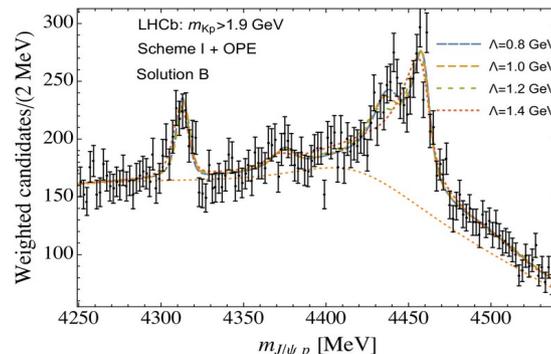

π
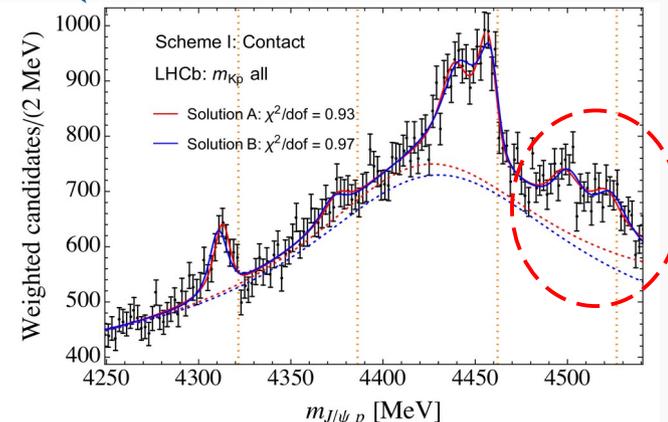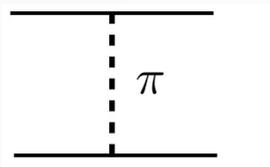
Long range: OPE

Determined by exp. data

☞ No solution A

☞ Solution B:
Cut-off dependent

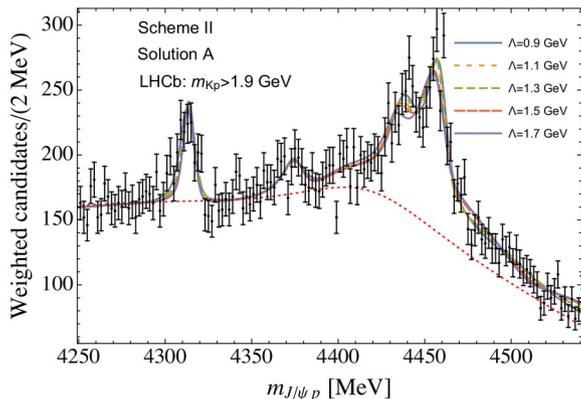☞ $\Lambda_{\text{soft}} \sim 700$ MeV

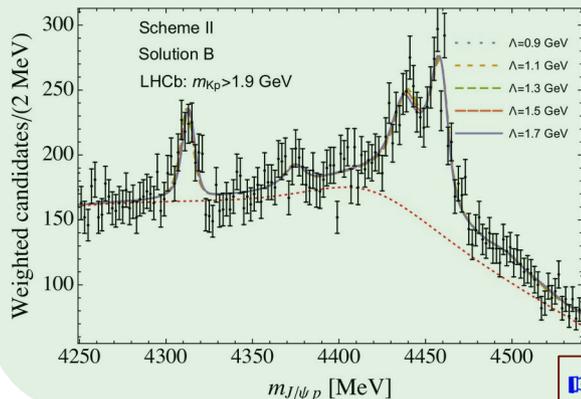MLD et al., PRL124,072001(2020)
MLD et al., JHEP08,157 (2021)

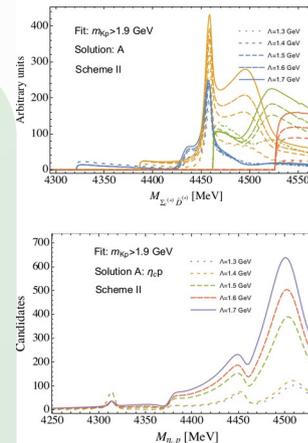$+ \Lambda_c \bar{D}^{(*)}$

contact + OPE + S-D

Solution A

Solution B

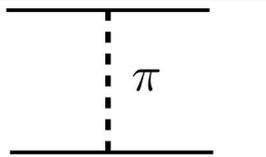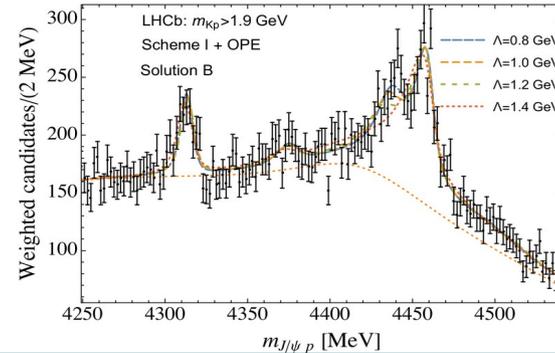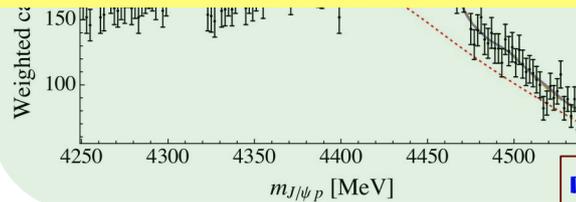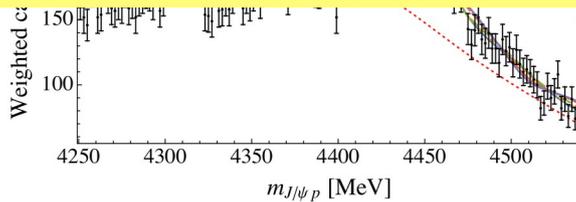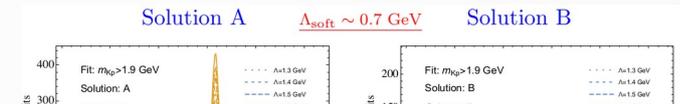Solution A $\Lambda_{\text{soft}} \sim 0.7$ GeV   Solution B

☞ Overdetermined. w/ $\Lambda_c \bar{D}^{(*)}$ $\Lambda_{\text{soft}} \sim 0.9$ GeV

☞ Cutoff-independent only for solution B

contact + OPE

☞ No solution A

☞ Solution B:
Cut-off dependent

☞ $\Lambda_{\text{soft}} \sim 700$ MeV

π

Long range: OPE

Determined by exp. data

LHCb: $m_{Kp} > 1.9$ GeV
Scheme I + OPE
Solution B

Λ=0.8 GeV
Λ=1.0 GeV
Λ=1.2 GeV
Λ=1.4 GeV

Weighted candidates/(2 MeV)

$m_{J/\psi\, p}$ [MeV]

$\Lambda_c \bar{D}^{(*)}$

contact + OPE + S-D

Solution A $\Lambda_{\text{soft}} \sim 0.7$ GeV   Solution B

Fit: $m_{Kp} > 1.9$ GeV
Solution: A

Fit: $m_{Kp} > 1.9$ GeV
Solution: B

Λ=1.3 GeV
Λ=1.4 GeV
Λ=1.5 GeV

Fit B shows a much more natural pattern than fit A

⇒   **P_c(4440) is 3/2⁻   and P_c(4457) is 1/2⁻**

⇒   **experimentally testable via** $\Lambda_b \to K\Sigma^{(*)}D^{(*)}$ and $\Lambda_b \to K\eta_c p$

Weighted c

$m_{J/\psi\, p}$ [MeV]

Weighted c

$m_{J/\psi\, p}$ [MeV]

$M_{\eta_c p}$ [MeV]

$M_{\eta_c p}$ [MeV]

☞ Overdetermined. w/ $\Lambda_c \bar{D}^{(*)}$ $\Lambda_{\text{soft}} \sim 0.9$ GeV

☞ Cutoff-independent only for solution B

Poles and quantum numbers:

P. Ling et al., Eur.Phys.J.C 81, 819 (2021)

	thr. ([MeV])	solution A J^P	solution A Pole [MeV]	solution B J^P	solution B Pole [MeV]
$P_c(4312)$	$\Sigma_c\bar{D}$ (4321.6)	$\frac{1}{2}^-$	$4314(1) - 4(1)i$	$\frac{1}{2}^-$	$4312(2) - 4(2)i$
$P_c(4380)$	$\Sigma_c^*\bar{D}$ (4386.2)	$\frac{3}{2}^-$	$4377(1) - 7(1)i$	$\frac{3}{2}^-$	$4375(2) - 6(1)i$
$P_c(4440)$	$\Sigma_c\bar{D}^*$ (4462.1)	$\frac{1}{2}^-$	$4440(1) - 9(2)i$	$\frac{3}{2}^-$	$4441(3) - 5(2)i$
$P_c(4457)$	$\Sigma_c\bar{D}^*$ (4462.1)	$\frac{3}{2}^-$	$4458(2) - 3(1)i$	$\frac{1}{2}^-$	$4462(4) - 5(3)i$
P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{1}{2}^-$	$4498(2) - 9(3)i$	$\frac{1}{2}^-$	$4526(3) - 9(2)i$
P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{3}{2}^-$	$4510(2) - 14(3)i$	$\frac{3}{2}^-$	$4521(2) - 12(3)i$
P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{5}{2}^-$	$4525(2) - 9(3)i$	$\frac{5}{2}^-$	$4501(3) - 6(4)i$

? ❓

All

p — p

$\Sigma_c^{(*)}$

$\bar{D}^{(*)}$

P_c

Madgraph5
+
Phythia8

$$\mathcal{M}[P_c(E)] \approx \sum_\alpha \int \frac{d^3\mathbf{q}}{(2\pi)^3} \mathcal{M}\left[\left(\Sigma_c^{(*)}\bar{D}^{(*)}\right)^\alpha(\mathbf{q}) + \text{all}\right] \times G_\alpha(E,\mathbf{q}) \times T^\alpha_{P_c}(E),$$
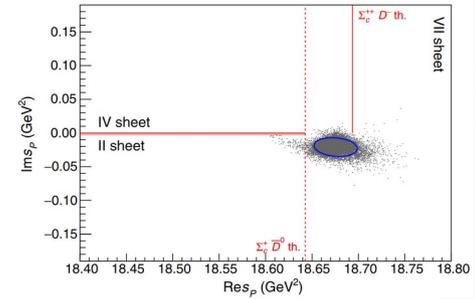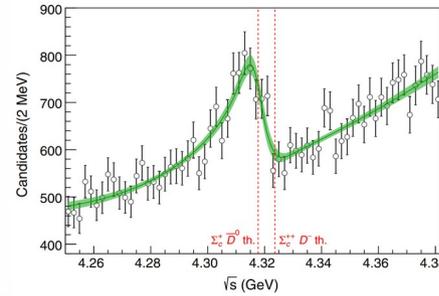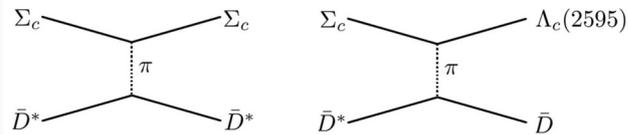

A

B

(Some) More Molecular Interpretations...

- the $P_c(4312)^+$ peak as a virtual (unbound) state
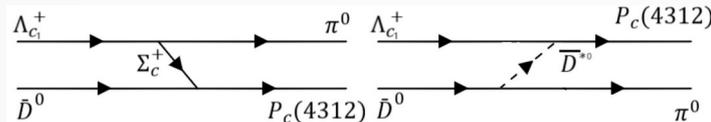
  JPAC, PRL123, 092001 (2019)

- $J^P(4457) = 1/2^+$ and $J^P(4440) = 3/2^-$

  Burns et al., PRD100, 114033(2019)

FIG. 1. Elastic and inelastic t-channel pion-exchange diagrams in the $\Sigma_c \bar{D}^* - \Lambda_c(2595)\bar{D}$ system.

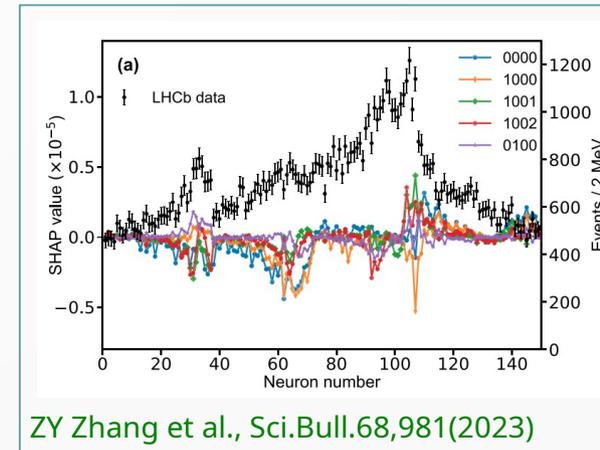- $P_c(4457)$ interpreted as a $J^P = 1/2^+$ state

JZ Wu et al., CPL41,091202(2024)

- interpreting the $P_c(4457)$ pentaquark as a $I = \frac{3}{2}$ $\bar{D}^*\Sigma_c$ bound state (with spin $J = \frac{1}{2}$)

$$|P_c(4457)^+\rangle = \cos\theta_I |\bar{D}^{*0}\Sigma_c^+\rangle + \sin\theta_I |D^{*-}\Sigma_c^{++}\rangle$$
FZ Peng et al.,2211.09154

ZY Zhang et al., Sci.Bull.68,981(2023)
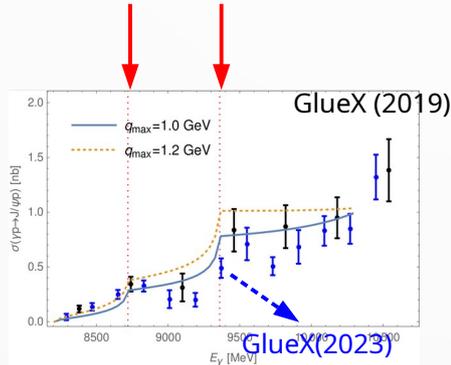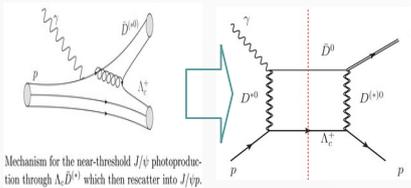
$$T_{\gamma p \to J/\psi p} = g_{\gamma \psi} T_{J/\psi p \to J/\psi p}$$

Q Wang et al., PRD92(2015)
JJ Wu et al.,PRC100(2019)

P_c?

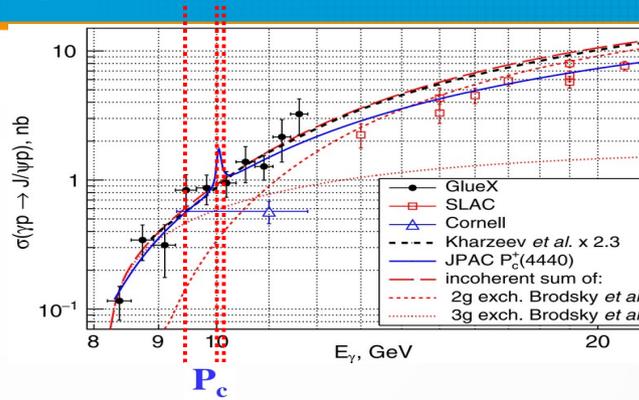$$M_N = \langle \frac{\beta}{2g} F^2 + \sum_f \gamma_m m_f \overline{\psi}_f \psi_f \rangle_H + \sum_f m_f \langle \overline{\psi}_f \psi_f \rangle_H$$
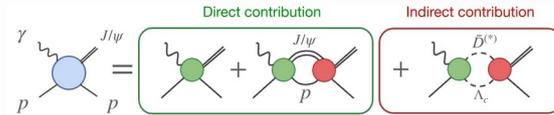
Mechanism for the near-threshold J/ψ photoproduction through $\Lambda_c^+ \bar{D}^{(*)}$ which then rescatter into $J/\psi p$.

GlueX (2019)

GlueX(2023)
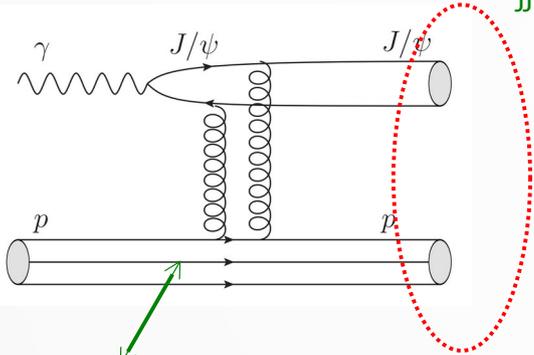
The $\Lambda_c^+ \bar{D}^0$ threshold is only 116 MeV above the $J/\psi p$ threshold, rendering the contribution from the $\Lambda_c \bar{D}$ channel potentiallly sizeable.
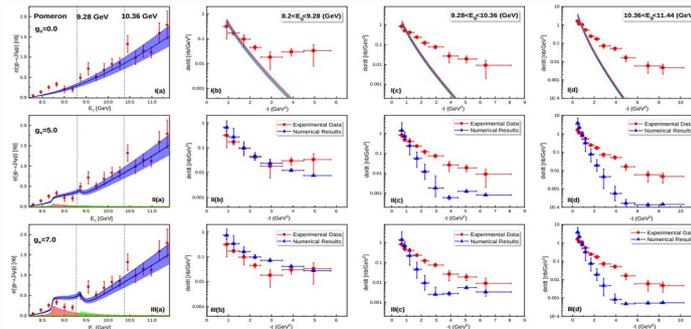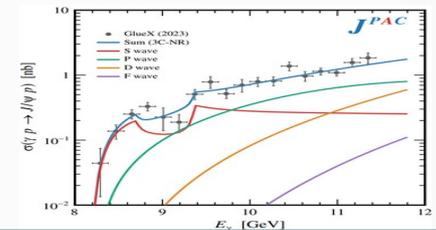
MLD et al., EPJC80,1053(2021)

GlueX,PRL123,072001(2019)

No evidence for Pc.

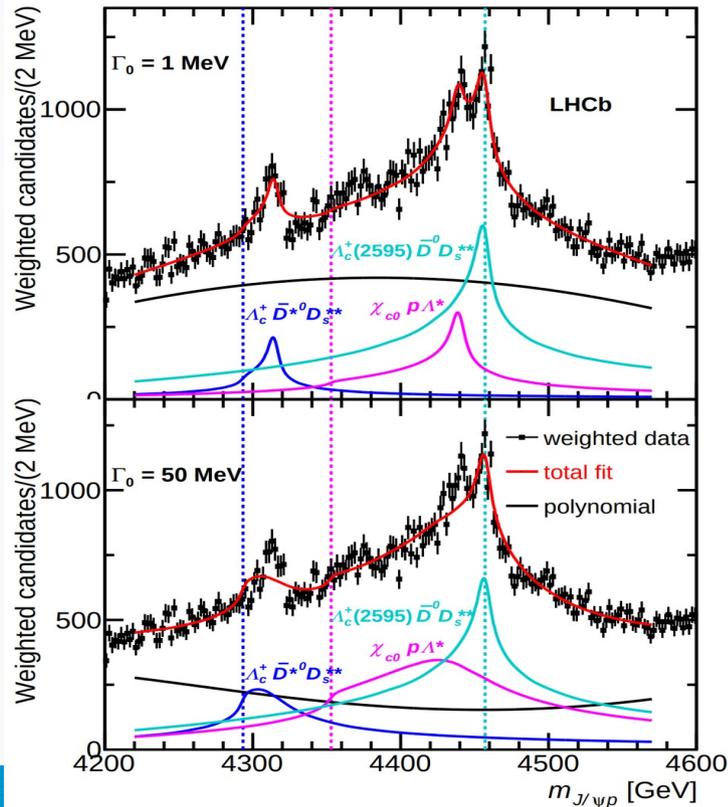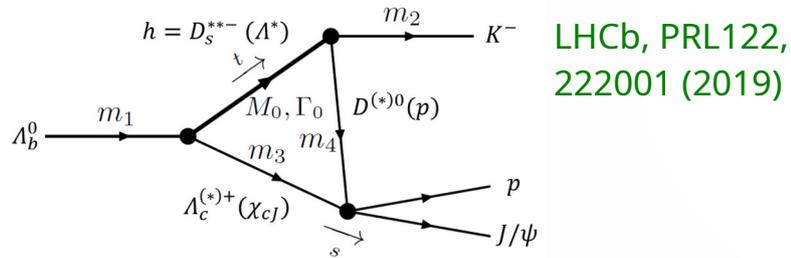Direct contribution   Indirect contribution

JPAC, PRD108,054018(2023)

MX Duan et al., 2409.10364

The production of Pc suppressed

A similar result by
X Zhang, 2410.1015

The inclusion of the open charm channels and intermediate P_c states can significantly improve the descriptions of the differential cross section data

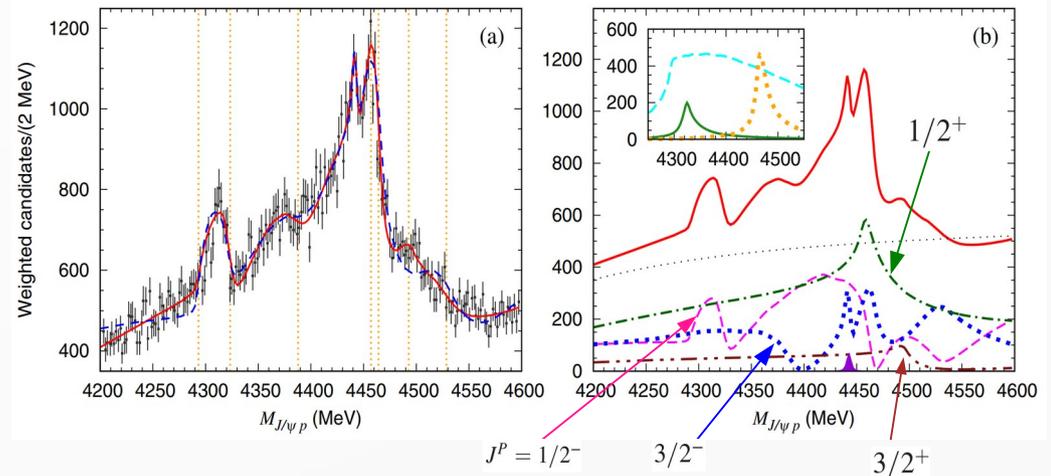# Triangle Diagrams

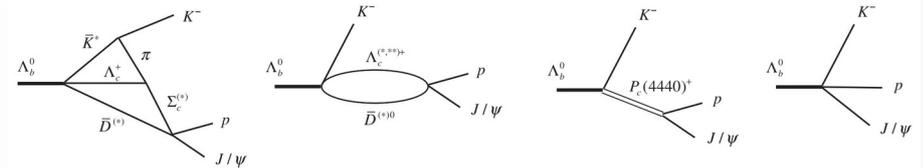LHCb, PRL122, 222001 (2019)

Nakamura, PRD103,L111503 (2021)

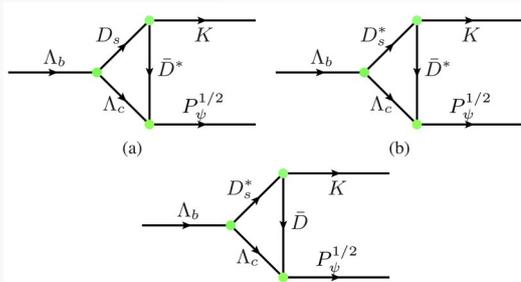$P_c(4312)^+$, $P_c(4380)^+$, and $P_c(4457)^+$ as double triangle cusps
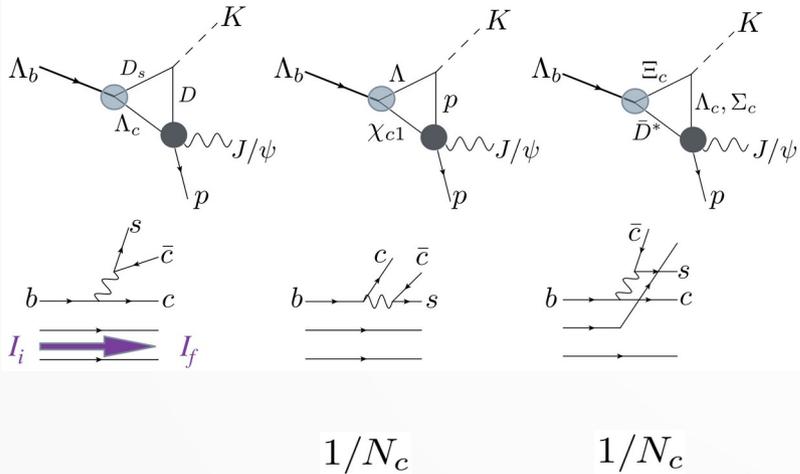
double triangle amplitudes reproduce the peak structures of $P_c(4312)^+$, $P_c(4380)^+$, and $P_c(4457)^+$

Only the $P_c(4440)^+$ peak is due to a resonance

A Production/Rescattering Model

Burns et al., PRD106,054029 (2022)

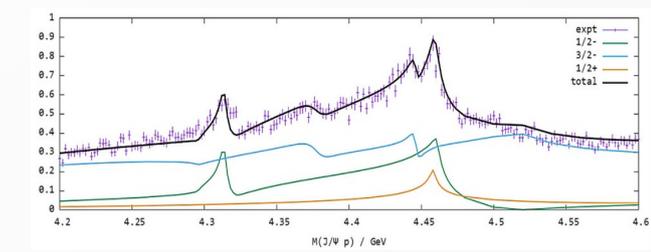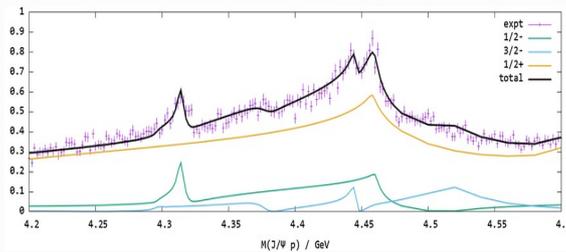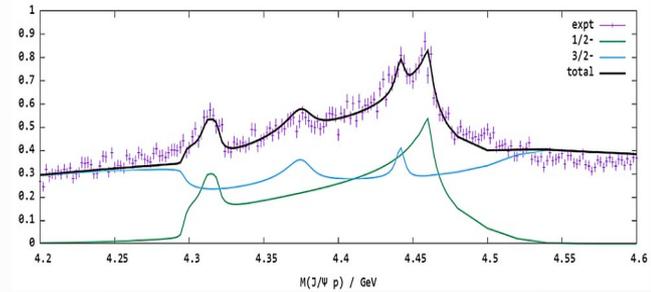$1/2^-$: $\quad \Lambda_c\bar{D}, \Lambda_c\bar{D}^*, \Sigma_c\bar{D}, \Sigma_c\bar{D}^*, \Sigma_c^*\bar{D}^*, NJ/\psi, N\eta_c$

$3/2^-$: $\quad \Lambda_c\bar{D}^*, \Sigma_c^*\bar{D}, \Sigma_c\bar{D}^*, \Sigma_c^*\bar{D}^*, NJ/\psi$

$1/2^+$: $\quad \Lambda_c(2595)\bar{D}, \Lambda_c(2595)\bar{D}^*, \Lambda_c(2625)\bar{D}^*, NJ/\psi(^2P_{1/2}), NJ/\psi(^4P_{1/2}), N\eta_c(^2P_{1/2})$

ZW Liu et al., PRD108,114022 (2023)
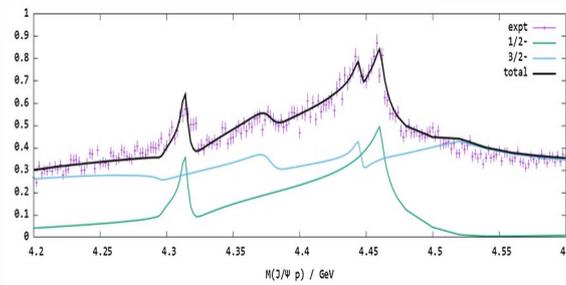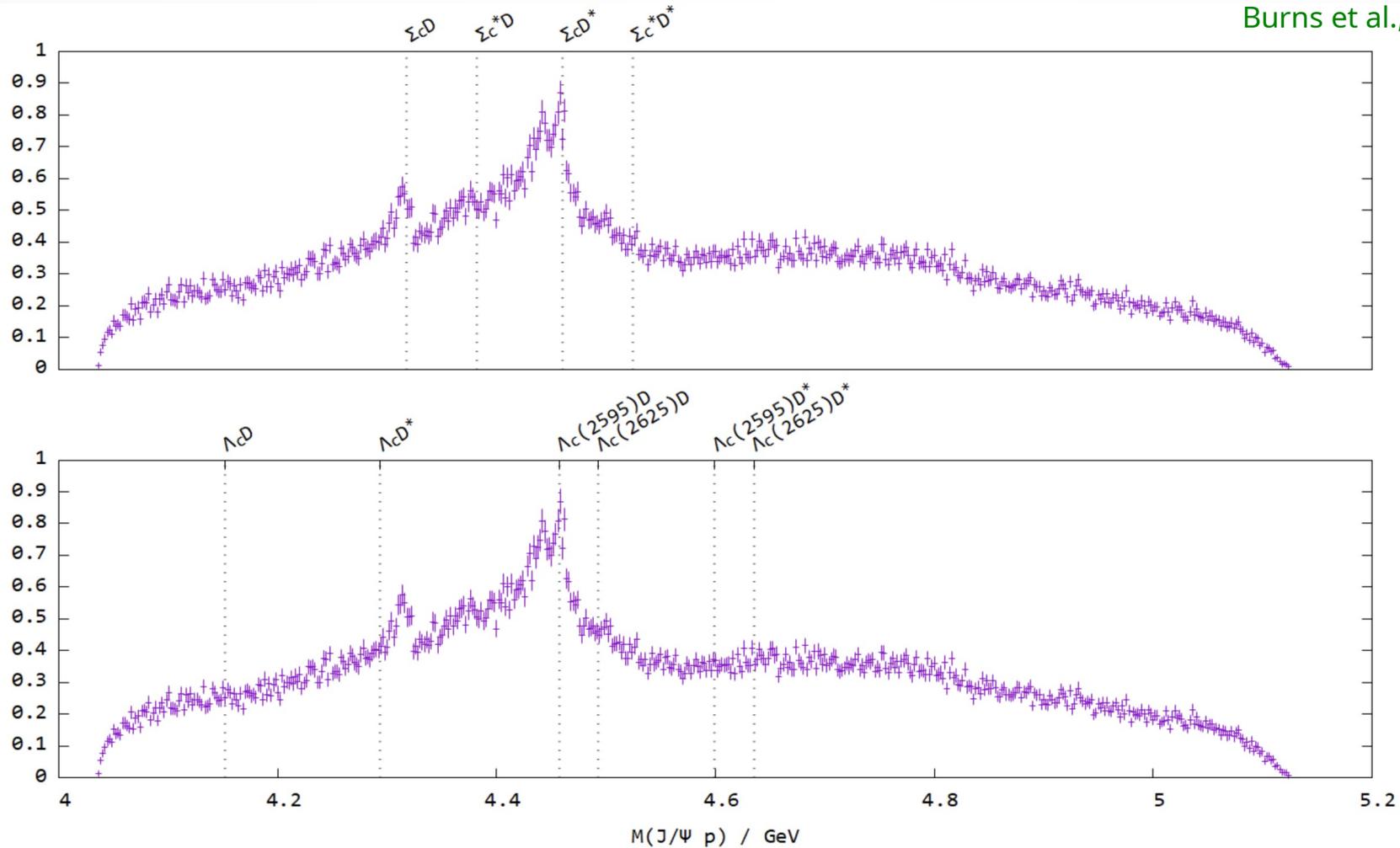
● **Weakly bound $\Sigma_c^{(*)}D^{(*)}$ resonances are required:**
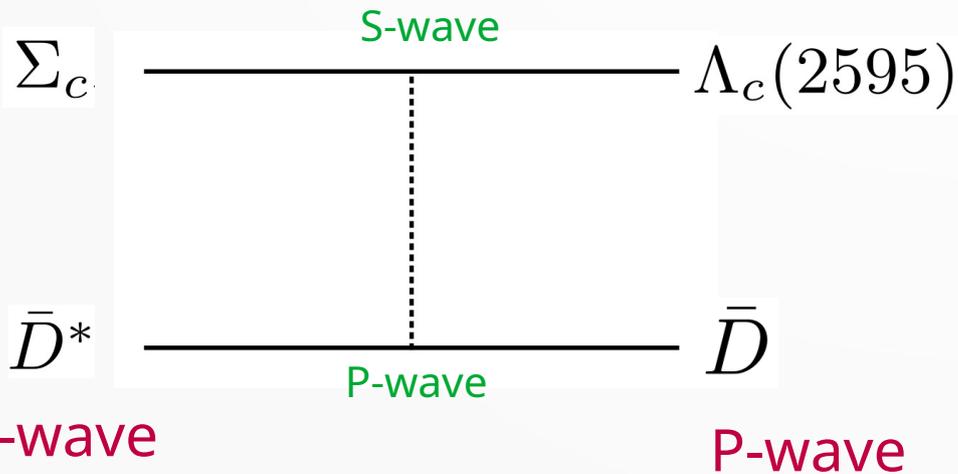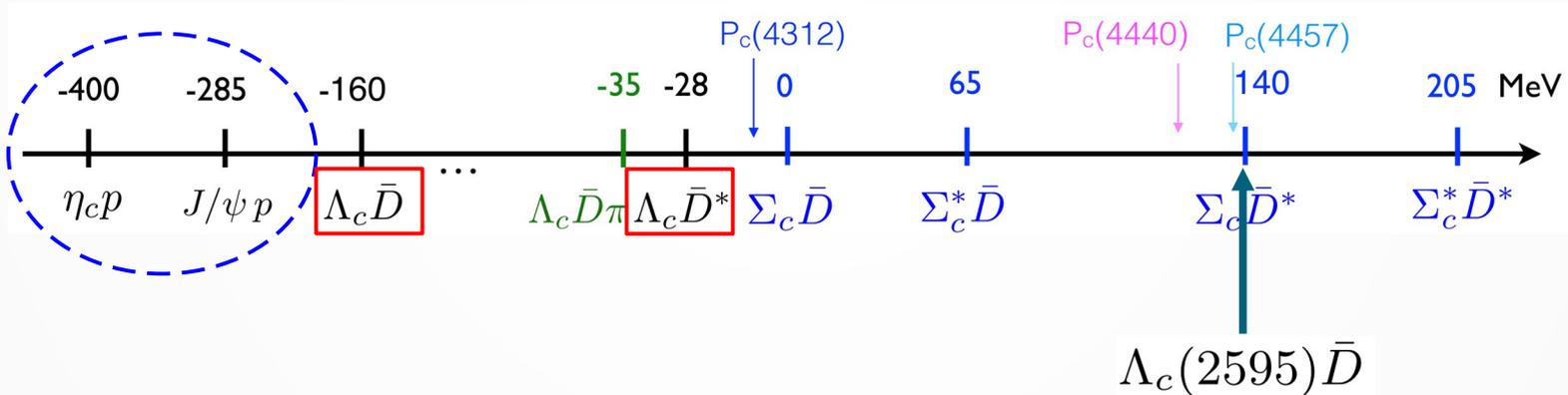
- 4312 ($\Sigma_c D$, 1/2-)
- 4380 ($\Sigma_c^* D$, 3/2-)
- 4440 ($\Sigma_c D^*$, 3/2-)
- 4457 (1/2- $\Sigma_c D^*$ threshold cusp / 1/2+ triangle)

Burns et al., PRD106,054029 (2022)

Including Λc(2595)D

$$\Lambda_c(2595)\bar{D}$$

$\Lambda_c(2595)^+$ **DECAY MODES**

$\Lambda_c^+\pi\pi$ and its submode $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the submode seems to dominate.

ode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level P(MeV/c)
Γ_1	$\Lambda_c^+\pi^+\pi^-$	[1]	117 ⌄
Γ_2	$\Sigma_c(2455)^{++}\pi^-$	$(24\pm7)\%$	3 ⌄
Γ_3	$\Sigma_c(2455)^0\pi^+$	$(24\pm7)\%$	3 ⌄
Γ_4	$\Lambda_c^+\pi^+\pi^-$ 3-body	$(18\pm10)\%$	117 ⌄
Γ_5	$\Lambda_c^+\pi^0$	[2] not seen	258 ⌄
Γ_6	$\Lambda_c^+\gamma$	not seen	288 ⌄

Σ_c

S-wave

$\Lambda_c(2595)$

$\bar{D}^*$

P-wave

$\bar{D}$

S-wave

P-wave

$$\mathcal{L}_{D^*_{s1}} = g_{D^*_{s1}} D^0 \bar{D}^{*,i}_{s1} \partial^i \bar{K}$$

1 $D^{*-}_{s1}(2860)$ K^-

$\bar{D}^0$ 3

Λ^0_b

$\Lambda^+_c(2595)$

2

J/ψ

p

$$T^J(E) = \left[1 - V^J(E) \cdot G(E)\right]^{-1} \cdot V^J(E)$$

$$T^J_{4i}(E) = \sum_{\alpha=1}^{3} T^J_{4\alpha}(E) G_\alpha(E) \mathcal{V}^J_{\alpha i}$$

$$\mathcal{L}_b = g_{\Lambda_b} \bar{\Lambda}^*_c \sigma \cdot \mathbf{D}^*_{s1} \Lambda^0_b$$

$$\mathcal{A}^J(E) = g(I^{(1)}(p_K) - I(p_K)) p^2_K T^J_{4i}(E)$$

$$I(q) \equiv i \int \frac{\mathrm{d}^4 l}{(2\pi)^4} \frac{1}{(l^2 - m_1^2)((P-l)^2 - m_2^2)((l-q)^2 - m_3^2)},$$

$$q^i I^{(1)}(q) \equiv i \int \frac{\mathrm{d}^4 l}{(2\pi)^4} \frac{l^i}{(l^2 - m_1^2)((P-l)^2 - m_2^2)((l-q)^2 - m_3^2)}.$$

Production of the LHCb Pc states
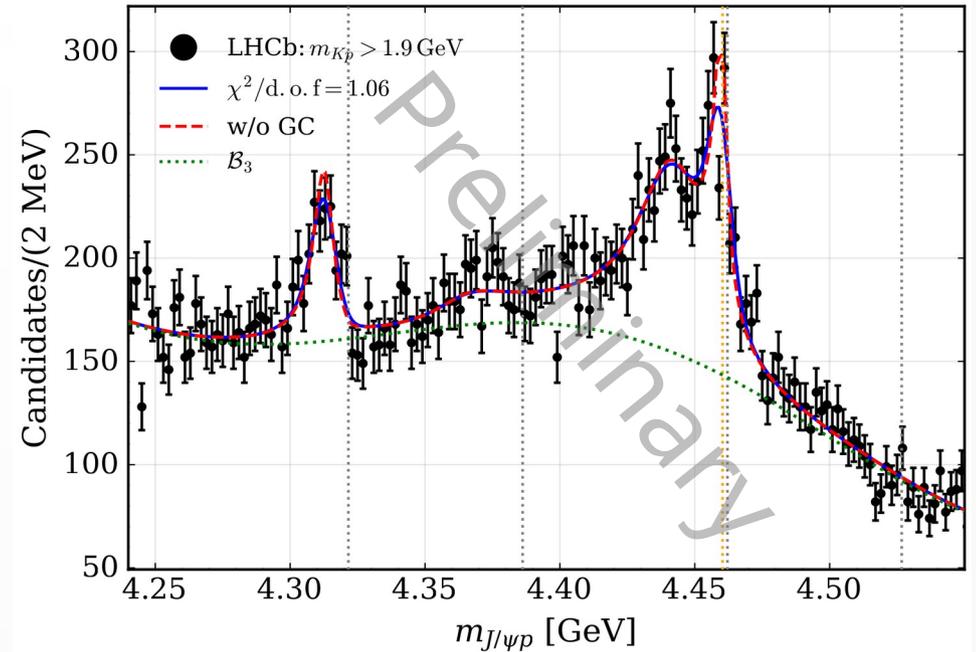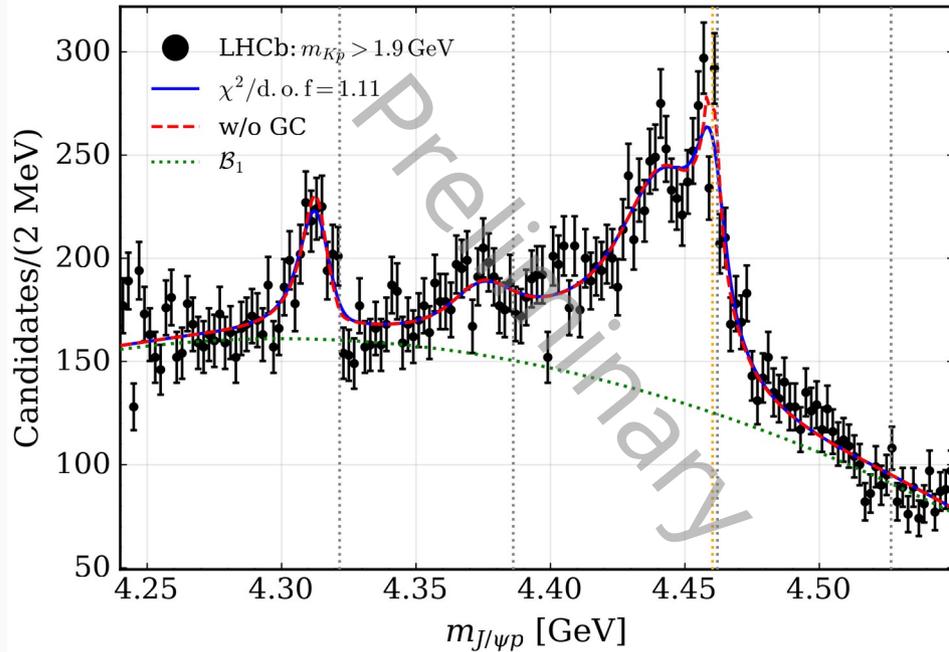
$$\mathcal{B}_1(E) = b_0 + b_1 E^2 + b_2 E^4$$

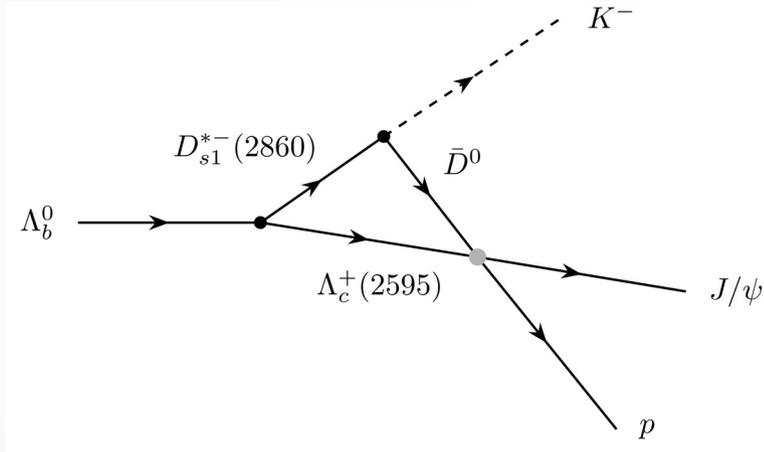$$\mathcal{B}_3(E) = b_0 + b_1 E^2 + b_2 E^4 + \frac{b_3^2}{(E - b_4)^2 + b_5^2}$$

Solution B! ⇒ **P$_c$(4440) is 3/2$^-$ and P$_c$(4457) is 1/2$^-$**

$\Lambda_c(2595)\bar{D}$ not significant!

consistent with Yalikun et al., PRD104,094039(2021)

Production of the LHCb Pc states

$$R = \frac{\Gamma(\Lambda_b^0 \to P_c^+ K^- \to J/\psi p K^-)}{\Lambda_b^0 \to D_{s1}^*(2860)\Lambda_c(2595)} \approx 5\%$$

	J^P	Pole [MeV]	DC (threshold [MeV])	g_{DC}	RS
$P_c(4312)$	$\frac{1}{2}^-$	$4313(2) - 6(2)i$	$\Sigma_c \bar{D}$ (4321.6)	$2.83(23) + 0.40(22)i$	RS_{++++}
$P_c(4380)$	$\frac{3}{2}^-$	$4373(9) - 16(3)i$	$\Sigma_c^* \bar{D}$ (4386.2)	$3.13(40) + 0.48(23)i$	RS_{++++}
$P_c(4440)$	$\frac{3}{2}^-$	$4442(4) - 18(7)i$	$\Sigma_c \bar{D}^*$ (4462.1)	$3.28(63) + 0.47(42)i$	RS_{-+++}
$P_c(4457)$	$\frac{1}{2}^-$	$4465(8) - 5(4)i$	$\Sigma_c \bar{D}^*$ (4462.1)	$2.01(34) + 0.95(57)i$	RS_{-++-}
P_c	$\frac{1}{2}^-$	$4535(11) - 10(4)i$	$\Sigma_c^* \bar{D}^*$ (4526.7)	$1.83(43) + 1.88(95)i$	RS_{--+-}
P_c	$\frac{3}{2}^-$	$4533(18) - 22(8)i$	$\Sigma_c^* \bar{D}^*$ (4526.7)	$2.61(39) + 1.75(85)i$	RS_{--+-}
P_c	$\frac{5}{2}^-$	$4491(13) - 28(6)i$	$\Sigma_c^* \bar{D}^*$ (4526.7)	$4.52(51) + 0.60(18)i$	RS_+

Charmonium-pentaquark states (III)

P_c state in $B_s^0 \to J/\psi p \bar{p}$

$B_s^0 \to J/\psi p \bar{p}$ Dalitz plot

LHCb 9 fb^{-1}

New P_c structure
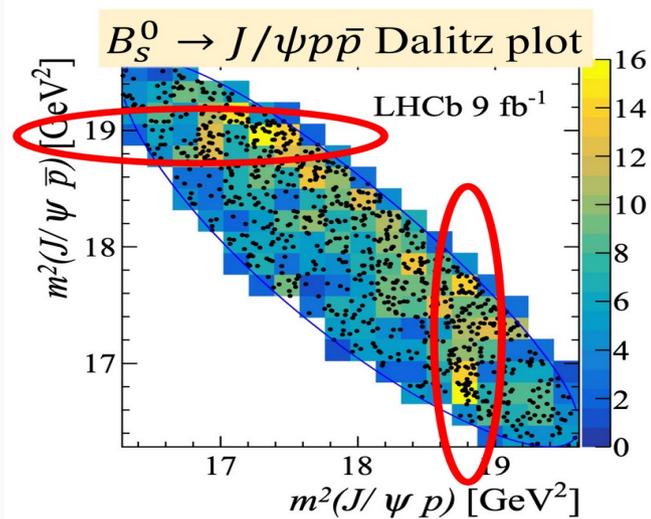
- New pentaquark candidate: $P_c(4337)^+ \to J/\psi p > 3\sigma$

$$M = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV}, \quad \Gamma = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$

- No evidence of P_c^+ states observed in $\Lambda_b^0 \to J/\psi p K^-$

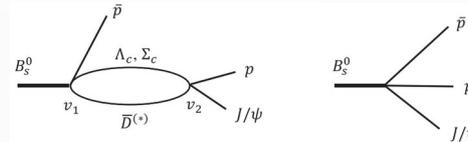$$P_c(4312)\ \textbf{?}$$

Proposals

Compact pentaquark   C.R. Deng, PRD105, 116021 (2022)

Hadroncharmonium: $\chi_{c0}(1S)p$ bound state

Ferretti et al., Sci.Bull.67,1209(2022)

$P_c(4312)^+$ and $P_c(4337)^+$ as interfering $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}^*$ threshold cusps
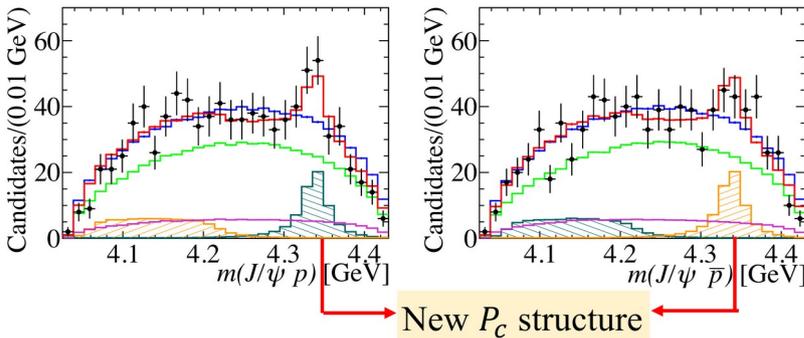

Nakamura et al.,PRD104,L091503(2021)

A few of possibilities are reviewed, including $\bar{D}^* \Lambda_c$ and $\bar{D} \Sigma_c$ states

$\bar{D}^*\text{-}\Lambda_c\text{-}\bar{D}\Sigma_c$ and $\bar{D}^*\Lambda_c\text{-}\bar{D}\Sigma_c^*$
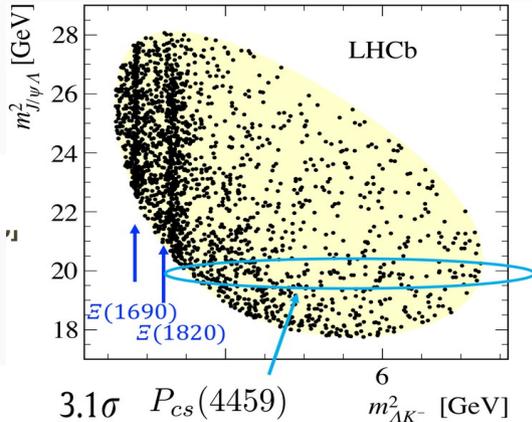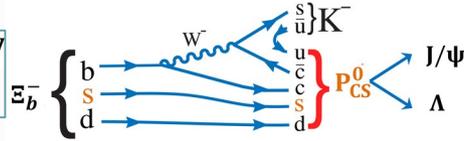
MJ Yan et al.,EPJC82,574 (2022)

.....

Hidden-charm Pentaquarks with strangeness (I)

- SU(3) partner P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi \Lambda K^-$

JJ Wu et al., PRL105, 232001(2010);
HX Chen et al.,PRC93,065203(2016) ...

LHCb, Sci.Bull.66,1278 (2021)

$4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV
$17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

3.1σ $P_{cs}(4459)$

Molecular Interpretation

B. Wang et al., PRD101,034018(2020)

System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{5}{2}}^{\#}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

MLD et al.,PRD104, 114034(2021)

Our different analyses clearly indicate the molecular nature of the $P_{cs}(4459)$ with a clear $\Xi_c\bar{D}^*$ dominant component.

······
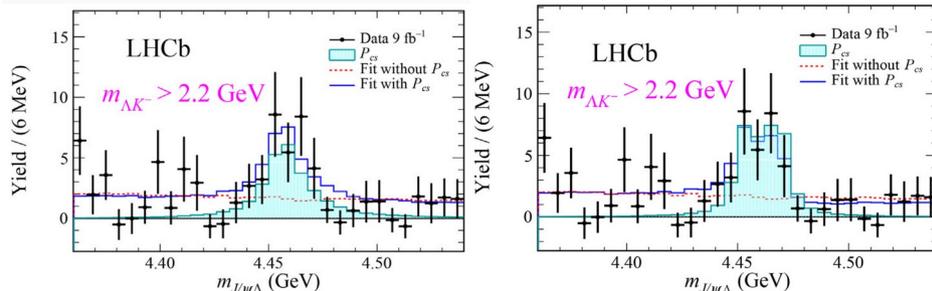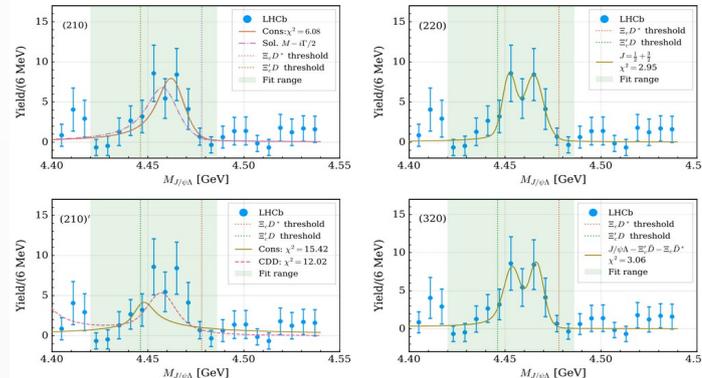
See review papers:
An updated review of the new hadron states, HX Chen et al., Rept.Prog.Phys.86,026201(2023)
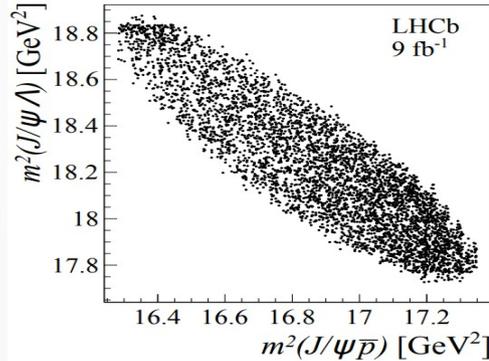ChPT for heavy hadrons and ChEFT for heavy hadronic molecules, L. Meng et al., Phys. Rept.1019,1(2023)

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

(Some) Proposals

- $P^\Lambda_{\psi s}(4338)^0$ is likely to be a $1/2^-$ compact P_{cs} pentaquark framework of MIT bag model   WX Zhang et al., PRD109,114037 (2024)

- HQSS+local hidden gauge   Feijoo et al., PLB839, 137760(2023)

$J^P = \frac{1}{2}^-$

| Poles		$\eta_c \Lambda$	$\bar{D}_s \Lambda_c$	$\bar{D} \Xi_c$	$\bar{D} \Xi'_c$
$4198.94 + i0.11$	g_i	$0.12 - i0.00$	$3.01 - i0.01$	$\mathbf{4.85 + i0.01}$	$0.01 - i0.03$
	$g_i G_i^{II}$	$-0.35 + i1.01$	$-19.24 + i0.05$	$\mathbf{-20.35 - i0.07}$	$-0.03 + i0.09$
$4422.79 + i7.75$	g_i	$0.71 - i0.08$	$0.05 + i0.00$	$-0.06 + i0.04$	$\mathbf{2.79 - i0.35}$
	$g_i G_i^{II}$	$1.14 + i10.71$	$0.76 + i1.82$	$-0.43 - i1.53$	$\mathbf{-26.54 + i0.64}$

$P_{cs}(4459)$ ← $4422.79 + i7.75$

$J^P = \frac{1}{2}^-, \frac{3}{2}^-$

Poles		$J/\psi \Lambda$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^* \Xi_c$	$\bar{D}^* \Xi'_c$
$4337.98 + i0.12$	g_i	$0.11 - i0.00$	$3.17 - i0.01$	$\mathbf{5.07 + i0.01}$	$0.00 - i0.04$
	$g_i G_i^{II}$	$-0.13 + i1.07$	$-18.57 + i0.06$	$\mathbf{-19.94 - i0.07}$	$-0.01 + i0.10$
$4565.73 + i15.58$	g_i	$0.70 - i0.16$	$0.09 - i0.03$	$-0.10 + i0.09$	$\mathbf{2.84 - i0.72}$
	$g_i G_i^{II}$	$6.24 + i21.04$	$2.07 + i3.40$	$-1.37 - i2.81$	$\mathbf{-26.31 + i1.15}$

$P^\Lambda_{\psi s}(4338)$ ← $4337.98 + i0.12$
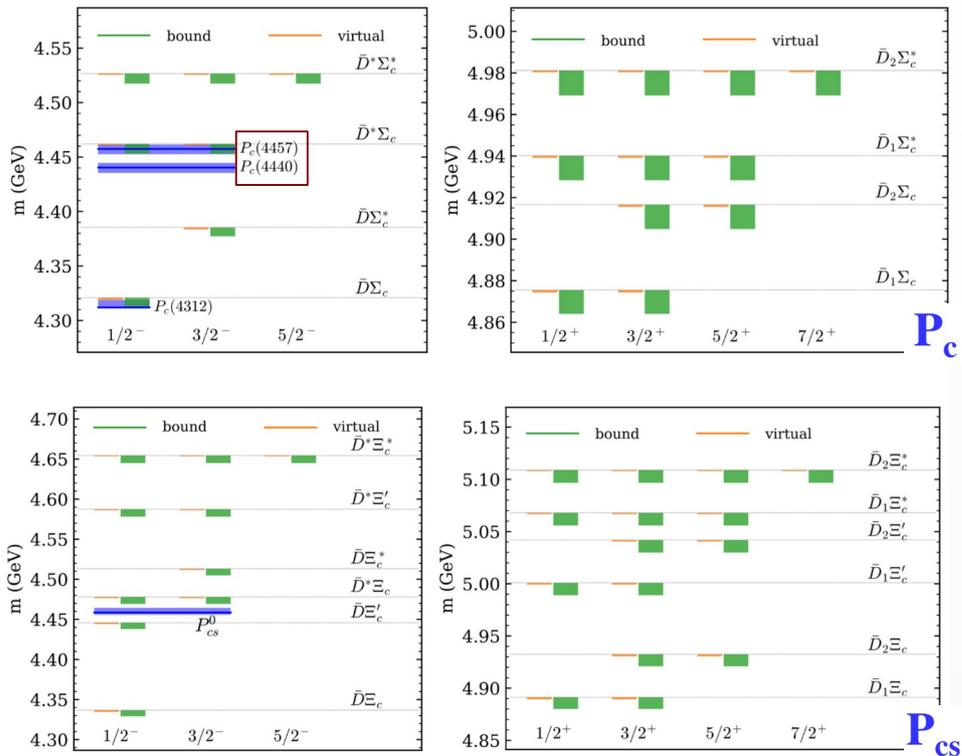
Burns et al., PLB838,137715 (2023)

- The LHCb state $P^\Lambda_{\psi s}(4338)$ as a triangle singularity
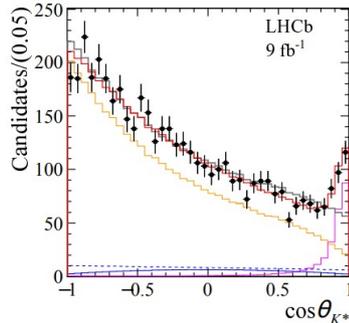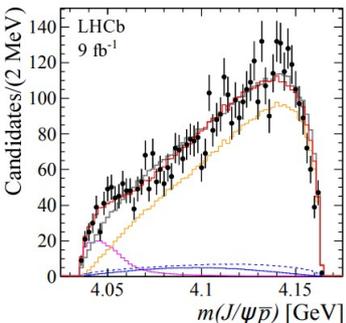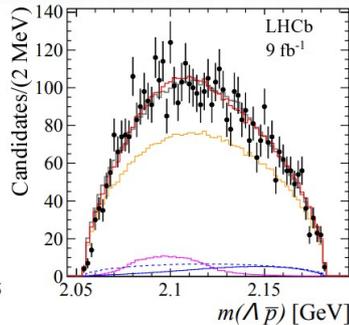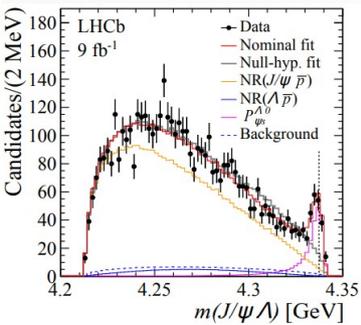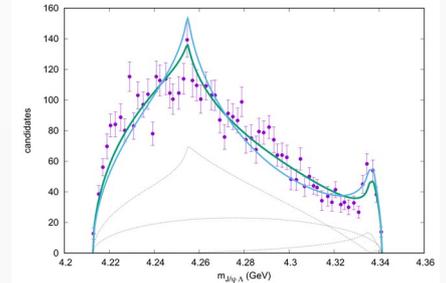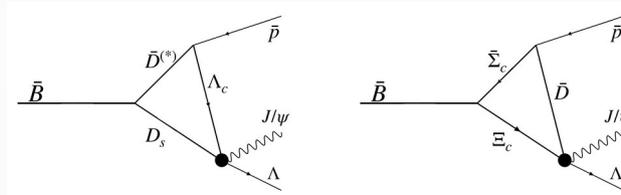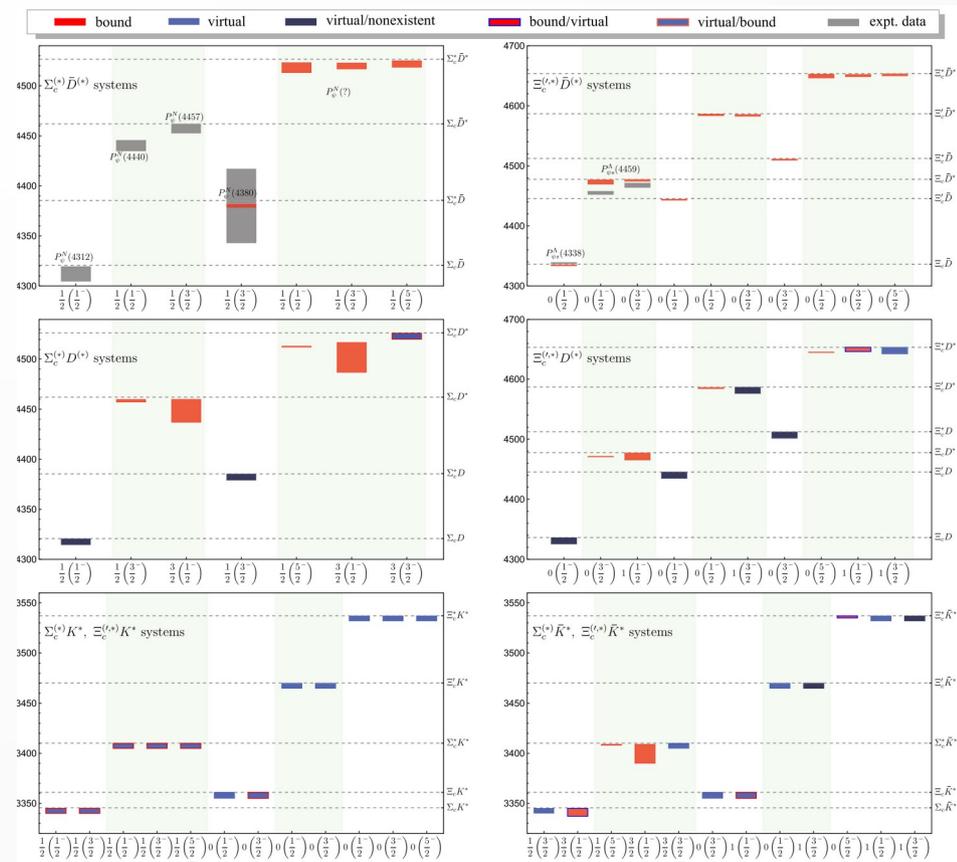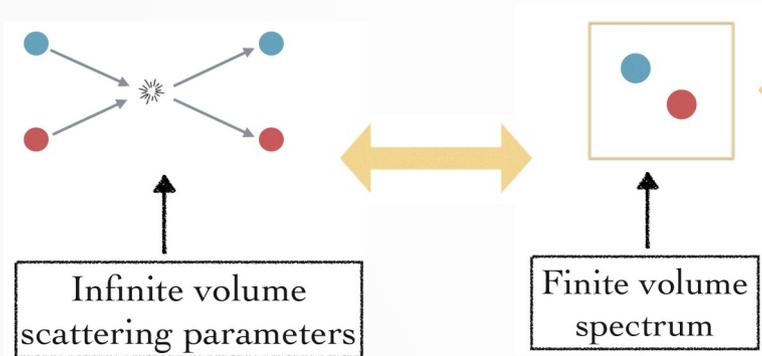

and much more works ...

More Pentaquarks ...

XK Dong et al., Progr.Phys.41,65(2021)

B Wang et al., PRD109,074035(2024)

$\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}^*$ scattering$(J^P = \dfrac{1}{2}^-)$

HY Xing et al., 2210.08555

✦ Five operators:

$\mathscr{O}_1 = \Sigma_c(\mathbf{p})\bar{D}(-\mathbf{p})\ (|\mathbf{p}| = 0)$

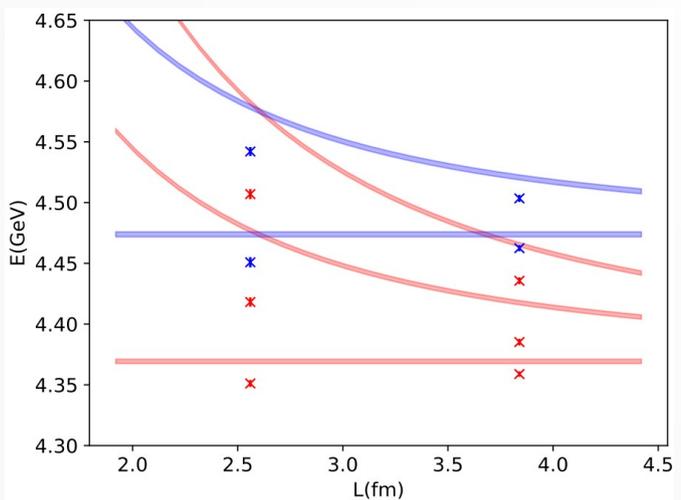$\mathscr{O}_2 = \Sigma_c(\mathbf{p})\bar{D}(-\mathbf{p})\ (|\mathbf{p}| = 1)$

$\mathscr{O}_3 = \Sigma_c(\mathbf{p})\bar{D}(-\mathbf{p})\ (|\mathbf{p}| = \sqrt{2})$

$\mathscr{O}_4 = \Sigma_c(\mathbf{p})\bar{D}^*(-\mathbf{p})\ (|\mathbf{p}| = 0)$

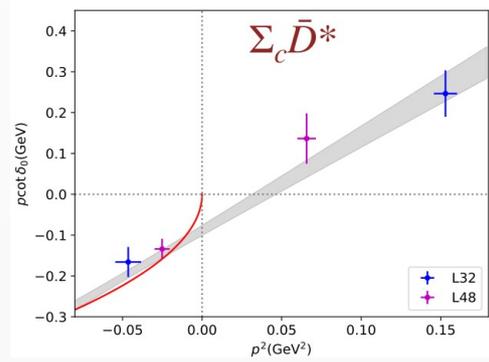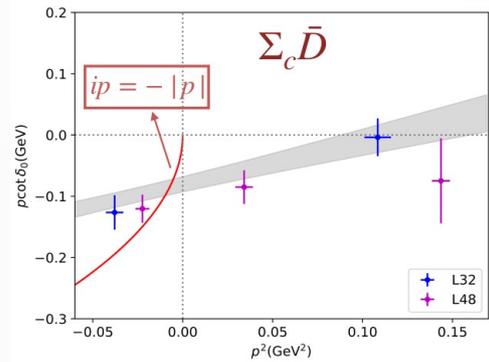$\mathscr{O}_5 = \Sigma_c(\mathbf{p})\bar{D}^*(-\mathbf{p})\ (|\mathbf{p}| = 1)$

Single-Channel

$\Sigma_c\bar{D} : P_c(4312)$?
$a_0 = -2.0(3)(5)\text{fm}$
$E_B = 6(2)(2)\text{MeV}$

$\Sigma_c\bar{D}^* : P_c(4440)/P_c(4457)$?
$a_0 = -2.3(5)(1)\text{fm}$
$E_B = 7(3)(1)\text{MeV}$

✦ The finite-volume energies lie below the free energies, indicating rather strong attractive interactions.
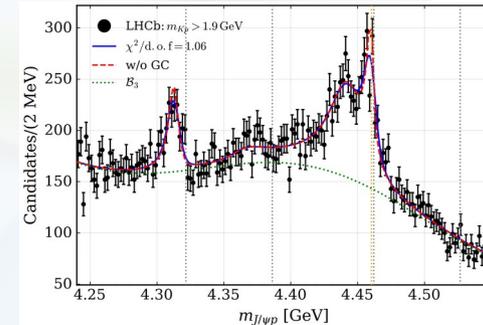
Coupled-Channel still going!
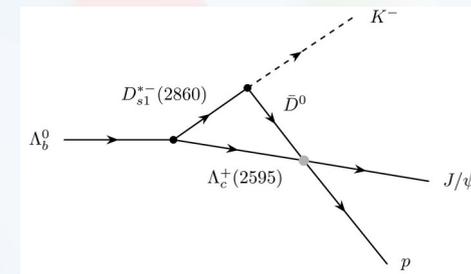
Conclusions

- **Molecular interpretation of the Pc's and 7 Pc's are predicted from HQSS**

- **A narrow Pc(4380), different from the broad one reporeted by LHCb in 2015**

- **Production through the triangle diagram**

- **The missing Pc's from HQSS in LHCb is naturally explained**

$$R = \frac{\Gamma(\Lambda_b^0 \to P_c^+ K^- \to J/\psi p K^-)}{\Lambda_b^0 \to D_{s1}^*(2860)\Lambda_c(2595)} \approx 5\%$$

Propects

- **The missing Pc's from HQSS, Pc's with strangeness**

- **Lattice simulations**

- **STCF: charmonium-like, clearly defined IS&FS properies, full event reconstruction**

Pc: $e^+e^- \to p\bar{p}J/\psi,\ \Lambda_c\bar{D}^{(*)}\bar{p},\ \Sigma_c^{(*)}\bar{D}^{(*)}\bar{p}$ **Pcs(s):** $e^+e^- \to \Lambda\bar{\Lambda}J/\psi,\ \Sigma\bar{\Sigma}J/\psi,$ and $\Xi\bar{\Xi}J/\psi$ **Pcsss:** $e^+e^- \to \Omega\bar{\Omega}J/\psi$

Thank you very much for your attention!   29

Thank you very much for your attention!

backup

$$\Lambda_b^0 \qquad I(J^P) = 0(1/2^+)$$

Γ_{46}	$\Sigma_c(2455)^{++} D^- K^-$	$(6.0 \pm 0.8) \times 10^{-4}$	1448
Γ_{47}	$\Sigma_c(2455)^{++} D^{*-} K^-$	$(1.36 \pm 0.22) \times 10^{-3}$	1324
Γ_{48}	$\Sigma_c(2520)^{++} D^- K^-$	$(2.8 \pm 0.5) \times 10^{-4}$	1392
Γ_{49}	$\Sigma_c(2520)^{++} D^{*-} K^-$	$(5.4 \pm 1.1) \times 10^{-4}$	1262
Γ_{36}	$\Lambda_c^+ D^-$	$(4.6 \pm 0.6) \times 10^{-4}$	1886
Γ_{37}	$\Lambda_c^+ D_s^-$	$(1.10 \pm 0.10)\%$	1833
Γ_{38}	$\Lambda_c^+ D_s^{*-}$	$(1.83 \pm 0.18)\%$	1748
Γ_{39}	$\Lambda_c^+ \overline{D}^0 K^-$	$(2.13 \pm 0.20) \times 10^{-3}$	1581
Γ_{40}	$\Lambda_c^+ \overline{D}^{*0} K^-$	$(6.6 \pm 0.7) \times 10^{-3}$	1471