RUHR UNIVERSITÄT BOCHUM

Baryon molecules with two heavy quarks

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Physics opportunities with proton beams at SIS100

6-9 February 2024

Based on *PRL 14, 072001 (2020) ; JHEP 08 (2021)*

in collaboration with

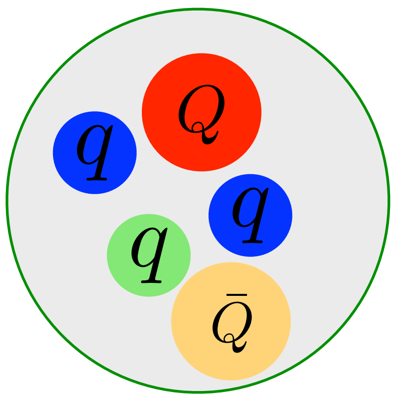
M. Du, F.-K. Guo, C. Hanhart, U.-G. Meißner, J.A. Oller and Q.Wang

Varieties of Exotic Baryons

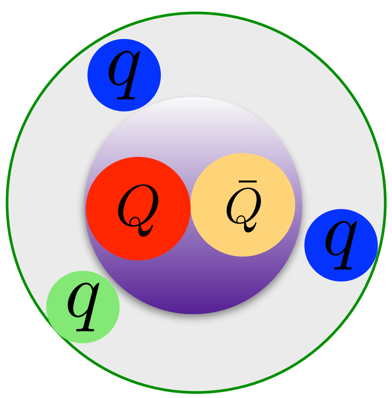
Existence of hadrons beyond conventional configurations:

Gell-Mann; Zweig 1964

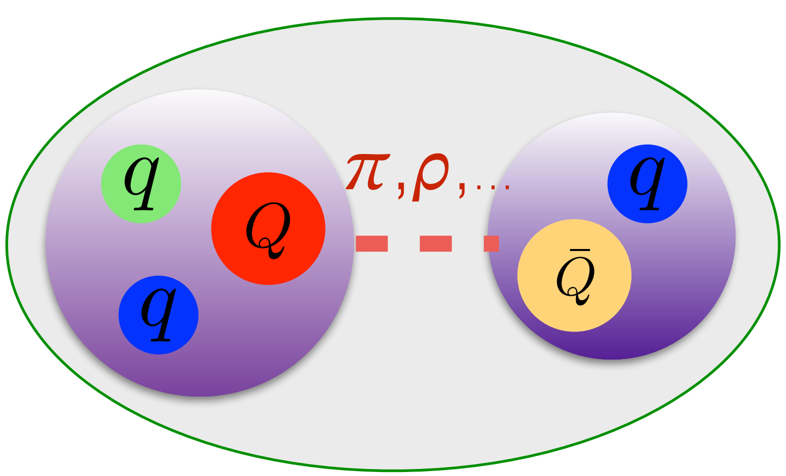
Jaffe, Strottman, Lipkin, …



Compact object typically formed from diquark interactions



Hadro-Quarkonium: Compact $Q\bar{Q}$ core surrounded by light quark cloud

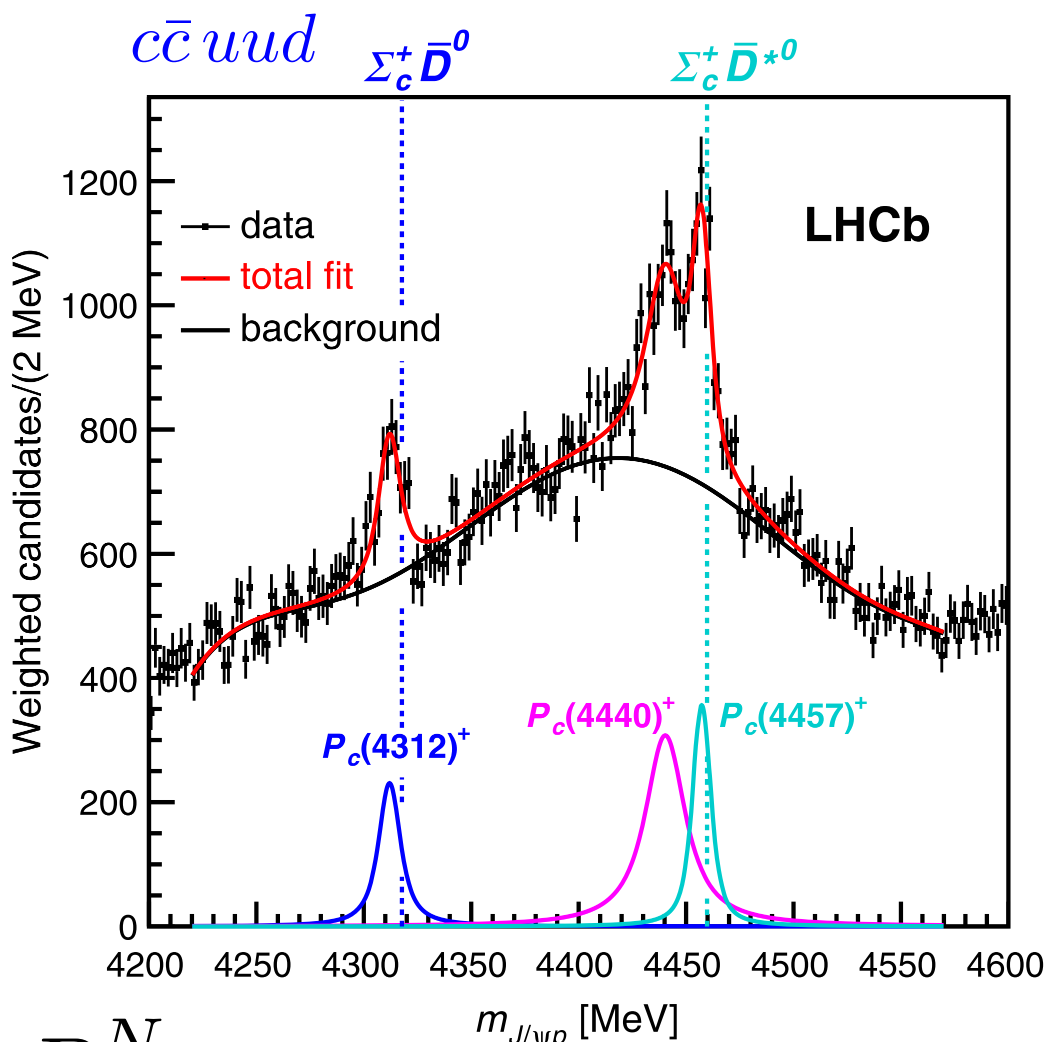


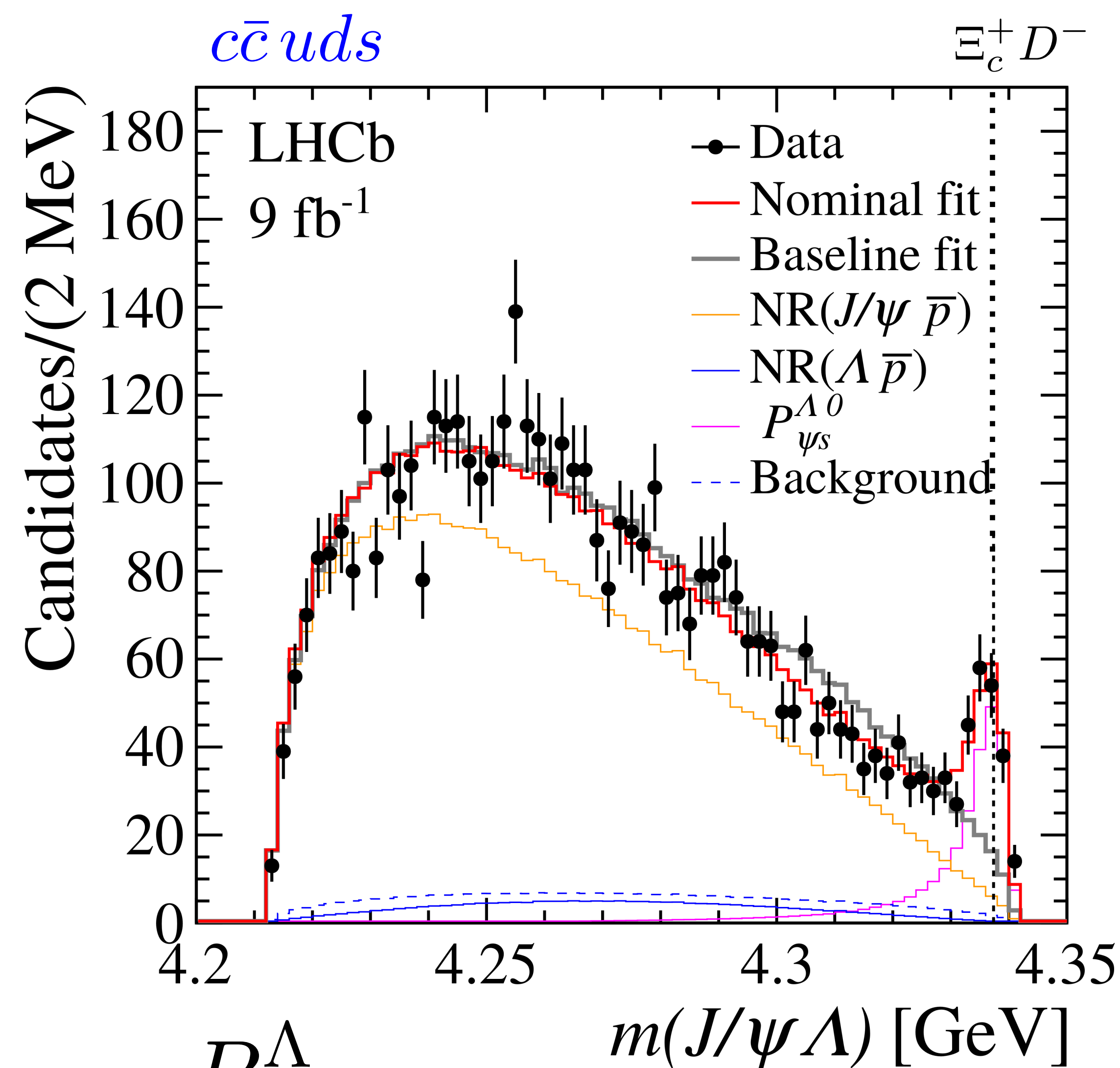
Molecule: Extended object composed of a Meson and Baryon

LHCb results: summary

Since 2015: $\Lambda_b \to J/\psi\, p\, K$ $\quad \Xi_b \to J/\psi\, \Lambda\, K$

$B_s \to J/\psi\, p\, \bar{p}$ $\quad B \to J/\psi\, \Lambda\, \bar{p}$





P_ψ^N

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

$P_{\psi s}^\Lambda$

	M [MeV]	Γ [MeV]
$P_{cs}(4338)$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$
$P_{cs}(4459)$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$

LHCb, PRL 122 222001 (2019)

LHCb: Sc. Bull. 66 1278 (2021); PRL 131, 031901 (2023)

LHCb results: summary

Since 2015: $\Lambda_b \to J/\psi\, p\, K$ $\quad \Xi_b \to J/\psi\, \Lambda\, K$

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P_ψ^N LHCb, PRL 122 222001 (2019)

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$P_{\psi s}^\Lambda$ LHCb: Sc. Bull. 66 1278 (2021); PRL 131, 031901 (2023)

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— All states have narrow widths and sit close to meson-baryon thresholds: $\Sigma_c D^{(*)}, \Xi_c D^{(*)}$

— Quantum numbers are basically unknown but

- P_c states are seen in *J/Ψ p* final states ⇒ I=1/2; P_{cs} in *J/Ψ Λ* ⇒ I=0
- $P_{cs}(4338)$ J^P = 1/2- preferred (1/2+ rejected 90%)

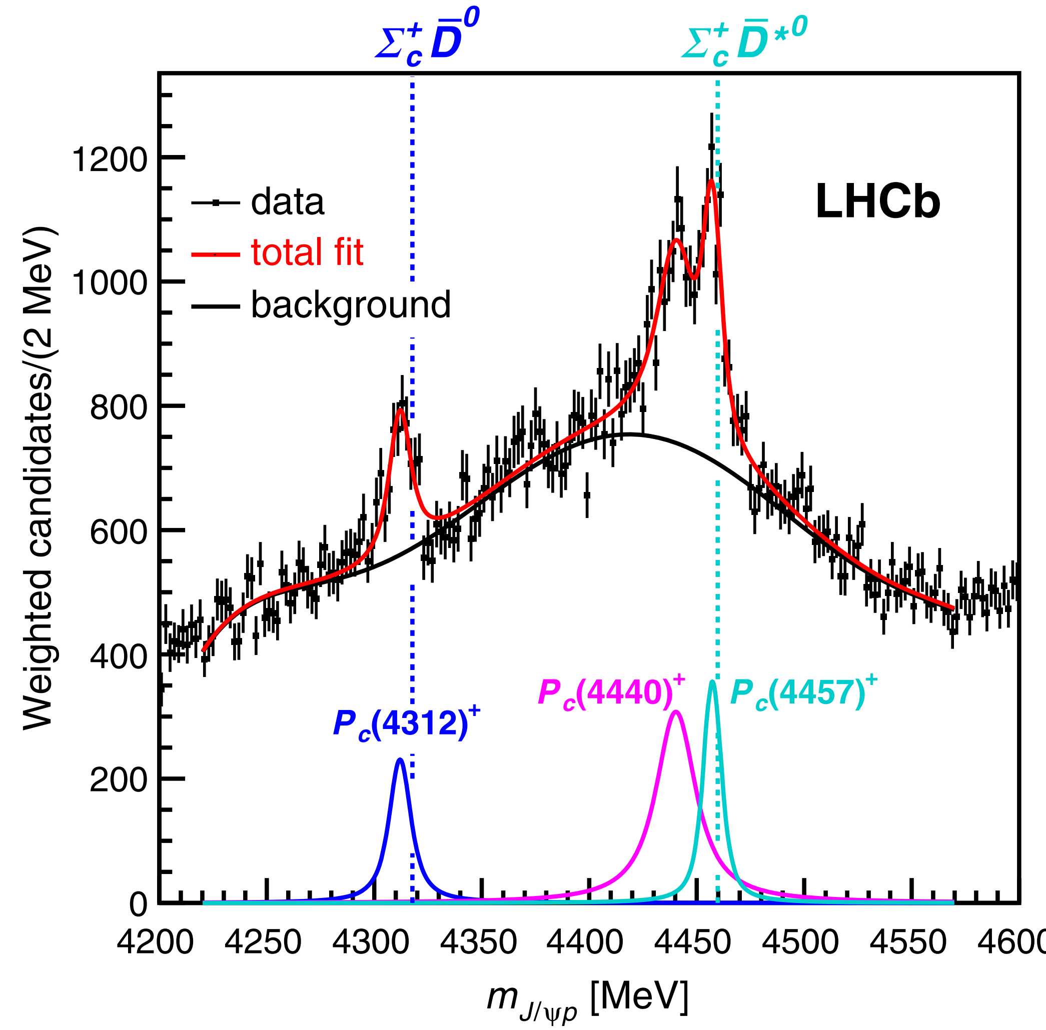
—Also $P_c(4337)$ $\quad M_{P_c} = 4337\ ^{+7}_{-4}\ ^{+2}_{-2}\ \mathrm{MeV}$ larger width, further away from thresholds

$\Gamma_{P_c} = 29\ ^{+26}_{-12}\ ^{+14}_{-14}\ \mathrm{MeV}$ LHCb, PRL 128, 062001 (2022)

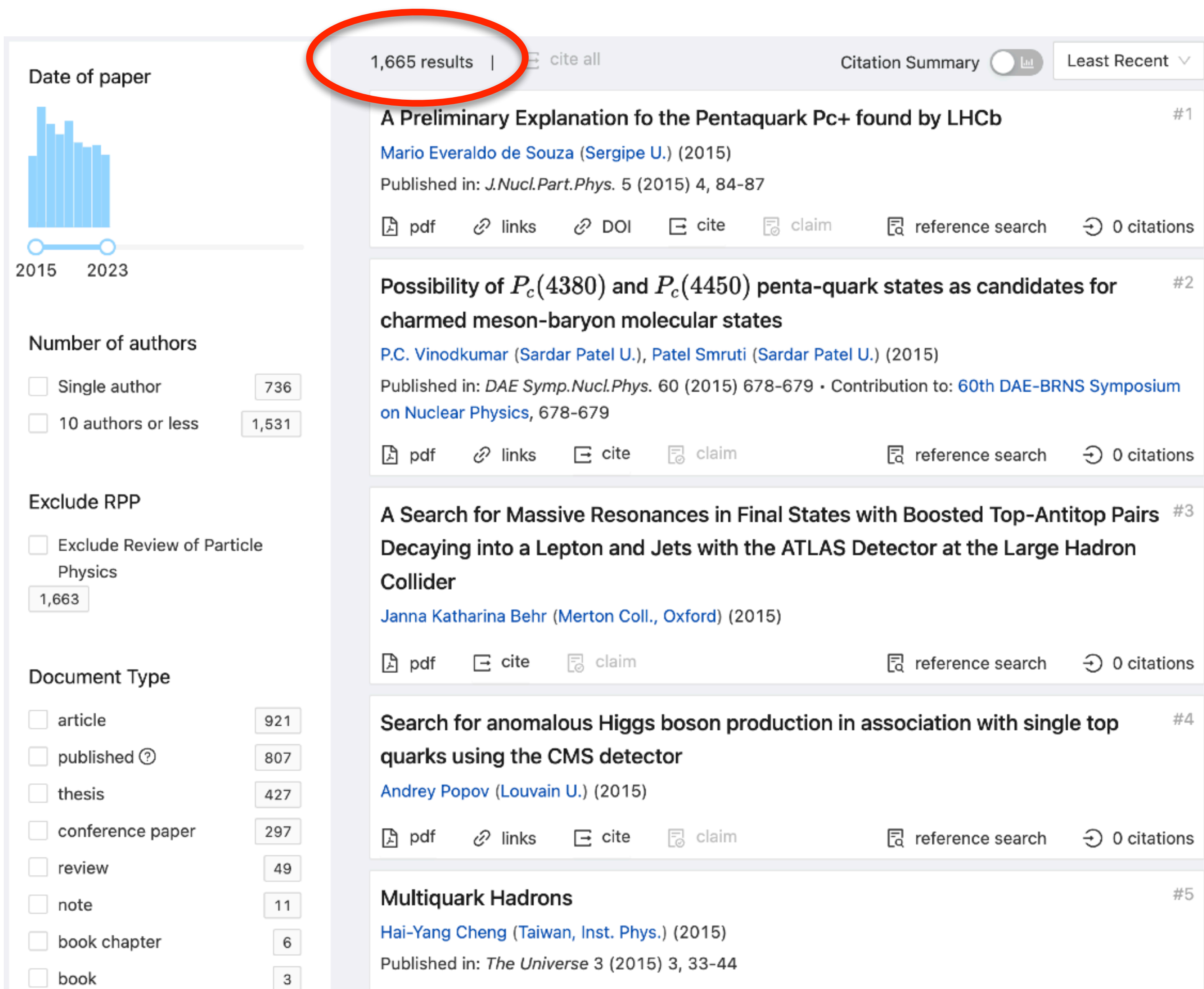
Theory response

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

LHCb, PRL 122 222001 (2019)



☛ Triggered enormous interest in the community


Date of paper
2015 2023
Number of authors
Single author 736
10 authors or less 1,531
Exclude RPP
Exclude Review of Particle Physics 1,663
Document Type
article 921
published 807
thesis 427
conference paper 297
review 49
note 11
book chapter 6
book 3

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A Preliminary Explanation fo the Pentaquark Pc+ found by LHCb #1
Mario Everaldo de Souza (Sergipe U.) (2015)
Published in: *J.Nucl.Part.Phys.* 5 (2015) 4, 84-87
pdf links DOI cite claim reference search 0 citations

Possibility of $P_c(4380)$ and $P_c(4450)$ penta-quark states as candidates for charmed meson-baryon molecular states #2
P.C. Vinodkumar (Sardar Patel U.), Patel Smruti (Sardar Patel U.) (2015)
Published in: *DAE Symp.Nucl.Phys.* 60 (2015) 678-679 • Contribution to: 60th DAE-BRNS Symposium on Nuclear Physics, 678-679
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A Search for Massive Resonances in Final States with Boosted Top-Antitop Pairs Decaying into a Lepton and Jets with the ATLAS Detector at the Large Hadron Collider #3
Janna Katharina Behr (Merton Coll., Oxford) (2015)
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Search for anomalous Higgs boson production in association with single top quarks using the CMS detector #4
Andrey Popov (Louvain U.) (2015)
pdf links cite claim reference search 0 citations

Multiquark Hadrons #5
Hai-Yang Cheng (Taiwan, Inst. Phys.) (2015)
Published in: *The Universe* 3 (2015) 3, 33-44

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Theory response

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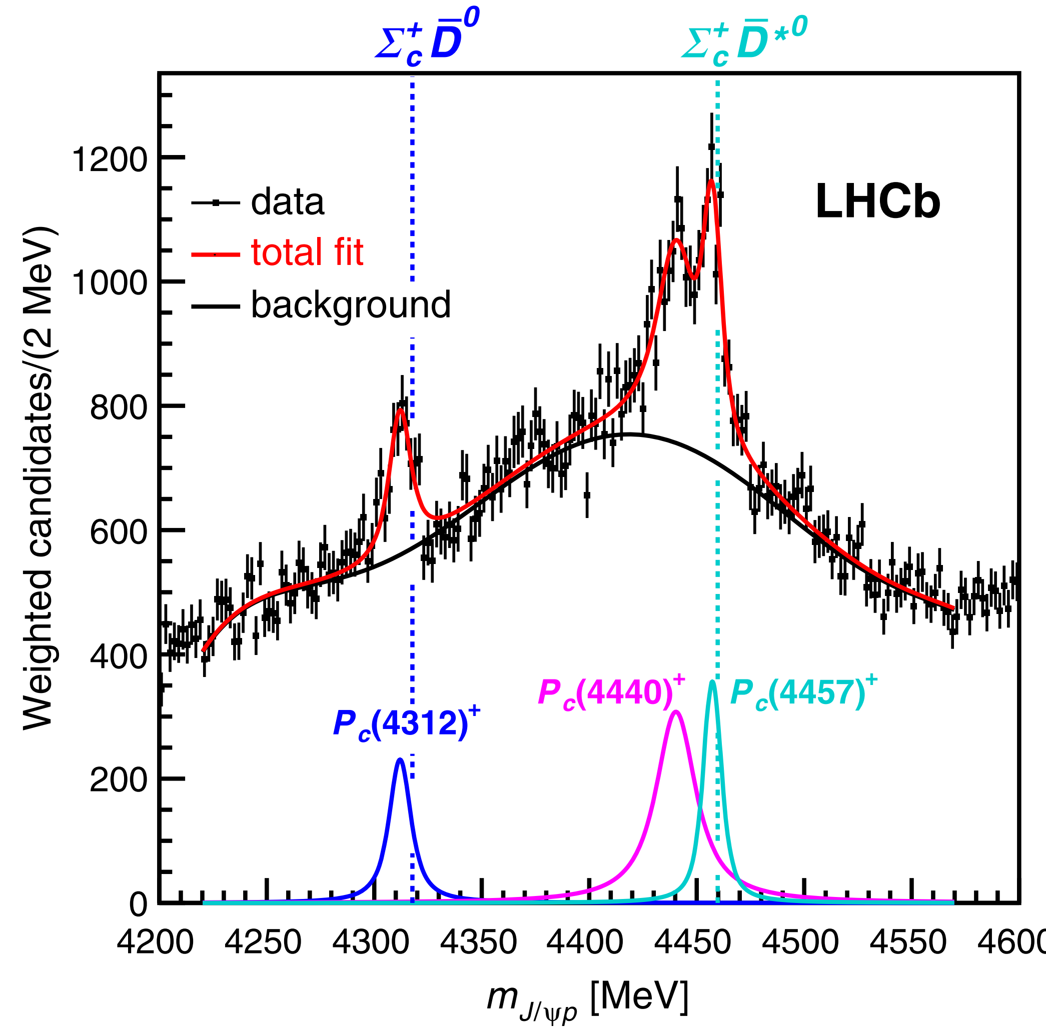

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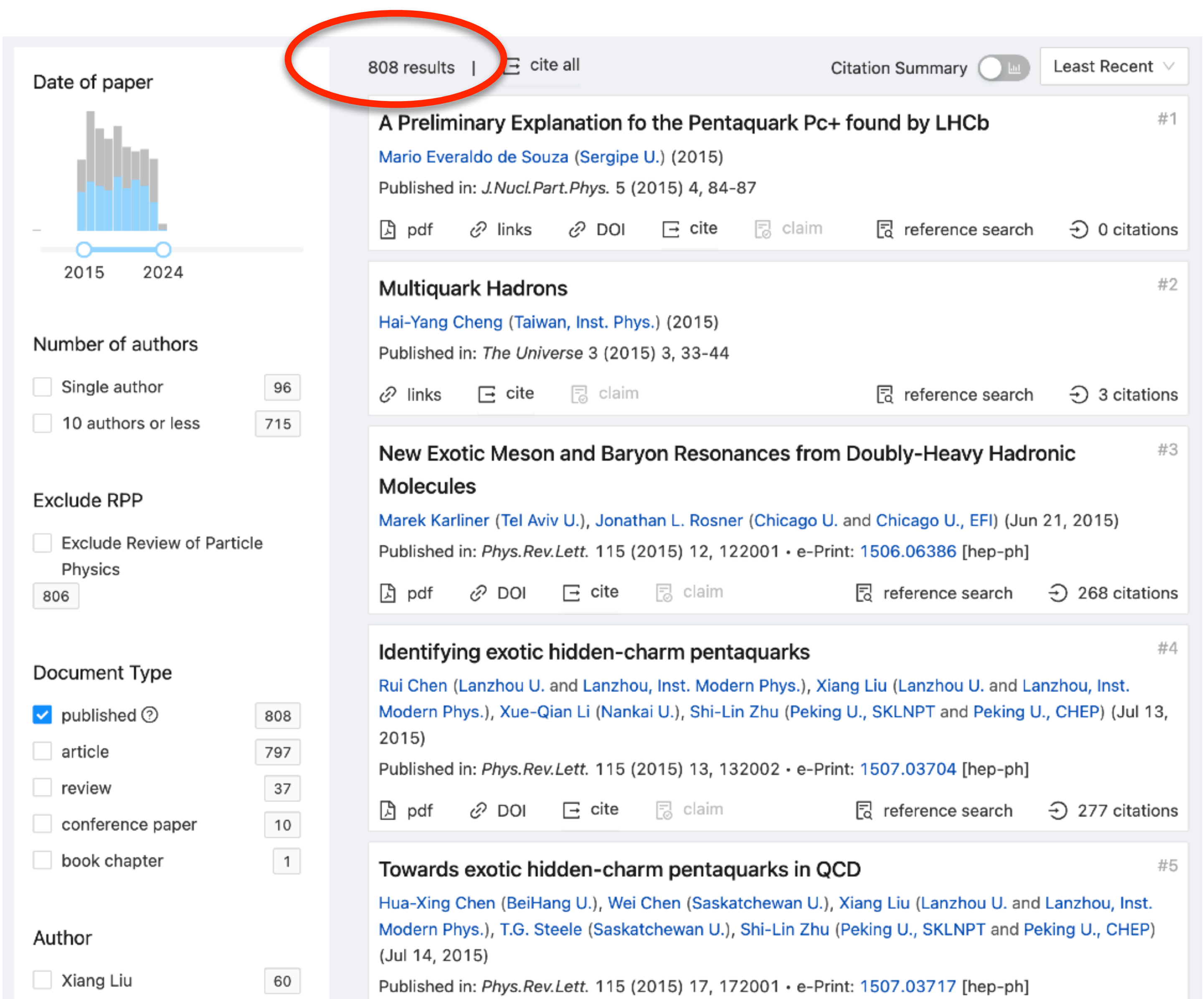

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Recent Reviews:

Esposito et al., Phys.Rept. 668 (2017)

Lebed et al. Prog. Part. Nucl. Phys. 93 (2017)

Guo et al., Rev. Mod. Phys. 90 (2018)

Brambilla et al., Phys.Rept. 873 (2020)

Chen et al., Rept. Prog. Phys. 86 (2023)

Meng et al., Phys.Rept. 1019 (2023)

Theoretical approaches (selected articles)

— Hadroquarkonium
Eides et al. (2019), Ferretti et al (2019), …

* Pc(4312) as a χc0(1P) N hadrocharmonium with JP= 1/2+
* Pc(4440) and Pc(4457) hadrocharmonia ψ(2S) N with JP = 1/2−, 3/2−. Mass difference: hyperfine splitting
* Widths are due to decays to charmonium N channels

— Compact
Ali et al. (2019), Cheng et al (2019), Lebed et al (2019), …

* build on binding light diquark to the doubly heavy triquark with orbital interactions in the light diquark system

Ali et al. (2019)

* Pc(4312)	$3/2^-$	4240 ± 29
* Pc(4440)	$3/2^+$	4440 ± 35
* Pc(4457)	$5/2^+$	4457 ± 35

— lowest state is 70 MeV below Pc(4312)
— states with various Parities
— pattern is different to Hadroquarkonium

— Triangle singularities

* Only near Pc(4457) due to $D^*_{s1}(2860)\Lambda_c\bar{D}^*$. But too broad widths of the ingredients. LHCb, PRL 122 222001 (2019)
  Still can affect line shapes quantitatively

* P_{cs}(4338) as $\Sigma_c(2800)\Xi_c\bar{D}$ triangle singularity Burns, Swanson (2023)

— Double-triangle singularities
Nakamura 2020

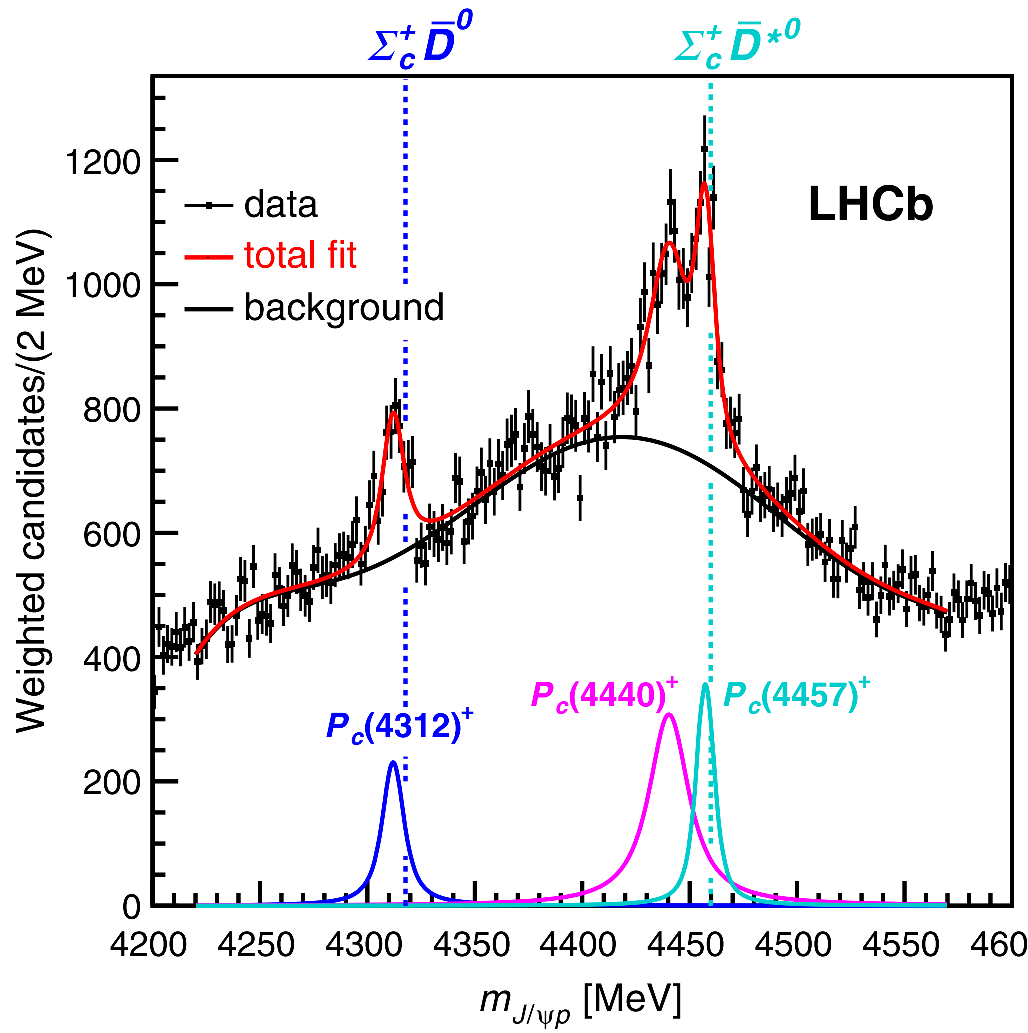
* Explicit Pc(4440); data can be understood as interference of various mechanisms; many parameters

Pentaquarks as hadronic molecules

— 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 $\Sigma_c D^*$

—All states have negative parities



LHCb, PRL 122 222001 (2019)

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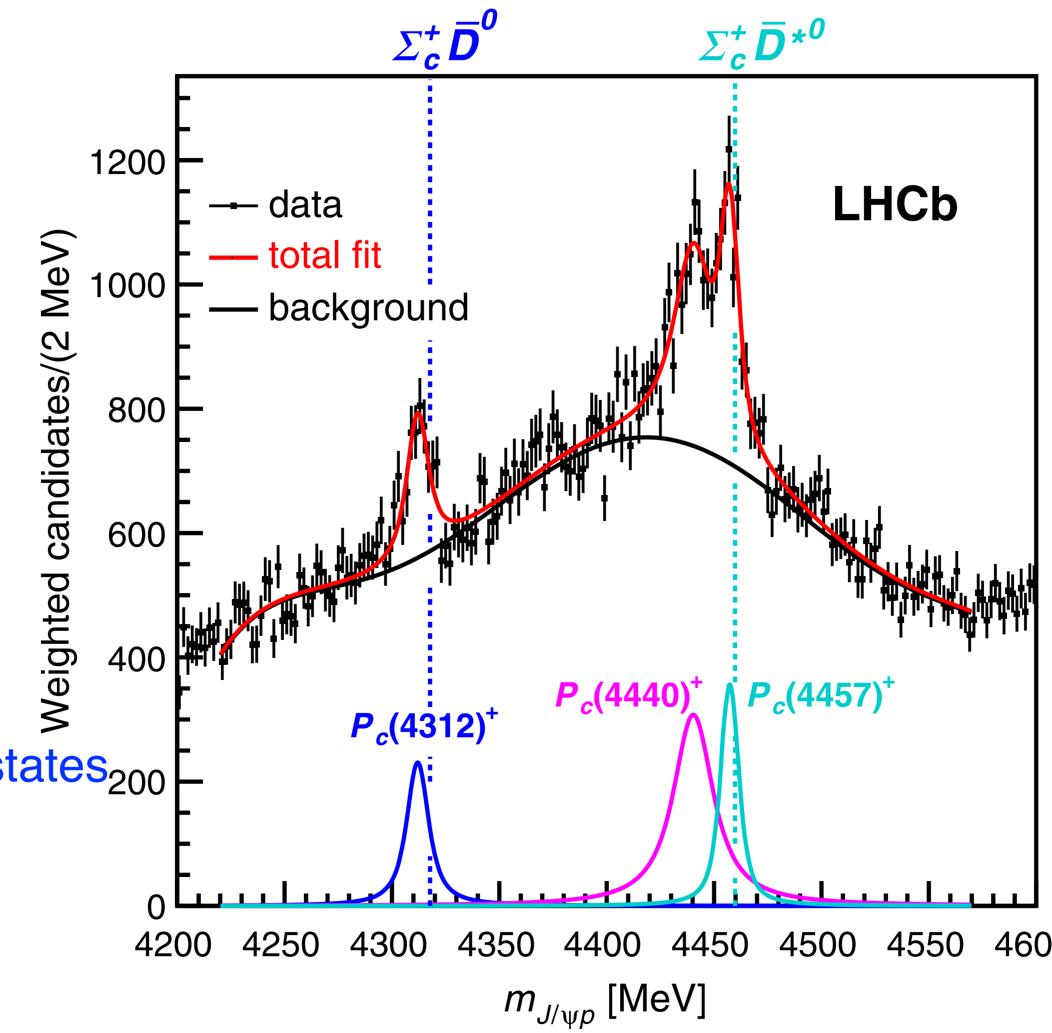


LHCb, PRL 122 222001 (2019)

⟹ 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

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

⟹ 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)

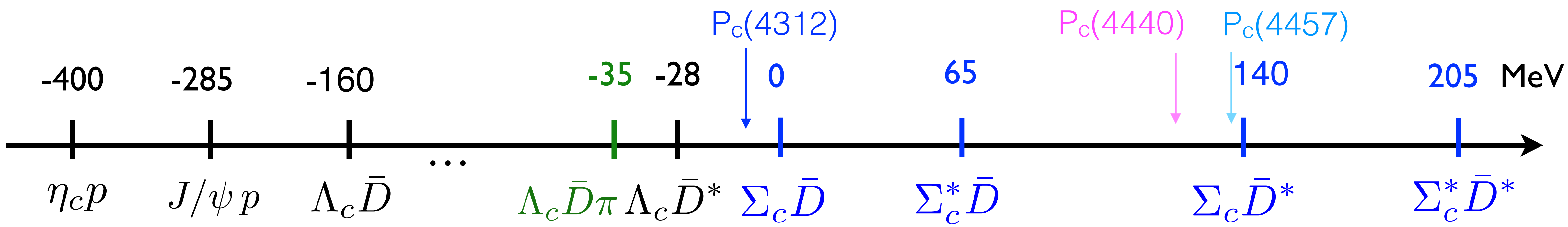
related works: Xiao et al. PRD 100 014021 (2019), Sakai et al. PRD 100 074007 (2019), .

—Pc(4312) as a virtual state JPAC Fernández-Ramírez et al *PRL* 123 (2019)

Pentaquarks in an EFT approach

our works: Du et al. PRL 14, 072001 (2020) and JHEP 08, 157 (2021)

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



☛ Extracting poles and residues from data and not from Breit-Wigner masses

☛ 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)

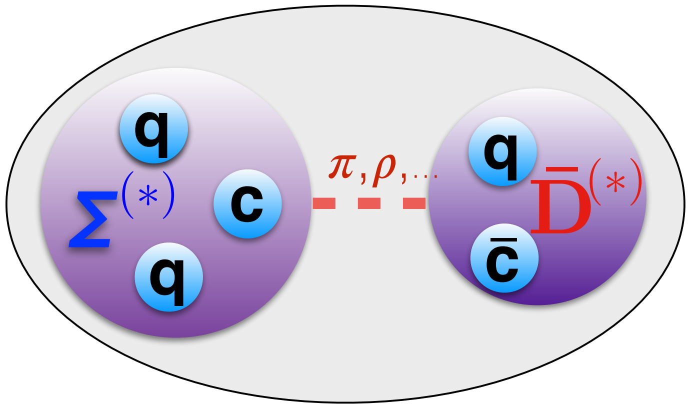
and for $\Lambda_b \to K\,\Lambda_c D$: Piucchi phd thesis (2019)

☛ Is there a room for $\Lambda_c D^{(*)}$ interactions?

☛ The role of one-pion exchange

Chiral EFT approach at low energies

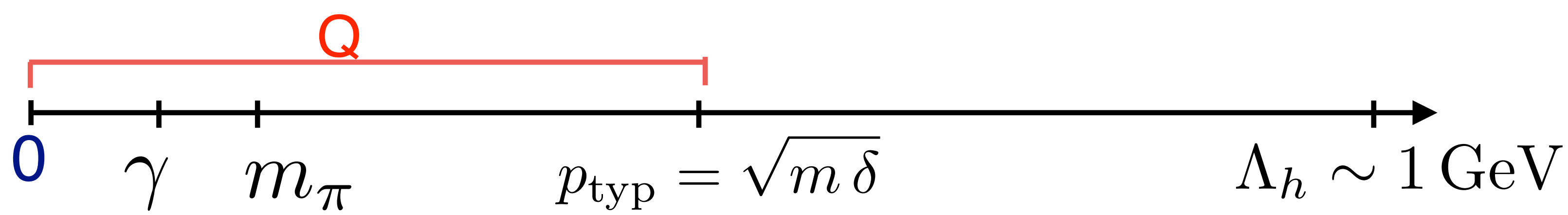
also see talk by Evgeny Epelbaum on Wednesday



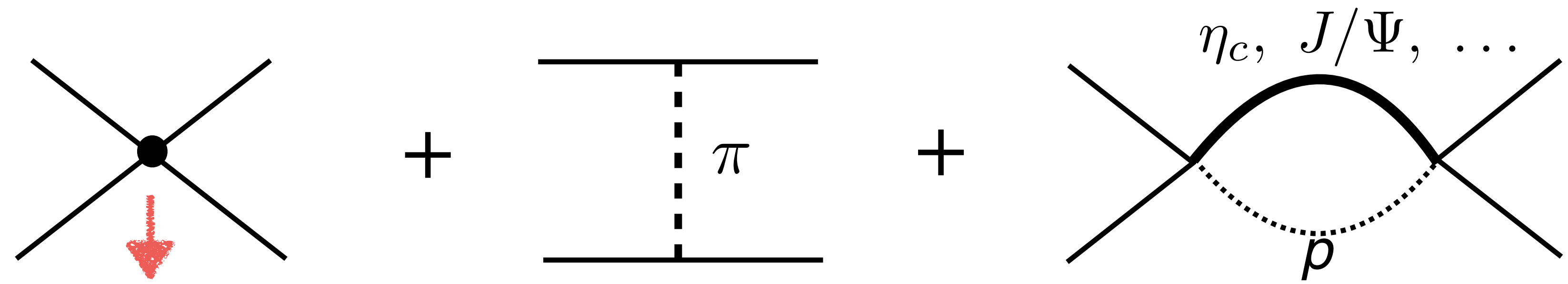
- Elastic coupled-channel $\Sigma_c^{(*)} \bar{D}^{(*)}$ potential to a given order in Q/Λ_h

M. Du et al. JHEP 08 (2021)

☛ 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

three-body unitarity from $\Lambda_c \bar{D} \pi$ cuts is fully incorporated

Some details on the OPE

- Pionic Lagrangian: $\mathcal{L} = \frac{g_1}{4}\langle \sigma \cdot u_{ab} \bar{H}_b \bar{H}_a^\dagger \rangle + i g_2 \epsilon_{ijk} S_{ab}^{i\dagger} u_{bc}^j S_{ca}^k - \frac{1}{\sqrt{2}} g_3 \left(S_{ab}^{i\dagger} u_{bc}^i T_{ca} + T_{ab}^\dagger u_{bc}^i S_{ca}^i \right)$

  $\bar{D}^{(*)}\bar{D}^{(*)}\pi$ | $\Sigma_c^{(*)}\Sigma_c^{(*)}\pi$ | $\Sigma_c^{(*)}\Lambda_c\pi$

  with g_1 = 0.57 from D* →Dπ width, g_2 and g_3 are taken from lattice Detmold et al., PRD 85, 114508 (2012)

- Exemplary potential:

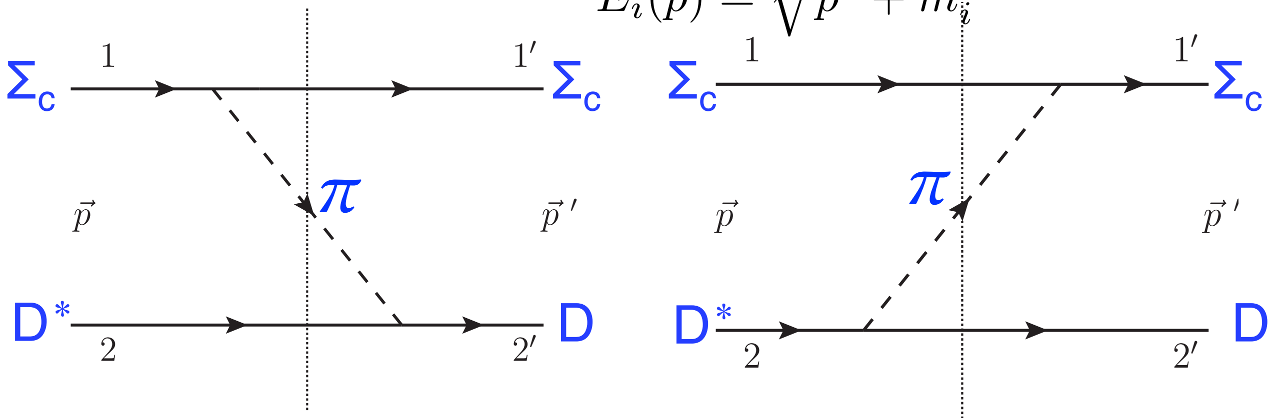
$$V_{\Sigma_c \bar{D}^* \to \Sigma_c \bar{D}}(\mathbf{p}, \mathbf{p}') \propto \frac{g_1 g_2}{f_\pi^2} (\tau_1 \cdot \tau_2^c)(\epsilon_{\bar{D}^*} \cdot \mathbf{q})(\sigma \cdot \mathbf{q}) \left(\frac{1}{G_{\Sigma_c \bar{D}\pi}} + \frac{1}{G_{\Sigma_c \bar{D}^*\pi}} \right)$$

☛ TOPT propagators

$$G_{\Sigma_c \bar{D}\pi} = 2E_\pi(q)\left(E_\pi(q) + E_{\Sigma_c}(p) + E_{\bar{D}}(p') - \sqrt{s} \right)$$

$$G_{\Sigma_c \bar{D}^*\pi} = 2E_\pi(q)\left(E_\pi(q) + E_{\Sigma_c}(p') + E_{\bar{D}^*}(p) - \sqrt{s} \right)$$

$$E_i(p) = \sqrt{p^2 + m_i^2}$$



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- Pionic Lagrangian: $$\mathcal{L} = \frac{g_1}{4}\underbrace{\langle \sigma \cdot u_{ab} \bar{H}_b \bar{H}_a^\dagger \rangle}_{\bar{D}^{(*)}\bar{D}^{(*)}\pi} + i g_2 \underbrace{\epsilon_{ijk} S_{ab}^{i\dagger} u_{bc}^j S_{ca}^k}_{\Sigma_c^{(*)}\Sigma_c^{(*)}\pi} - \frac{1}{\sqrt{2}} g_3 \underbrace{\left(S_{ab}^{i\dagger} u_{bc}^i T_{ca} + T_{ab}^\dagger u_{bc}^i S_{ca}^i \right)}_{\Sigma_c^{(*)}\Lambda_c\pi}$$

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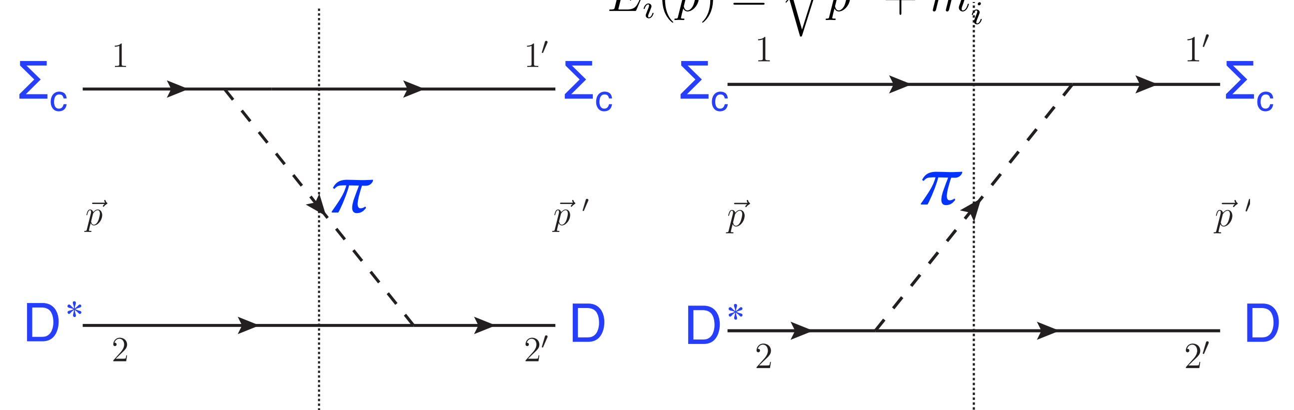
- Exemplary potential:

$$V_{\Sigma_c \bar{D}^* \to \Sigma_c \bar{D}}(\mathbf{p}, \mathbf{p}') \propto \frac{g_1 g_2}{f_\pi^2} (\tau_1 \cdot \tau_2^c)(\epsilon_{\bar{D}^*} \cdot \mathbf{q})(\sigma \cdot \mathbf{q}) \left(\frac{1}{G_{\Sigma_c \bar{D}\pi}} + \frac{1}{G_{\Sigma_c \bar{D}^*\pi}} \right)$$

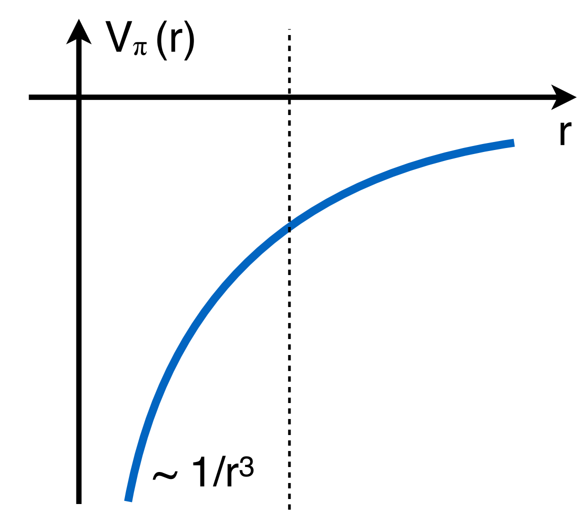
☛ TOPT propagators

$$G_{\Sigma_c \bar{D}\pi} = 2E_\pi(q)\left(E_\pi(q) + E_{\Sigma_c}(p) + E_{\bar{D}}(p') - \sqrt{s}\right)$$
$$G_{\Sigma_c \bar{D}^*\pi} = 2E_\pi(q)\left(E_\pi(q) + E_{\Sigma_c}(p') + E_{\bar{D}^*}(p) - \sqrt{s}\right)$$

$$E_i(p) = \sqrt{p^2 + m_i^2}$$



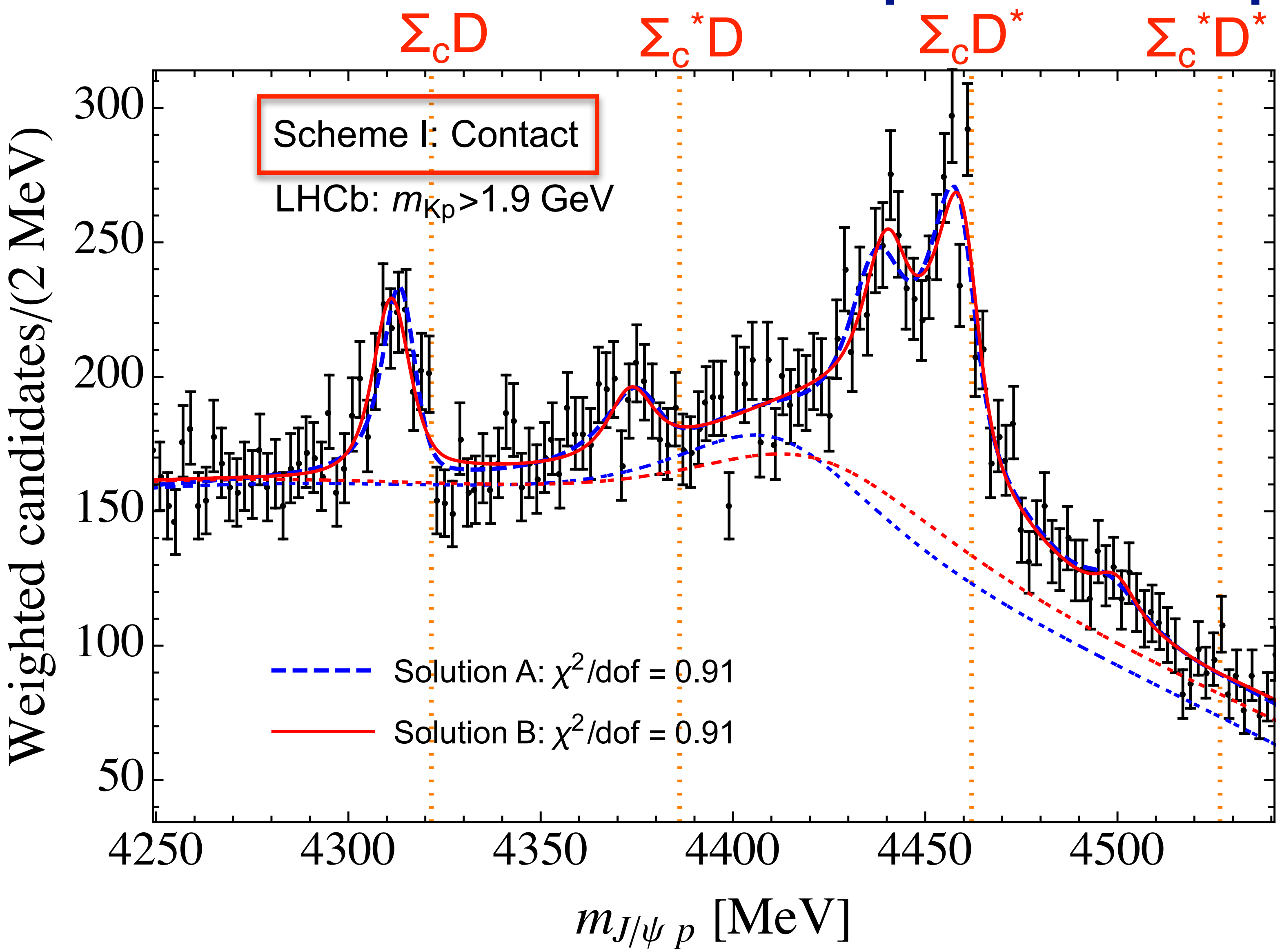
- Central part: S-wave to S-wave transitions
- Tensor part: S-wave to D-wave transitions



- At short distances OPE is not well defined w/o contact terms

Line shape and Pc poles

Du et al. PRL 124, 072001 (2020)
JHEP 08 (2021)

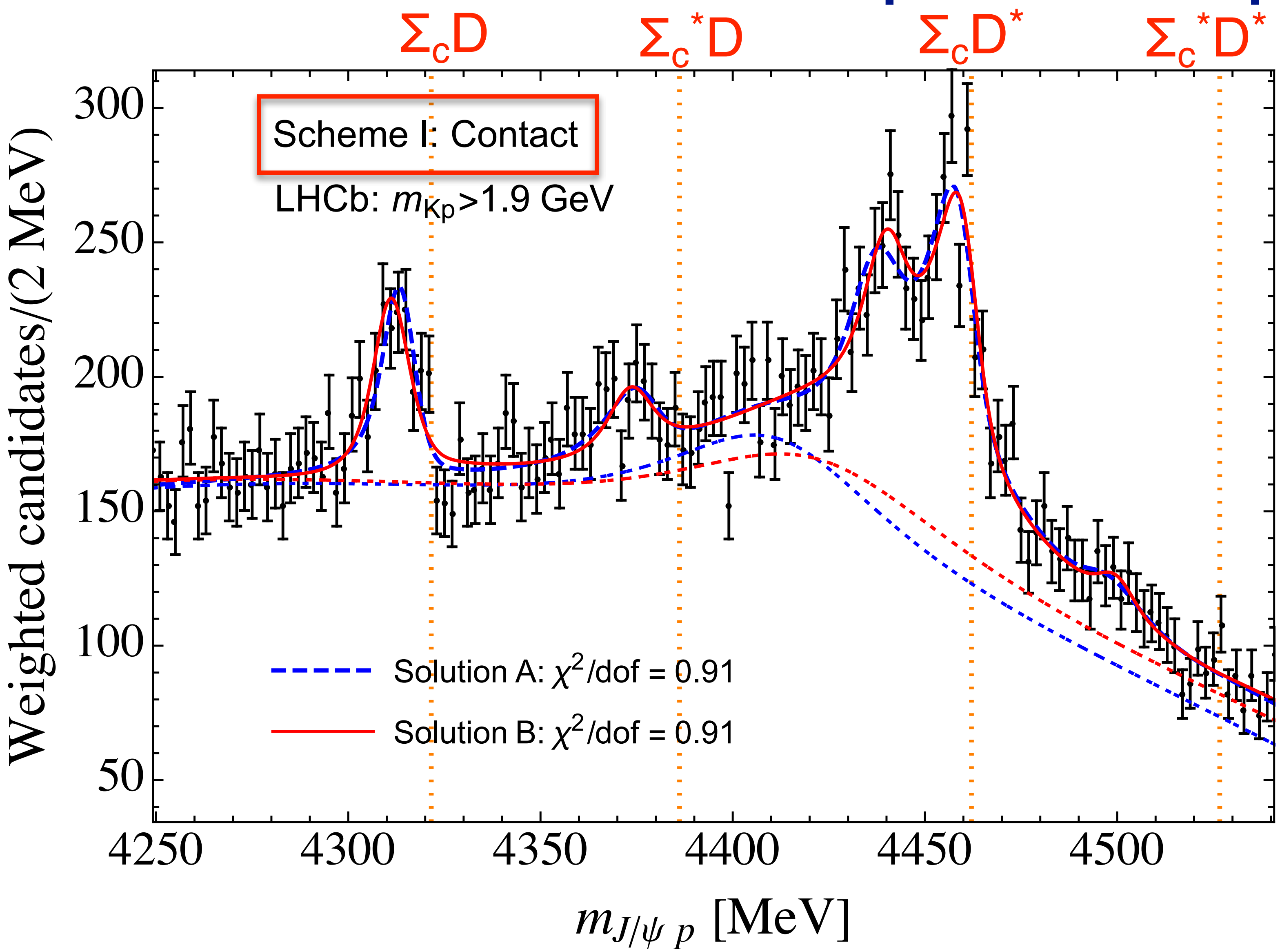


Poles and quantum numbers:

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

Line shape and Pc poles

Du et al. PRL 124, 072001 (2020)
JHEP 08 (2021)



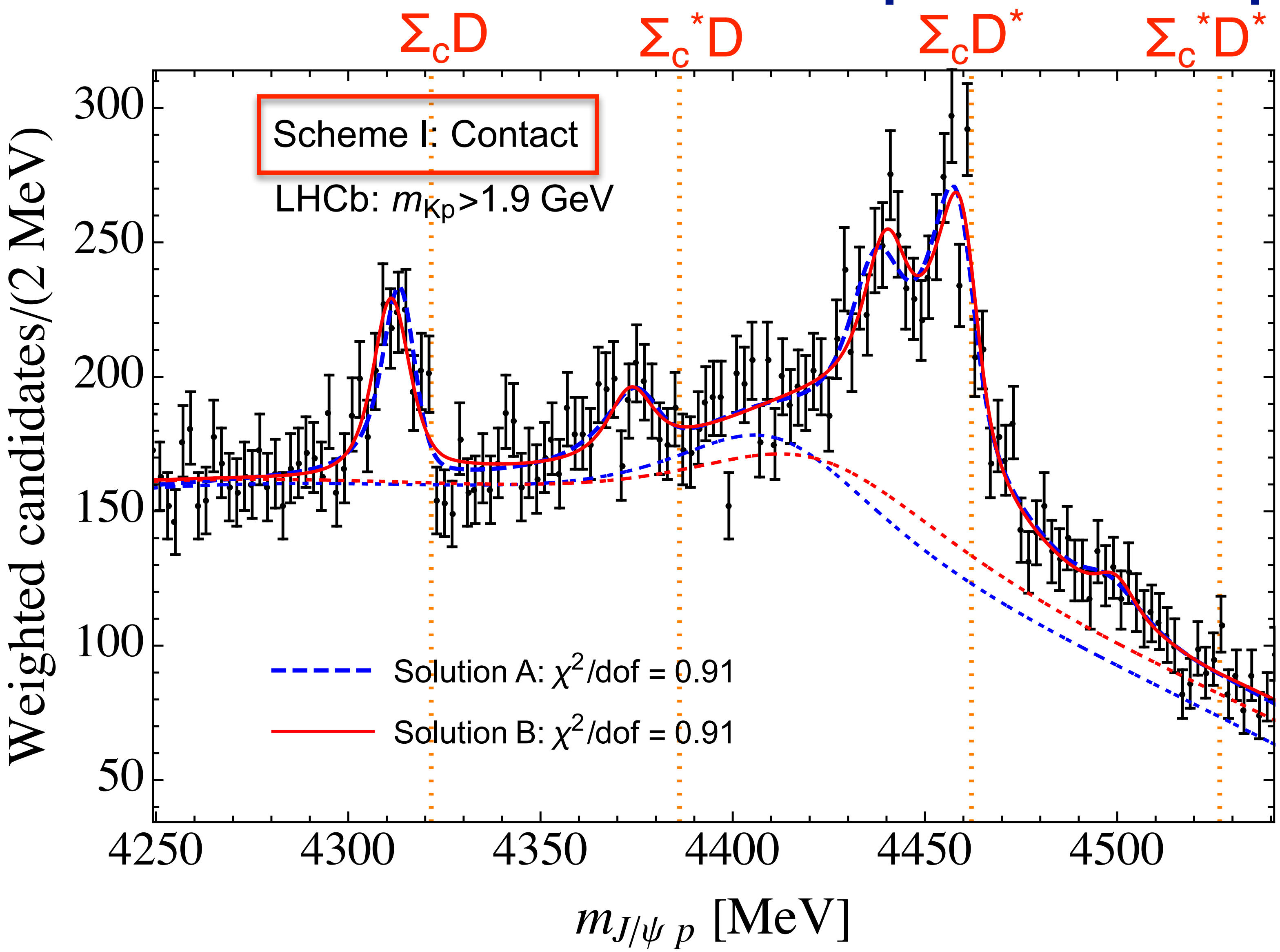
- $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ are well understood as $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c D^*$ quasi-bound states, respectively

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)	$\mathbf{\frac{1}{2}}^-$	$4440(1) - 9(2)i$	$\mathbf{\frac{3}{2}}^-$	$4441(3) - 5(2)i$
$P_c(4457)$	$\Sigma_c \bar{D}^*$ (4462.1)	$\mathbf{\frac{3}{2}}^-$	$4458(2) - 3(1)i$	$\mathbf{\frac{1}{2}}^-$	$4462(4) - 5(3)i$
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)	$\frac{5}{2}^-$	$4525(2) - 9(3)i$	$\frac{5}{2}^-$	$4501(3) - 6(4)i$

Line shape and Pc poles

Du et al. PRL 124, 072001 (2020)
JHEP 08 (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

- Two fits with equal χ^2 yield:

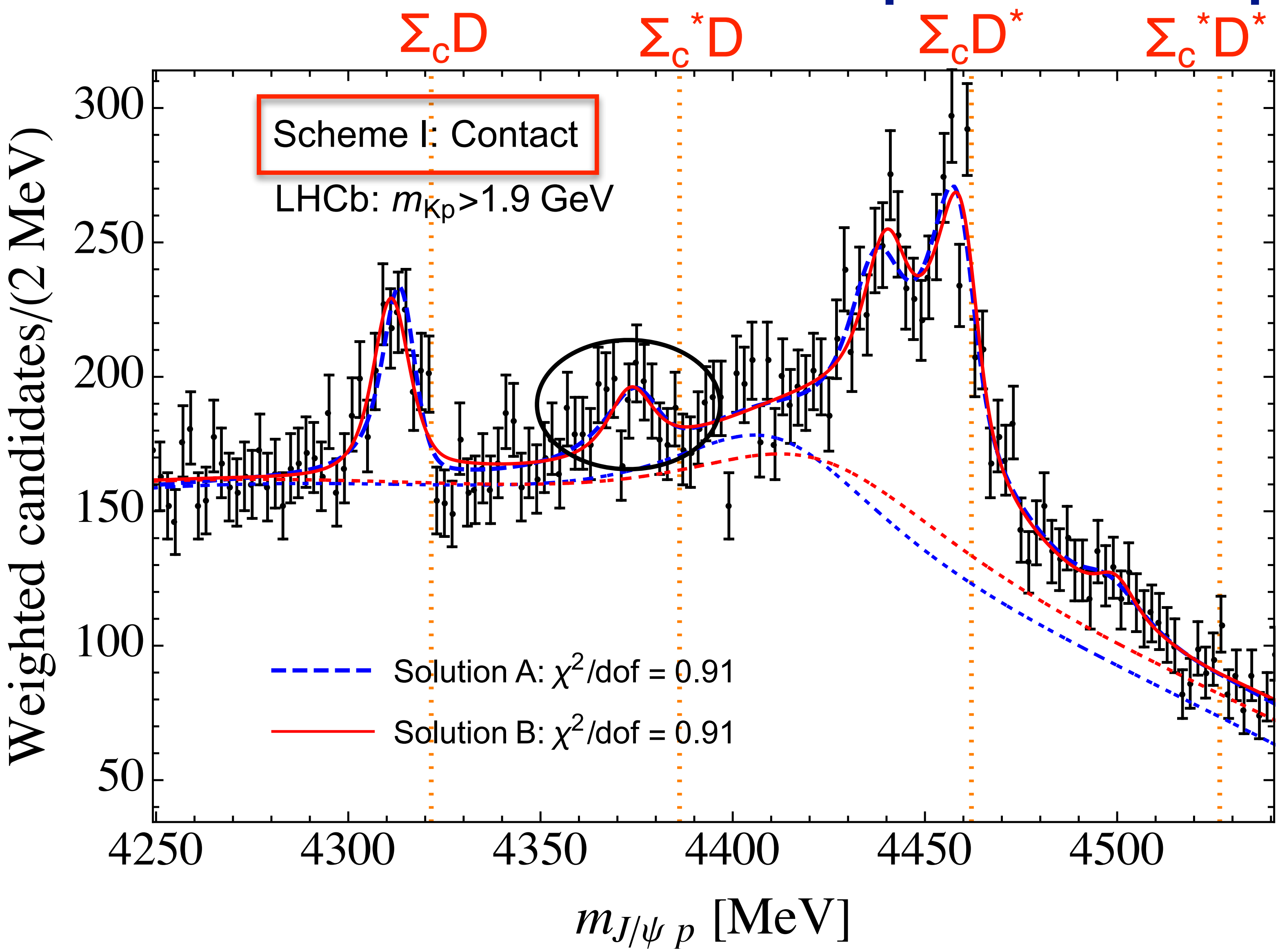
	$P_c(4440)$	$P_c(4457)$
Fit A:	$1/2^-$	$3/2^-$
Fit B:	$3/2^-$	$1/2^-$

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

Line shape and Pc poles

Du et al. PRL 124, 072001 (2020)
JHEP 08 (2021)



- Pc(4312), Pc(4440), Pc(4457) are well understood as $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c D^*$ quasi-bound states, respectively
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	Pc(4440)	Pc(4457)
Fit A:	$1/2^-$	$3/2^-$
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- A narrow Pc(4380) state predicted as a $\Sigma_c{}^* D$ $3/2^-$ molecule is seen in data

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	thr. ([MeV])	J^P	Pole [MeV]	J^P	Pole [MeV]
$P_c(4312)$	$\Sigma_c\bar{D}$ (4321.6)	$\frac{1}{2}^-$	$4314(1)-4(1)i$	$\frac{1}{2}^-$	$4312(2)-4(2)i$
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P_c	$\Sigma_c^*\bar{D}^*$ (4526.7)	$\frac{1}{2}^-$	$4498(2)-9(3)i$	$\frac{1}{2}^-$	$4526(3)-9(2)i$
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Line shape and Pc poles

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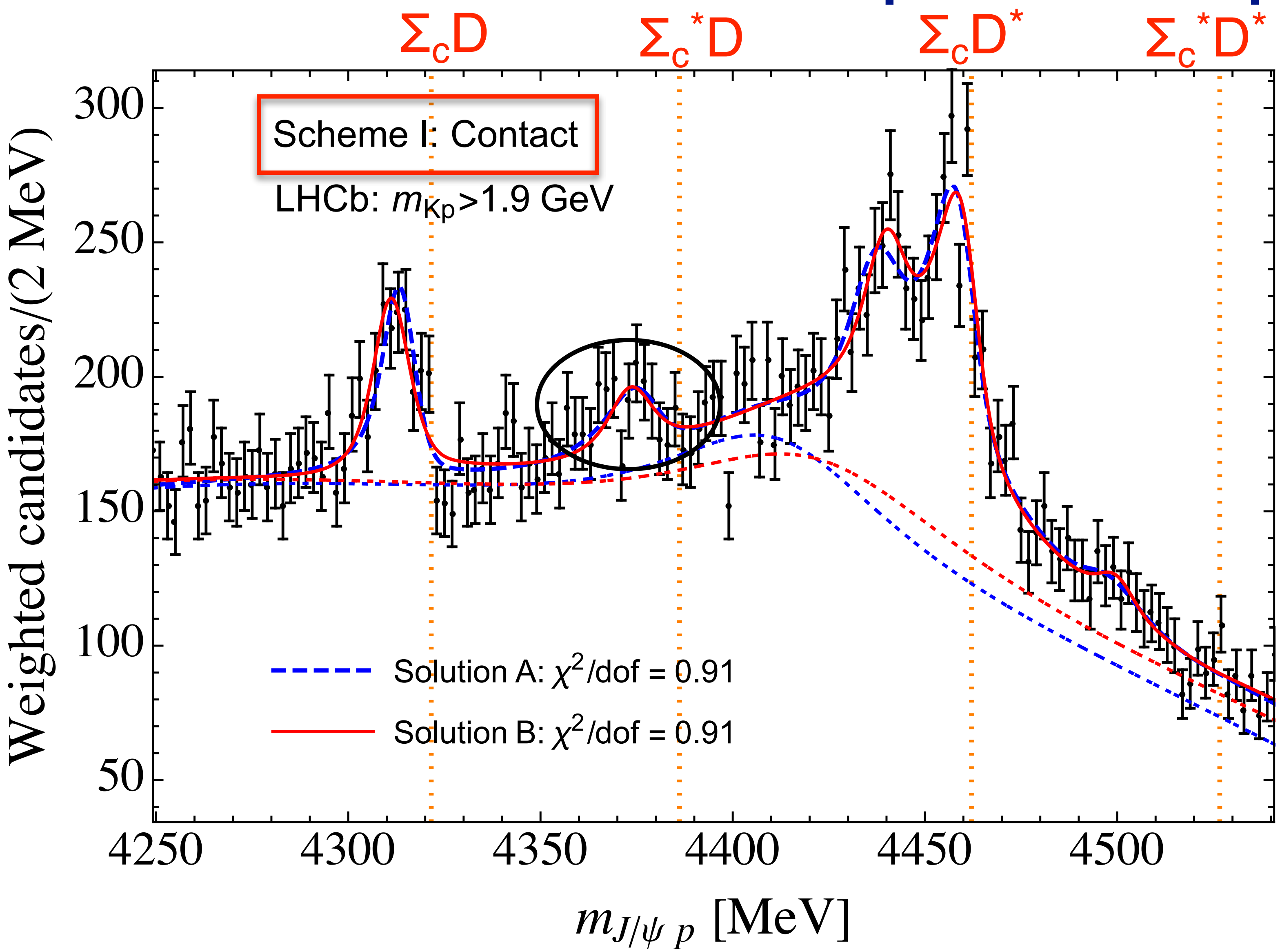

- $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ are well understood as $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma_c D^*$ quasi-bound states, respectively
  - Two fits with equal χ^2 yield:

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

- A narrow Pc(4380) state predicted as a Σ_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)	$\frac{1}{2}^-$	$4314(1)-4(1)i$	$\frac{1}{2}^-$	$4312(2)-4(2)i$
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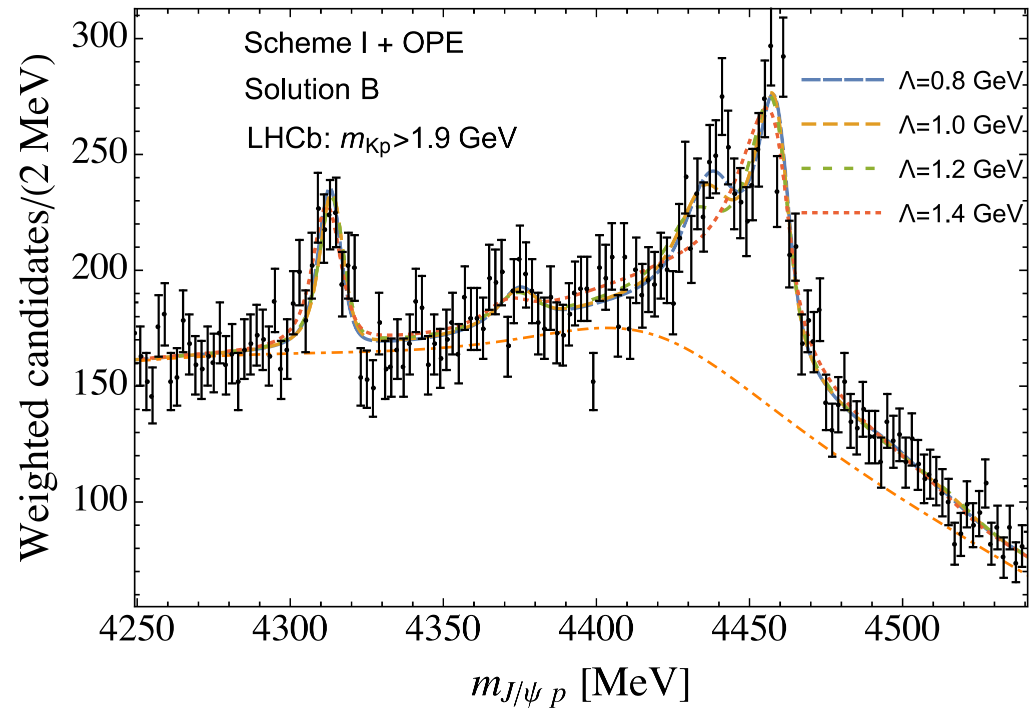
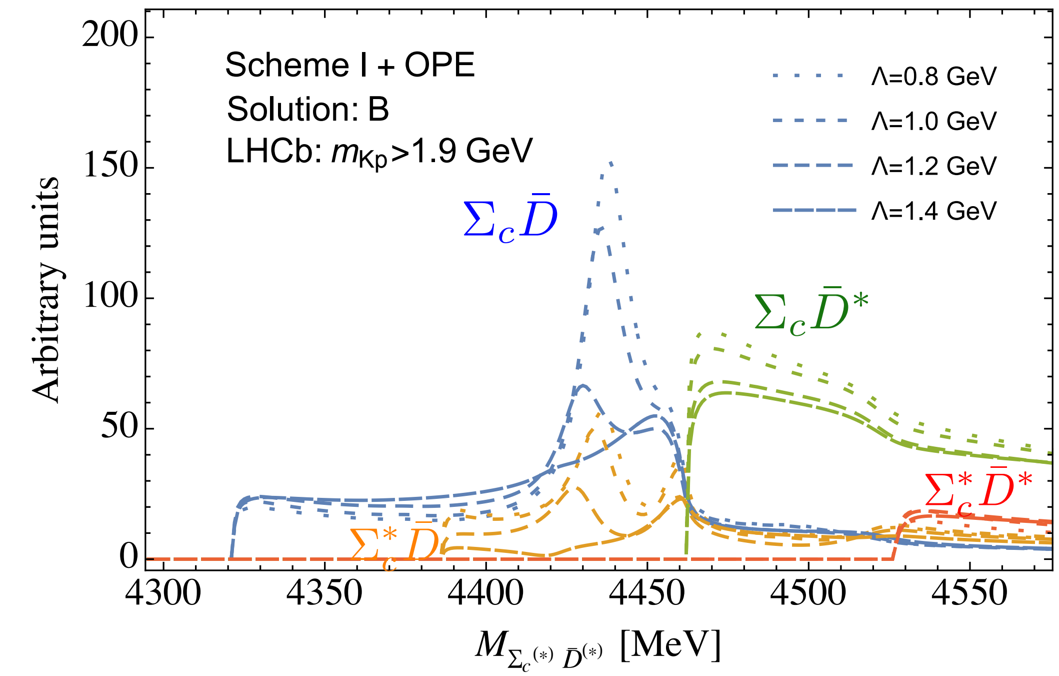
But what happens if we include pions?

Fit B

Unrenormalized OPE

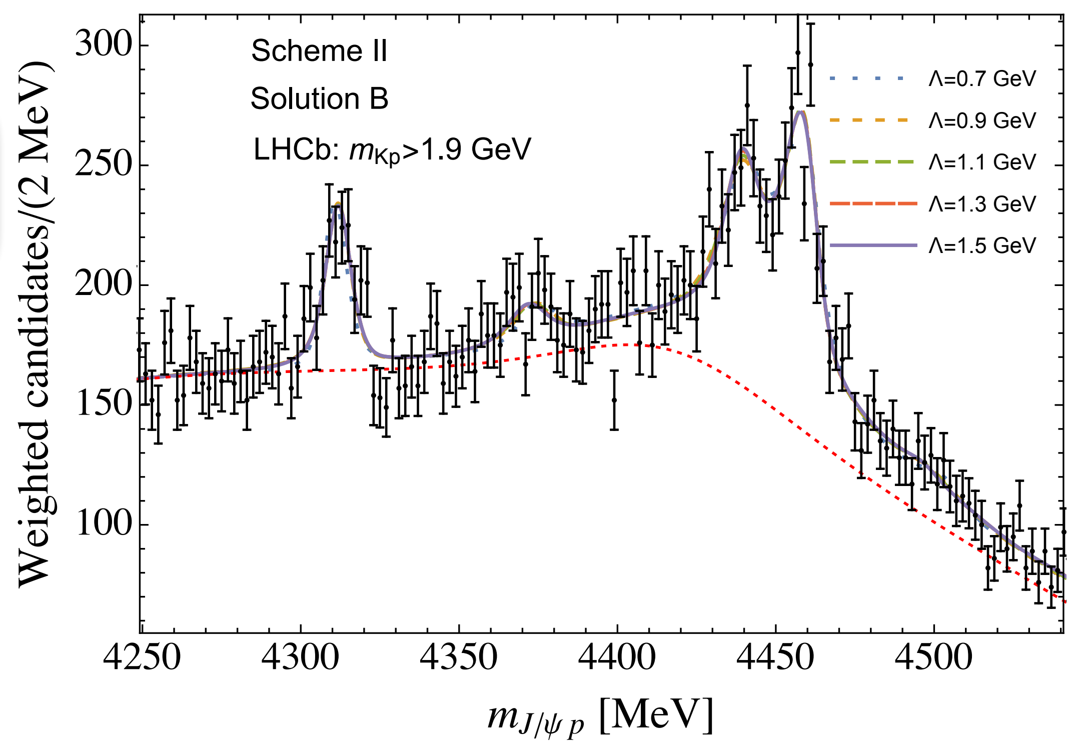
Large cutoff dependence!

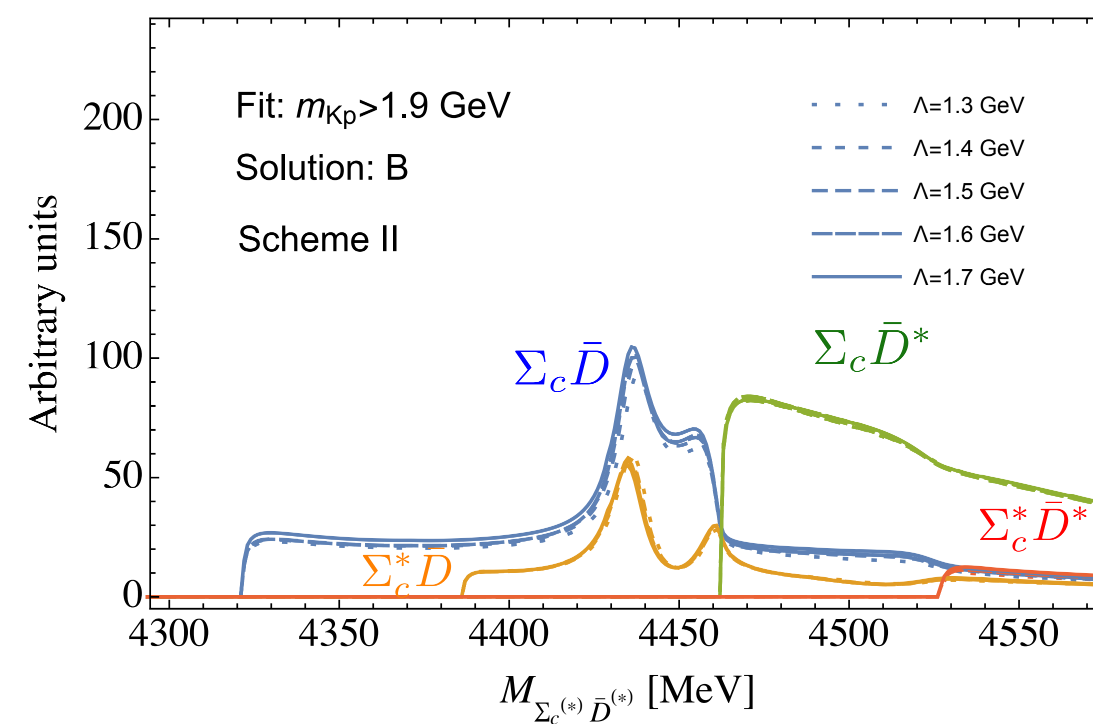




With S-D contact term

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)

Wang et al. PRD 98, 074023 (2018),
VB et al. PRD 99, 094013 (2019)

But what happens if we include pions?

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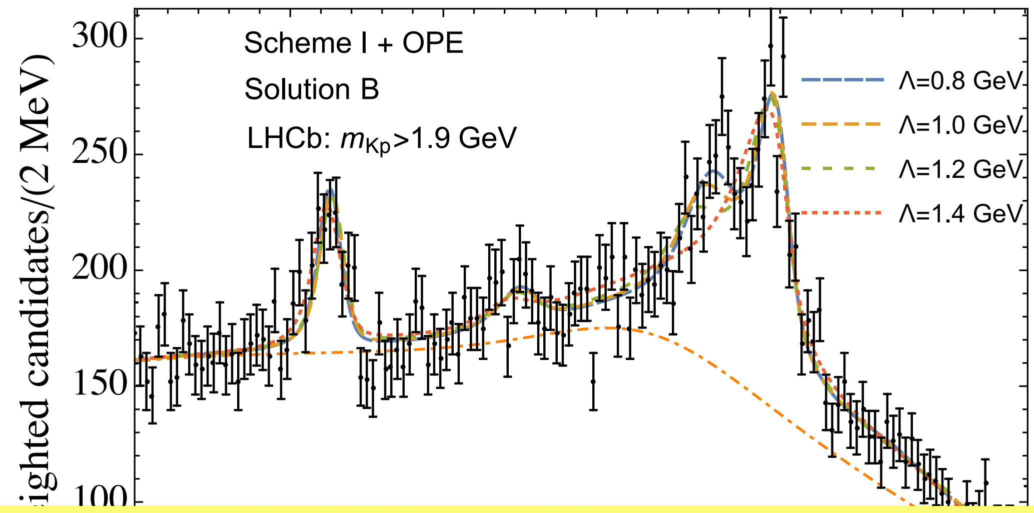
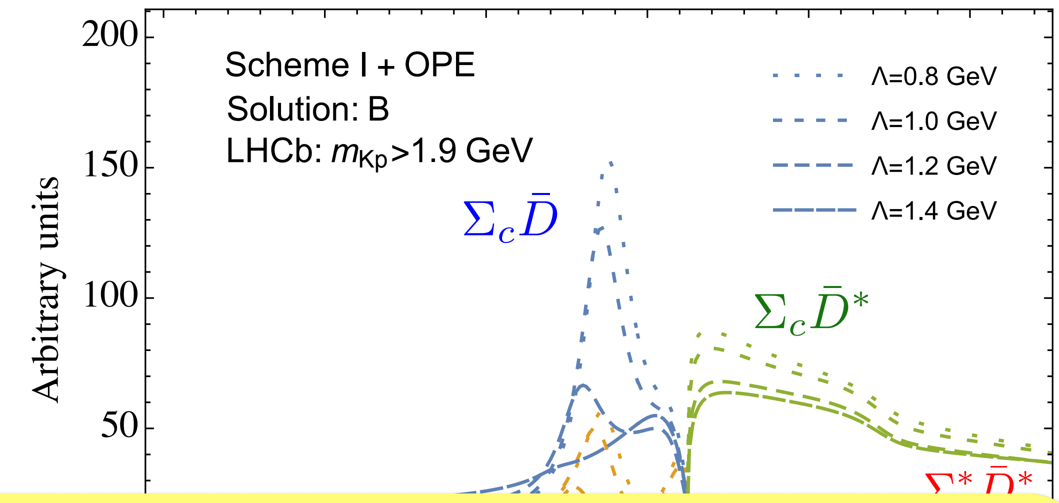
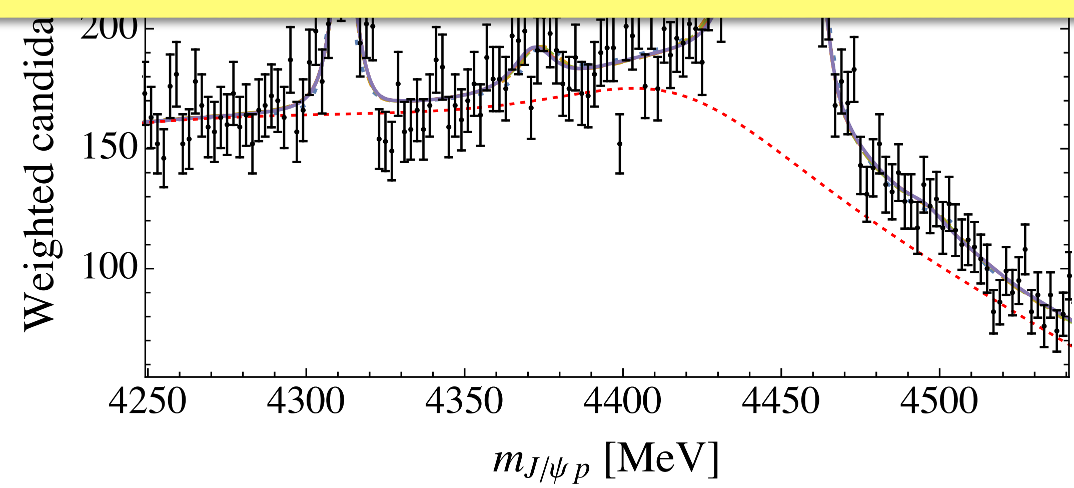


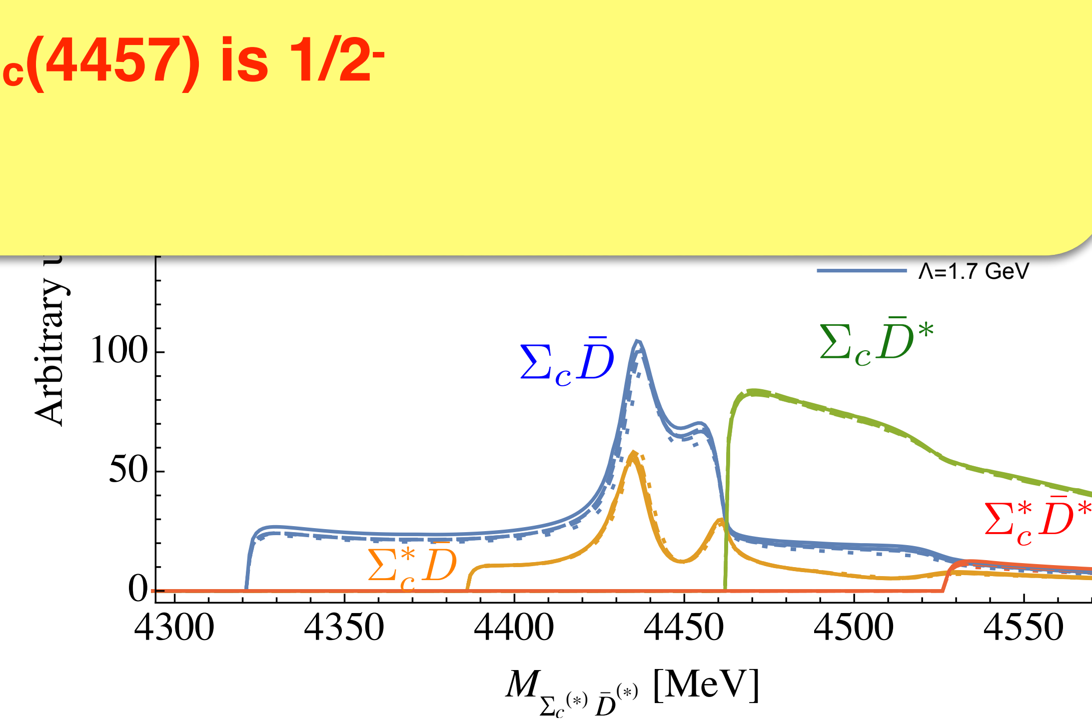


Fit B survives the inclusion of the OPE, fit A does not

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

cutoff independent results!





- Renormalizability require S-wave-to-D-wave contact term to appear together with OPE
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Wang et al. PRD 98, 074023 (2018),
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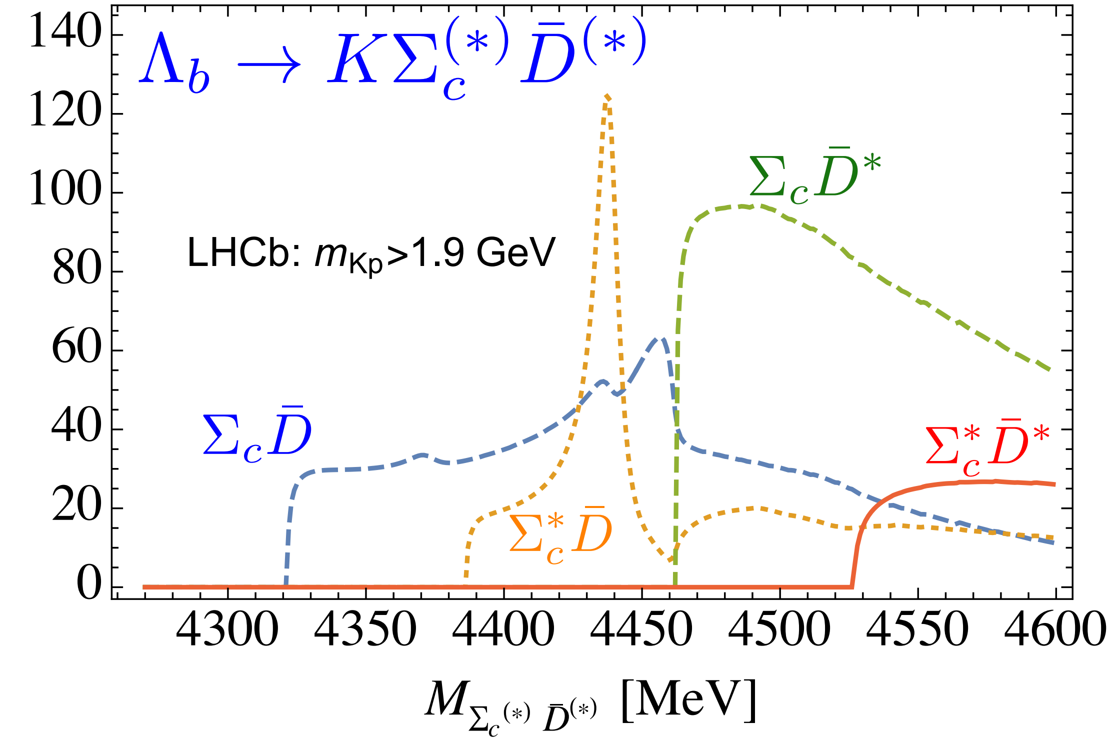
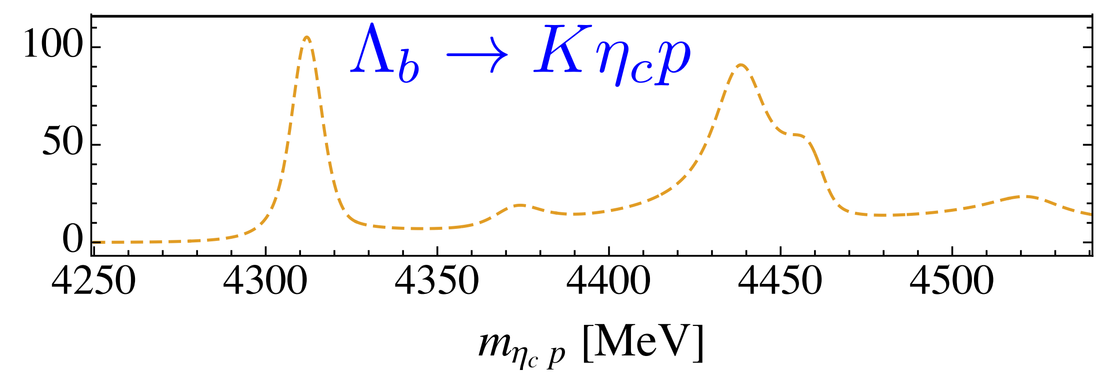
Predictions for other final states

- Strong threshold enhancements

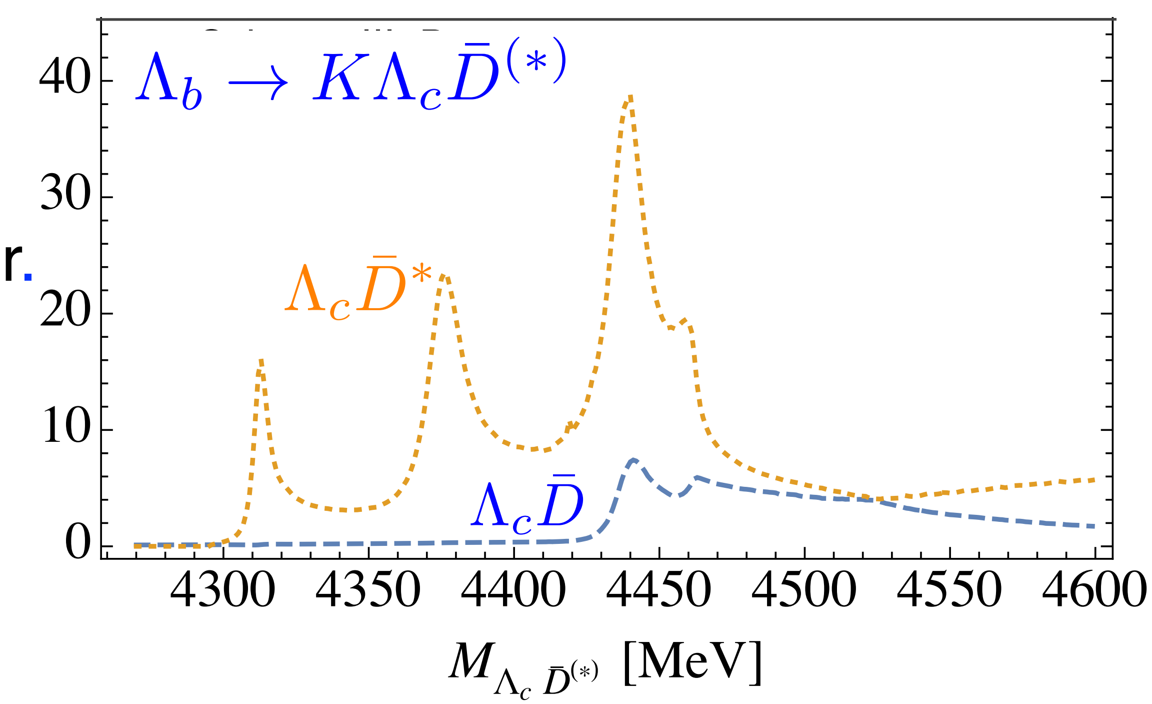


- Pc peaks are clearly visible



- $J/\Psi\ p$ data are not enough to pin down $\Lambda_c\bar{D}^{(*)}$ inter.

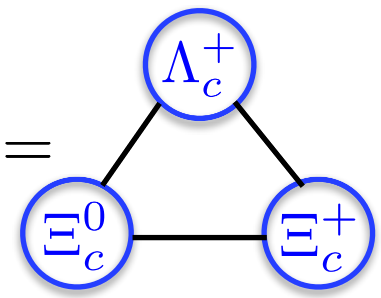
Qualitative picture: more peaks in $\Lambda_c\bar{D}^*$ than in $\Lambda_c\bar{D}$



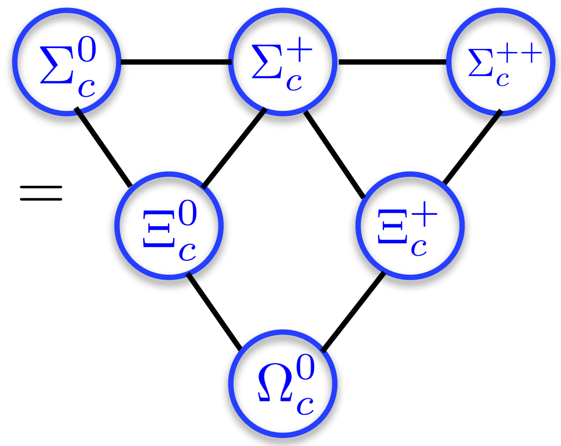
Pentaquarks as Baryon-AntiMeson molecules

- Baryonic SU(3) multiplets of S=1/2 antitriplet, S=1/2 sextet and S=3/2 sextet

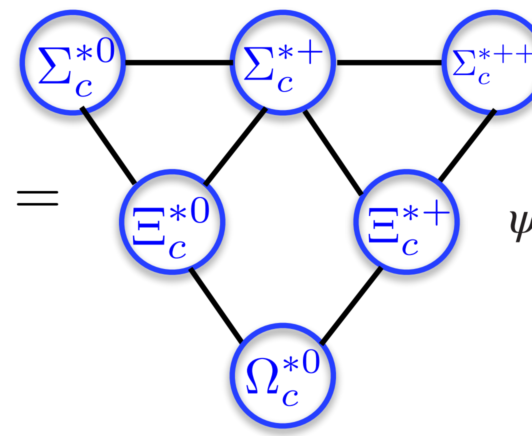
$B_{\bar{3}} =$



$B_6 =$

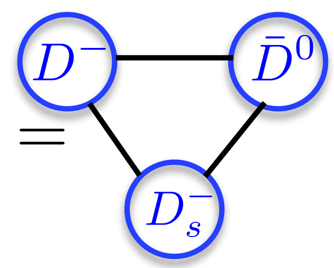


$B_6^{*\mu} =$

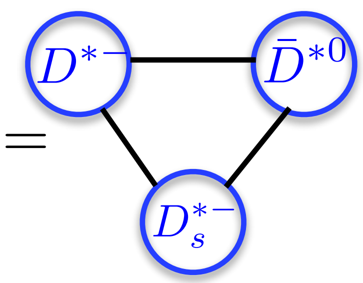


$$\psi^\mu = \mathcal{B}_6^{*\mu} - \frac{1}{\sqrt{3}}(\gamma^\mu + v^\mu)\gamma^5\mathcal{B}_6$$

- Anticharmed mesons form triplet $P =$



$P^*_\mu =$



$$\tilde{\mathcal{H}} = [\tilde{P}^*_\mu\gamma^\mu + i\tilde{P}\gamma_5]\frac{1-\not{v}}{2}$$

- Meson-Baryon interactions: $\bar{3}\times 3 = 8 + 1$ and $6 \times 3 = 10 + 8$

P_{cs} as $\Xi_c\bar{D}^{(*)}$ $\qquad$ P_c as $\Sigma_c^{(*)}\bar{D}^{(*)}$

$$\mathcal{L}_{\tilde{\mathcal{H}}\mathcal{B}_{\bar{3}}} = \tilde{D}_a\langle\bar{\tilde{\mathcal{H}}}\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\mathcal{B}}_{\bar{3}}\mathcal{B}_{\bar{3}}] + \tilde{D}_b\langle\bar{\tilde{\mathcal{H}}}\gamma^\rho\gamma_5\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\mathcal{B}}_{\bar{3}}\gamma_\rho\gamma_5\mathcal{B}_{\bar{3}}]$$
$$+ \tilde{E}_a\langle\bar{\tilde{\mathcal{H}}}\lambda^i\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\mathcal{B}}_{\bar{3}}\lambda_i\mathcal{B}_{\bar{3}}]$$
$$+ \tilde{E}_b\langle\bar{\tilde{\mathcal{H}}}\gamma^\rho\gamma_5\lambda^i\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\mathcal{B}}_{\bar{3}}\gamma_\rho\gamma_5\lambda_i\mathcal{B}_{\bar{3}}],$$

$$\mathcal{L}_{\tilde{\mathcal{H}}\mathcal{B}_6^{(*)}} = D_a\langle\bar{\tilde{\mathcal{H}}}\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\psi}^\mu\psi_\mu]$$
$$+ iD_b\epsilon_{\sigma\mu\nu\rho}v^\sigma\langle\bar{\tilde{\mathcal{H}}}\gamma^\rho\gamma_5\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\psi}^\mu\psi^\nu]$$
$$+ E_a\langle\bar{\tilde{\mathcal{H}}}\lambda^i\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\psi}^\mu\lambda_i\psi_\mu]$$
$$+ iE_b\epsilon_{\sigma\mu\nu\rho}v^\sigma\langle\bar{\tilde{\mathcal{H}}}\gamma^\rho\gamma_5\lambda^i\tilde{\mathcal{H}}\rangle\mathrm{Tr}[\bar{\psi}^\mu\lambda_i\psi^\nu]$$

- 8 LECs + LECs from coupled channels $\tilde{\mathcal{H}}\mathcal{B}_{\bar{3}} - \tilde{\mathcal{H}}\mathcal{B}_6$

For detailes see, e.g., review by Meng et al., Phys.Rept. 1019 (2023)

Strange molecular pentaquarks

Chen et al. (2022), Karliner and Rosner (2022), Meng et al 2022, Yan et al. (2023), Nakamura and Wu (2023), …

- Without coupled-channels $V_{\rm CT}^{1/2^-}(\Xi_c\bar{D}\to\Xi_c\bar{D}) = V_{\rm CT}^{1/2^-}(\Xi_c\bar{D}^*\to\Xi_c\bar{D}^*) = V_{\rm CT}^{3/2^-}(\Xi_c\bar{D}^*\to\Xi_c\bar{D}^*)$

  ⇒ same binding energies of P_{cs} (4338) and P_{cs} (4459)

  but $M(P_{cs}(4338)) - M(\Xi_c\bar{D}) \approx -3$ MeV ⇒ above threshold!

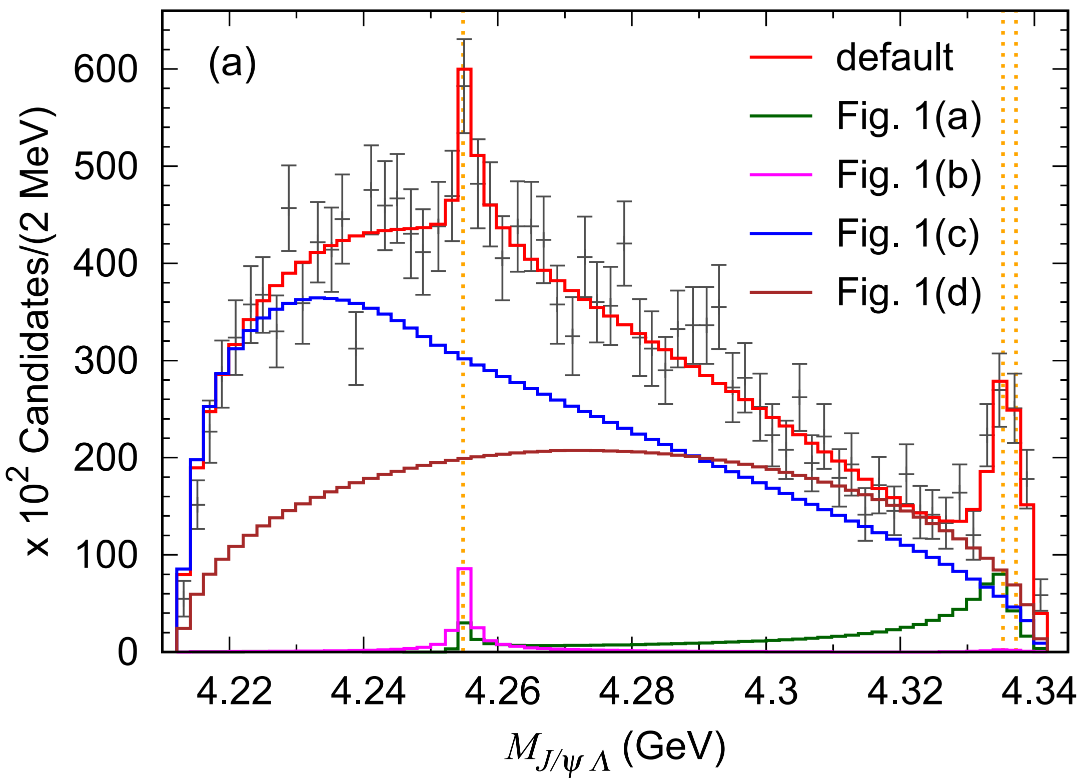
  $M(P_{cs}(4459)) - M(\Xi_c\bar{D}^*) \approx 19$ MeV

- Coupled-channel contact $\Xi_c\bar{D}\to\Lambda_c\bar{D}_s$

  Nakamura and Wu, PRD 108, L011501 (2023)

  — accounts for the P_{cs}(4338) width

  — predicts a virtual state near $\Lambda_c\bar{D}_s$



- But no full coupled channel analysis of P_{cs} (4338) and P_{cs} (4459) yet

  $\Lambda_c\bar{D}_s,\ \Xi_c\bar{D},\ \Lambda_c\bar{D}_s^*,\ \Xi_c\bar{D}^*,\ \Xi_c'\bar{D},\ \Xi_c'\bar{D}^*,\ \Xi_c^*\bar{D}^*$ J=1/2

  $\Lambda_c\bar{D}_s^*,\ \Xi_c\bar{D}^*,\ \Xi_c^*\bar{D},\ \Xi_c'\bar{D}^*,\ \Xi_c^*\bar{D}^*$ J=3/2

  — the OPE can also contribute here

Conclusions

- $P_{c(s)}$ sit near S-wave meson-baryon thresholds: Molecular interpretation is very tempting and consistent with available data.

- But other scenarios such as hadrocharmonia and compact pentaquarks are also possible

- Key Info: Studying $P_{c(s)}$ in various final states and determining their quantum numbers

  Positive parities exclude molecules for $P_{c(s)}$

- Sensitivity to production process: $\Lambda_b(\Xi_b)$ decays, $B_{(s)}$ decays

  $J/\Psi\ p$ photoproduction Talk by D. Winney

SIS100: $pp \to p\Sigma_c^{(*)}\bar{D}^{(*)},\ p\Lambda_c\bar{D}^{(*)}\ ppJ/\psi;\ p\,\Lambda_c\bar{D}_s^{(*)}K,\ p\,\Xi_c^{(\prime *)}\bar{D}^{(*)}K,\ \ldots$

- Pentaquarks in lattice QCD: first results Skerbis, Prelovsek (2019); HAL QCD (2018); Xing et al. (2022)

– Lüscher method fails in the presence of singularities (left-hand cuts) from long-range interactions

– New method to extract infinite volume amplitudes from FV energy levels with cuts Meng et al arXiv: 2312.01930 see also Du et al. PRL 2023

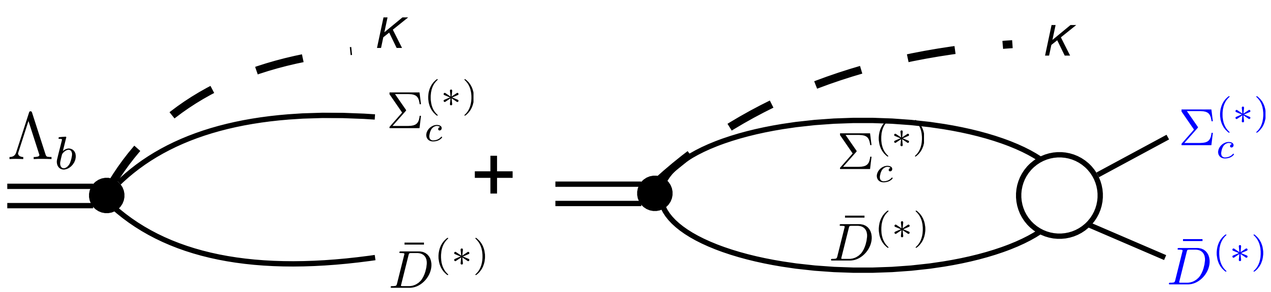
Backup

Formalism: production and inelastic channels

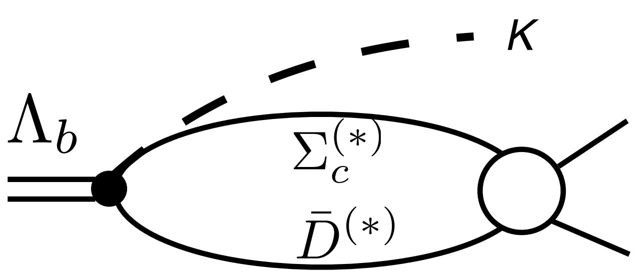
— Weak production $\Lambda_b^0 \to K\,\Sigma^{(*)}D^{(*)}$

7 states

$U_{\rm el} =$



$U_{\rm inel} =$



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

— No direct inelastic transitions

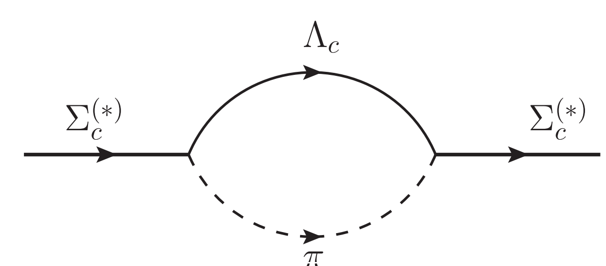
— via couplings to elastic channels

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

Green function:

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

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



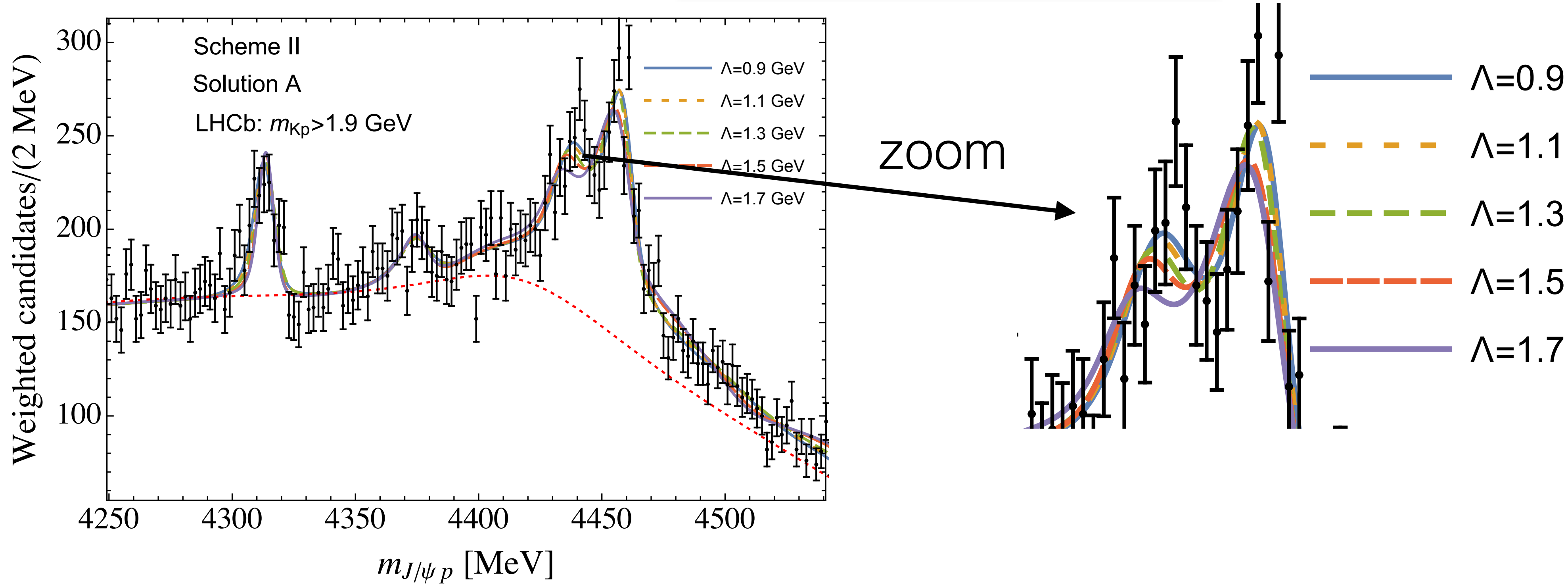
generates $\bar{D}\Lambda_c\pi$ cut

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

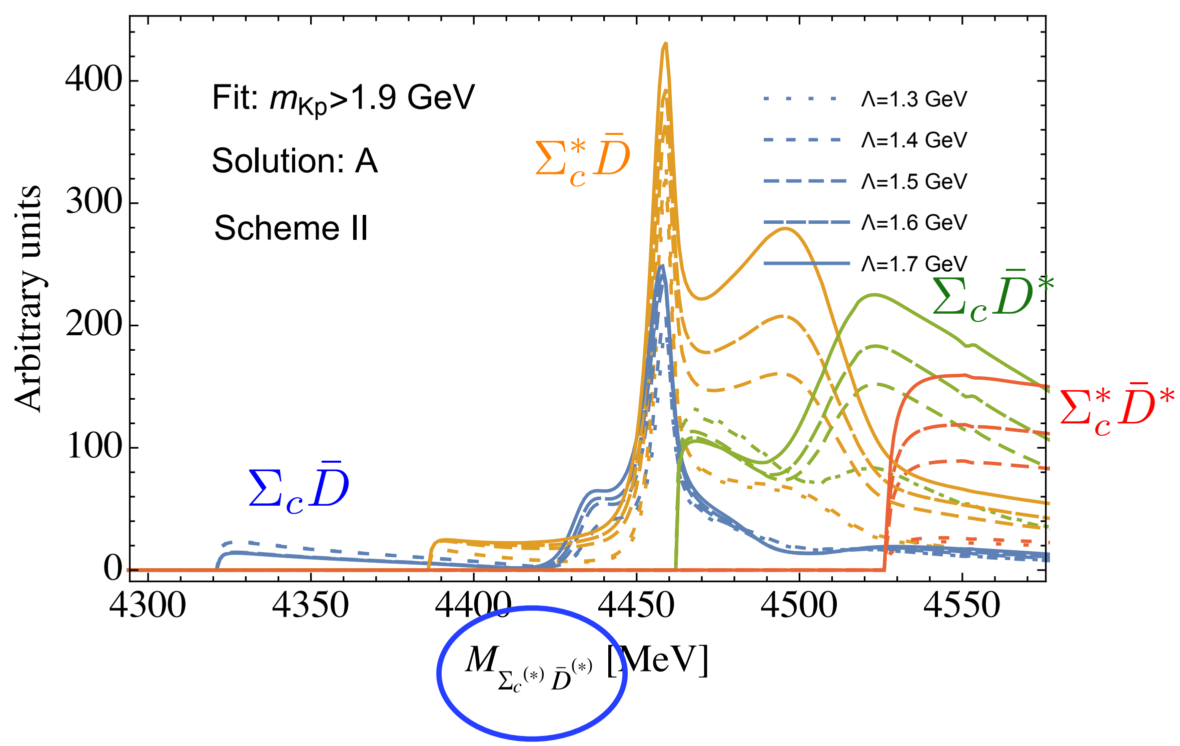
Fit A

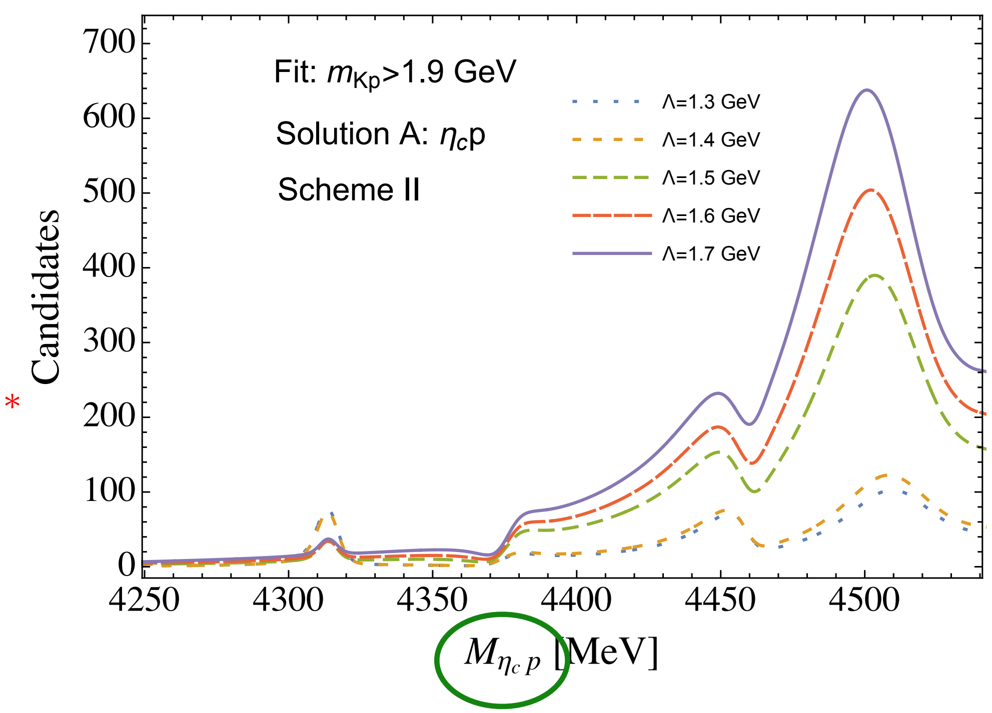
scheme II = contact +OPE

Fitted



Predicted





- Fit A does not exist without the S-D contact term at all
- The inclusion of the S-D term does not help much

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

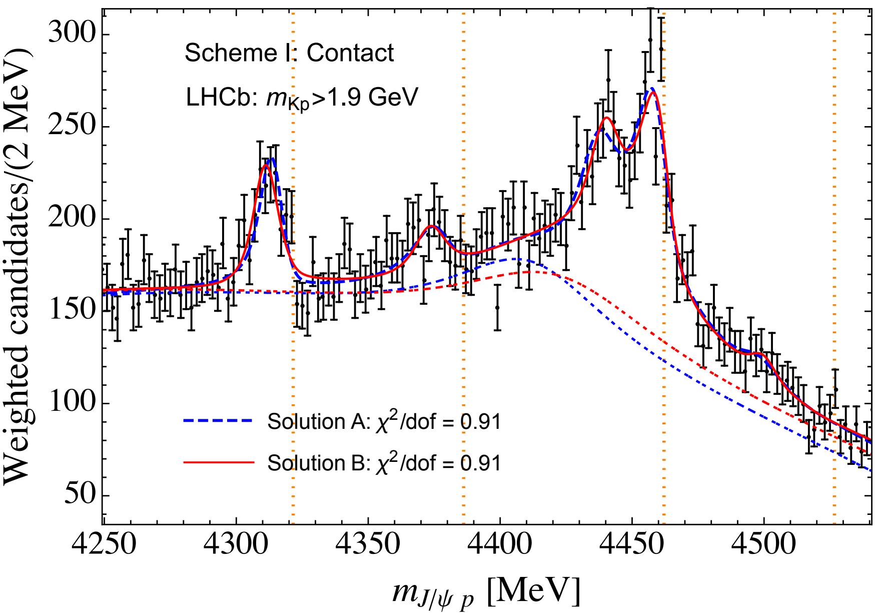
scheme I = contact

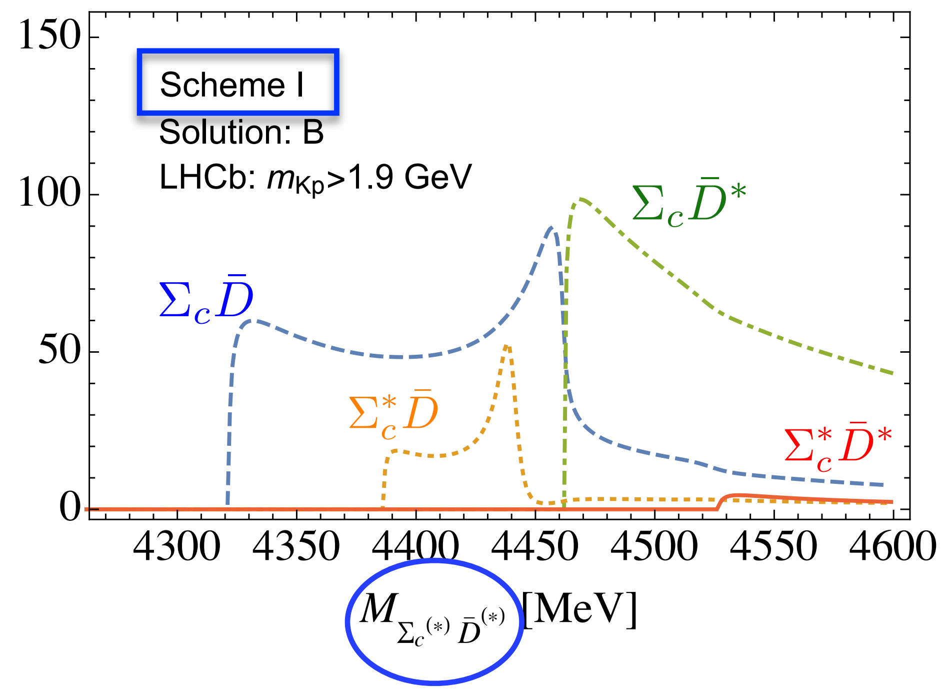
scheme II = contact +OPE

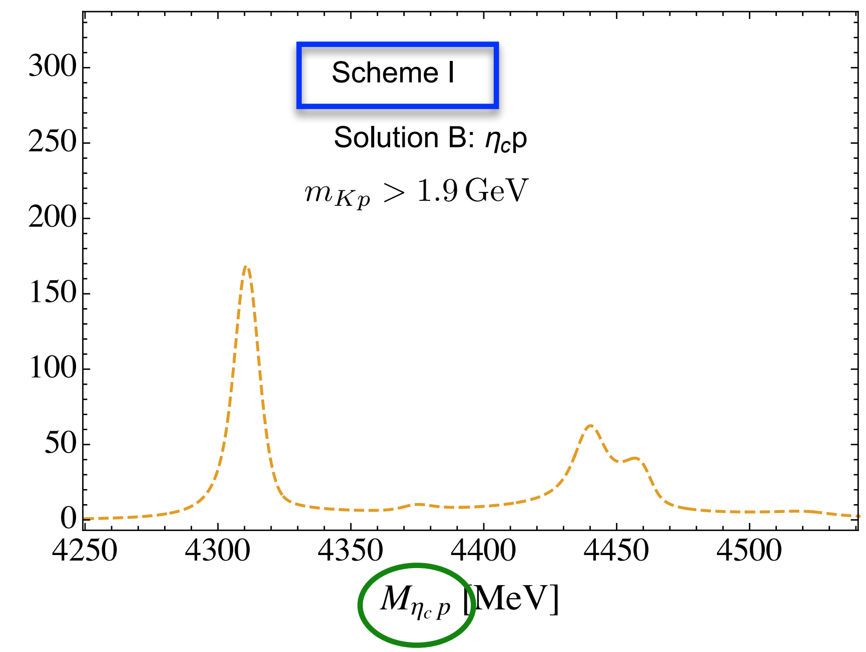
The effect from OPE:

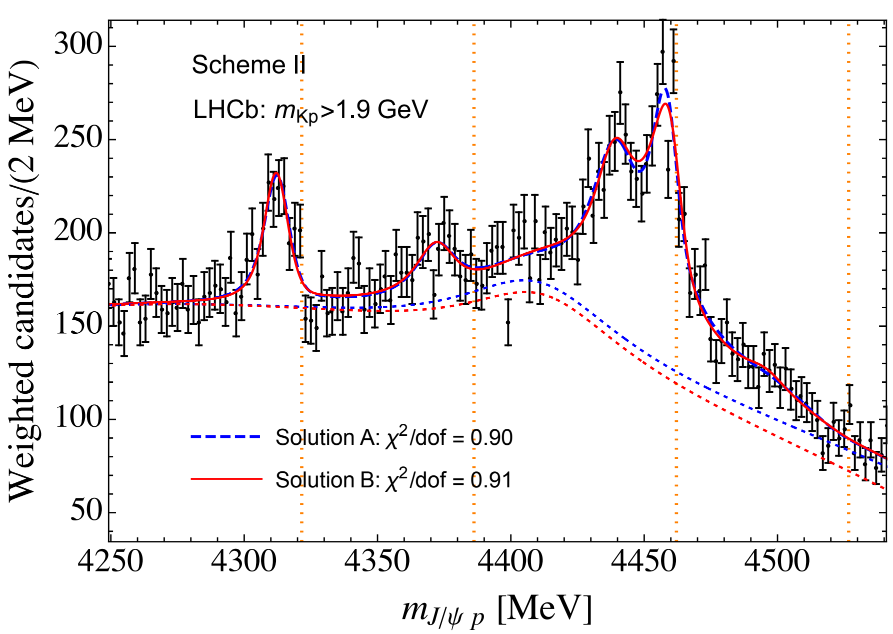
Fitted

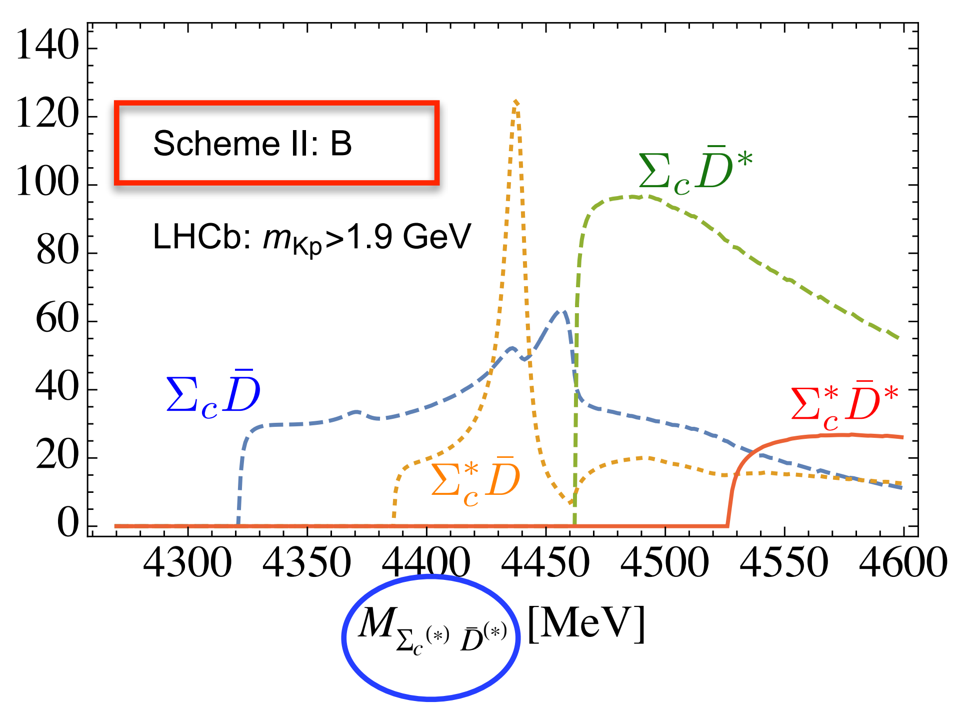
Predicted

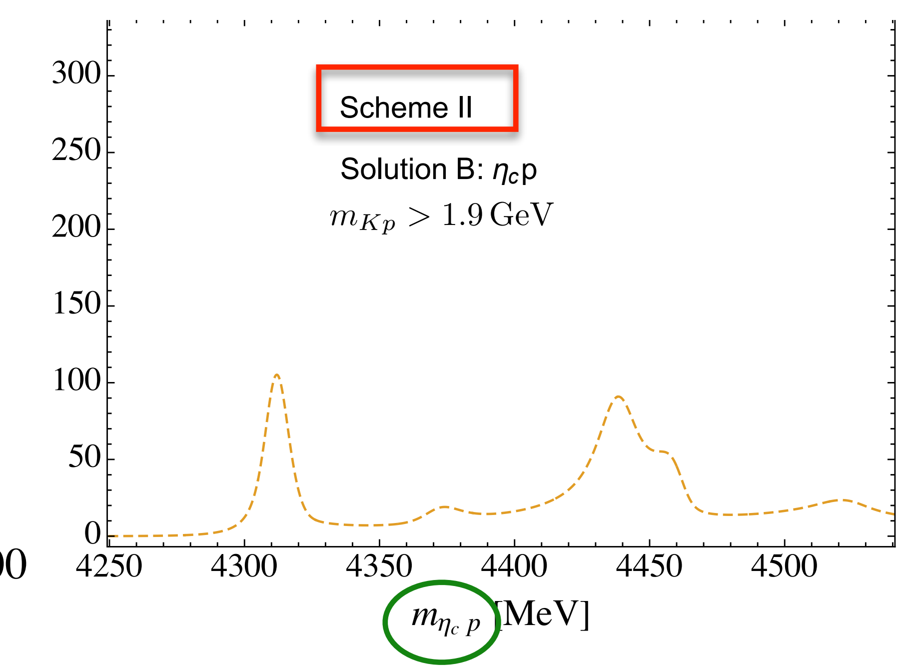






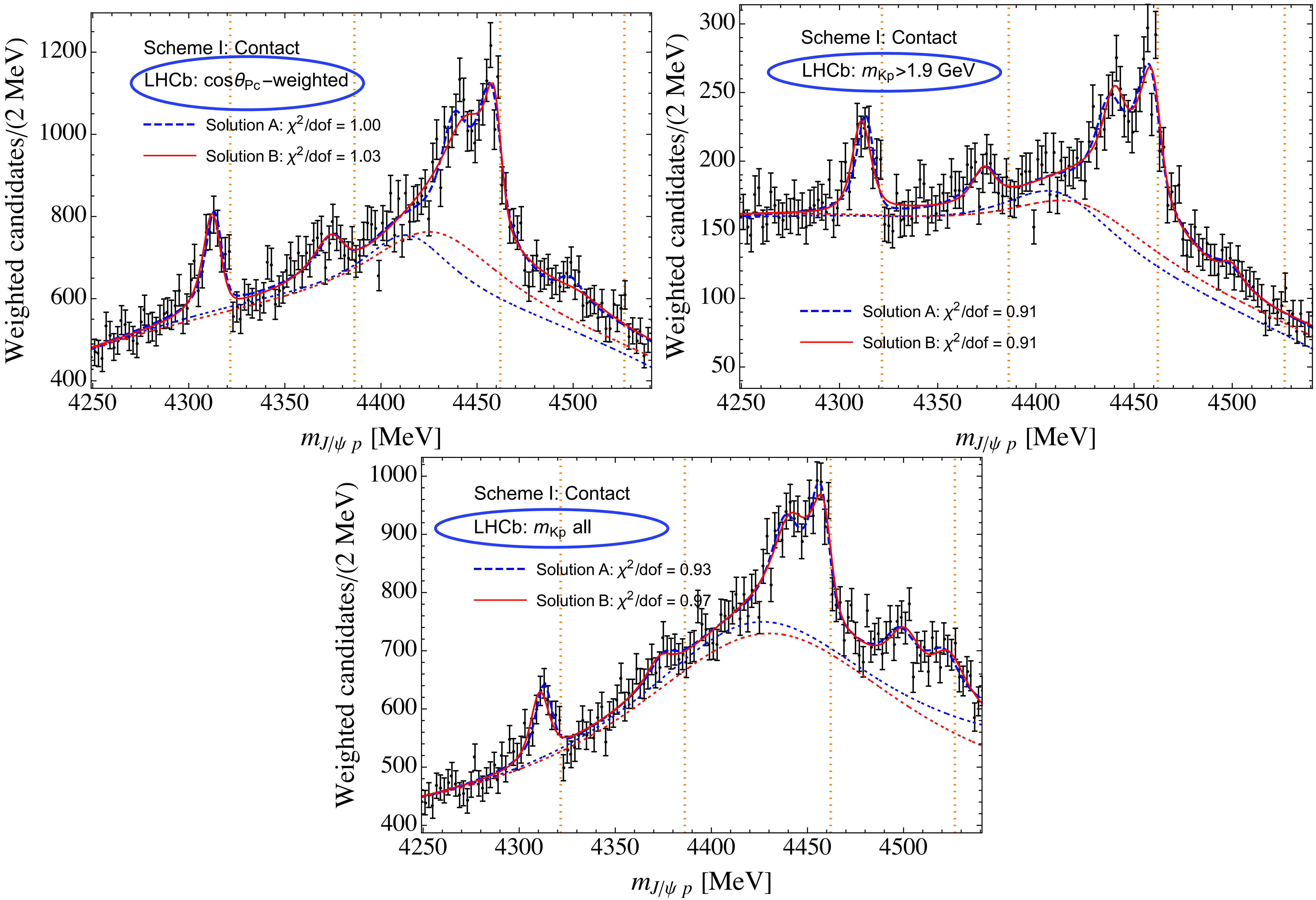






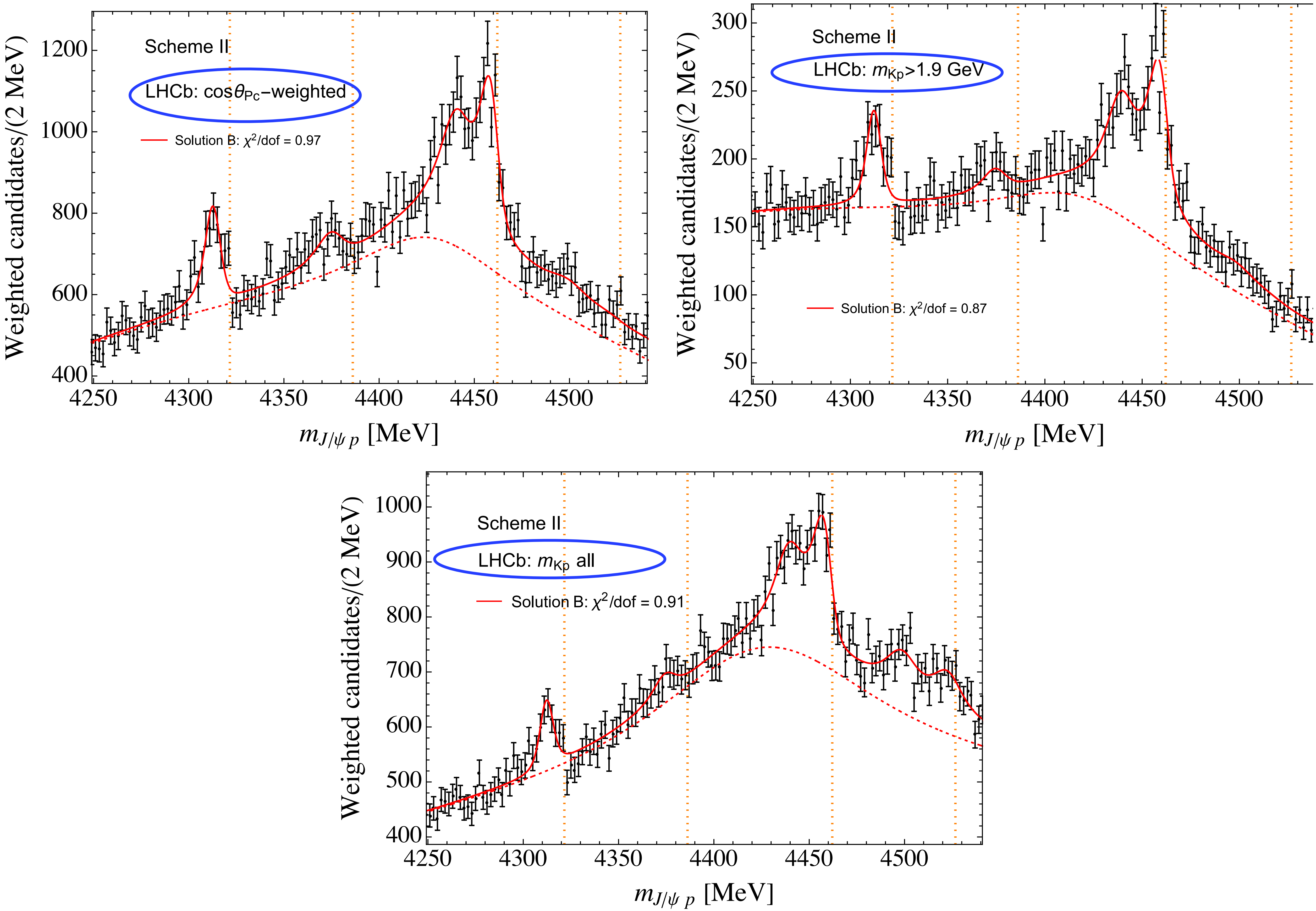
- Qualitatively similar results: threshold enhancements in the dominant channels
- The inclusion of OPE has a visible impact on the peaks strength

"Contact" Fits to three sets of LHCb data



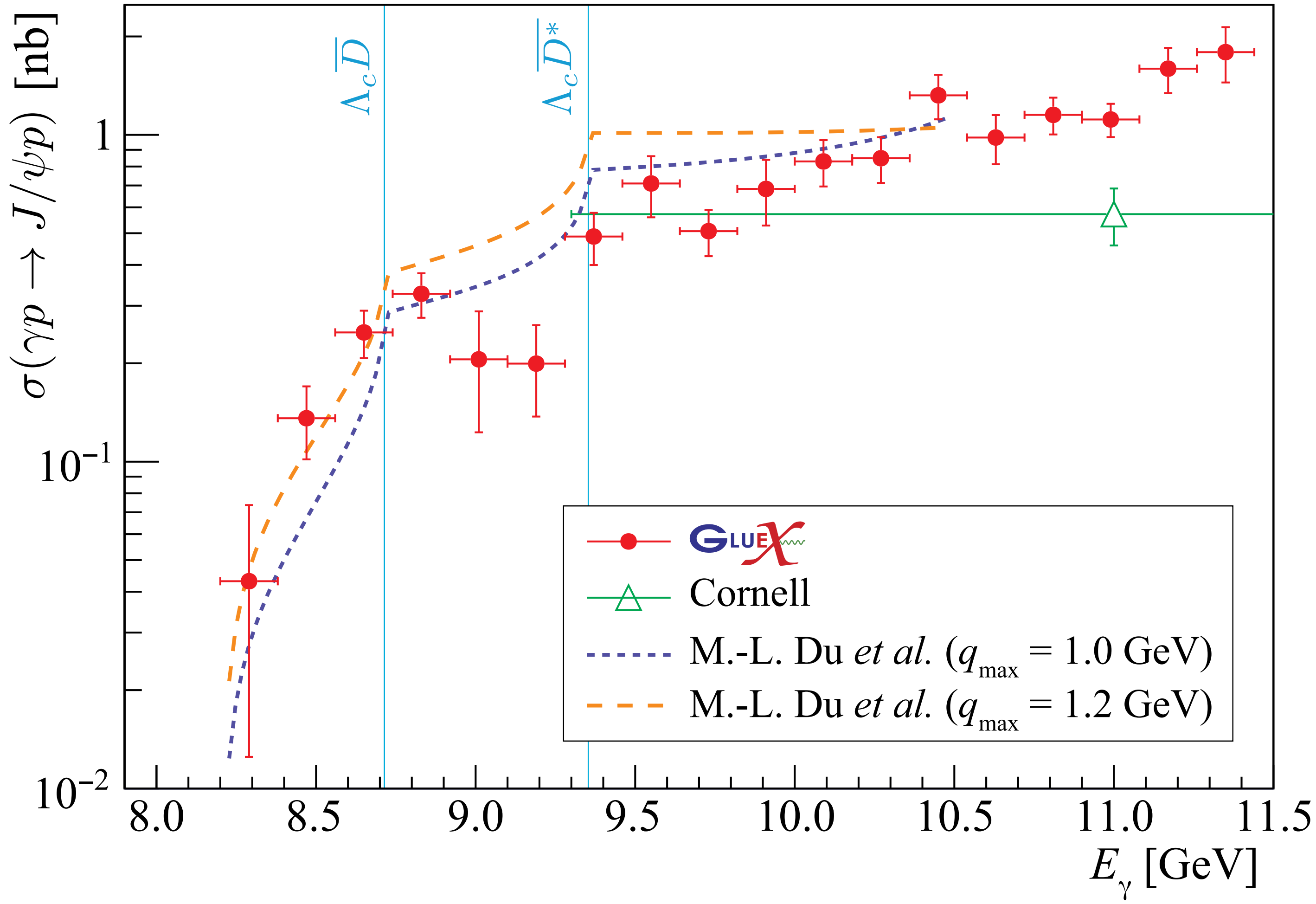
⇒ Consistent values for the Pc's poles from all fits

Pionful Fits to three sets of LHCb data



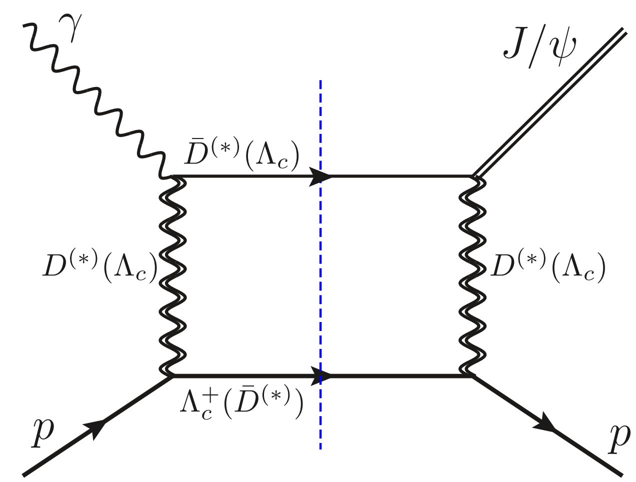
⇒ Consistent values for the Pc's poles from all fits

GlueX photoproduction



GlueX, PRC 108, 2023

Our results: Du et al. EPJC 80 (2020)



see also JPAC PRD 108 (2023)

talk by Daniel Winney Wednesday

Gluex data analysis by Strakovsky et al. PRC 108 (2023) :

—Interference of a resonance with background

— dip in data can be described if a resonance mass is 77 MeV below LHCb peak