Molecular interpretation of the LHCb P_c states from an analysis of $J/\psi p$ spectrum

Meng-Lin Du

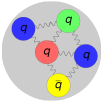
IFIC, University of Valencia
HISKP, Universität Bonn

In collaboration with V. Baru, F.-K. Guo, C. Hanhart, U.-G. Meißner, J. A. Oller, and Q. Wang

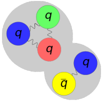
Based on PRL124(2020)072001 and arXiv: 2102.07159 (2021)

19th International Conference on Hadron Spectroscopy and Structure

Penta-Quark States



Pentaquark
↪ Compact object formed from q and $\bar{q}$



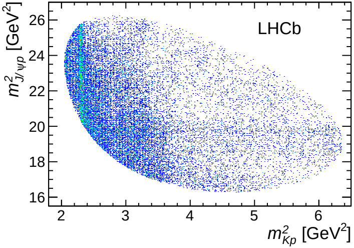
Hadronic-Molecule
↪ Extended object made of Baryon and Meson

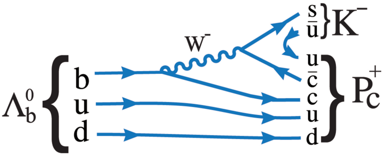
- $\Lambda(1405)$
  ↪ $\bar{K}N$ predicted by Dalitz and Tuan, 1959 PRL2,425
  ↪ $\Lambda(1405) \to \Sigma\pi$ observed by Alston et al., PRL6,698
- "$\theta(1540)$"
  predicted by Diakonov et al., 1997 ($Z(1530)^+$) ZPA359, 305
  ↪ NOT supported by many high statistics experiments
- N^* and Λ^* with hidden charm Wu et al., PRL 105, 232001 (2011)
  ↪ and many more works...

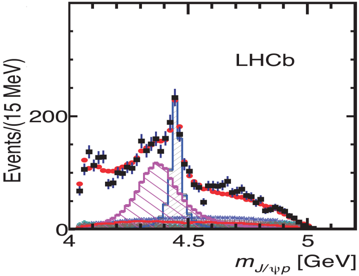
Charmonium-pentaquark states (I)

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

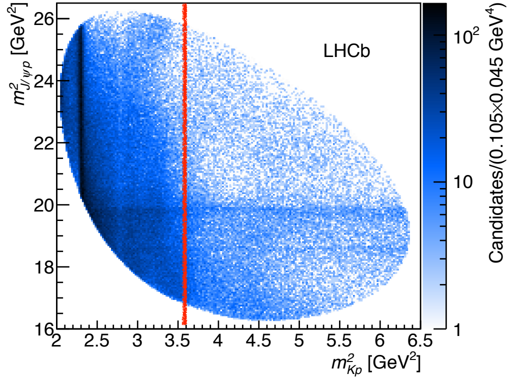
$P_c(4450)^+$: $M = 4449.8 \pm 1.7 \pm 2.5$ MeV

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

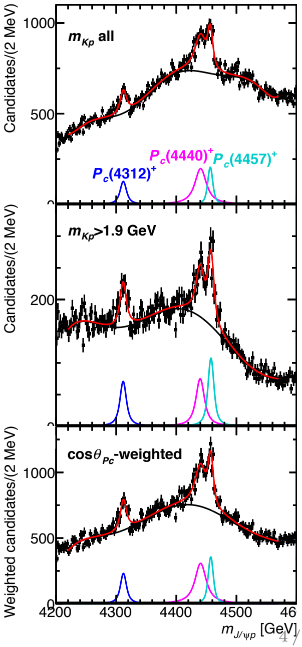
Preferred Parity: Opposite

Charmonium-pentaquark states (II)

LHCb, PRL 122, 222001 (2019)



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



Charmonium-pentaquark (theoretical)

- Compact pentaquark — Cheng et al., PRD100(2019)054002

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

- Compact diquark model — Ali et al., JHEP1910(2019)256

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

- P_cs as double triangle cusps — Nakamura, PRD103(2020)L111503
- $P_c(4312)$: virtual state — Fernández-Ramírez et al., PRL123(2019)092001
- K-matrix: $J/\psi p - \Sigma_c \bar{D} - \Sigma_c \bar{D}^*$ — Kuang et al., EPJC80(2020)433

  $\hookrightarrow$ P_cs have same J^P. $P_c(4312)$: $\Sigma_c \bar{D}$, $P_c(4457)$: ? cusp effect
- Molecule (HQSS) — Liu et al., PRL122,242001 (2019)

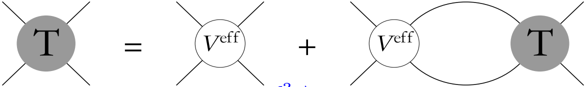
	Molecule	J^P	M (MeV)		Molecule	J^P	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	4311.8 − 4313.0	B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	4306.3 − 4307.7
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	4376.1 − 4377.0	B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	4370.5 − 4371.7
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	4440.3*	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

and many more works...

- quantum numbers? line shape? the existence of $P_c(4380)$?

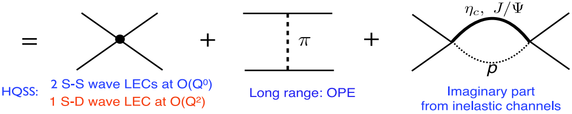
EFT approach at low energies: $\Sigma_c^{(*)}\bar{D}^{(*)}$ $(\Lambda_c \bar{D}^{(*)})$

Lippmann-Schwinger Equation:



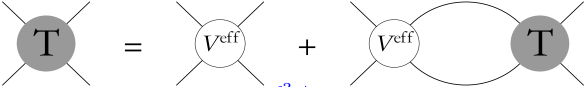
$$T^J_{\alpha\gamma}(E,p,p') = V^J_{\alpha\gamma}(E,p,p') - \sum_\beta \int \frac{d^3\vec{q}}{(2\pi)^3} V^J_{\alpha\beta}(E,p,q) G_\beta(E,q) T^J_{\beta\gamma}(E,q,p')$$

☞ $V^{\rm eff}_{\rm LO}$ =



EFT approach at low energies: $\Sigma_c^{(*)}\bar{D}^{(*)}$ $(\Lambda_c\bar{D}^{(*)})$

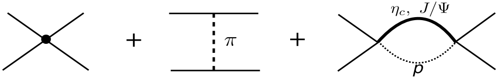
Lippmann-Schwinger Equation:



$$T^J_{\alpha\gamma}(E,p,p') = V^J_{\alpha\gamma}(E,p,p') - \sum_\beta \int \frac{d^3\vec{q}}{(2\pi)^3} V^J_{\alpha\beta}(E,p,q) G_\beta(E,q) T^J_{\beta\gamma}(E,q,p')$$

☞

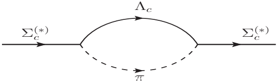
$V^{\rm eff}_{\rm LO}$ =



☞ Green function: $\Gamma(\Sigma_c^* \to \Lambda_c\pi) = 15.0$ MeV $\sim \Gamma(P_c)$

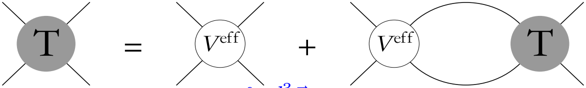
$$G_\beta(E,\mathbf{q}) = \frac{m_{\Sigma_c^{(*)}} m_{D^{(*)}}}{E_{\Sigma_c^{(*)}}(\mathbf{q}) E_{D^{(*)}}(\mathbf{q})} \frac{1}{E_{\Sigma_c^{(*)}}(\mathbf{q}) + E_{D^{(*)}}(\mathbf{q}) - E - \frac{\tilde{\Sigma}_R^{(*)}(s)}{2E_{\Sigma_c^{(*)}}(\mathbf{q})}},$$

$\hookrightarrow$ The self-energy: $\tilde{\Sigma}_R^{(*)}(s) \sim ig^2 \frac{p^3}{\sqrt{s}}$



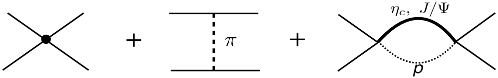
EFT approach at low energies: $\Sigma_c^{(*)}\bar{D}^{(*)}$ $(\Lambda_c\bar{D}^{(*)})$

Lippmann-Schwinger Equation:



$$T^J_{\alpha\gamma}(E,p,p') = V^J_{\alpha\gamma}(E,p,p') - \sum_\beta \int \frac{d^3\vec{q}}{(2\pi)^3} V^J_{\alpha\beta}(E,p,q) G_\beta(E,q) T^J_{\beta\gamma}(E,q,p')$$

☞ $V^{\rm eff}_{\rm LO}$ =



HQSS: 2 S-S wave LECs at O(Q⁰)
1 S-D wave LEC at O(Q²)

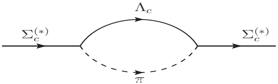
Long range: OPE

Imaginary part
from inelastic channels

☞ Green function: $\Gamma(\Sigma_c^* \to \Lambda_c\pi) = 15.0$ MeV $\sim \Gamma(P_c)$

$$G_\beta(E,\mathbf{q}) = \frac{m_{\Sigma_c^{(*)}} m_{D^{(*)}}}{E_{\Sigma_c^{(*)}}(\mathbf{q}) E_{D^{(*)}}(\mathbf{q})} \frac{1}{E_{\Sigma_c^{(*)}}(\mathbf{q}) + E_{D^{(*)}}(\mathbf{q}) - E - \frac{\tilde{\Sigma}_R^{(*)}(s)}{2E_{\Sigma_c^{(*)}}(\mathbf{q})}},$$

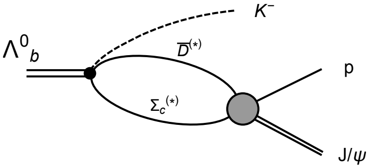
↪ The self-energy: $\tilde{\Sigma}_R^{(*)}(s) \sim ig^2 \frac{p^3}{\sqrt{s}}$



↪ Nonrelativistic limit:

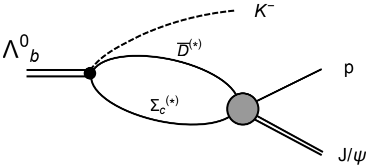
$$G_\beta(E,\mathbf{q}) = \frac{1}{\frac{\mathbf{q}^2}{2\mu} + m_{D^{(*)}} + m_{\Sigma_c^{(*)}} - E}.$$

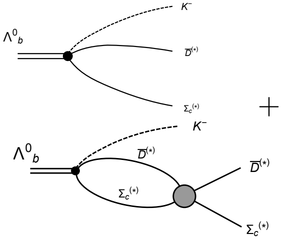
$\Lambda_b^0 \to K^- J/\psi p$



☞ $m_{J/\psi p} \sim 4440$ MeV
$\hookrightarrow$ $|\mathbf{p}| \sim 810$ MeV
$\hookrightarrow$ $J/\psi p(S)$, $J/\psi p(D)$

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

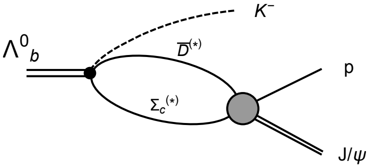


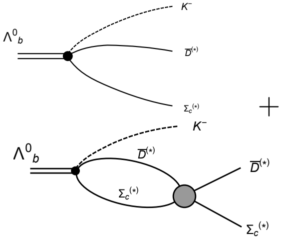


☞ $m_{J/\psi p} \sim 4440$ MeV
$\hookrightarrow$ $|\mathbf{p}| \sim 810$ MeV
$\hookrightarrow$ $J/\psi p(S)$, $J/\psi p(D)$

☞ Weak production:
$\hookrightarrow$ S-wave $\Sigma_c^{(*)}\bar{D}^{(*)}$
$\hookrightarrow$ 7 parameters: P_α^J

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





☞ $m_{J/\psi p} \sim 4440$ MeV
↪ $|\mathbf{p}| \sim 810$ MeV
↪ $J/\psi p(S)$, $J/\psi p(D)$

☞ Weak production:
↪ S-wave $\Sigma_c^{(*)}\bar{D}^{(*)}$
↪ 7 parameters: P_α^J

☞

$$\text{channels} \quad \begin{cases} \underline{\Sigma_c^{(*)}\bar{D}^{(*)}(S/D)}, \Lambda_c\bar{D}^{(*)}(S/D) & \to \ \alpha, \beta, \gamma \\ J/\psi p(S/D), \eta_c p(S/D) & \to \ i, j, k \end{cases}$$

☞

$$U_\alpha^J(E,p) \ = \ P_\alpha^J(E,p) - \sum_\beta \int \frac{d\mathbf{q}^3}{(2\pi)^3} V_{\alpha\beta}^J(E,p,q) G_\beta(E,q) U_\beta^J(q),$$

$$U_i^J(E,p) \ = \ \sum_\beta \int \frac{d\mathbf{q}^3}{(2\pi)^3} \mathcal{V}_{\beta i} G_\beta(E,q) U_\beta^J(q).$$

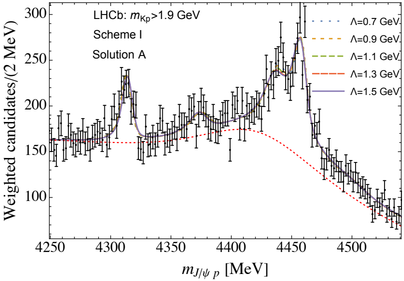
Fit Schemes

☞ Fit schemes:

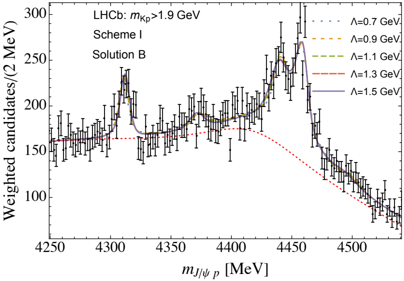
- Scheme I: pure contact potential w/o $\Lambda_c\bar{D}^{(*)}$
- Scheme II: Scheme I + OPE + S-D counter term w/o $\Lambda_c\bar{D}^{(*)}$
  $\hookrightarrow$ coupled channel
- Scheme III: contact + OPE + S-D counter terms w/ $\Lambda_c\bar{D}^{(*)}$

Scheme I: pure contact potential w/o $\Lambda_c\bar{D}^{(*)}$

Solution A



Solution B



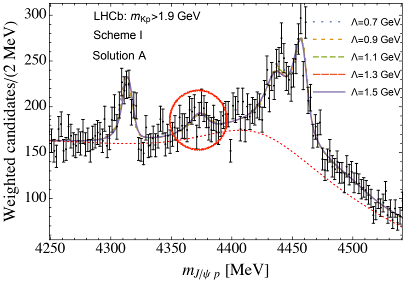
- $\Lambda > \Lambda_{\rm soft} \sim \sqrt{2\mu\delta} \sim 0.7$ GeV
- Cutoff-independent for both solution A and B

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

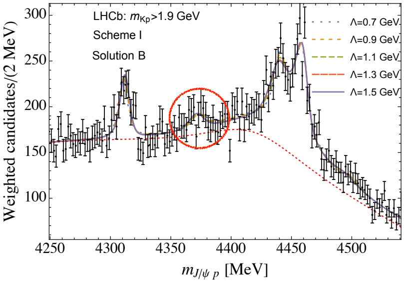
- No need for $\Lambda_c\bar{D}^{(*)}$

Scheme I: pure contact potential w/o $\Lambda_c\bar{D}^{(*)}$

Solution A



Solution B



☞ $\Lambda_{\text{soft}} \sim \sqrt{2\mu\delta} \sim 0.7$ GeV

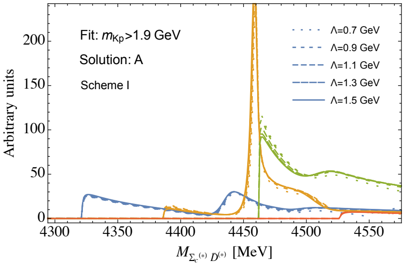
☞ Cutoff-independent for both solution A and B

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

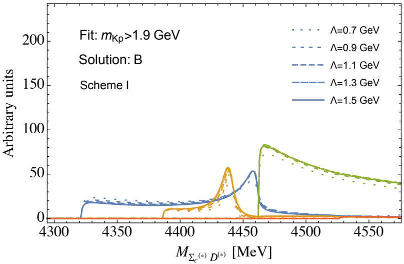
☞ No need for $\Lambda_c\bar{D}^{(*)}$

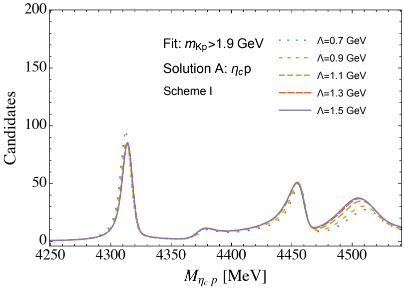
Scheme I: pure contact potential w/o $\Lambda_c \bar{D}^{(*)}$

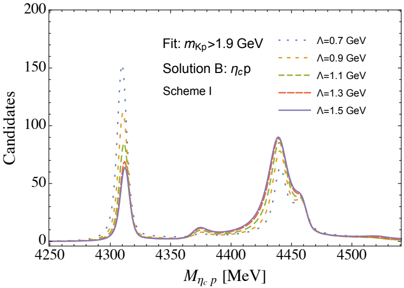
Solution A



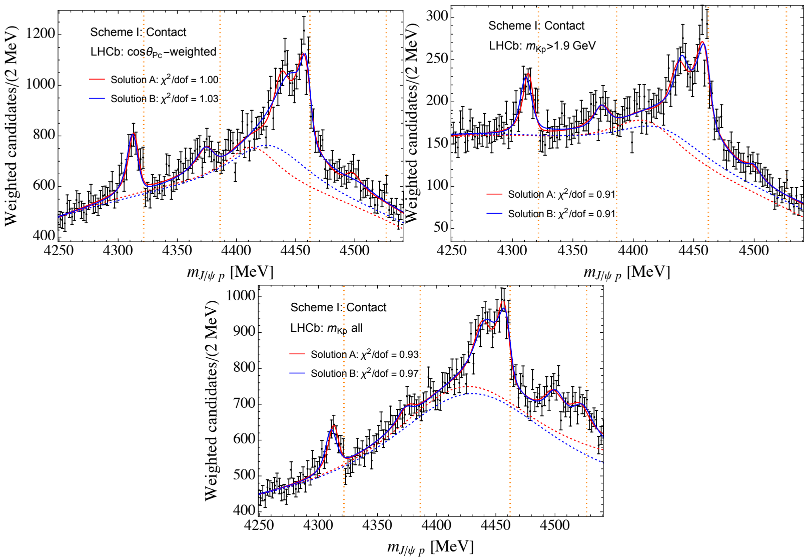
Solution B







Scheme I: Contact fits to three sets of LHCb data



Scheme I: pole positions

		Solution A		Solution B	
	DC ([MeV])	J^P	Pole [MeV]	J^P	Pole [MeV]
$P_c(4312)$	$\Sigma_c \bar{D}$ (4321.6)	$\frac{1}{2}^-$	$4314(1) - 4(1)i$	$\frac{1}{2}^-$	$4312(2) - 4(2)i$
$\mathbf{P_c(4380)}^*$	$\Sigma_c^* \bar{D}$ (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)	$\frac{5}{2}^-$	$4525(2) - 9(3)i$	$\frac{5}{2}^-$	$4501(3) - 6(4)i$

☞ * NOT the broad $P_c(4380)$ reported by LHCb in 2015

☞ Bound states with respect to the dominant channel (DC)

☞ $\Sigma_c^* \bar{D}^*$ states are not seen yet, production rate suppressed?

↪ prompt production in the pp collision in the LHC

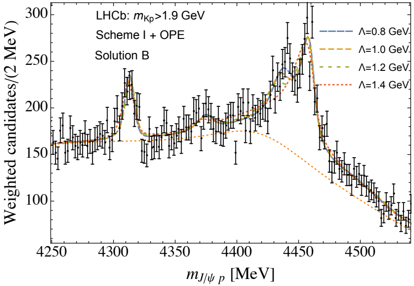
P. Ling, X.-H. Dai, MLD and Q. Wang, arXiv:2104.11133

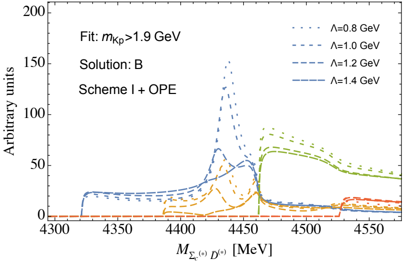
Scheme I + OPE w/o $\Lambda_c\bar{D}^{(*)}$

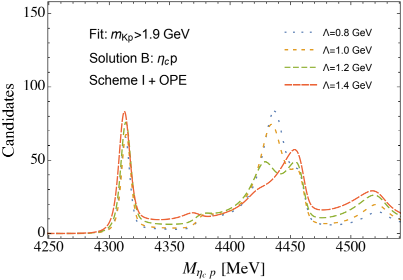
☞ No solution A

☞ Solution B:
Cut-off dependent

☞ $\Lambda_{\rm soft} \sim 700$ MeV

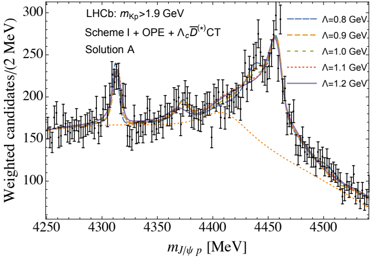


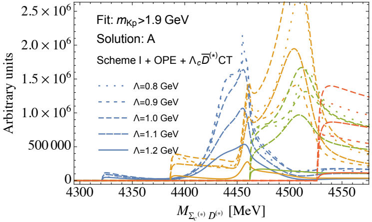




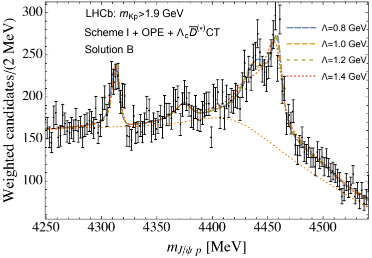
Scheme I + OPE + CT for $\Lambda_c \bar{D}^{(*)}$

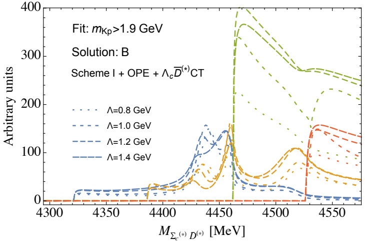
Solution A





Solution B

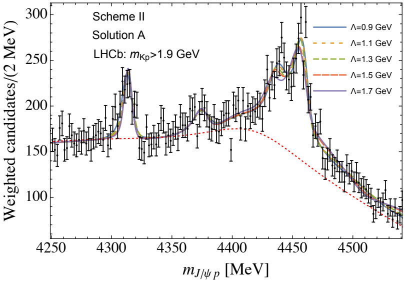




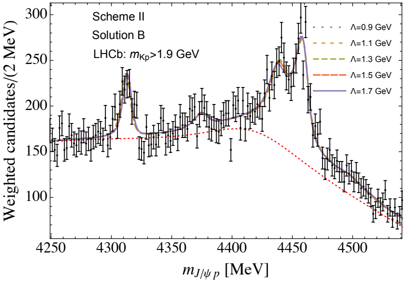
- Cut-off dependent
- $\Lambda_{soft} \sim 900$ MeV $\Lambda_c \bar{D}^{(*)}$

Scheme II: contact + OPE + S-D w/o $\Lambda_c \bar{D}^{(*)}$

Solution A



Solution B

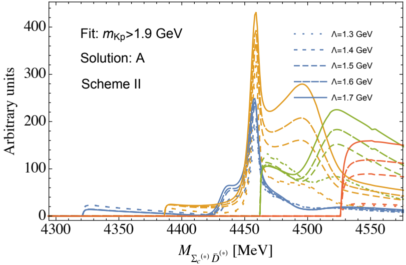


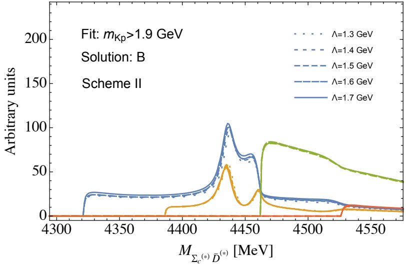
☞ $\Lambda_{\text{soft}} \sim 0.7$ GeV

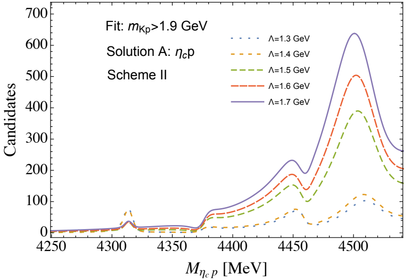
☞ Cutoff-independent only for solution B

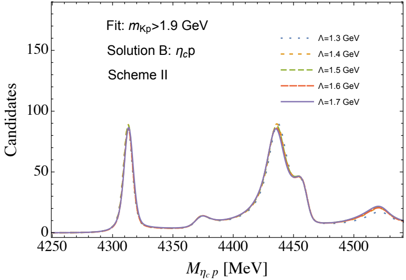
Scheme II: contact + OPE + S-D w/o $\Lambda_c \bar{D}^{(*)}$

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





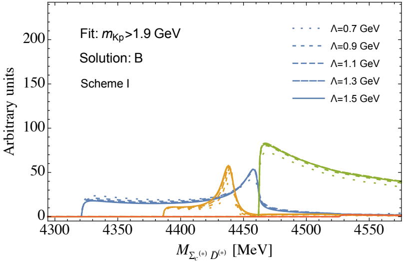




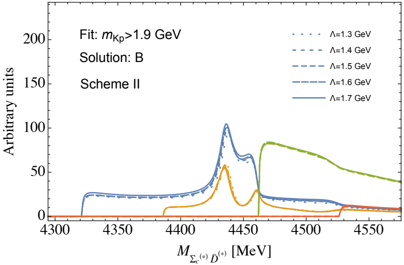
Scheme I vs Scheme II w/o $\Lambda_c \bar{D}^{(*)}$ $\Lambda_{\rm soft} \sim 0.7$ GeV

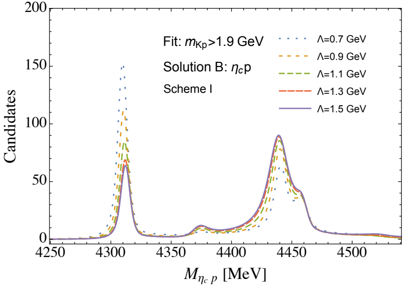
Solution B

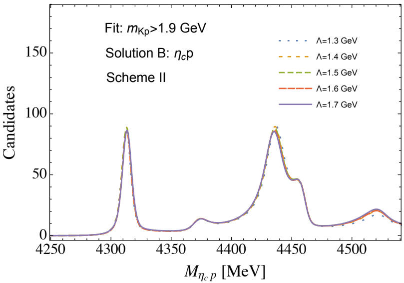
Scheme I: pure contact



Scheme II: contact + OPE + SD

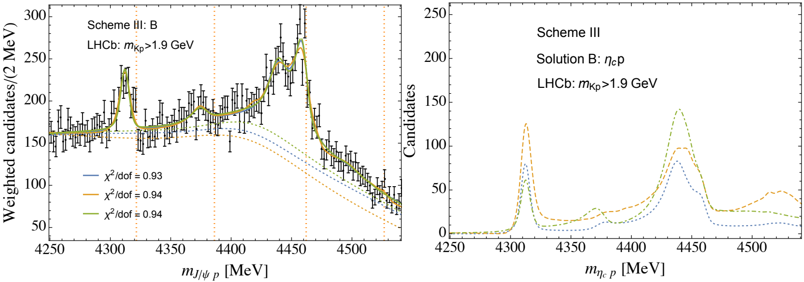






Scheme III: CT + OPE + SD w/ $\Lambda_c\bar{D}^{(*)}$ $\Lambda_{\rm soft} \sim 0.9$ GeV

Solution B

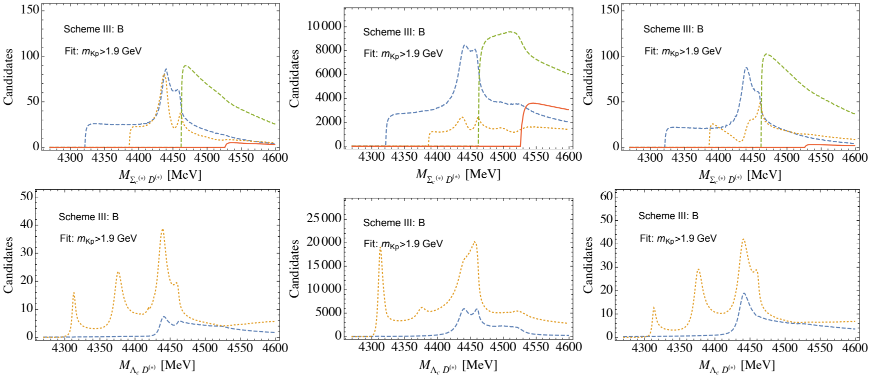


☞ $\Lambda = 1.3$ GeV.

☞ Overdetermined.

Scheme III: CT + OPE + SD w/ $\Lambda_c\bar{D}^{(*)}$ $\Lambda_{\rm soft} \sim 0.9$ GeV

Solution B



☞ $J/\psi p$ data alone are not enough to constrain $\Lambda_c\bar{D}^{(*)}$ interactions.

Summary & Outlook

☞ Solving Lippmann-Schwinger equation with respect to

- Unitarity, three-body cut
  ↪ width of $\Sigma_c^{(*)}$
- Coupled-channels
  ↪ cut-off independence: OPE → SD counter term
- Heavy quark spin symmetry
  ↪ 7 $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states

☞ Preferred spin assignment (Solution B)

$$\begin{array}{lcll} P_c(4312) & : & 1/2^-, & (\bar{D}\Sigma_c) \\ P_c(4440) & : & 3/2^-, & (\bar{D}^*\Sigma_c) \\ P_c(4457) & : & 1/2^-, & (\bar{D}^*\Sigma_c) \end{array}$$

☞ We can not say much about $\Lambda_c\bar{D}^{(*)}$ interaction without data in this channel.

☞ A narrow $P_c(4380)$, different from the broad one reported by LHCb in 2015.

Thank you very much for your attention!