The 6th International Workshop on Future Tau Charm Facilities
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Doubly heavy pentaquarks: Status and Perspectives

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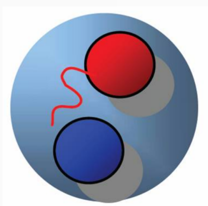
Interpretation of the LHCb Pc states as Hadronic Molecules and Hints of a Narrow Pc(4380)
Revisting the nature of the Pc states
Prompt production of the hidden charm pentaquarks in the LHC
Insights into the nature of the Pcs(4459)
Deciphering the mechanism of near-threshold J/ψ photoproduction
...

Outline

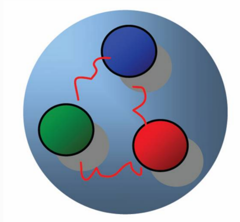
- A brief history
- LHCb pentaquarks
- Hidden-charm pentaquarks with strangeness
  ---- also see in JJ Wu's talk
- Lattice simulations
- Conclusions an Propects

Conventional hadrons vs. Exotic hadrons

Conv. Hadrons



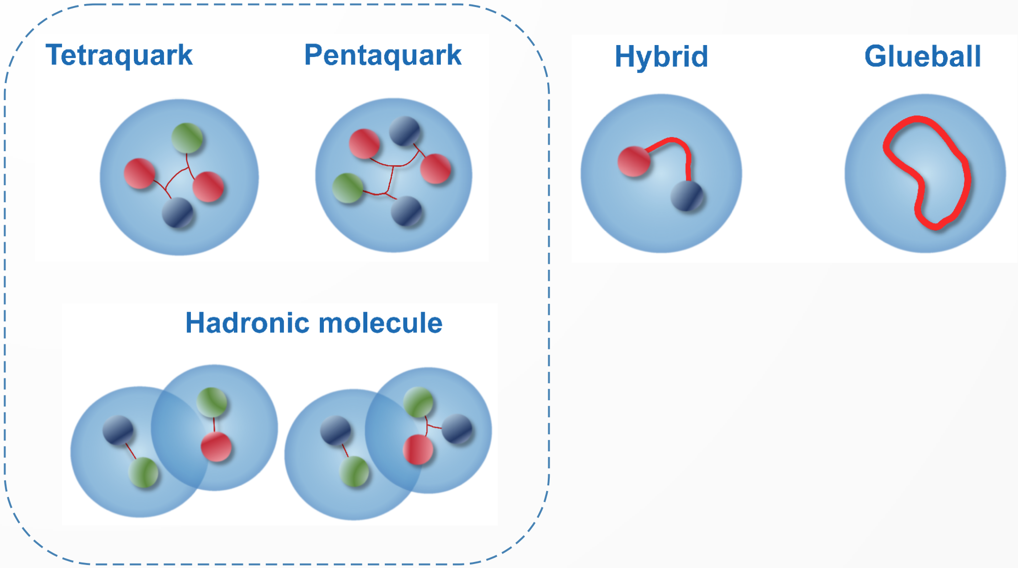
meson



baryon

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

Exotic Hadrons



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 SU_3 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 $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ 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: $\bar{K}N$ molecule predicted by Dalitz-Tuan, PRL2,425
  - 1961: $\Lambda(1405) \to \Sigma\pi$ observed by Alston et al., PRL6, 698
  - 1995: $\bar{K}N$ dynamically generated, by Kaiser et al., NPA954, 325
  - 2001: two-pole structure by $\bar{K}N - \Sigma\pi$ by Oller et al., PLB500, 263

  ......

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

  also see JX Lu's talk...

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

  - 1997: predicted w/ chiral soliton model by Diakonov et al., ZPA359, 305
  - 2003: $\theta^+(1540) \to K^+n$ 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

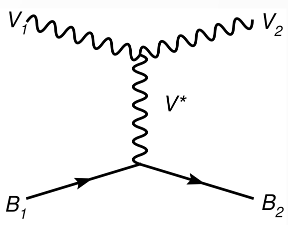
Hidden-charm Pentaquarks: Predictions

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

(I,S)	State	M_R [MeV] Γ_R [MeV]	$\lvert g_R \rvert$
$(\frac{1}{2},0)$	$\pi\Delta$	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



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

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

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

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

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

- Chiral quark model, W.L. Wang et al., PRC84, 015203 (2011)
  Hyperfine interaction, S.G. Yuan et al., EPJA48, 61 (2012)
  ……

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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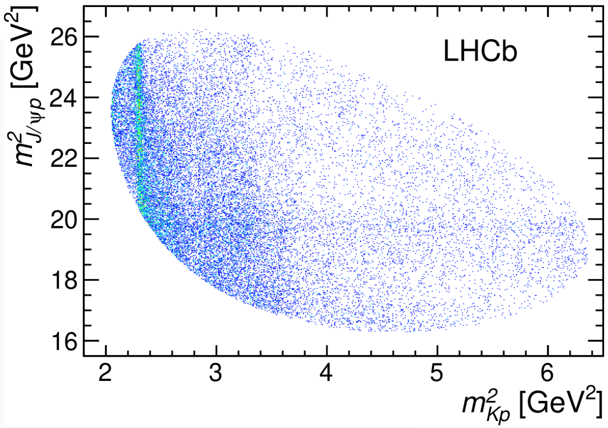
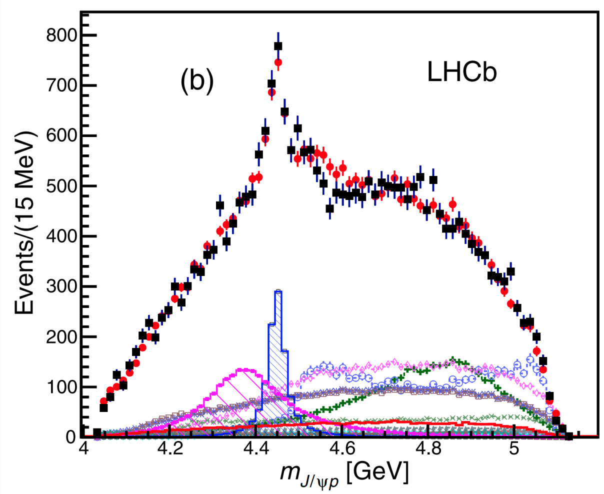
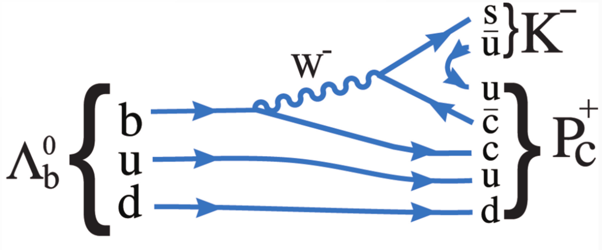
Charmonium-pentaquark states (I)

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

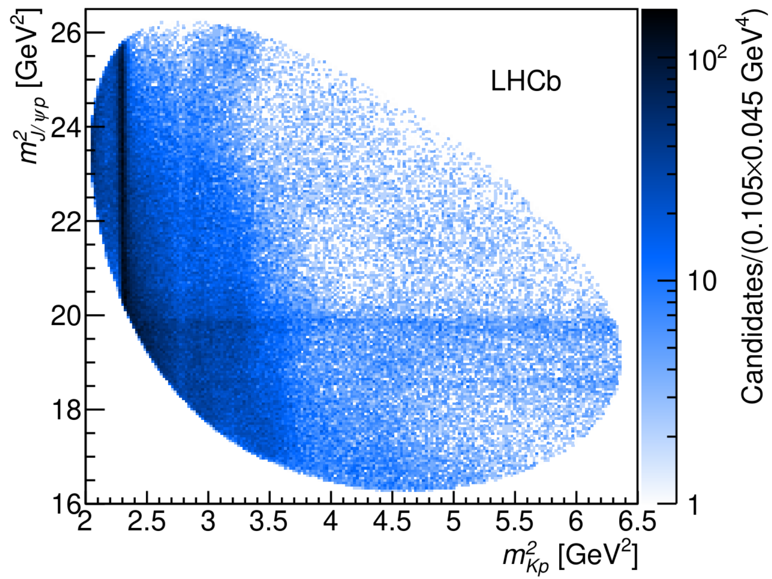
$P_c(4450)^+$: $M = 4449.8 \pm 1.7 \pm 2.5$ MeV

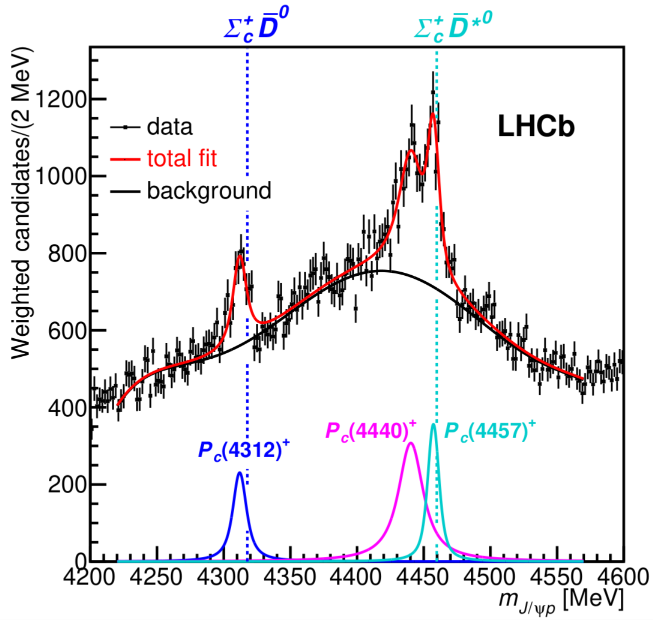
$\Gamma = 39 \pm 5 \pm 19$ MeV

Preferred Parity: Opposite

Charmonium-pentaquark states (II)

LHCb, PRL 122, 222001 (2019)



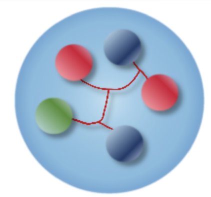


the $P_c(4440)^+$ and $P_c(4457)^+$ states. The six-dimensional amplitude analysis reported in Ref. [9], which provided evidence for the $P_c(4380)^+$ state, is also obsolete since it used the single $P_c(4450)^+$ state and it lacked the $P_c(4312)^+$ state. Therefore, the results presented in the Letter 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.

$P_c(4450)^+$ → $P_c(4440)^+$, $P_c(4457)^+$

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)

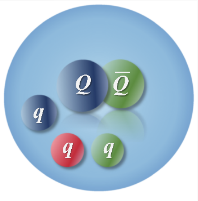
$P_c(4312),\ P_c(4440),\ P_c(4457)$: $J^P = 3/2^-,\ 1/2^-,\ 3/2^-$

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

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

R. Zhu et al., PLB797, 134869(2019)
Giron et al., JHEP05, 061 (2019)
……

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

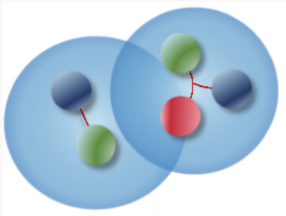


Hadron-Charmonium

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)
……

Kinematic effect

Kuang et al., EPJC80,433 (2020)
Nakamura, PRD103, L111503(2021)
Burns et al., PRD106,054029(2022)
……

Heavy Quark Spin Symmetry (HQSS)

- For a heavy-quark Q ($c$harm, $b$ottom) with $m_Q \gg \Lambda_{\rm QCD}$

☞ 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)

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

$j_\ell = \frac{1}{2} \oplus \frac{3}{2}$ → LO Contact Interaction: Only 2 LECs

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

7 Pc states!

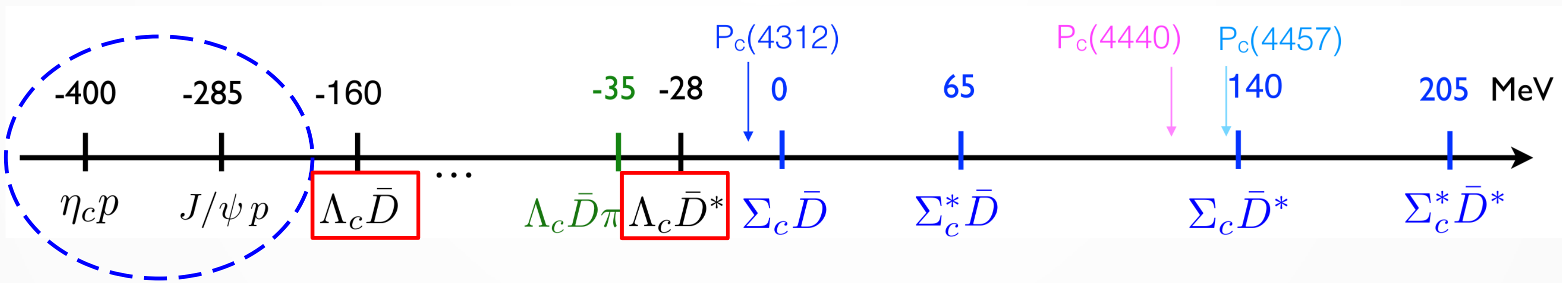
Xiao et al., PRD88, 56012 (2013)

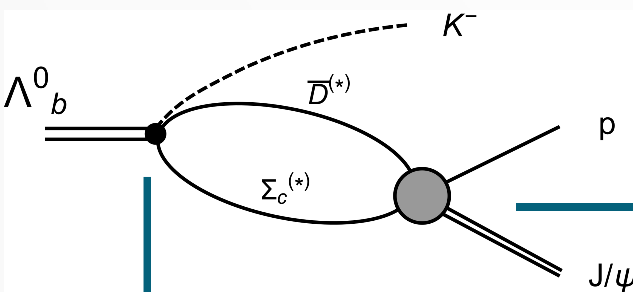
Liu et al., PRL122,242001 (2019)

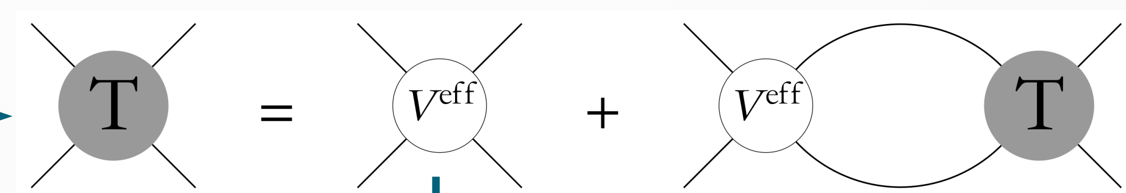
Molecular Interpretation [EFT]

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

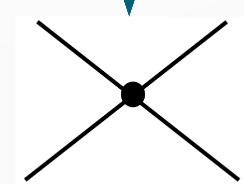
- A coupled-channel analysis of the LHCb spectra using an EFT approach







7 LECs for contact Production



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

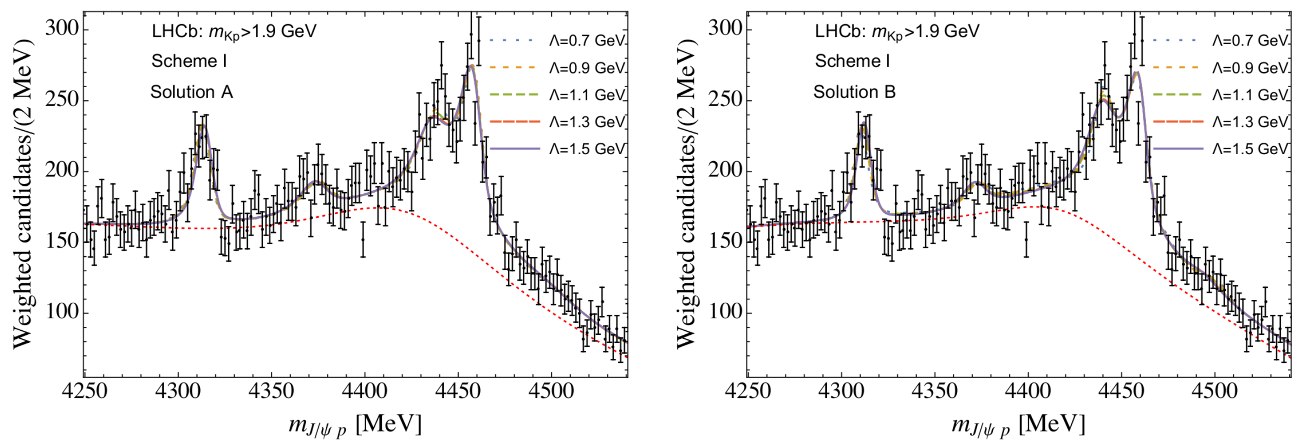
$\bar{D}^{(*)}\Sigma_c^{(*)}(S) \to J/\Psi p(S),\ J/\Psi p(D)$

2 LECs

"Contact" Fits to the LHCb data

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

Solution A   Solution B

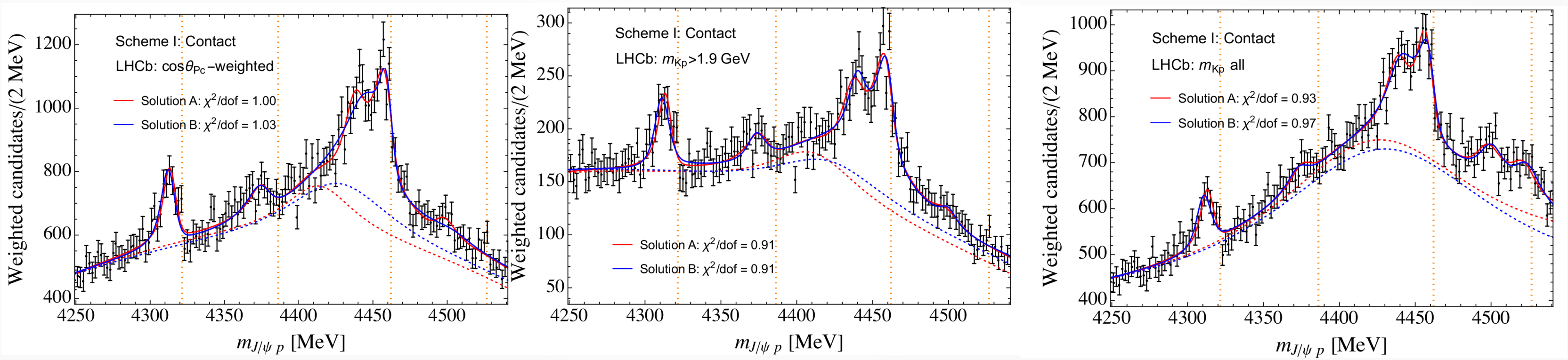


- ☞ $\Lambda > \Lambda_{\rm soft} \sim \sqrt{2\mu\delta} \sim 0.7$ GeV
- ☞ Cutoff-independent for both solution A and B

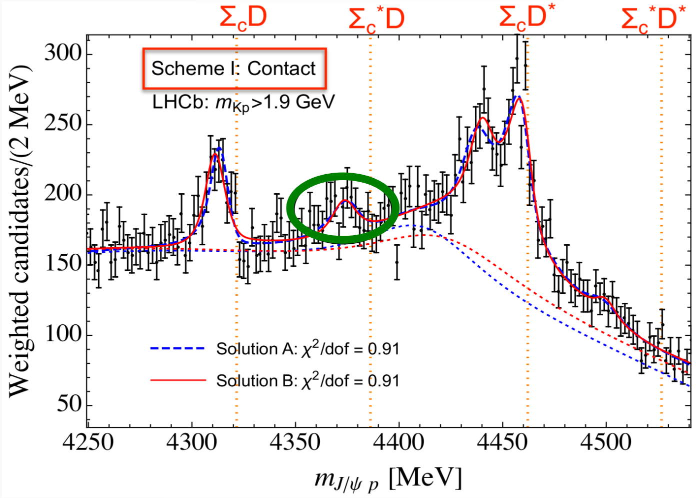
$\Sigma_c \bar{D}^*$	$P_c(4440)$	$P_c(4457)$
Fit A	$\frac{1}{2}^-$	$\frac{3}{2}^-$
Fit B	$\frac{3}{2}^-$	$\frac{1}{2}^-$

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

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



Line shape and Pc Poles: Contact



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

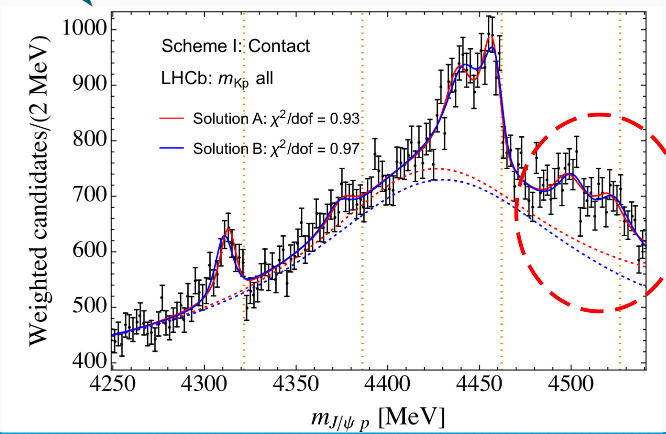
- $\Sigma_c{}^*D^*$ states are not seen yet, their production rate is suppressed ?

↪ prompt production in the pp collision in the LHC

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

Poles and quantum numbers:

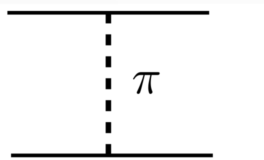
	thr. ([MeV])	solution A J^P	solution A Pole [MeV]	solution B J^P	solution B Pole [MeV]
$P_c(4312)$	$\Sigma_c\bar{D}$ (4321.6)	$\frac{1}{2}^-$	$4314(1)-4(1)i$	$\frac{1}{2}^-$	$4312(2)-4(2)i$
$P_c(4380)$	$\Sigma_c^*\bar{D}$ (4386.2)	$\frac{3}{2}^-$	$4377(1)-7(1)i$	$\frac{3}{2}^-$	$4375(2)-6(1)i$
$P_c(4440)$	$\Sigma_c\bar{D}^*$ (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)	$\frac{5}{2}^-$	$4525(2)-9(3)i$	$\frac{5}{2}^-$	$4501(3)-6(4)i$



Including OPE

contact + OPE

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



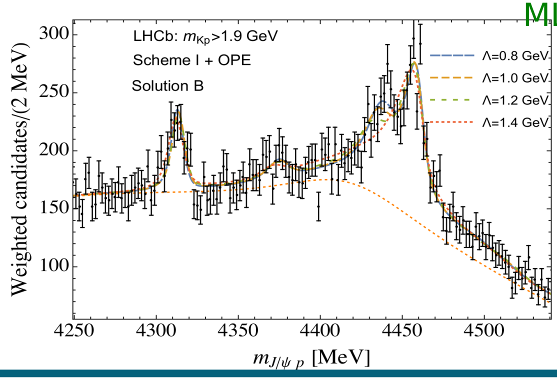
Long range: OPE

Determined by exp. data

☞ No solution A

☞ Solution B:
Cut-off dependent

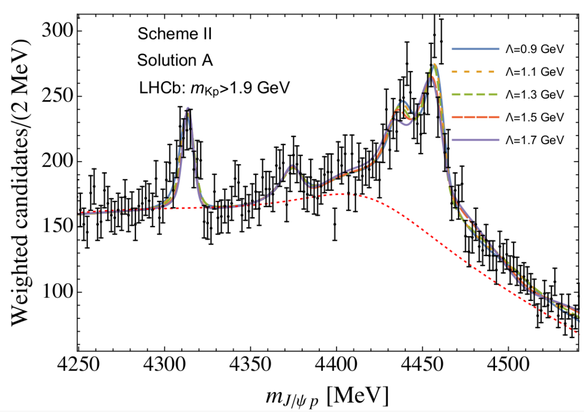
☞ $\Lambda_{\rm soft} \sim 700$ MeV



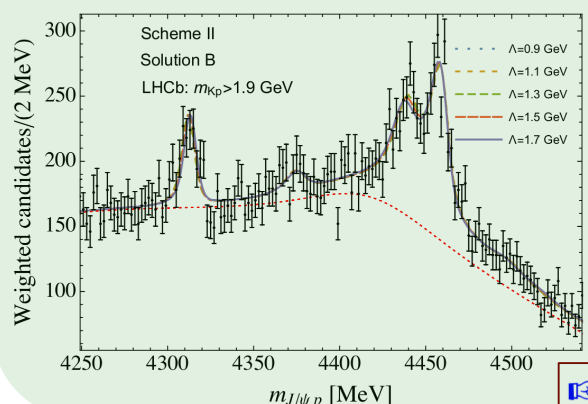
$+\ \Lambda_c \bar{D}^{(*)}$

contact + OPE + S-D

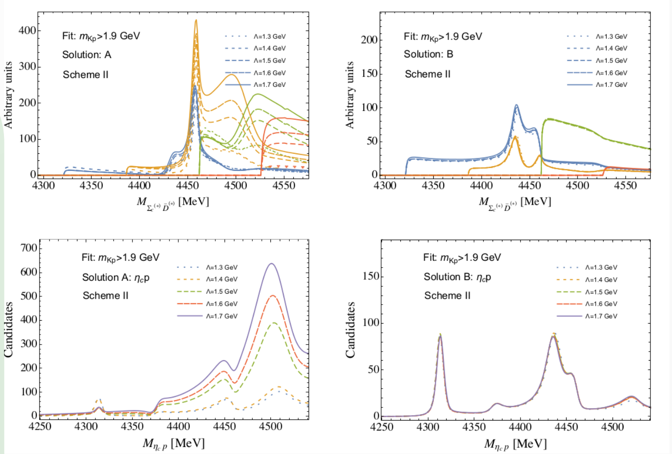
Solution A



Solution B



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



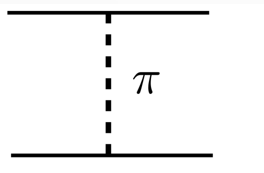
☞ Overdetermined. w/ $\Lambda_c \bar{D}^{(*)}$ $\Lambda_{\rm soft} \sim 0.9$ GeV

☞ Cutoff-independent only for solution B

Including OPE

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

$\text{contact} + \text{OPE}$



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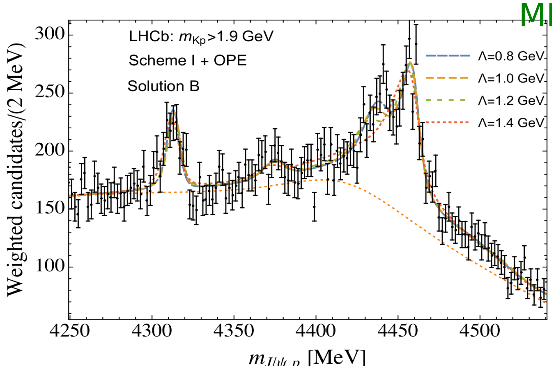


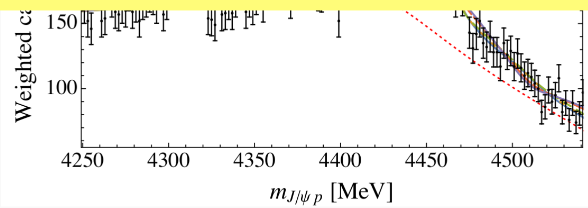
$\Lambda_c \bar{D}^{(*)}$

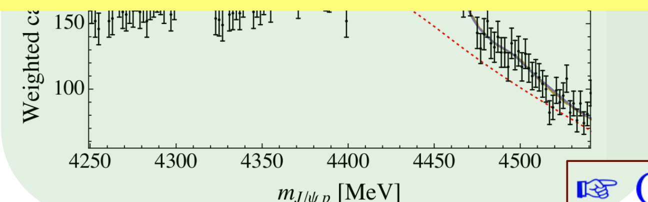
$\text{contact} + \text{OPE} + \text{S-D}$

Fit B shows a much more natural pattern than fit A

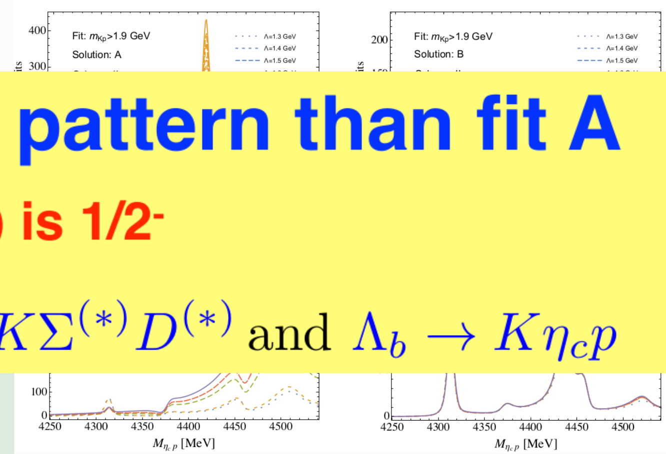
⇒ $P_c(4440)$ is $3/2^-$ and $P_c(4457)$ is $1/2^-$

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





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

$\Sigma_c^{(*)}\bar{D}^{(*)} - \Lambda_c(2595)\bar{D}$ Yalikun et al., PRD104,094039(2021)

Prompt production in the LHC

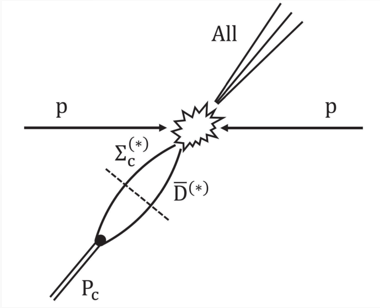
P. Ling et al., Eur.Phys.J.C 81, 819 (2021)

Poles and quantum numbers:

		solution A		solution B	
	thr. ([MeV])	J^P	Pole [MeV]	J^P	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)	$\frac{5}{2}^-$	$4525(2)-9(3)i$	$\frac{5}{2}^-$	$4501(3)-6(4)i$

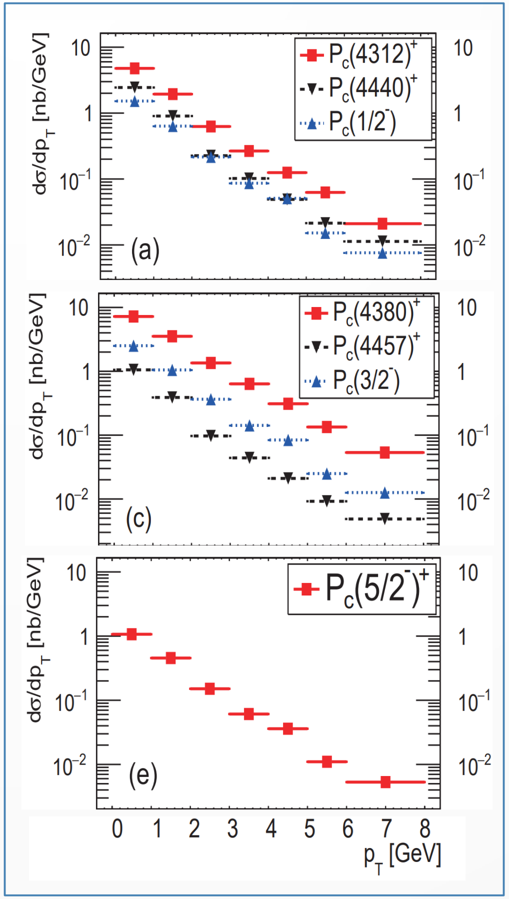
?

?

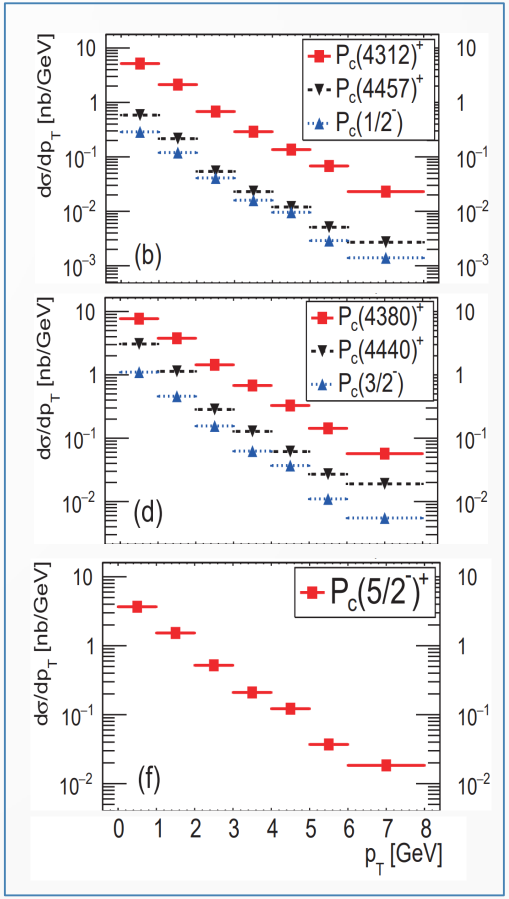


Madgraph5
+
Phythia8

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



A

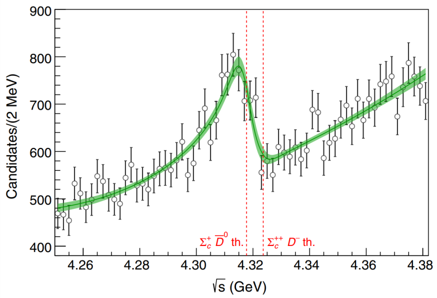


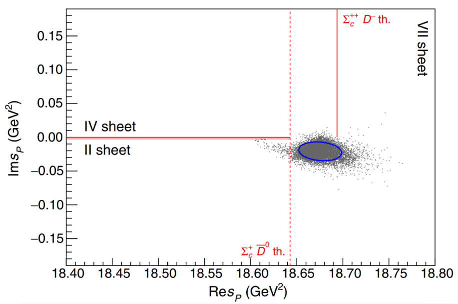
B

(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)

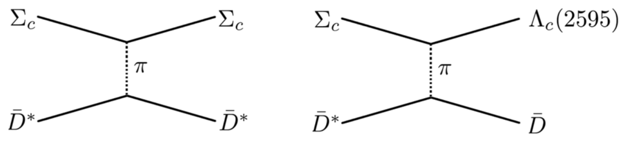
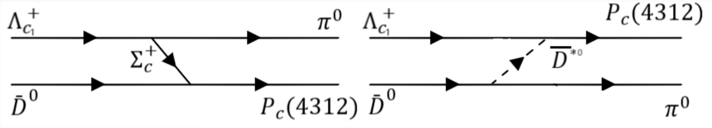


FIG. 1. Elastic and inelastic t-channel pion-exchange diagrams in the $\Sigma_c\bar{D}^* - \Lambda_c(2595)\bar{D}$ system.

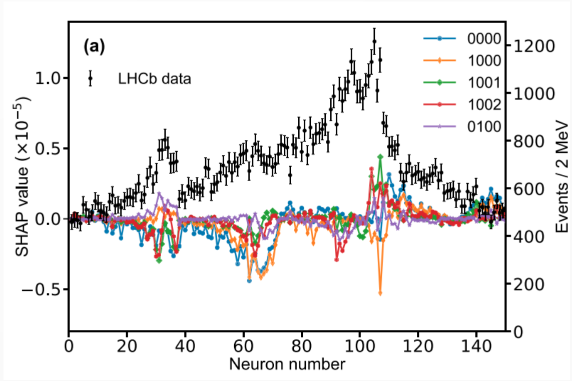
- $P_c(4457)$ interpreted as a $J^P = 1/2^+$ state



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

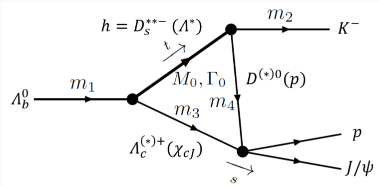
- interpreting the $P_c(4457)$ pentaquark as a $I = \frac{3}{2}$ $\bar{D}^*\Sigma_c$ bound state (with spin $J = \frac{1}{2}$)

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

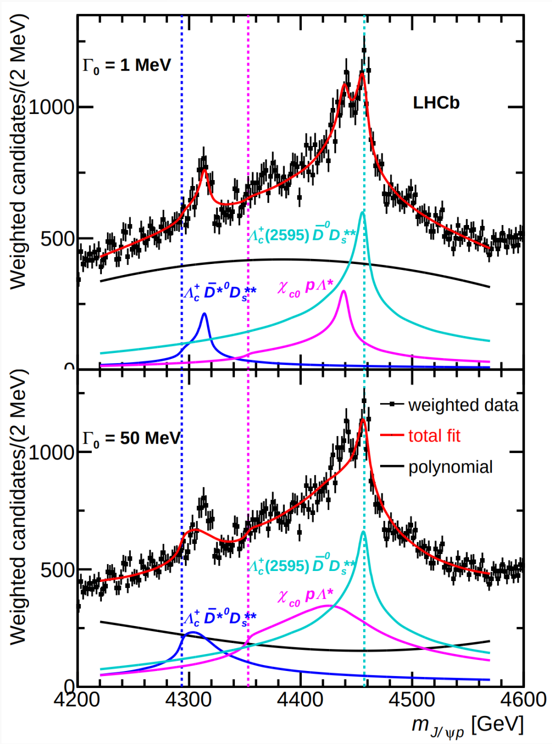


ZY Zhang et al., Sci.Bull.68,981(2023)

Triangle Diagrams



LHCb, PRL122, 222001 (2019)

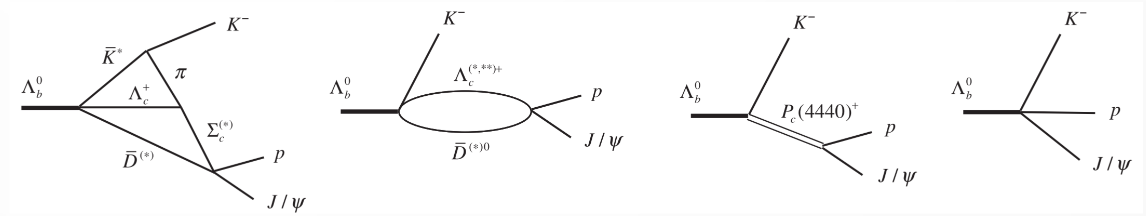


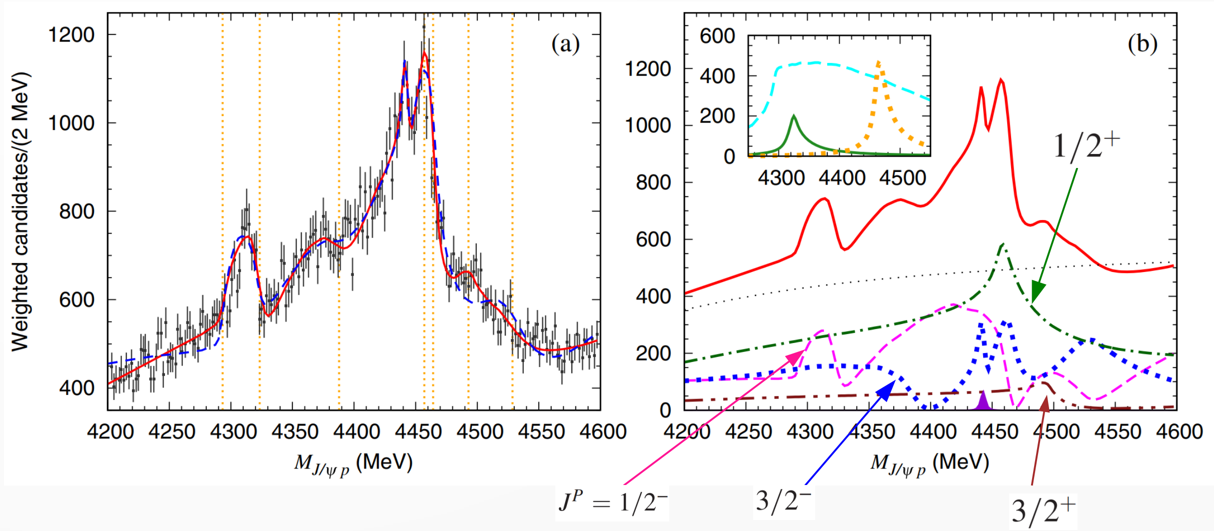
Nakamura, PRD103,L111503 (2021)

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

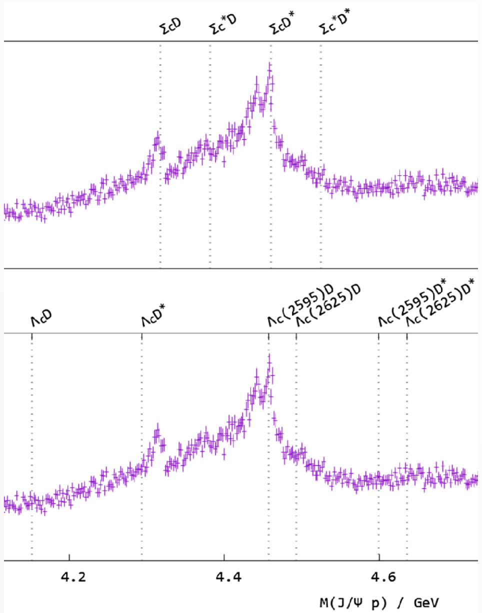
double triangle amplitudes reproduce the peak structures of $P_c(4312)^+$, $P_c(4380)^+$, and $P_c(4457)^+$

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



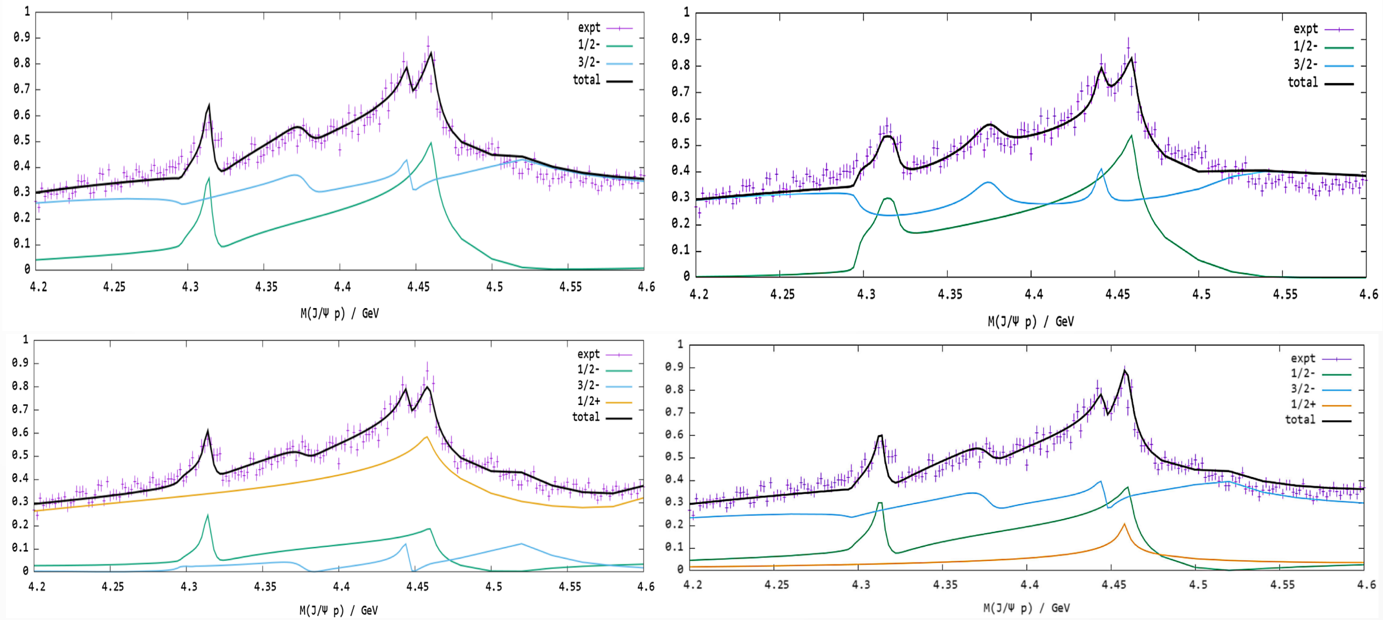


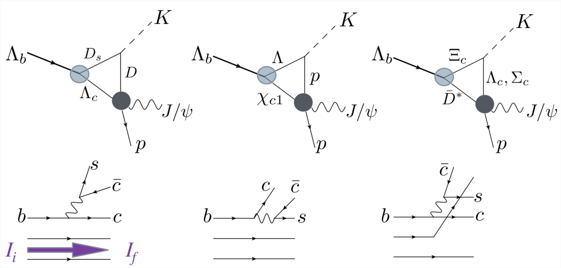
A Production/Rescattering Model



$1/2^-$:	$\Lambda_c\bar{D}, \Lambda_c\bar{D}^*, \Sigma_c\bar{D}, \Sigma_c\bar{D}^*, \Sigma_c^*\bar{D}^*, NJ/\psi, N\eta_c$
$3/2^-$:	$\Lambda_c\bar{D}^*, \Sigma_c^*\bar{D}, \Sigma_c\bar{D}^*, \Sigma_c^*\bar{D}^*, NJ/\psi$
$1/2^+$:	$\Lambda_c(2595)\bar{D}, \Lambda_c(2595)\bar{D}^*, \Lambda_c(2625)\bar{D}^*, NJ/\psi(^2P_{1/2}), NJ/\psi(^4P_{1/2}), N\eta_c(^2P_{1/2})$

Burns et al., PRD106,054029 (2022)





$1/N_c$ $1/N_c$

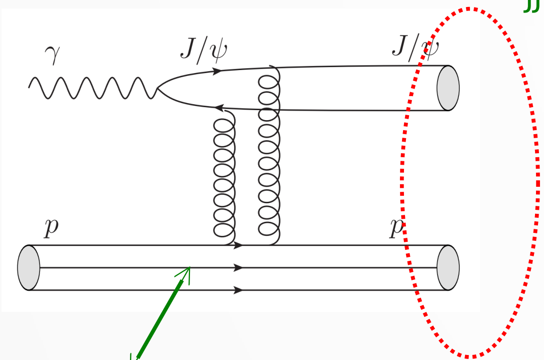
	Case 2a/3	Case 2b	Case 4	Case 5
$1/2^-$ pole	$4312 - 2.4i$	$4308 - 5.2i$	$4312 - 2.6i$	$4312 - 2.4i$
$3/2^-$ pole	$4376.5 - 9.0i$	$4375 - 10.7i$	$4376.5 - 9.1i$	$4376.5 - 8.9i$
$3/2^-$ pole	$4444 - 2.56i$	$4440 - 3.3i$	$4444.5 - 2.56i$	$4444 - 2.56i$
$1/2^+$ pole				$4458 - 0i$

~~HQSS~~

A look at the J/ψ photoproduction

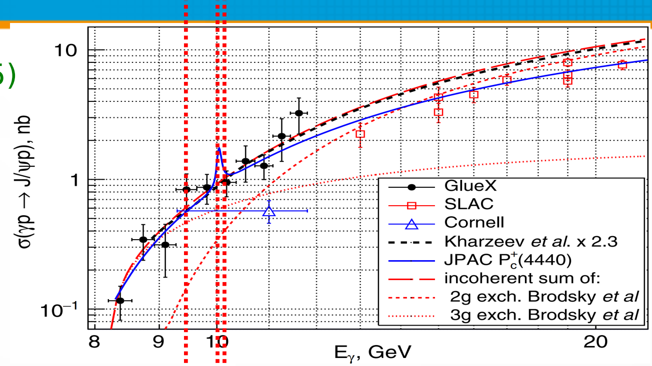
$$T_{\gamma p\to J/\psi p}=g_{\gamma\psi}T_{J/\psi p\to J/\psi p}$$

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



$\mathbf{P_c}$?

$$M_N = \langle\frac{\beta}{2g}F^2+\sum_f \gamma_m m_f\overline{\psi}_f\psi_f\rangle_{\rm H}+\sum_f m_f\langle\overline{\psi}_f\psi_f\rangle_{\rm H}$$

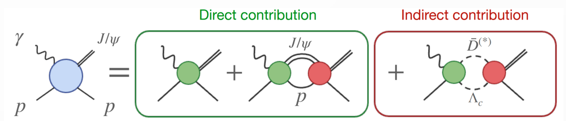


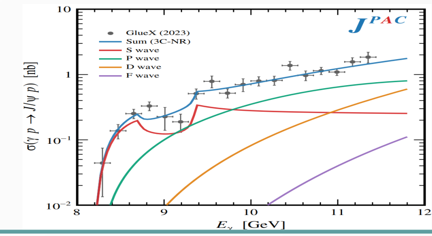
$\mathbf{P_c}$

GlueX,PRL123,072001(2019)

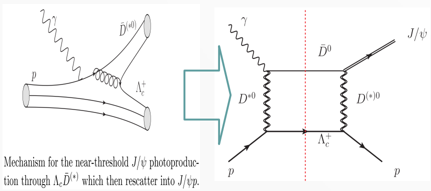
No evidence for Pc.

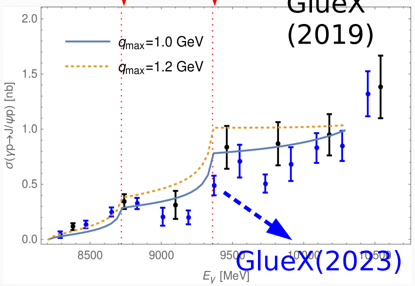
~~*Hadron-Charmonium*~~?





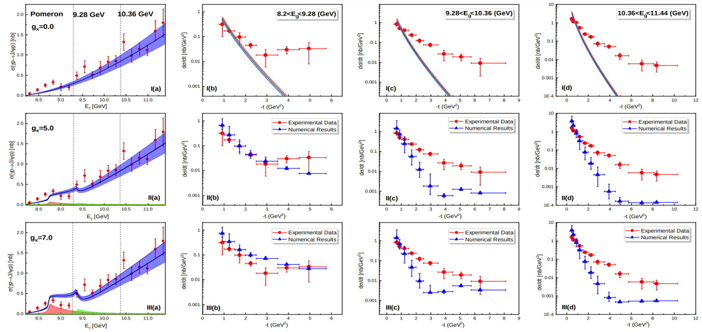
JPAC, PRD108,054018(2023)





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)



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

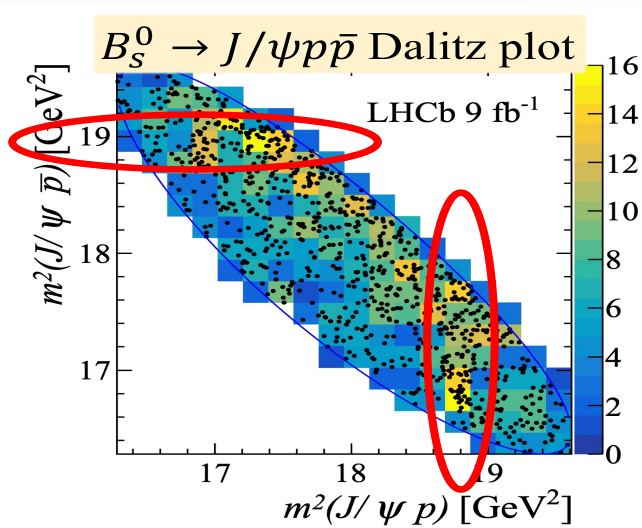
MX Duan et al., 2409.10364

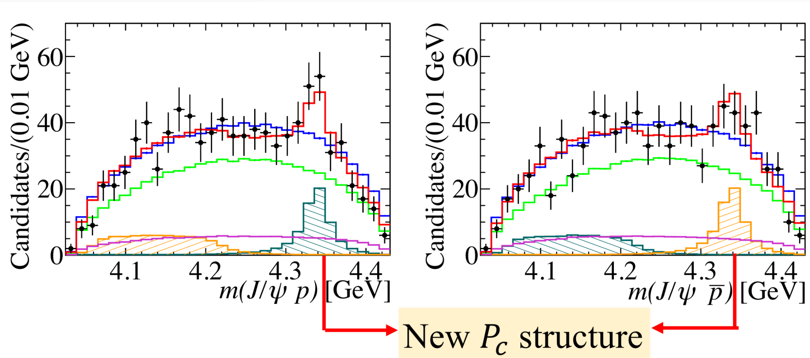
The production of Pc suppressed

A similar result by X Zhang, 2410.1015

Charmonium-pentaquark states (III)

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





LHCb, PRL128,062001(2022)

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

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

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

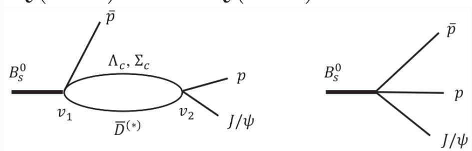
$P_c(4312)$?

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)

---see JJ Wu's talk

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

$\bar{D}^*\Lambda_c$-$\bar{D}\Sigma_c$ and $\bar{D}^*\Lambda_c$-$\bar{D}\Sigma_c^*$

MJ Yan et al.,EPJC82,574 (2022)

.....

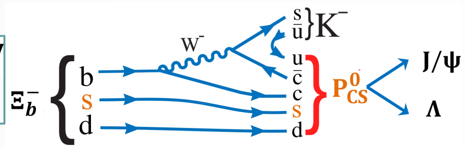
Hidden-charm Pentaquarks with strangeness (I)

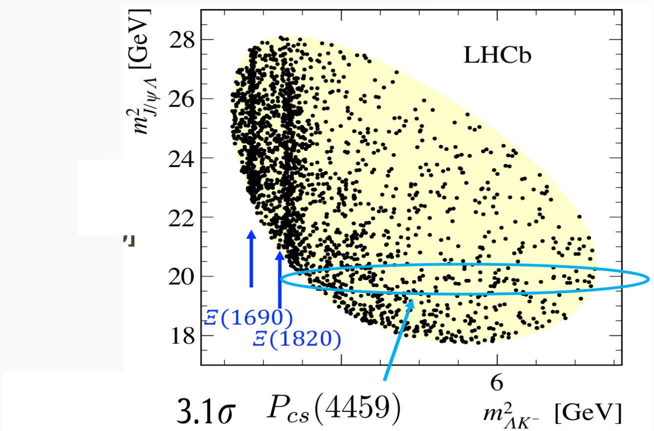
- SU(3) partner P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi \Lambda K^-$

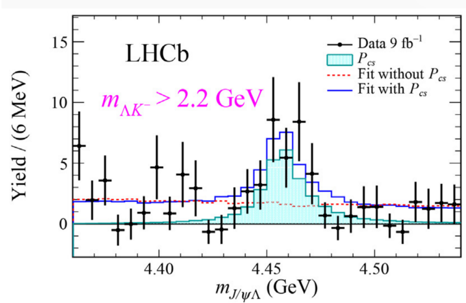
JJ Wu et al., PRL105, 232001(2010);
HX Chen et al.,PRC93,065203(2016) ...

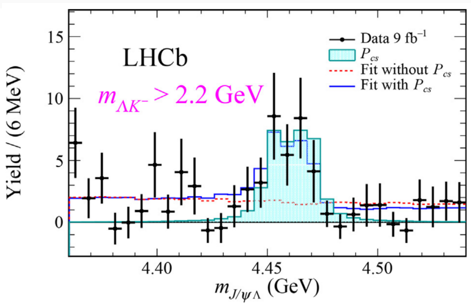
LHCb, Sci.Bull.66,1278 (2021)

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









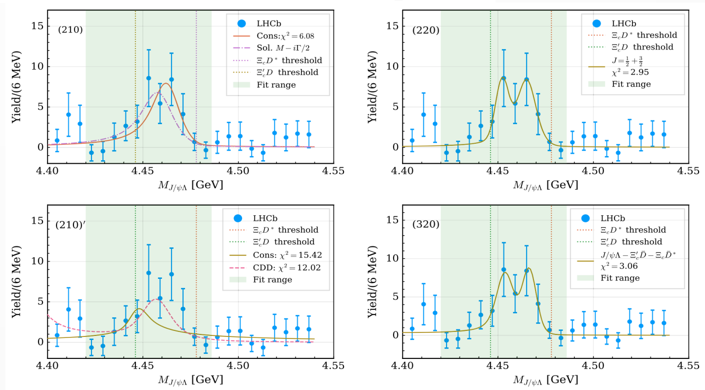
Molecular Interpretation

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.



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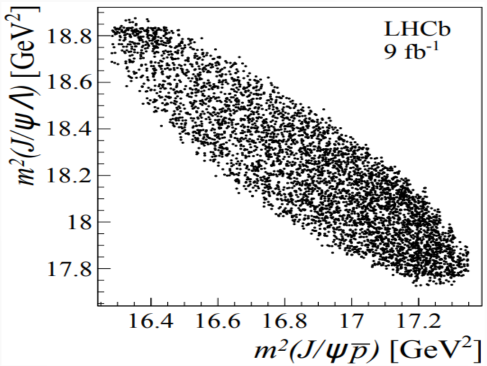
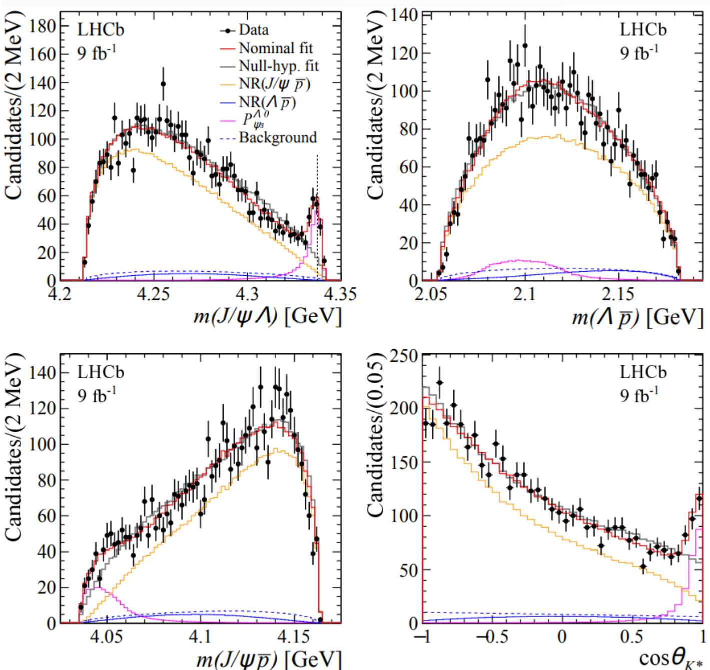
See review papers:
An updated review of the new hadron states, HX Chen et al., Rept.Prog.Phys.86,026201(2023)
ChPT for heavy hadrons and ChEFT for heavy hadronic molecules, L. Meng et al., Phys. Rept.1019,1(2023)

Hidden-charm Pentaquarks with strangeness (II)

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





---see also JJ Wu's talk

(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)

$J^P = \frac{1}{2}^-$ — $P_{cs}(4459)$ ← 4422.79 + i7.75

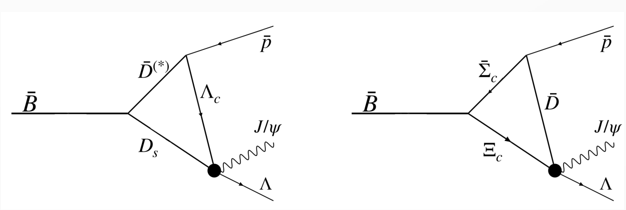
Poles		$\eta_c\Lambda$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
4198.94 + i0.11	g_i	0.12 − i0.00	3.01 − i0.01	**4.85+i0.01**	0.01 − i0.03
	$g_i G_i^{II}$	−0.35 + i1.01	−19.24 + i0.05	**−20.35−i0.07**	−0.03 + i0.09
4422.79 + i7.75	g_i	0.71 − i0.08	0.05 + i0.00	−0.06 + i0.04	**2.79−i0.35**
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

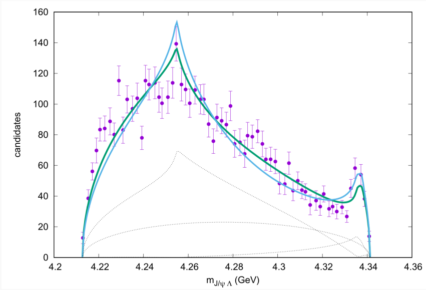
$J^P = \frac{1}{2}^-, \frac{3}{2}^-$ — $P^{\Lambda}_{\psi s}(4338)$ ← 4337.98 + i0.12

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	**5.07+i0.01**	0.00 − i0.04
	$g_i G_i^{II}$	−0.13 + i1.07	−18.57 + i0.06	**−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	**2.84−i0.72**
	$g_i G_i^{II}$	6.24 + i21.04	2.07 + i3.40	−1.37 − i2.81	**−26.31+i1.15**

Burns et al., PLB838,137715 (2023)

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



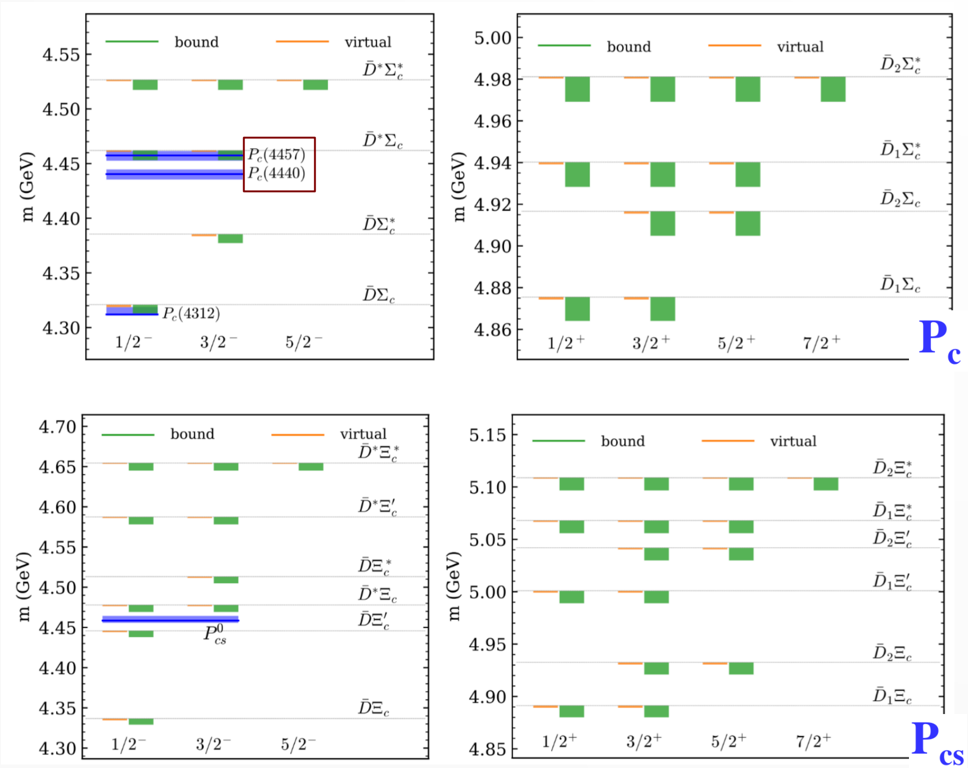


and much more works ...

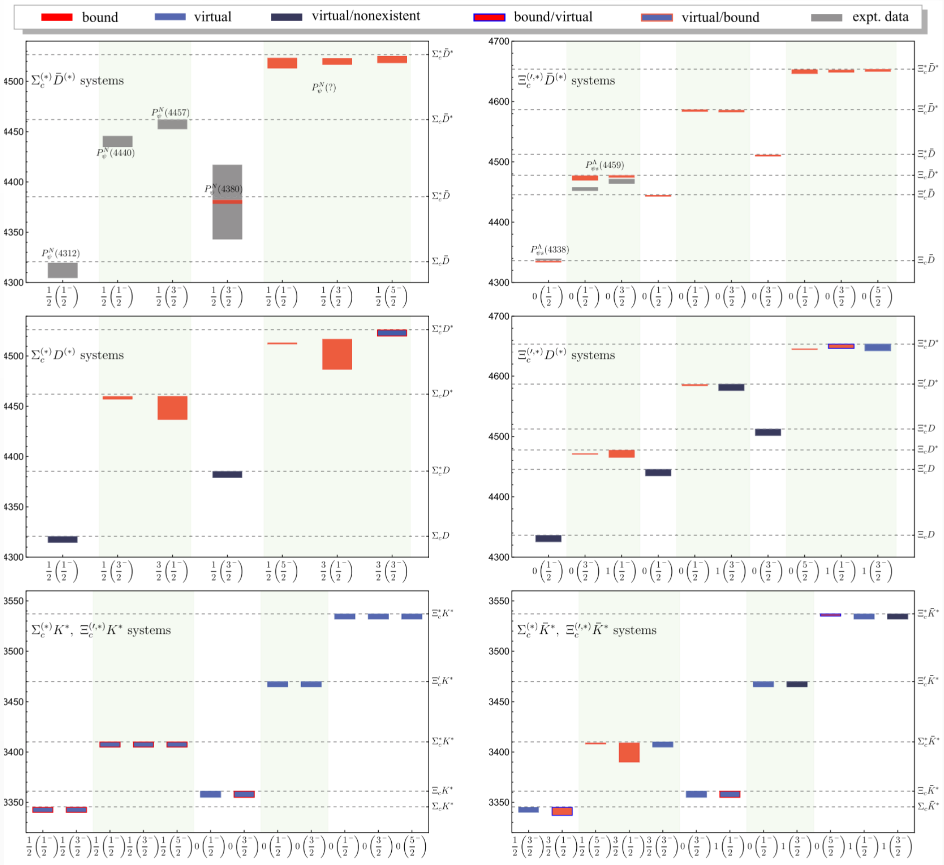
More Pentaquarks ...

See also in JJ Wu's talk..

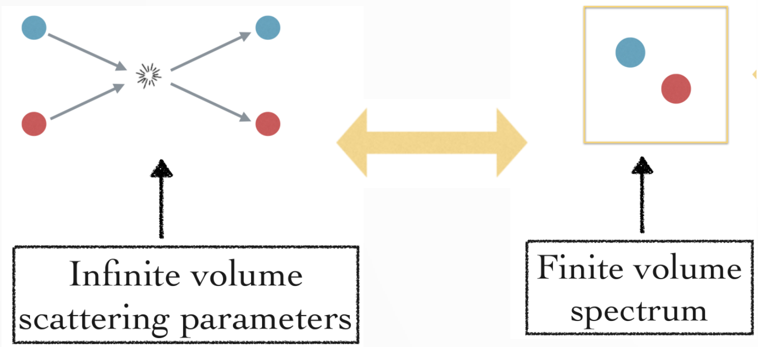
XK Dong et al., Progr.Phys.41,65(2021)



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



Lattice QCD study of the Pc states



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

✦ Five operators:

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

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

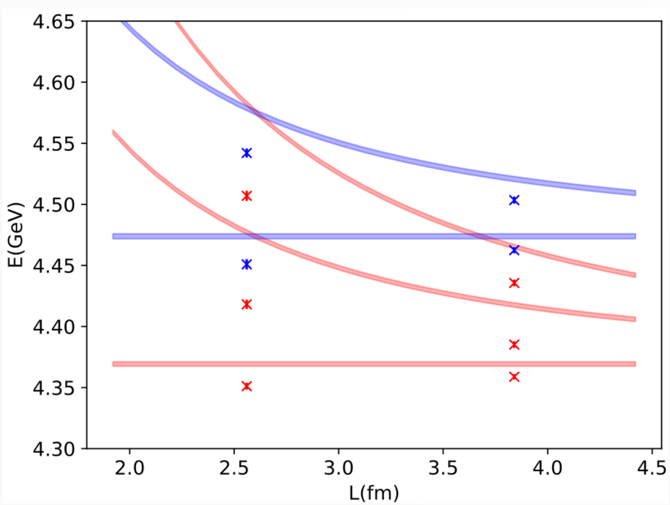
$\mathcal{O}_3 = \Sigma_c(\mathbf{p})\bar{D}(-\mathbf{p})\ (|\mathbf{p}| = \sqrt{2})$

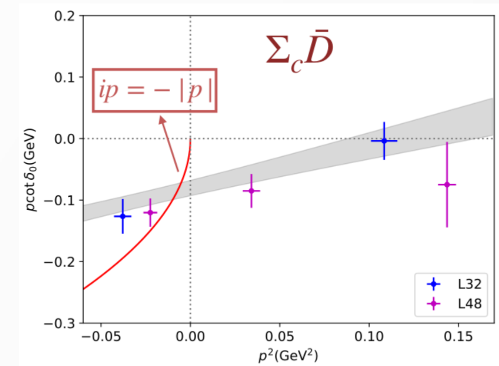
$\mathcal{O}_4 = \Sigma_c(\mathbf{p})\bar{D}^*(-\mathbf{p})\ (|\mathbf{p}| = 0)$

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

HY Xing et al., 2210.08555

Single-Channel

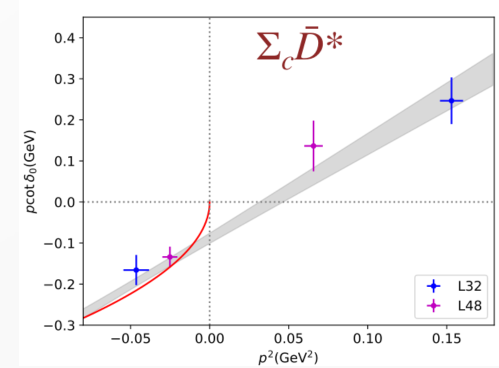




$\Sigma_c\bar{D}$: $P_c(4312)$?

$a_0 = -2.0(3)(5)$fm

$E_B = 6(2)(2)$MeV



$\Sigma_c\bar{D}^*$:$P_c(4440)/P_c(4457)$?

$a_0 = -2.3(5)(1)$fm

$E_B = 7(3)(1)$MeV

✦ The finite-volume energies lie below the free energies, indicating rather strong attractive interactions.

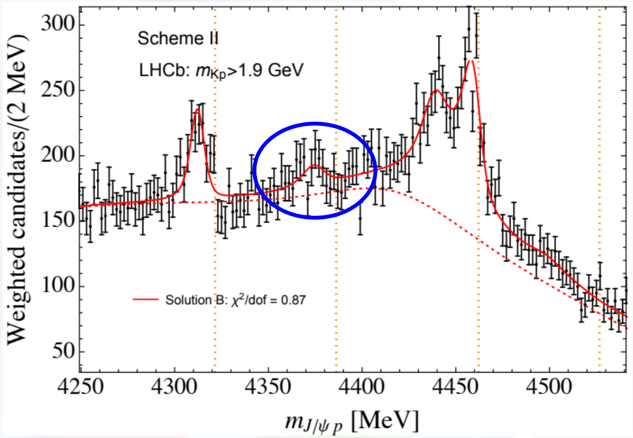
Coupled-Channel still going!

Conclusions and Propects

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**

	DC ([MeV])	J^P	Pole [MeV]
$P_c(4312)$	$\Sigma_c\bar{D}$ (4321.6)	$\frac{1}{2}^-$	$4313(1) - 3(1)i$
$P_c(4380)$	$\Sigma_c^*\bar{D}$ (4386.2)	$\frac{3}{2}^-$	$4376(1) - 6(2)i$
$P_c(4440)$	$\Sigma_c\bar{D}^*$ (4462.1)	$\frac{3}{2}^-$	$4441(2) - 6(2)i$
$P_c(4457)$	$\Sigma_c\bar{D}^*$ (4462.1)	$\frac{1}{2}^-$	$4461(2) - 5(2)i$
P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{1}{2}^-$	$4525(4) - 9(1)i$
P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{3}{2}^-$	$4520(3) - 12(3)i$
P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{5}{2}^-$	$4500(2) - 9(6)i$



Propects

- **The production mechanism of the LHCb pentaquarks**
- **The missing Pc's from HQSS, Pc's with strangeness**
- **Lattice simulations**
- **STCF: charmonium-like, clearly defined IS&FS properities, 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!

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