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Nature of the LHCb pentaquarks from an analysis of the J/ψ p spectrum

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in collaboration with

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PRL 14, 072001 (2020) and arXiv: 2102.07159 (2021)

P_c's from $\Lambda_b \to K\, J/\psi\, p$

<u>LHCb Run-1 2015:</u> one broad $P_c(4380)$ and one narrow $P_c(4450)$ state

LHCb, PRL 115 072001 (2015), PRL 117 082002 (2016)

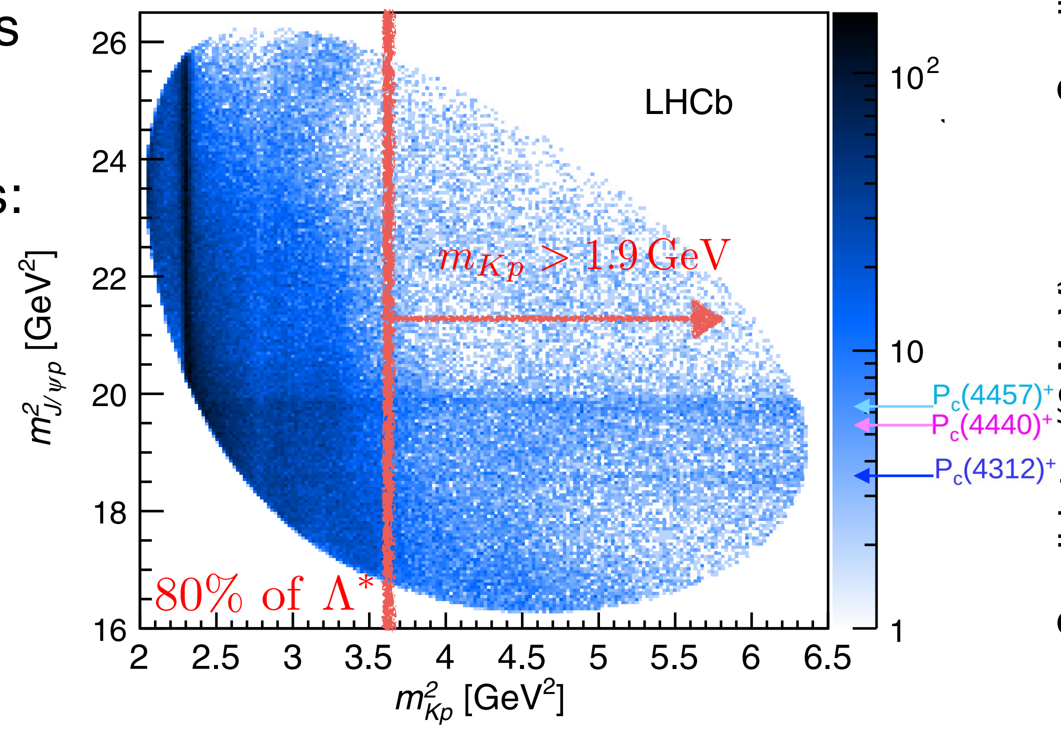
P_c's decay strongly into $J/\psi\, p$ → quark content $c\bar{c}\,uud$

<u>LHCb Run-2 2019:</u> LHCb, PRL 122 222001 (2019)

— order of magnitude larger statistics

— samples with kinematic constraints:

$\Longrightarrow$ suppress $\Lambda^* \to Kp$

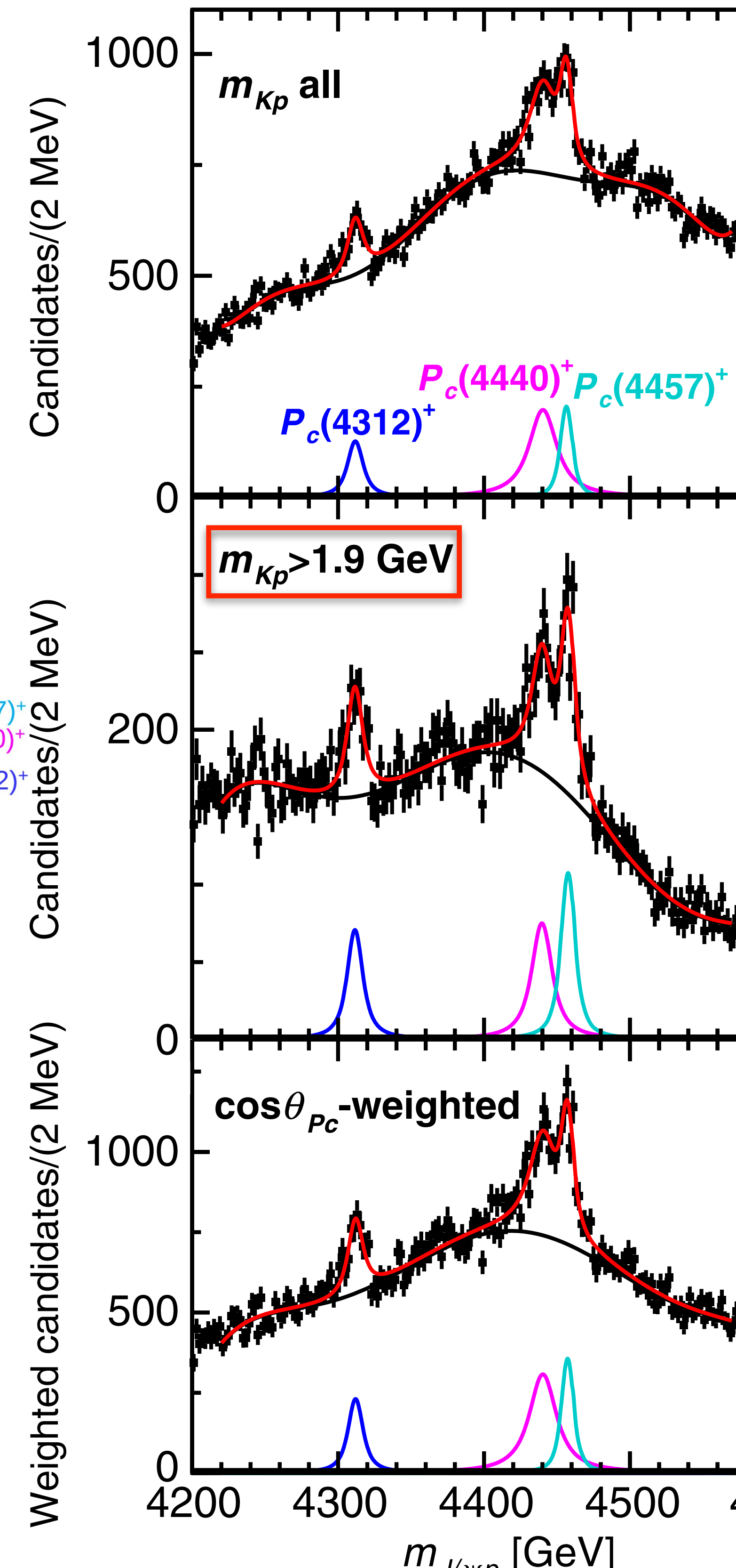


— New Pc(4312) state

— Pc(4450) split into two states

— Significance of a broad state dropped

State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(<20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$



Pentaquarks as hadronic molecules

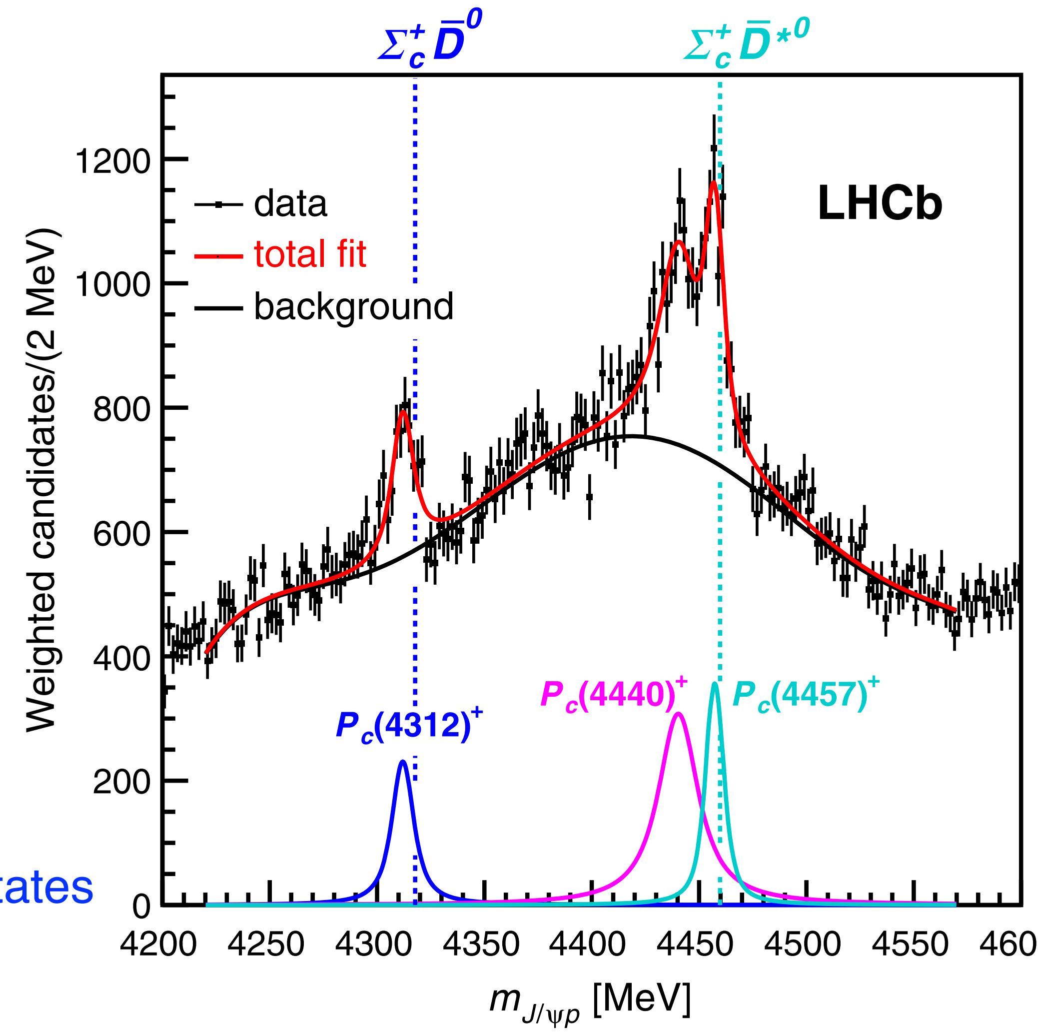
Disclaimer: I will not talk about P_c's as compact states, hadrocharmonia, triangle mechanisms…

Brambilla et al *Phys.Rept.* 873 (2020) 1

— All P_c's reside near S-wave hadronic thresholds:

$P_c(4312)$ — near $\Sigma_c D$, $P_c(4440)$ and $P_c(4457)$ — near $\Sigma_c D^*$

$\Longrightarrow$ Hint for a molecular scenario



LHCb, PRL 122 222001 (2019)

$\Longrightarrow$ Implications of QCD symmetries:

—chiral symmetry: one- and multi-pion exchanges

—heavy-quark spin symmetry (HQSS): there must be seven $\Sigma_c^{(*)}\bar{D}^{(*)}$ states

$$\mathcal{L}_{\rm LO} = -C_a\, \boldsymbol{S}_{ab}^\dagger \cdot \boldsymbol{S}_{ba} \langle \bar{H}_c^\dagger \bar{H}_c\rangle - C_b\, i\epsilon_{jik} S_{ab}^{j\dagger} S_{ba}^k \langle \bar{H}_c^\dagger \sigma^i \bar{H}_c\rangle$$

central — spin-spin

$\Longrightarrow$ First predictions for spin partners using masses of $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ as input and neglecting coupled-channels

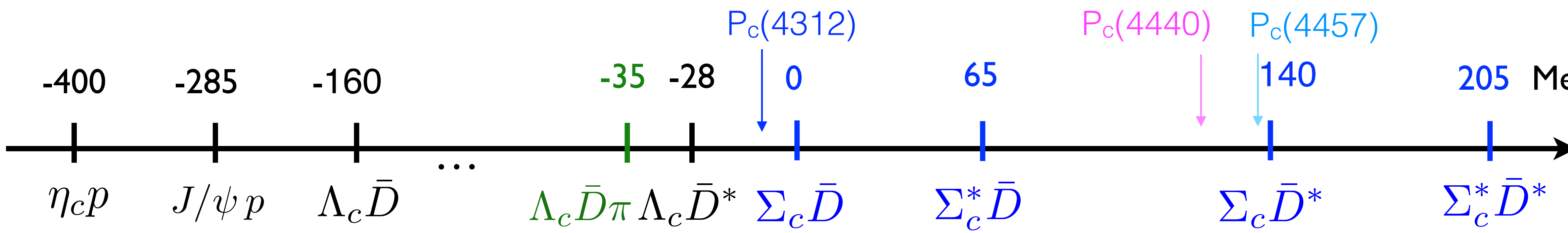
Liu et al, PRL 122 242001 (2019)

related works: Xiao et al. PRD 100 014021 (2019), Sakai et al. PRD 100 074007 (2019), …

This Talk is about

our works: PRL 14, 072001 (2020) and arXiv: 2102.07159 (2021)

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



☛ Fixing LECs from data and not from Breit-Wigner masses, as done before

$\Longrightarrow$ extracting poles and residues

☛ Parameter-free testable predictions for HQSS partners and line shapes in

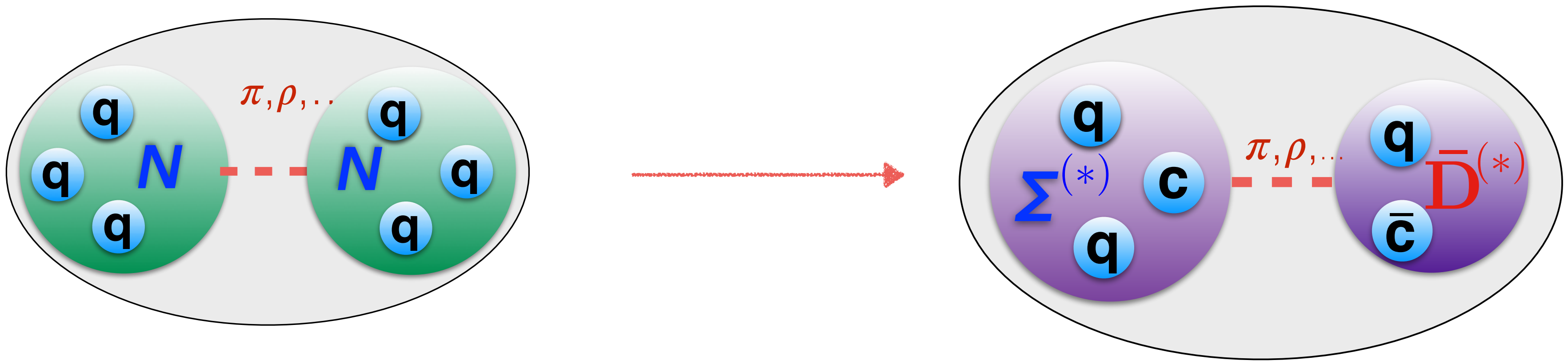
$\Lambda_b \to K\Sigma^{(*)}\bar{D}^{(*)}$ and $\Lambda_b \to K\eta_c p$

first data by LHCb for $\Lambda_b \to K\, \eta_c p$: PRD 102, 112012 (2020)

and for $\Lambda_b \to K\, \Lambda_c D$: Piucchi phd thesis (2019)

☛ The role of one-pion exchange

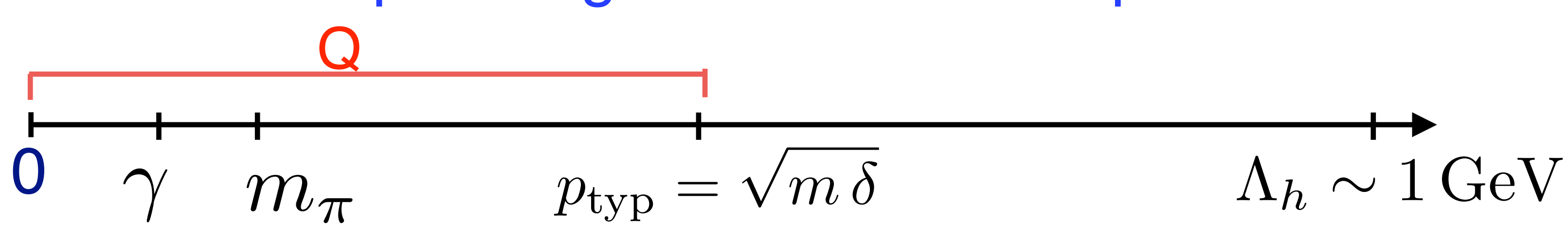
Chiral EFT approach at low energies



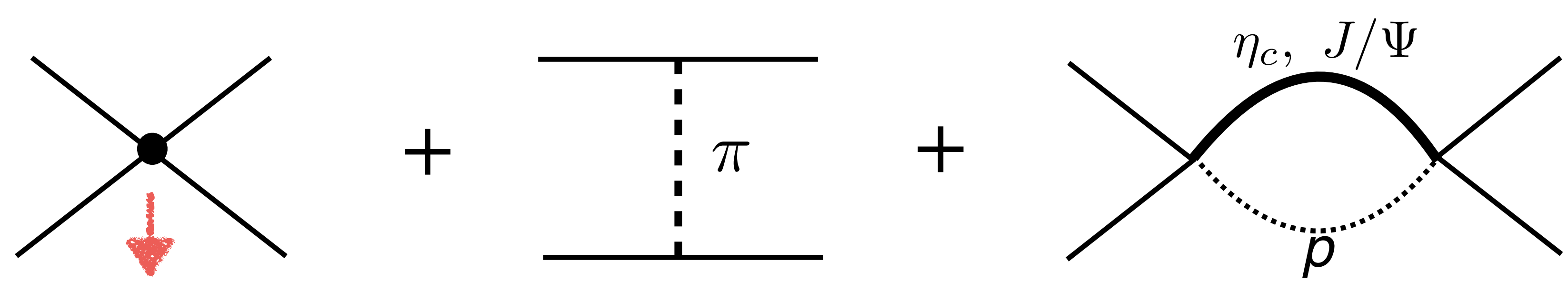
Voloshin, Okun (1976)

- Elastic coupled-channel $\Sigma_c^{(*)}\bar{D}^{(*)}$ potential to a given order in Q/Λ_h

☛ typical soft scale Q is quite large because of coupled-channels



☛ $V_{\rm LO}^{\rm eff}$ =



HQSS: 2 S-S wave LECs at O(Q^0)
1 S-D wave LEC at O(Q^2)

Long range: OPE

Imaginary part
from inelastic channels

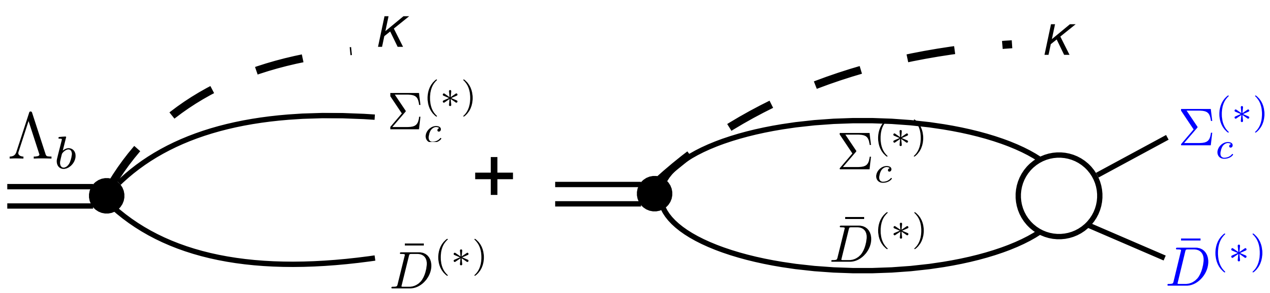
☛ If $\Sigma_c^{(*)}\bar{D}^{(*)} \to \Lambda_c\bar{D}^{(*)}$ are included, one more S-S and one S-D LECs plus OPE

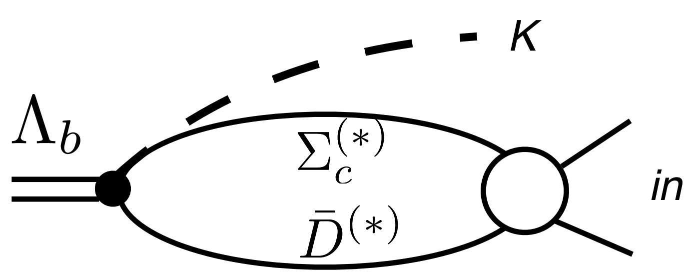
M. Du et al. arXiv: 2102.07159 (2021)

Formalism: production and inelastic channels

— Weak production $\Lambda_b^0 \to K\,\Sigma^{(*)}D^{(*)}$

7 states

$U_{\text{el}} =$ 

$U_{\text{inel}} =$ 

in= $J/\psi\,p$, $\eta_c\,p$, $\Lambda_c\bar{D}^{(*)}$

— No direct inelastic transitions

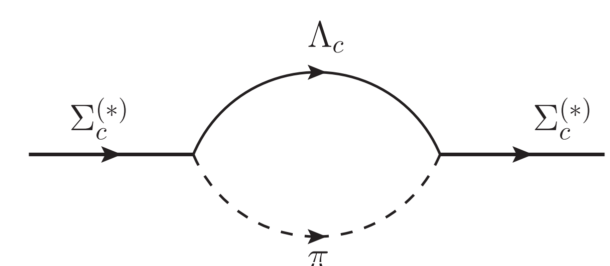
— via couplings to elastic channels

$$T_{\alpha\beta} = V^{\text{eff}}_{\alpha\beta} - \sum_\gamma \int \frac{d^3q}{(2\pi)^3} V^{\text{eff}}_{\alpha\gamma} G_\gamma T_{\gamma\beta}$$

Green function:

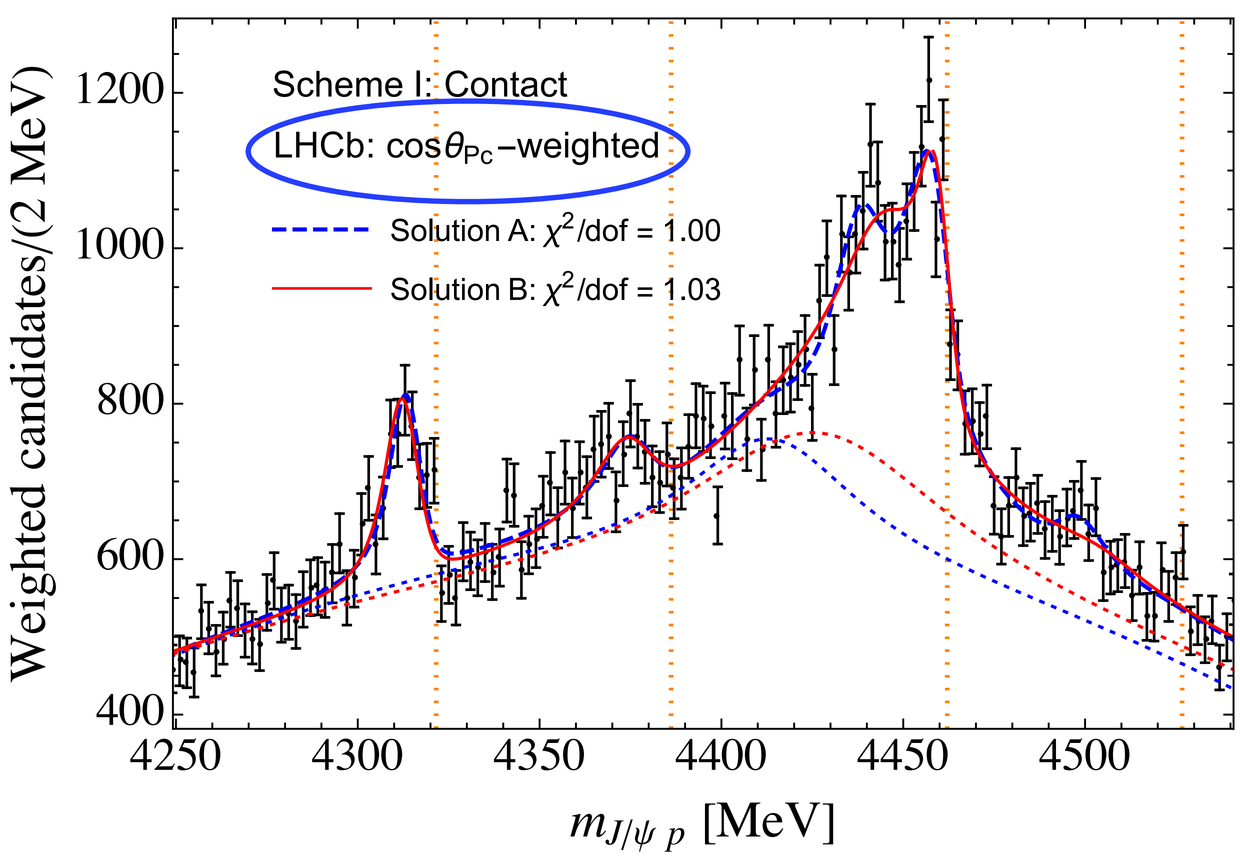
— Dynamical widths of $\Sigma_c^{(*)}$

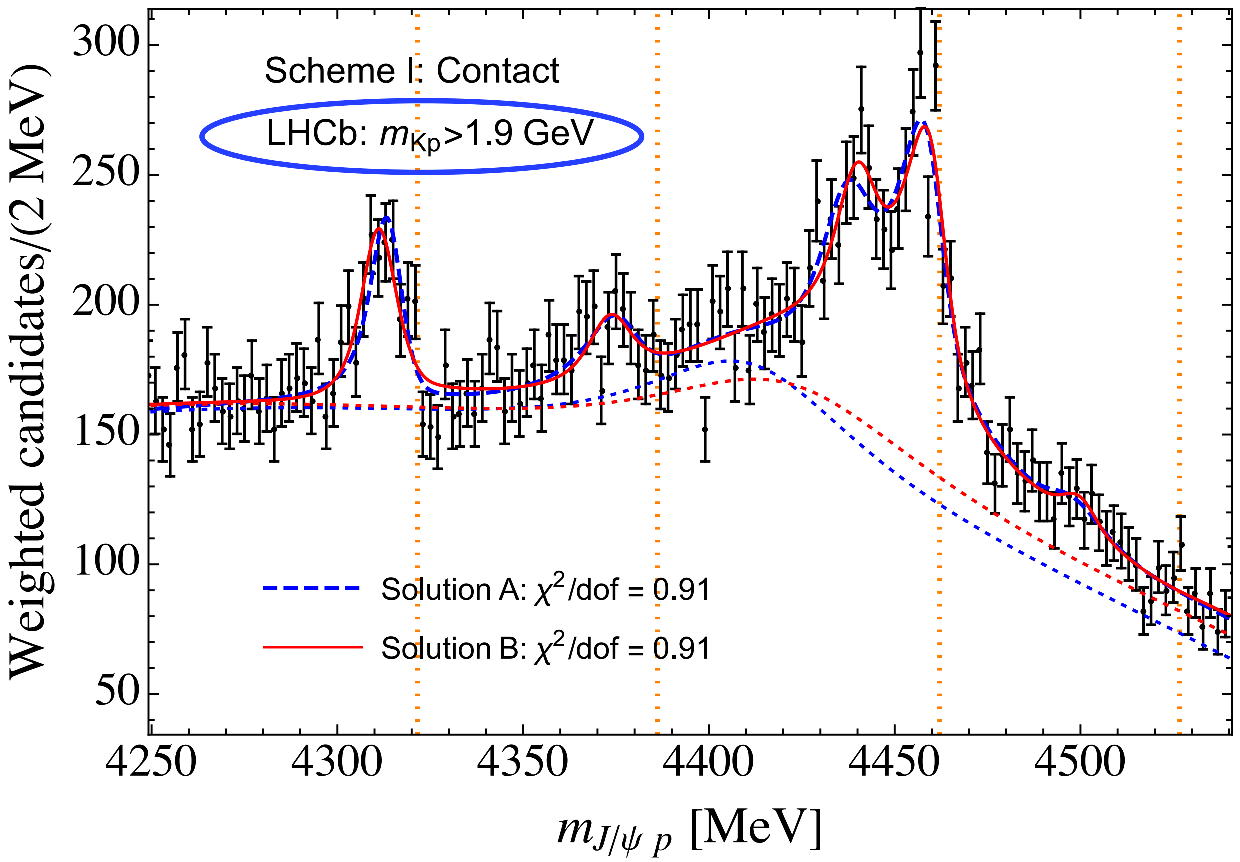
$$G_\beta(E,\boldsymbol{q}) = \frac{m_{\Sigma_c^{(*)}} m_{D^{(*)}}}{E_{\Sigma_c^{(*)}}(\boldsymbol{q}) E_{D^{(*)}}(\boldsymbol{q})} \frac{1}{E_{\Sigma_c^{(*)}}(\boldsymbol{q}) + E_{D^{(*)}}(\boldsymbol{q}) - E - \dfrac{\tilde{\Sigma}_R(s)}{2E_{\Sigma_c^{(*)}}(\boldsymbol{q})}}$$

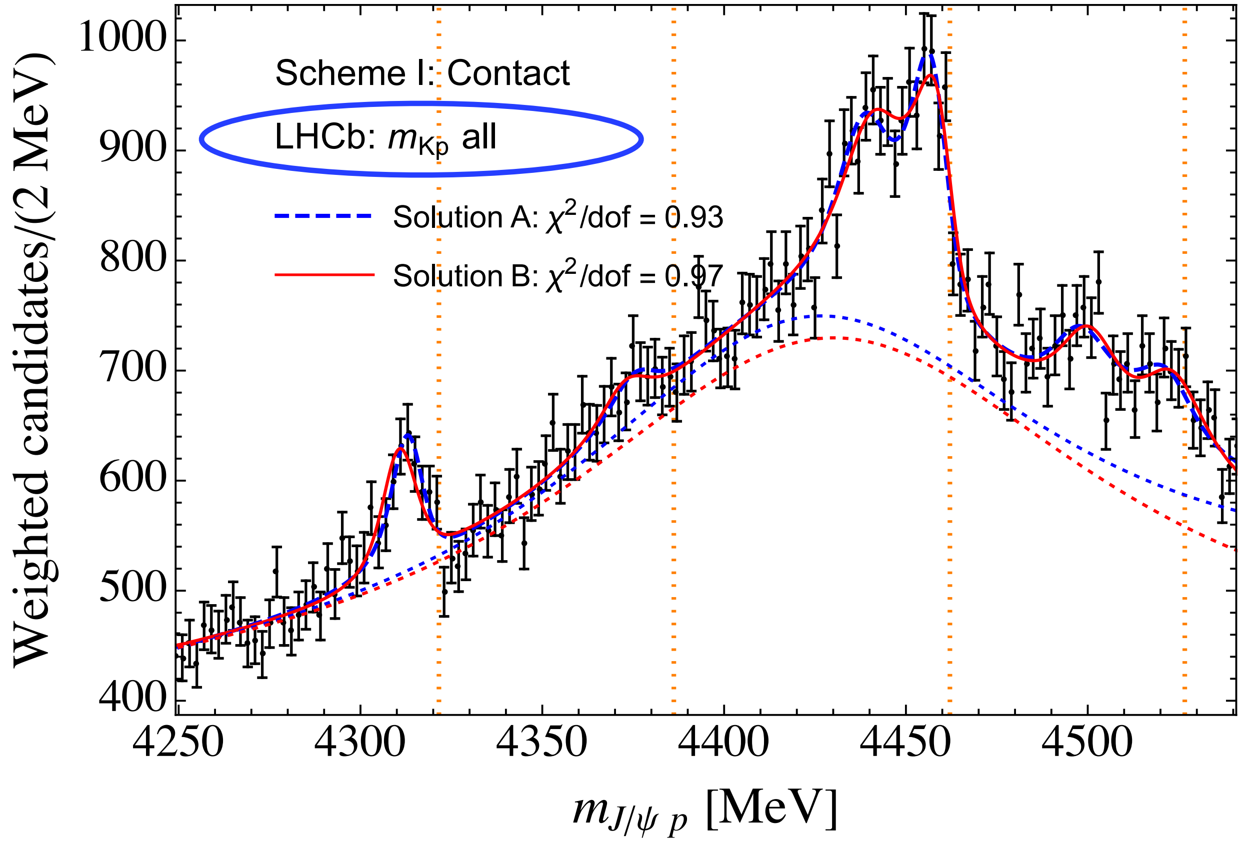


generates $\bar{D}\Lambda_c\pi$ cut

“Contact” Fits to three sets of LHCb data



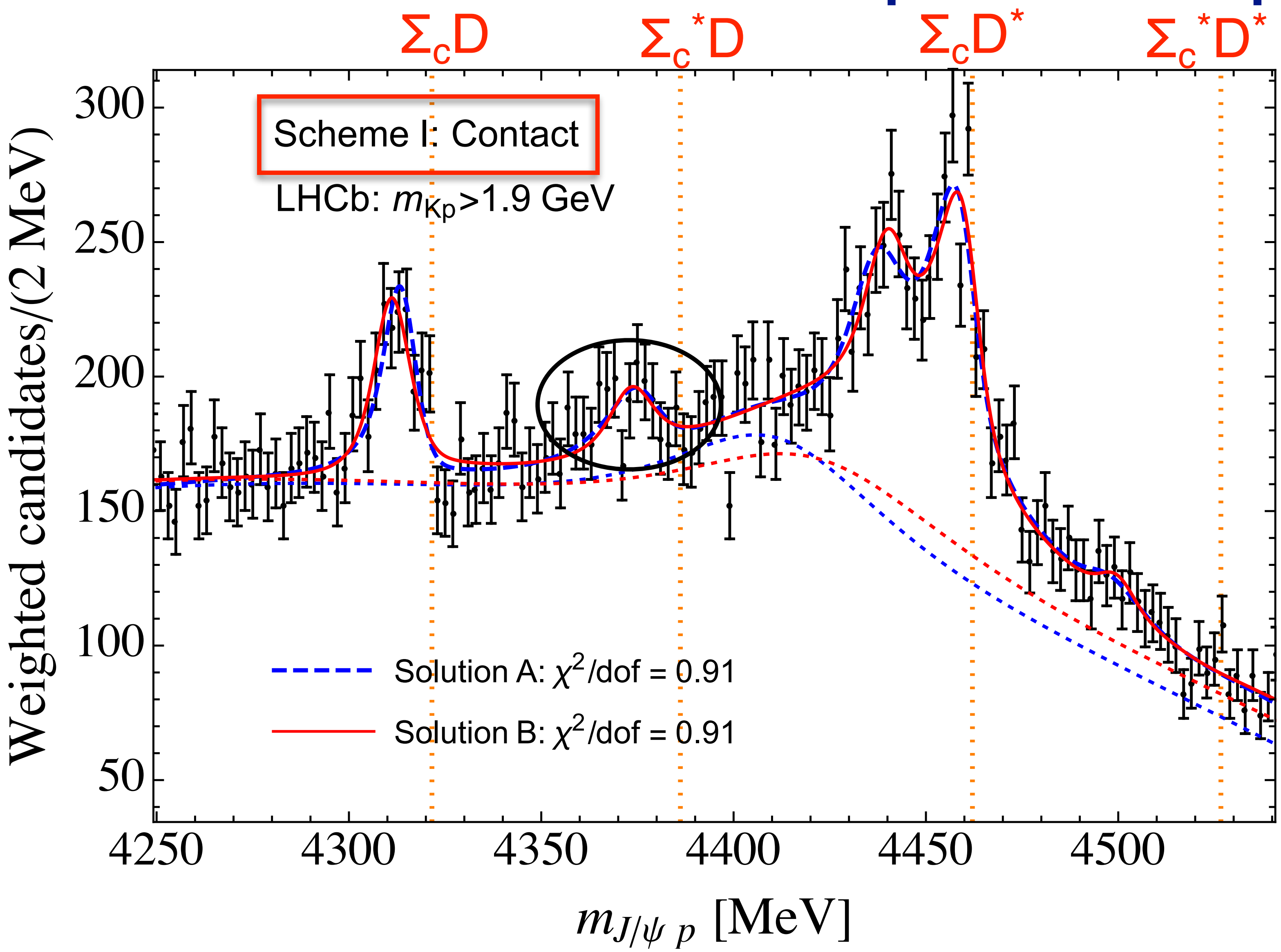




⇒ Consistent values for the Pc’s poles from all fits

Line shape and Pc poles

Du et al. PRL 124, 072001 (2020) and arXiv:2102.07159



- $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ are well understood as $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c D^*$ quasi-bound states, respectively

- Two fits with equal χ^2 yield:

	$P_c(4440)$	$P_c(4457)$
Fit A:	$1/2^-$	$3/2^-$
Fit B:	$3/2^-$	$1/2^-$

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

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

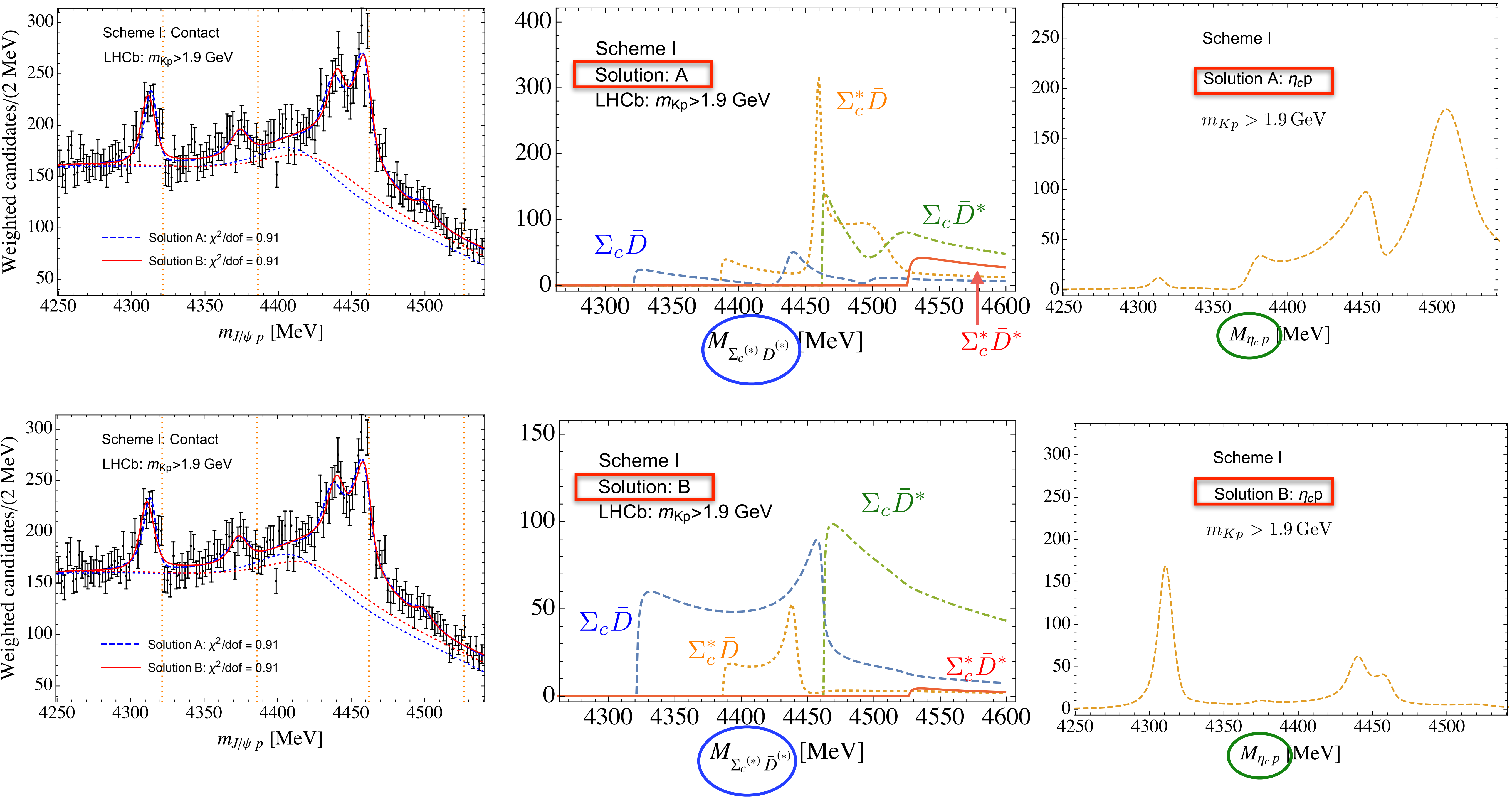
Poles and quantum numbers:

		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)	$\frac{5}{2}^-$	$4525(2)-9(3)i$	$\frac{5}{2}^-$	$4501(3)-6(4)i$

Predictions for $\Lambda_b \to K\Sigma^{(*)}D^{(*)}$ and $\Lambda_b \to K\eta_c p$

scheme I = contact

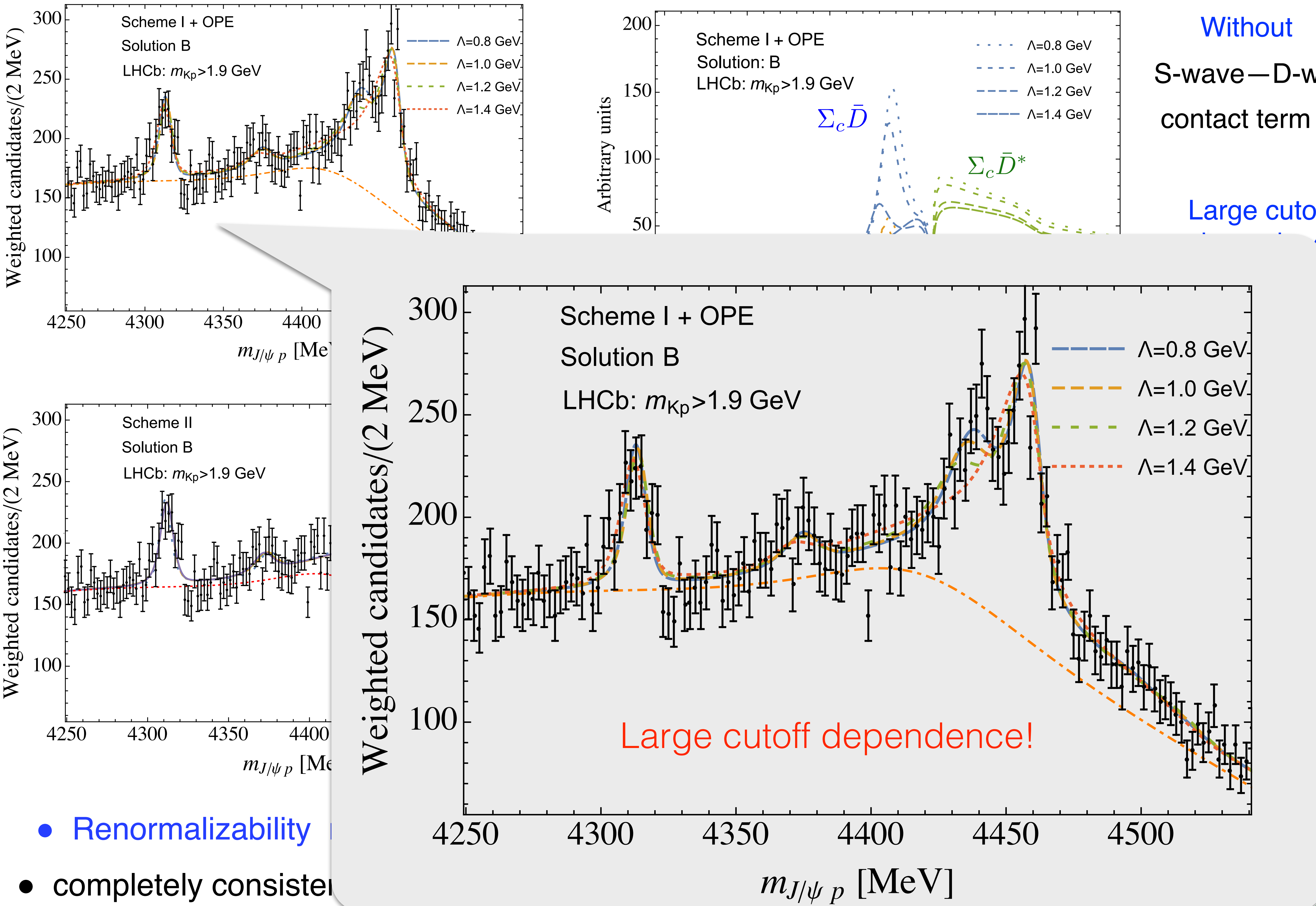
Fitted | Predicted



- Very different predictions for fits A and B

⇒ data in these channels will clearly distinguish between the two fits

But what happens if we include pions?



Without

S-wave—D-wave

contact term

Large cutoff

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dent

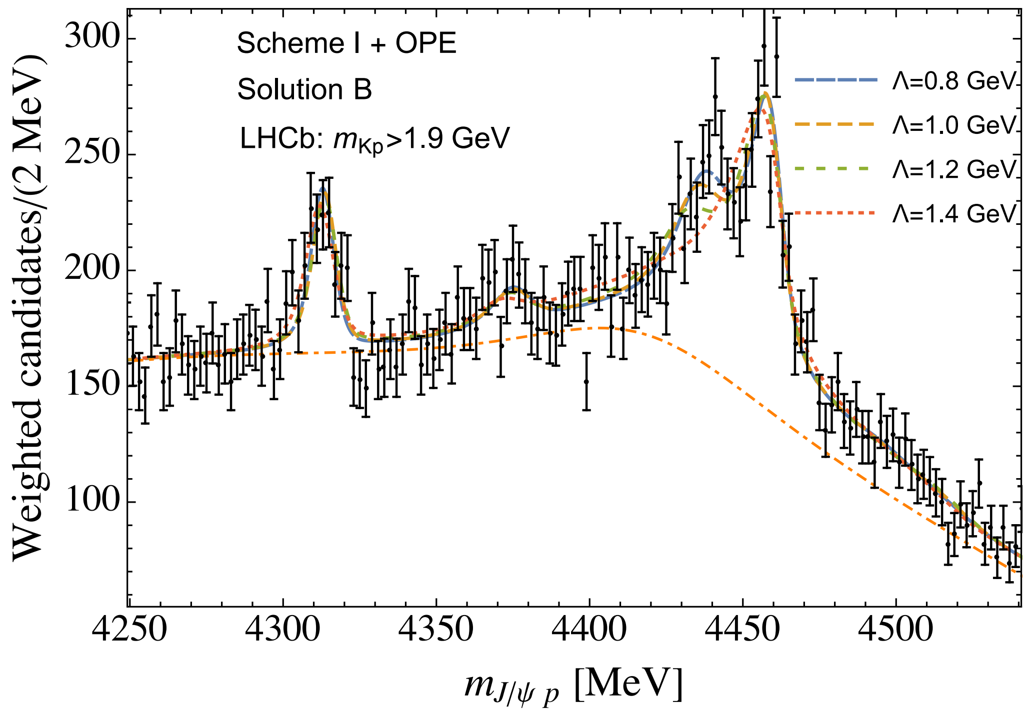
- Renormalizability

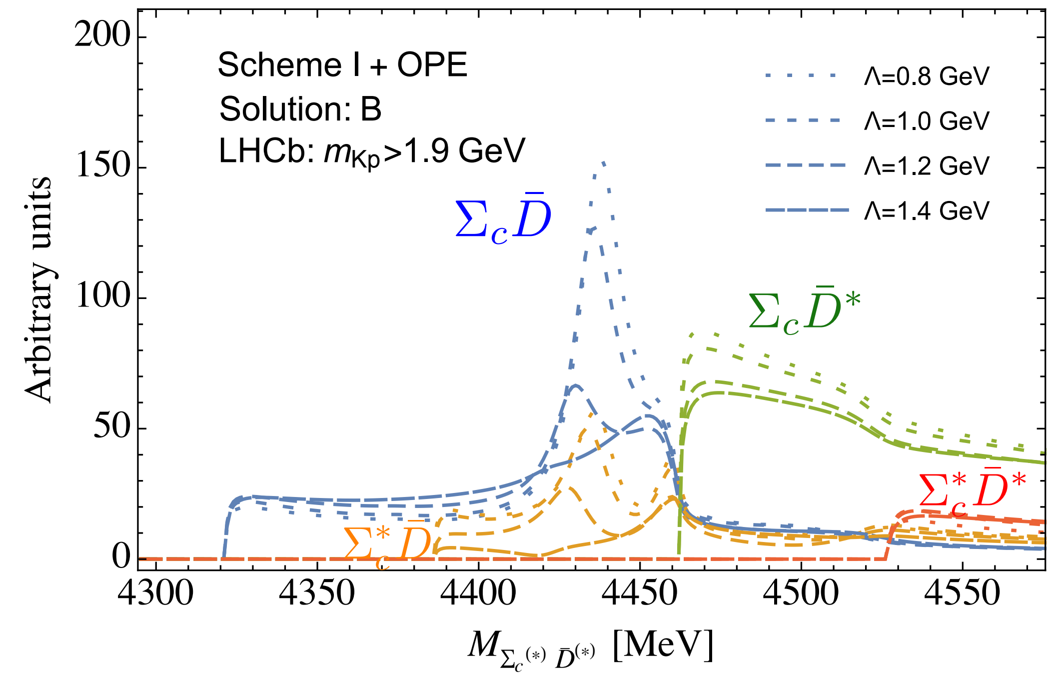
- completely consiste

.018),

PRD 99, 094013 (2019)

But what happens if we include pions?



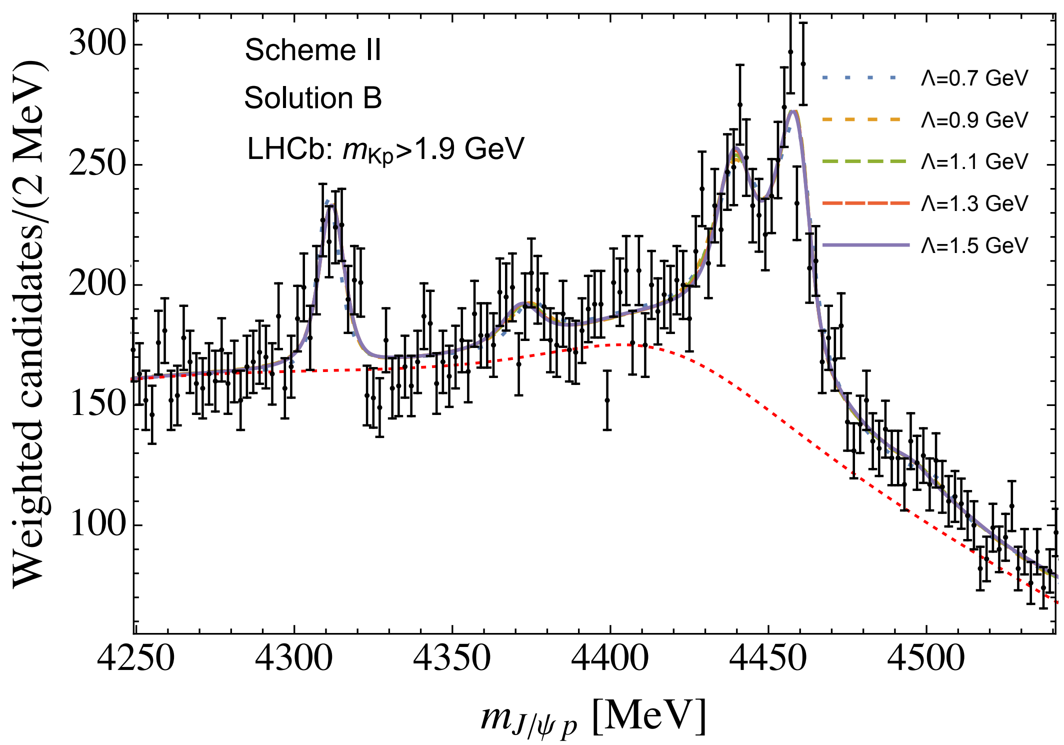


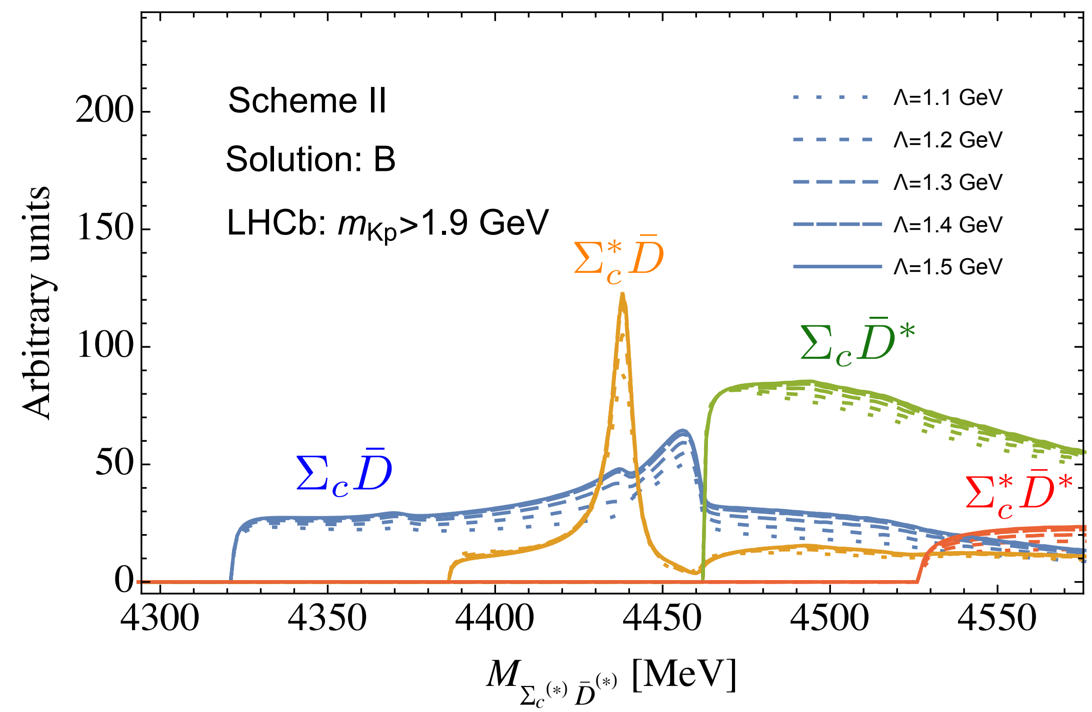
Without

S-wave—D-wave

contact term

Large cutoff dependence!





With S-D

contact term

cutoff independent results!

- Renormalizability require S-wave-to-D-wave contact term to appear together with OPE
- completely consistent with similar analyses of Zb(10610)/Zb(10650)

our works: PRD 98, 074023 (2018), PRD 99, 094013 (2019)

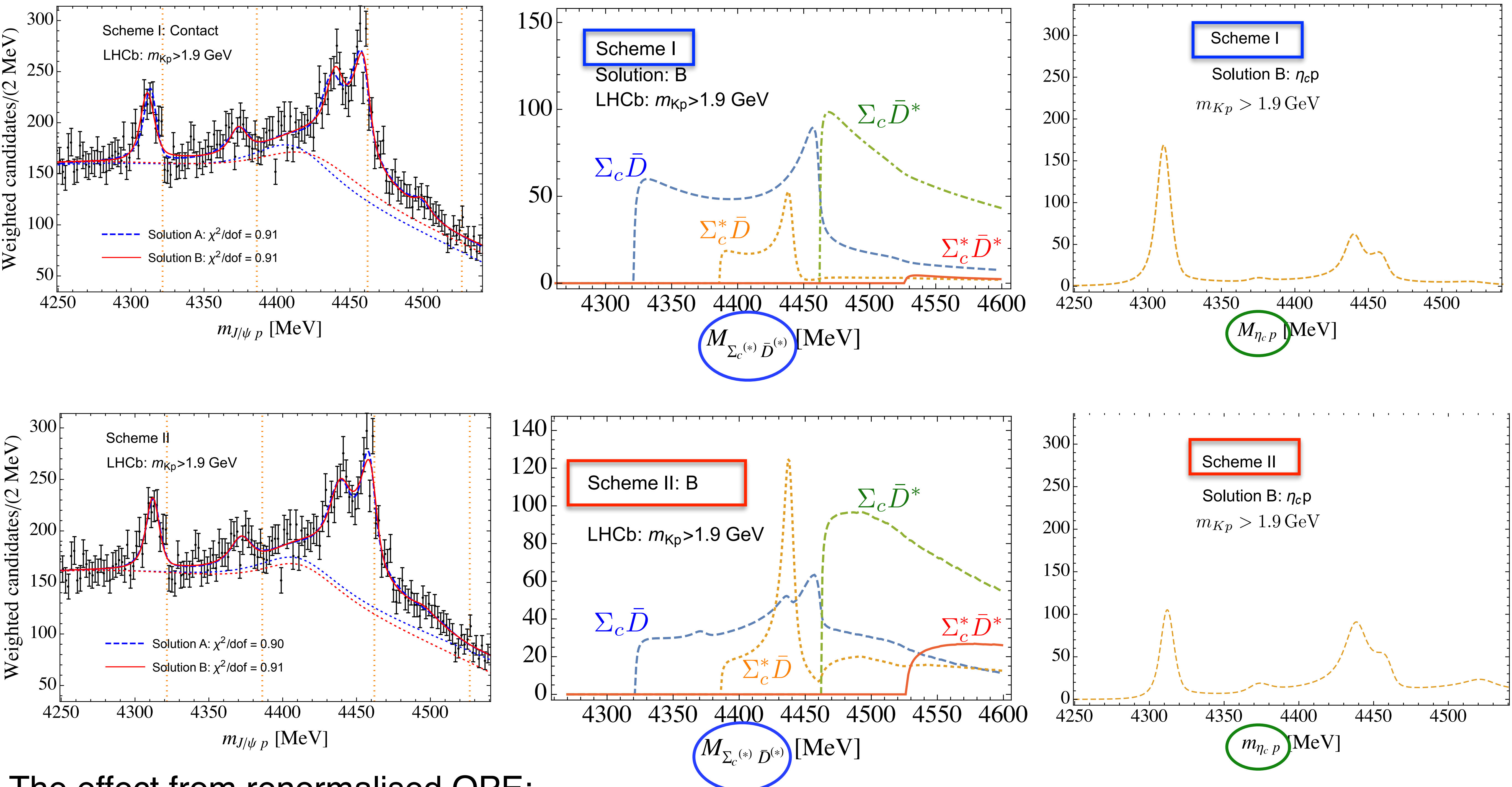
Predictions for $\Lambda_b \to K\Sigma^{(*)}D^{(*)}$ and $\Lambda_b \to K\eta_c p$ with pions

scheme I = contact

scheme II = contact +OPE

Fit B

Fitted | Predicted



The effect from renormalised OPE:

- Qualitatively similar results: the position of peaks is the same
- The inclusion of OPE has a visible impact on the peaks strength

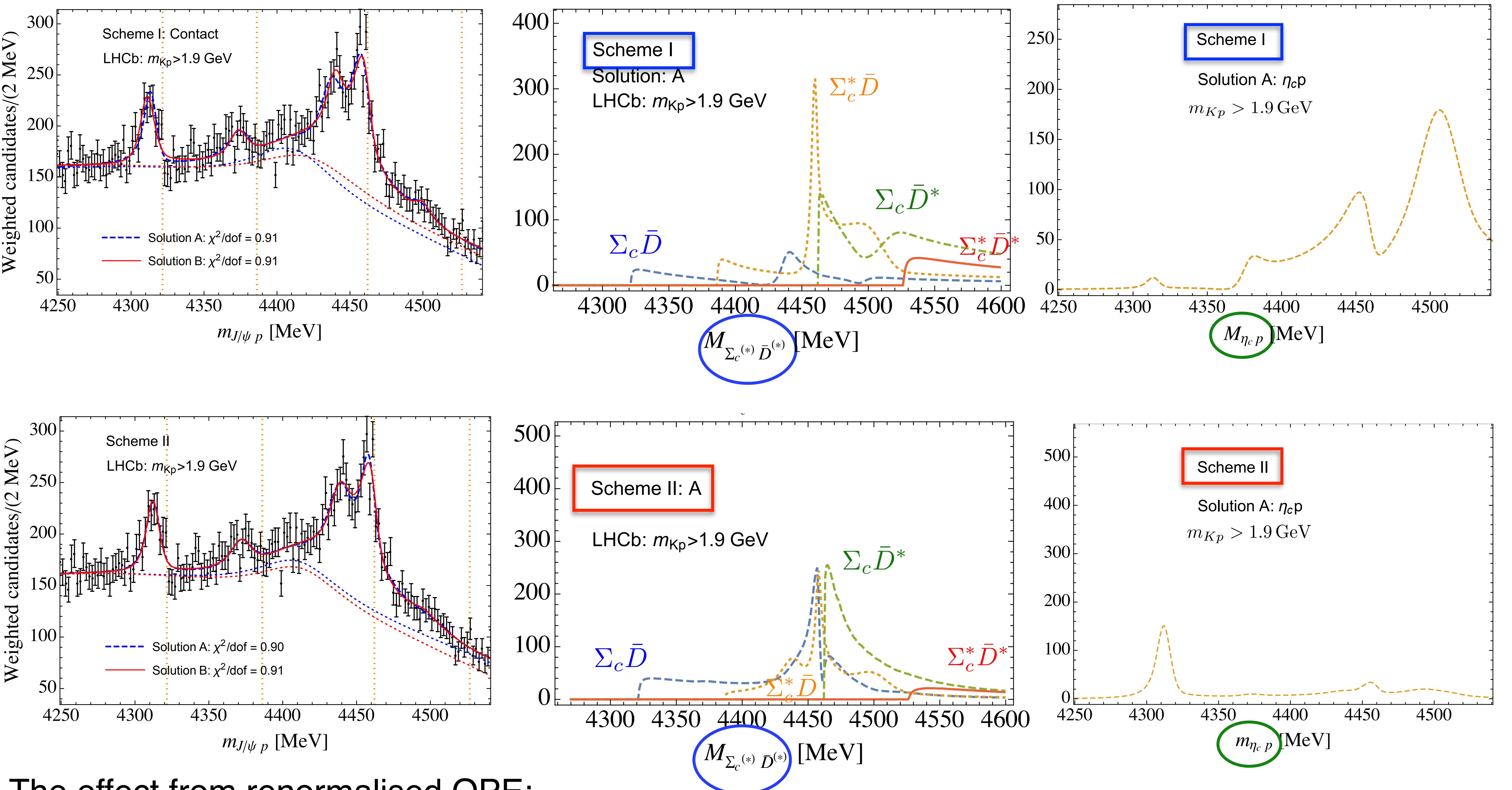
Predictions for $\Lambda_b \to K\Sigma^{(*)}D^{(*)}$ and $\Lambda_b \to K\eta_c p$ with pions

scheme I = contact

scheme II = contact +OPE

Fit A

Fitted | Predicted



<u>The effect from renormalised OPE:</u>

- Qualitatively different results for $\Sigma_c D$ and $\eta_c p$ in schemes I and II
- $\Sigma_c D$: $1/2^-$ $P_c(4440)$ in S-wave in scheme I vs $3/2^-$ $P_c(4457)$ in D-wave in scheme II

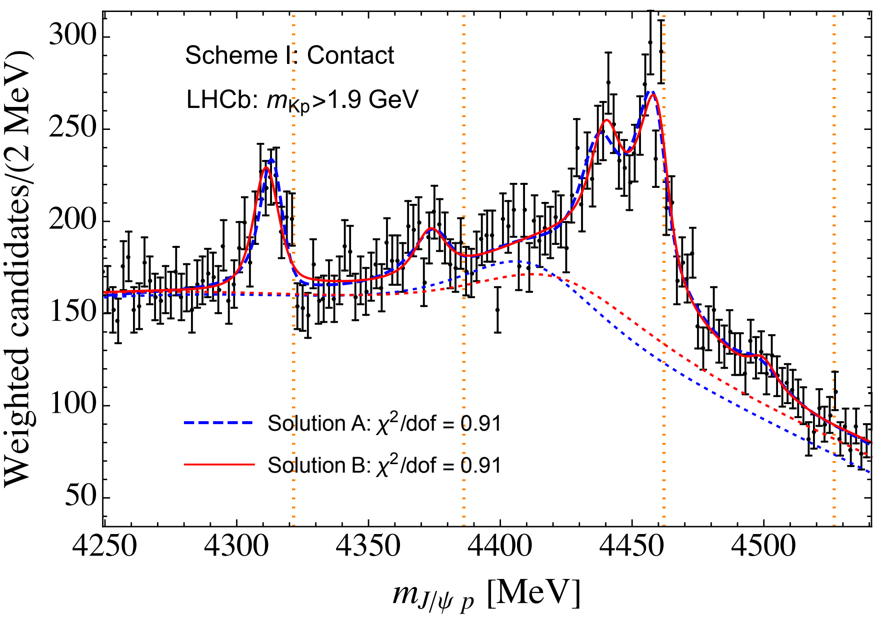
Predictions for $\Lambda_b \to K\Sigma^{(*)}D^{(*)}$ and $\Lambda_b \to K\eta_c p$ with pions

scheme I = contact

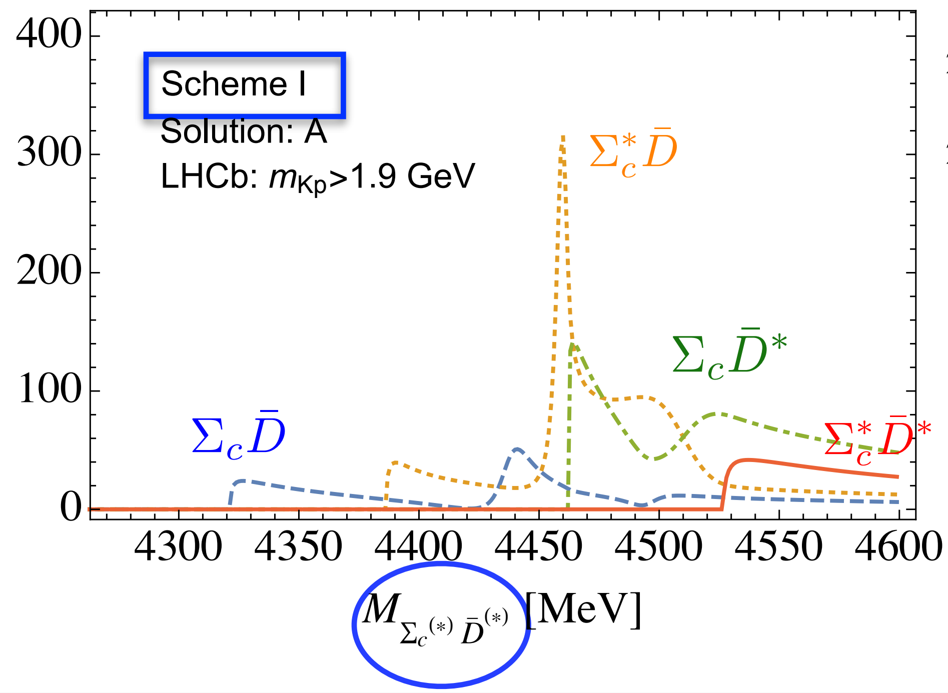
scheme II = contact +OPE

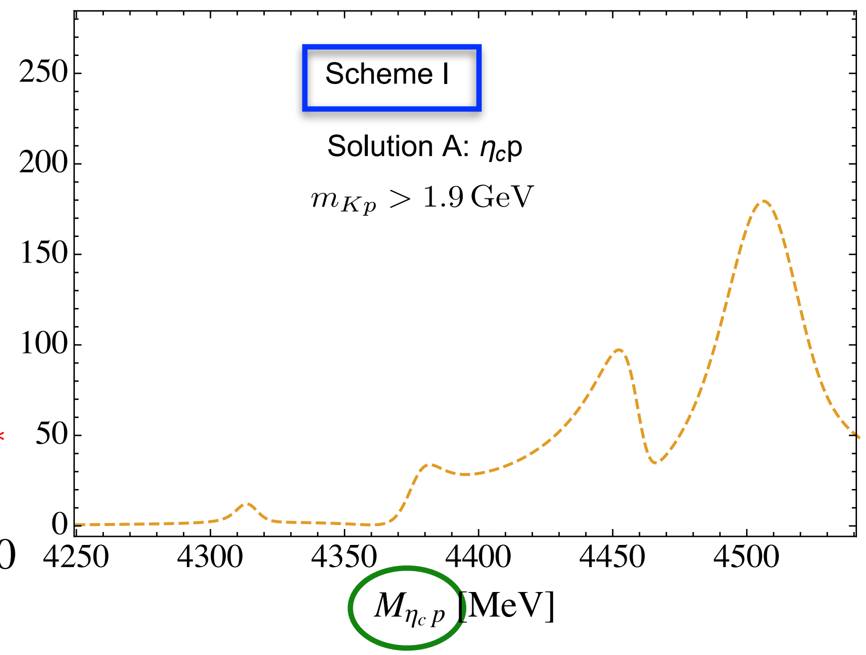
Fit A

Fitted



Predicted

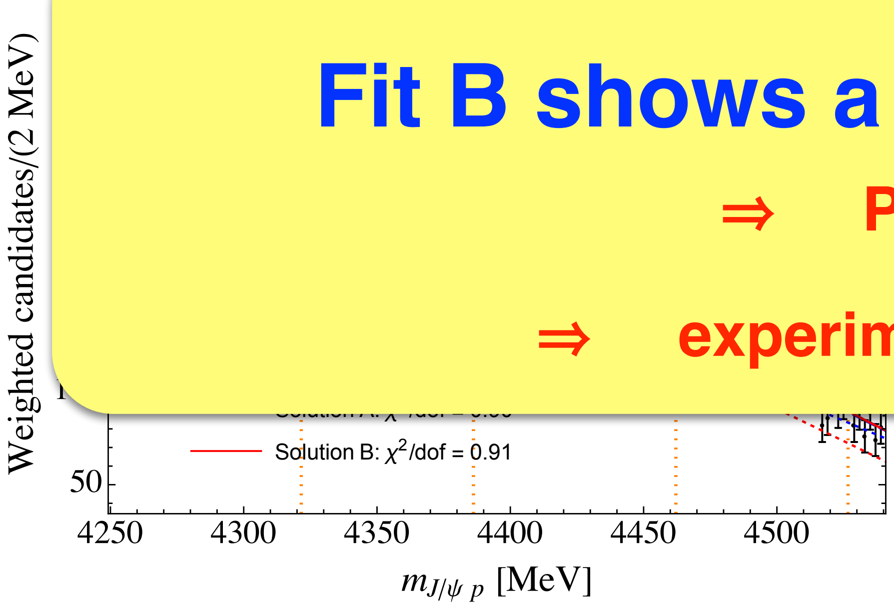


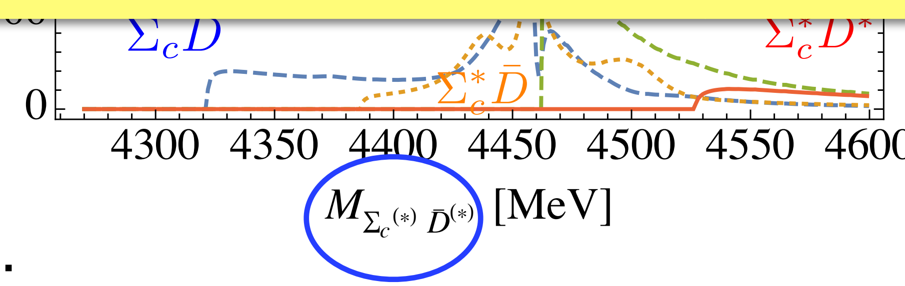


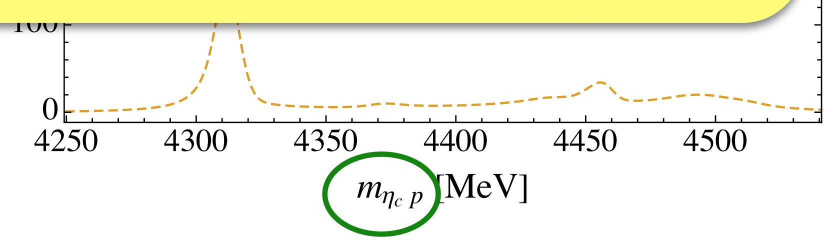
Fit B shows a much more natural pattern than fit A

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

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







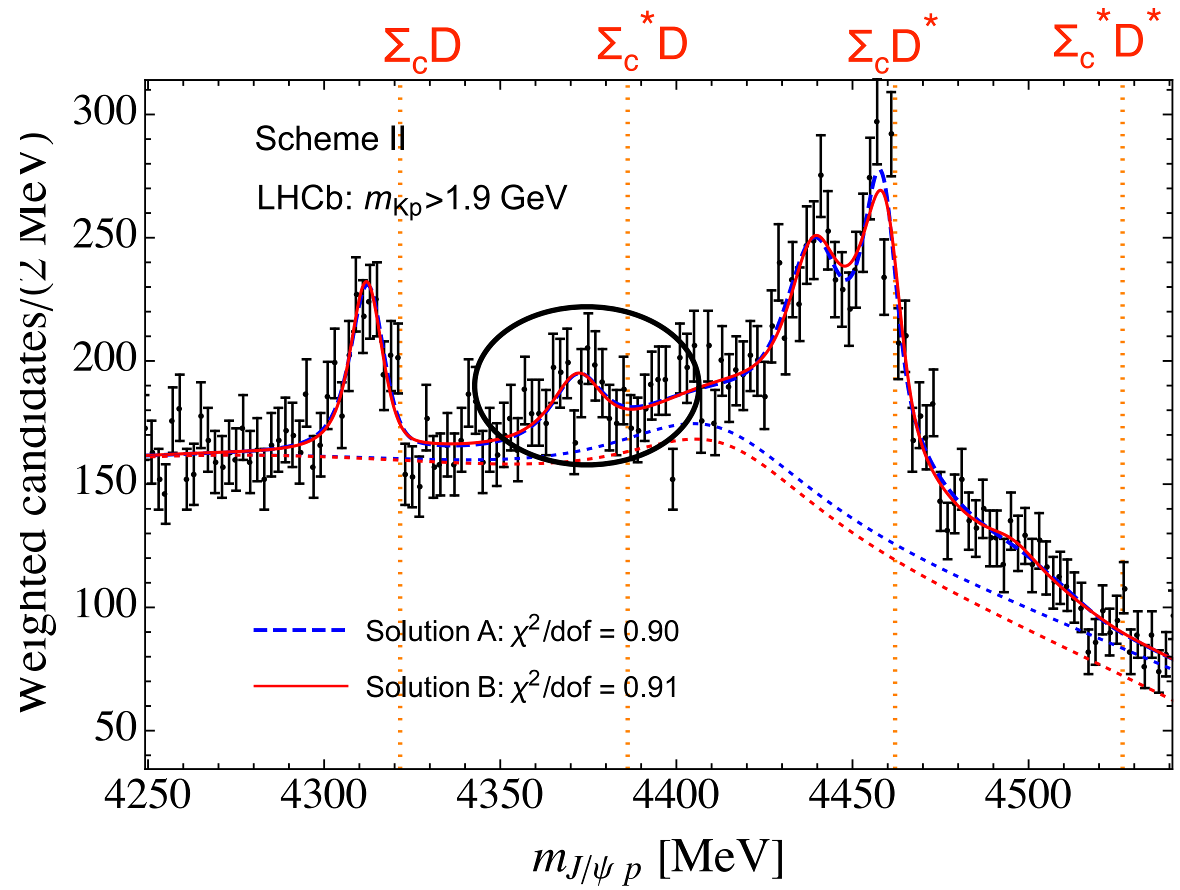
The effect from renormalised OPE:

- Qualitatively different results for $\Sigma_c D$ and $\eta_c p$ in schemes I and II
- $\Sigma_c D$: $1/2^-$ $P_c(4440)$ in S-wave in scheme I vs $3/2^-$ $P_c(4457)$ in D-wave in scheme II

Summary and Outlook

- A coupled-channel analysis of $\Lambda_b \to K\, P_c \to K\, J/\Psi\, p$ $\Longrightarrow$ P_c states as $\Sigma_c^{(*)}\bar{D}^{(*)}$ quasi-bound states

- A new $P_c(4380)$ as $\Sigma_c^* D$ $3/2^-$ is already in current data



- Testable predictions for spectra

$$\Lambda_b \to K\Sigma^{(*)}\bar{D}^{(*)} \text{ and } \Lambda_b \to K\eta_c p$$

-

	$P_c(4440)$	$P_c(4457)$	$\Sigma_c D^*$
Fit A:	$1/2^-$	$3/2^-$	
Fit B:	$3/2^-$	$1/2^-$	from fits with pions

☛ Data for $\Lambda_b \to K$ final, final $= \Sigma_c^{(*)}\bar{D}^{(*)}, \eta_c p$ and $\Lambda_c\bar{D}^{(*)}$ are needed

$\Longrightarrow$ $J/\Psi\, p$ data alone are not enough to constraint $\Lambda_c\bar{D}^{(*)}$ interactions

☛ Other data, e.g., $J/\Psi\, p$ photoproduction: sensitivity to production process