Strong decays of pentaquark states in molecule scenario

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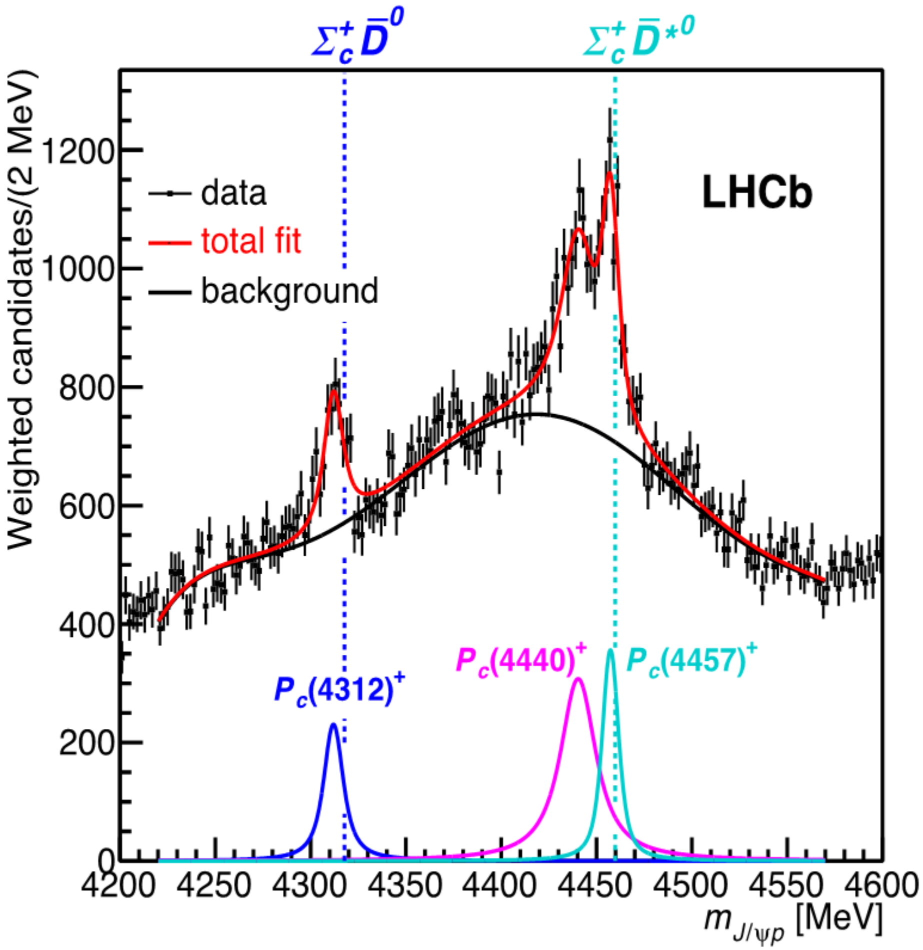
Based on Yonghui Lin, Bingsong Zou, arXiv:1908.05309

Motivation: LHCb Observables



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

LHCb, PRL 122, 222001 (2019)

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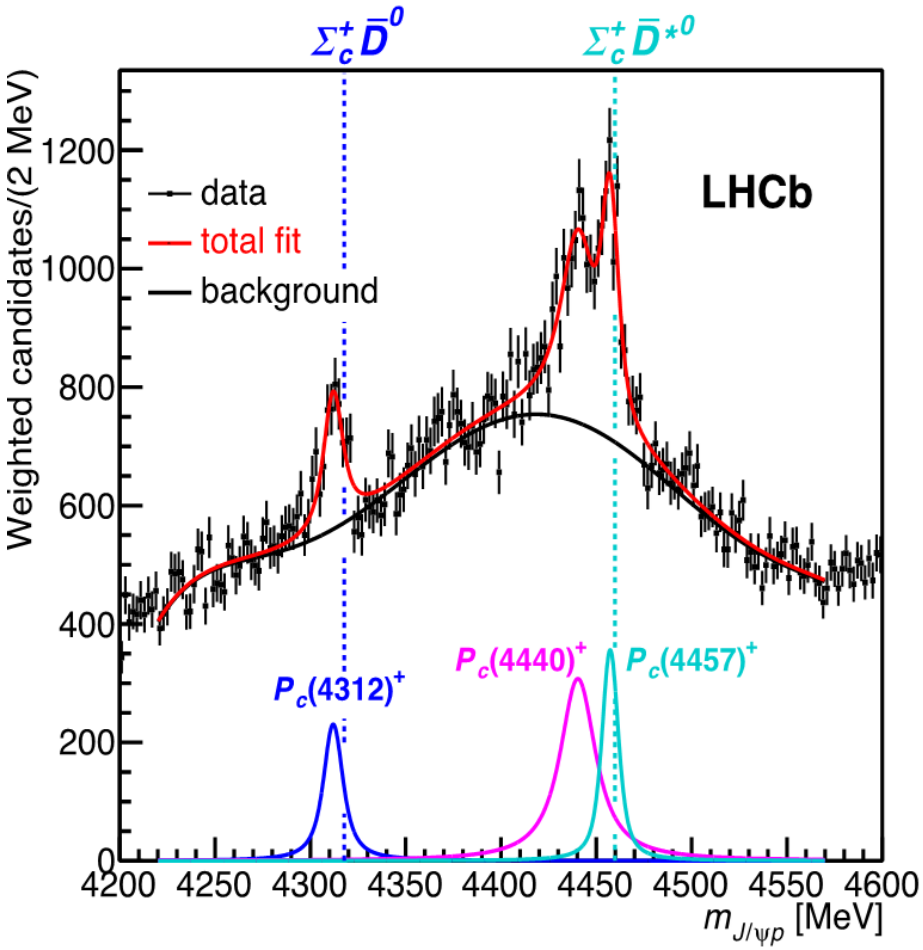

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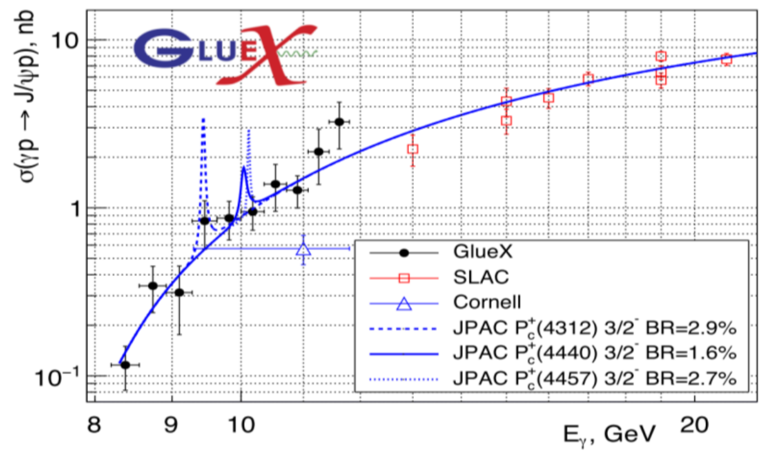
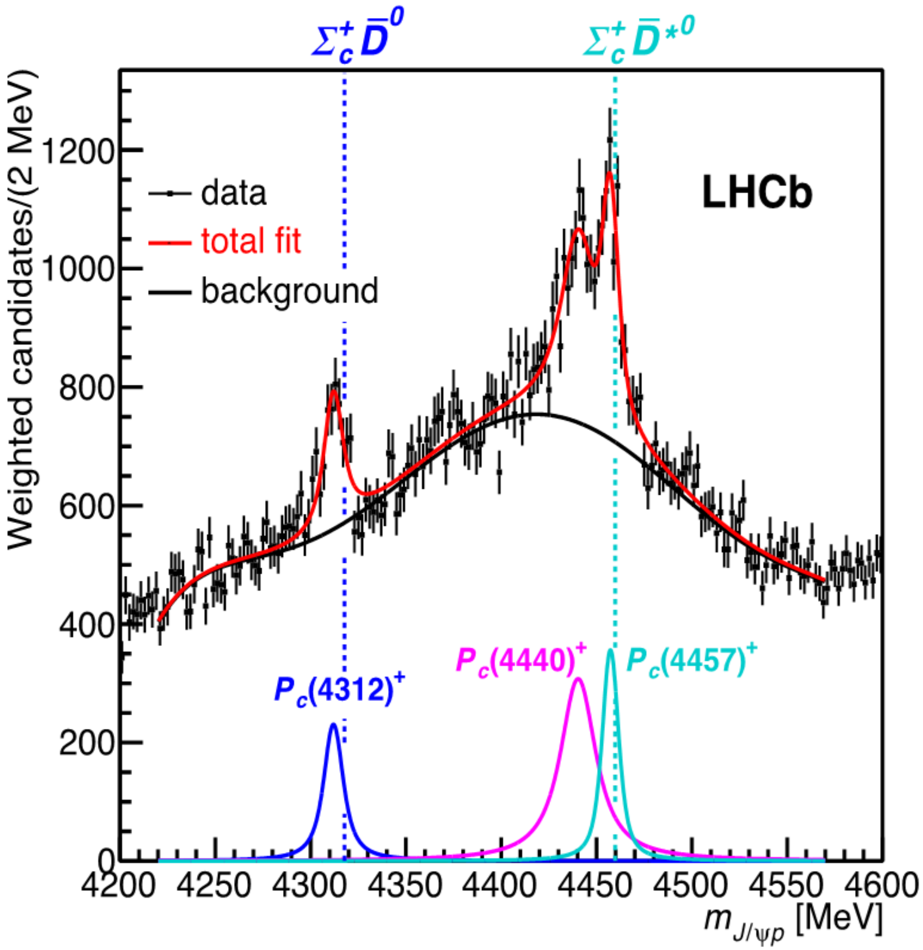


GlueX, PRL 123, 072001 (2019)

Model-dependent upper limits at 90% CL (assuming $J^P=3/2^-$):

- Br($P_c(4312)$ → J/ψ p) **< 4.6%**
- Br($P_c(4440)$ → J/ψ p) **< 2.3%**
- Br($P_c(4457)$ → J/ψ p) **< 3.8%**

Motivation: LHCb Observables



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Inner structure?

J^P?

Motivation: Predictions

- Many theoretical predictions for $\bar{D}^{(*)}\Sigma_c$ published before 2015, some in quantitative agreement with the newly LHCb data
  - J.-J. Wu $et\ al$, PRL 105, 232001 (2010)
  - W.-L. Wang $et\ al$, PRC 84, 015203 (2011)
  - Z.-C. Yang $et\ al$, CPC 36, 6 (2012)
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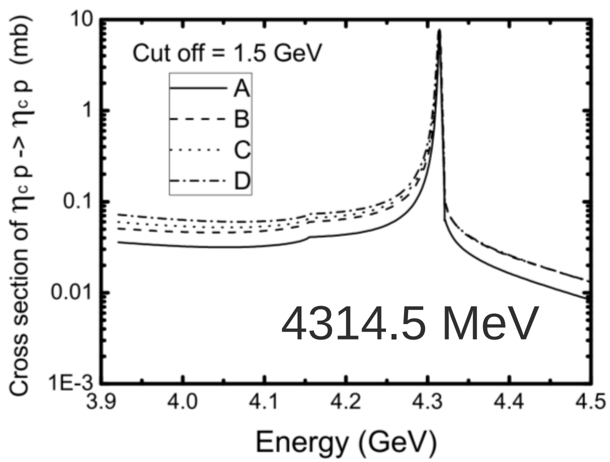


ΔE-binding energy

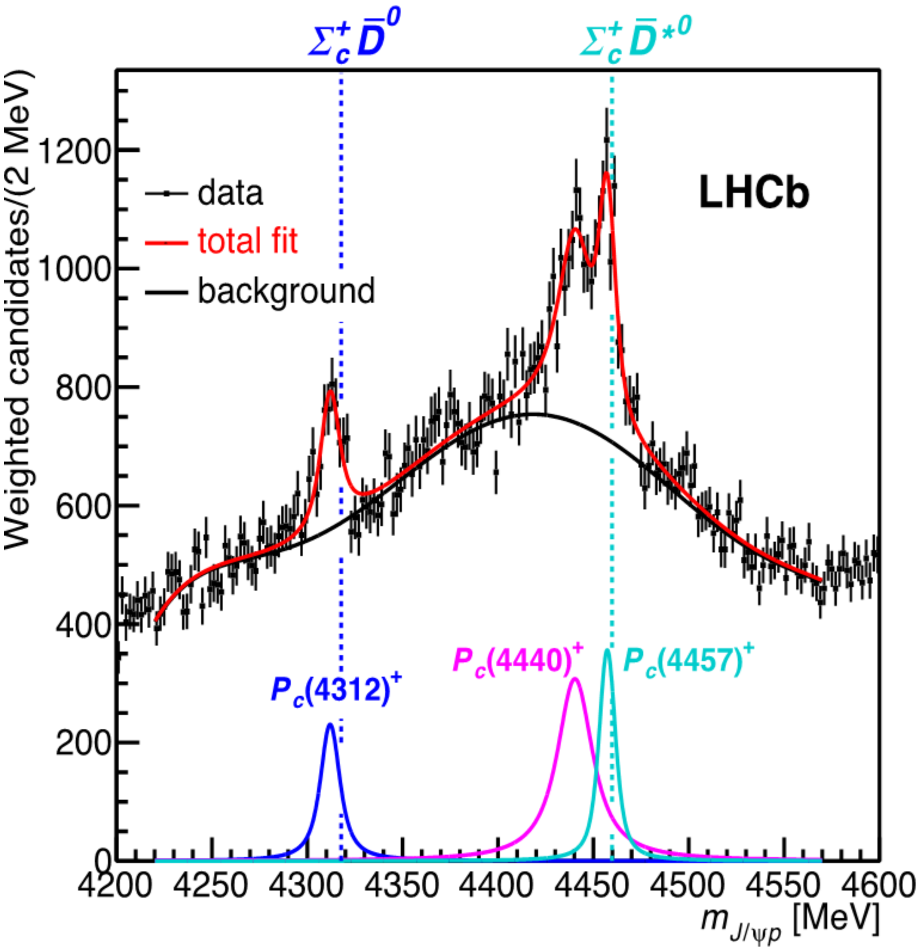
		PB System		VB System	
$J^p = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650				-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	$4318.964 - 0.362i$	1.826	$4459.513 - 0.417i$	2.667
	1500	$4314.531 - 1.448i$	6.259	$4454.088 - 1.662i$	8.092
	2000	$4301.115 - 5.835i$	19.68	$4438.277 - 7.115i$	23.90
$J^p = \frac{3}{2}^-$					
	650				-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	-	-	$4459.507 - 0.420i$	2.673
	1500	-	-	$4454.057 - 1.681i$	8.123
	2000	-	-	$4438.039 - 7.268i$	23.14

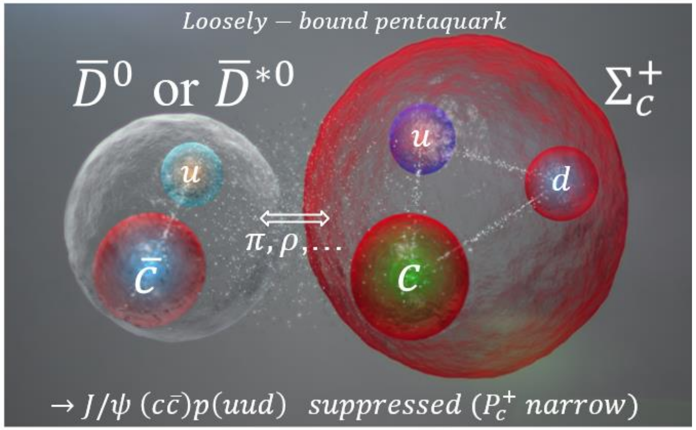
$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

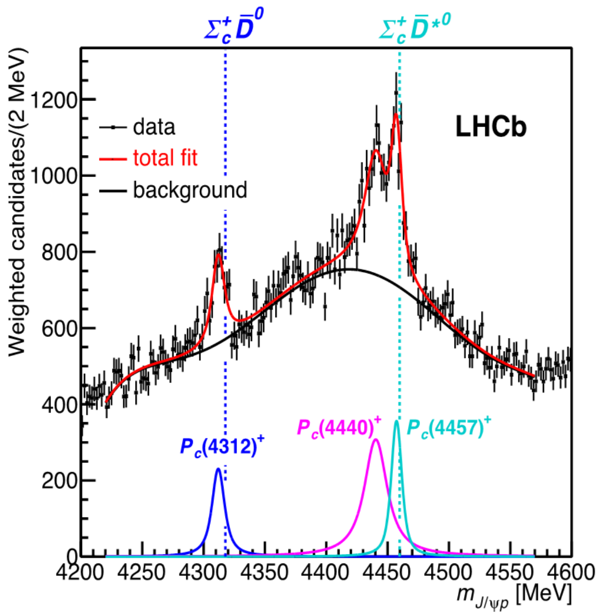
Motivation: S-Wave Molecule Assumption





Strong decays within the S-wave hadronic molecule scenarios, that is, $1/2^-$-$\bar{D}\Sigma_c$ for $P_c(4312)$, $1/2^-$- or $3/2^-$-$\bar{D}^*\Sigma_c$ for $P_c(4440)$, $P_c(4457)$

Decay Mechanism of P_c Molecules



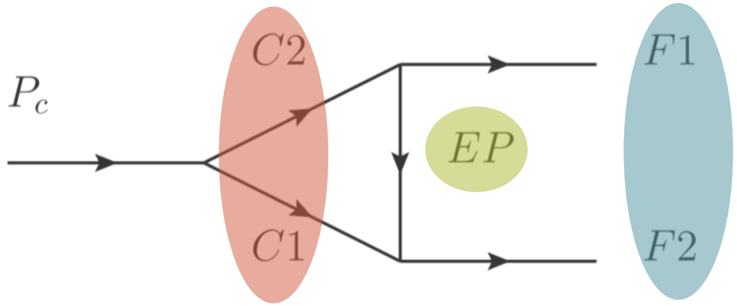
Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	$7.8-9.0$	$4311.8-4313.0$
A	$\boxed{\bar{D}\Sigma_c^*}$	$\frac{3}{2}^-$	$8.3-9.2$	$4376.1-4377.0$
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\boxed{\bar{D}^*\Sigma_c^*}$	$\frac{1}{2}^-$	$25.7-26.5$	$4500.2-4501.0$
A	$\boxed{\bar{D}^*\Sigma_c^*}$	$\frac{3}{2}^-$	$15.9-16.1$	$4510.6-4510.8$
A	$\boxed{\bar{D}^*\Sigma_c^*}$	$\frac{5}{2}^-$	$3.2-3.5$	$4523.3-4523.6$

M.-Z. Liu *et al*, PRL 122. 242001 (2019)

Initial P_c	Components	Final states	Exchanged particles
$P_c(4312)$	$\bar{D}\Sigma_c$	$J/\psi N,\ \omega p,\ \rho N$	$D,\ D^*$
		$\bar{D}^*\Lambda_c$	$\pi,\ \rho$
		$\bar{D}\Lambda_c$	ρ
		$\eta_c N$	D^*
		πN	$D^*,\ \Lambda_c,\ \Sigma_c$
$P_c(4440)$ $P_c(4457)$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c,\ \bar{D}\Lambda_c,\ \bar{D}\Sigma_c^*,\ \bar{D}\Sigma_c$	$\pi,\ \rho$
		$J/\psi N,\ \omega p,\ \rho N,\ \eta N$	$D^*,\ D$
		πN	$D^*,\ D,\ \Lambda_c,\ \Sigma_c$
		$\chi_{c0} N$	D^*
$P_c(4376)$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Lambda_c$	$\pi,\ \rho$
		$\bar{D}\Lambda_c,\ \bar{D}\Sigma_c$	ρ
		$J/\psi N,\ \omega p,\ \rho N$	$D^*,\ D$
		$\eta_c N$	D^*
		πN	$D^*,\ \Lambda_c,\ \Sigma_c$
		$\chi_{c0} N$	D
$P_c(4500)$ $P_c(4511)$ $P_c(4523)$	$\bar{D}^*\Sigma_c^*$	$\bar{D}^*\Lambda_c,\ \bar{D}\Lambda_c,\ \bar{D}\Sigma_c^*,\ \bar{D}\Sigma_c,\ \bar{D}\Sigma_c^*$	$\pi,\ \rho$
		$J/\psi N,\ \omega p,\ \rho N,\ \eta N$	$D^*,\ D$
		πN	$D^*,\ D,\ \Lambda_c,\ \Sigma_c$
		$\chi_{c0} N$	D^*

Decay Mechanism of P_c Molecules

1. Two-body triangle-loop decay



Initial P_c	Components	Final states	Exchanged particles
$P_c(4312)$	$\bar{D}\Sigma_c$	$J/\psi N$, ωp, ρN	D, D^*
		$\bar{D}^*\Lambda_c$	π, ρ
		$\bar{D}\Lambda_c$	ρ
		$\eta_c N$	D^*
		πN	D^*, Λ_c, Σ_c
$P_c(4440)$ $P_c(4457)$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$, $\bar{D}\Sigma_c^*$, $\bar{D}\Sigma_c$	π, ρ
		$J/\psi N$, ωp, ρN, ηN	D^*, D
		πN	D^*, D, Λ_c, Σ_c
		$\chi_{c0} N$	D^*
$P_c(4376)$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Lambda_c$	π, ρ
		$\bar{D}\Lambda_c$, $\bar{D}\Sigma_c$	ρ
		$J/\psi N$, ωp, ρN	D^*, D
		$\eta_c N$	D^*
		πN	D^*, Λ_c, Σ_c
		$\chi_{c0} N$	D
$P_c(4500)$ $P_c(4511)$ $P_c(4523)$	$\bar{D}^*\Sigma_c^*$	$\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$, $\bar{D}\Sigma_c^*$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$	π, ρ
		$J/\psi N$, ωp, ρN, ηN	D^*, D
		πN	D^*, D, Λ_c, Σ_c
		$\chi_{c0} N$	D^*

Decay Mechanism of P_c Molecules

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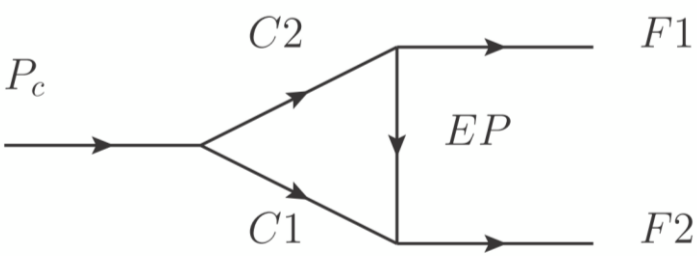
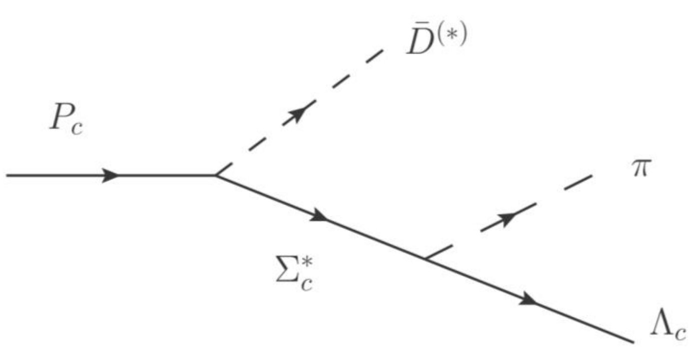


2. Three-body decay via tree diagram



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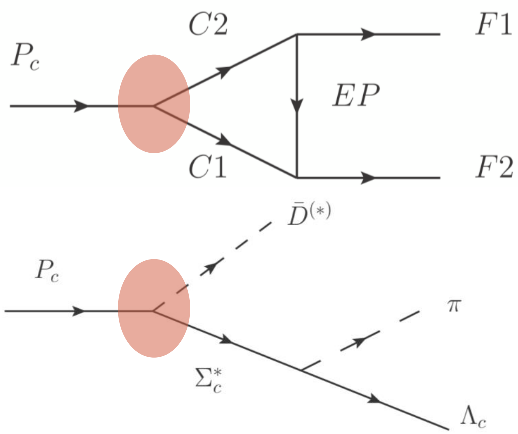
		$\eta_c N$	D^*
		πN	$D^*,\ \Lambda_c,\ \Sigma_c$
$P_c(4440)$ $P_c(4457)$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c,\ \bar{D}\Lambda_c,\ \bar{D}\Sigma_c^*,\ \bar{D}\Sigma_c$	$\pi,\ \rho$
		$J/\psi N,\ \omega p,\ \rho N,\ \eta N$	$D^*,\ D$
		πN	$D^*,\ D,\ \Lambda_c,\ \Sigma_c$
		$\chi_{c0} N$	D^*
$P_c(4376)$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Lambda_c$	$\pi,\ \rho$
		$\bar{D}\Lambda_c,\ \bar{D}\Sigma_c$	ρ
		$J/\psi N,\ \omega p,\ \rho N$	$D^*,\ D$
		$\eta_c N$	D^*
		πN	$D^*,\ \Lambda_c,\ \Sigma_c$
		$\chi_{c0} N$	D
$P_c(4500)$ $P_c(4511)$ $P_c(4523)$	$\bar{D}^*\Sigma_c^*$	$\bar{D}^*\Lambda_c,\ \bar{D}\Lambda_c,\ \bar{D}\Sigma_c^*,\ \bar{D}\Sigma_c,\ \bar{D}\Sigma_c^*$	$\pi,\ \rho$
		$J/\psi N,\ \omega p,\ \rho N,\ \eta N$	$D^*,\ D$
		πN	$D^*,\ D,\ \Lambda_c,\ \Sigma_c$
		$\chi_{c0} N$	D^*

Effective Lagrangian Approach

- The Lorentz covariant L-S scheme is used for the interactions of P_c to $\bar{D}^{(*)}\Sigma_c^{(*)}$ systems.



B.-S. Zou *et al*, PRC 67. 015204 (2003)

$$\mathcal{L}_{\bar{D}\Sigma_c P_c(1/2^-)} = g^{1/2^-}_{\bar{D}\Sigma_c P_c} \bar{\Sigma}_c P_c \bar{D},$$

$$\mathcal{L}_{\bar{D}^*\Sigma_c P_c(1/2^-)} = g^{1/2^-}_{\bar{D}^*\Sigma_c P_c} \bar{\Sigma}_c \gamma^5 \tilde{\gamma}^\mu P_c \bar{D}^*_\mu,$$

$$\mathcal{L}_{\bar{D}^*\Sigma_c P_c(3/2^-)} = g^{3/2^-}_{\bar{D}^*\Sigma_c P_c} \bar{\Sigma}_c P_{c\mu} \bar{D}^{*\mu},$$

$\tilde{\gamma}^\mu \equiv \tilde{g}^{\mu\nu}\gamma_\nu = \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)\gamma_\nu$, with p the momentum of P_c.

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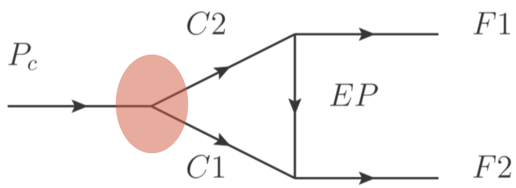

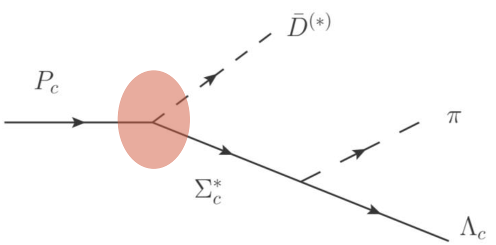

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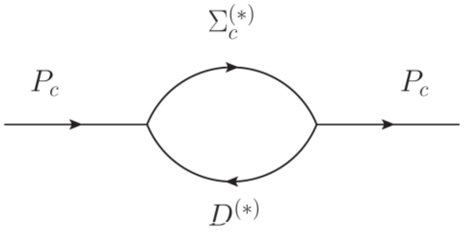
- Compositeness conditions for $g_{\bar{D}^{(*)}\Sigma_c^{(*)} P_c}$

$$1 - Z = \left.\frac{\partial E_T}{\partial \not{p}}\right|_{\not{p}=m_0}$$



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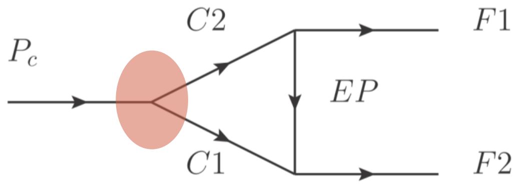

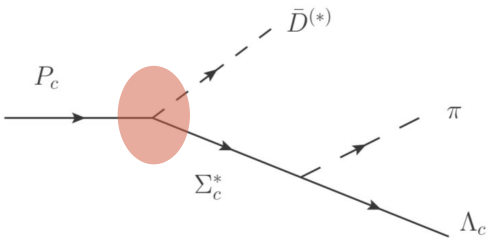

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- Compositeness conditions for $g_{\bar{D}^{(*)}\Sigma_c^{(*)}P_c}$

Working in the non-relativistic limit and expanding on the $\frac{\sqrt{2\mu E_B}}{\Lambda}$,

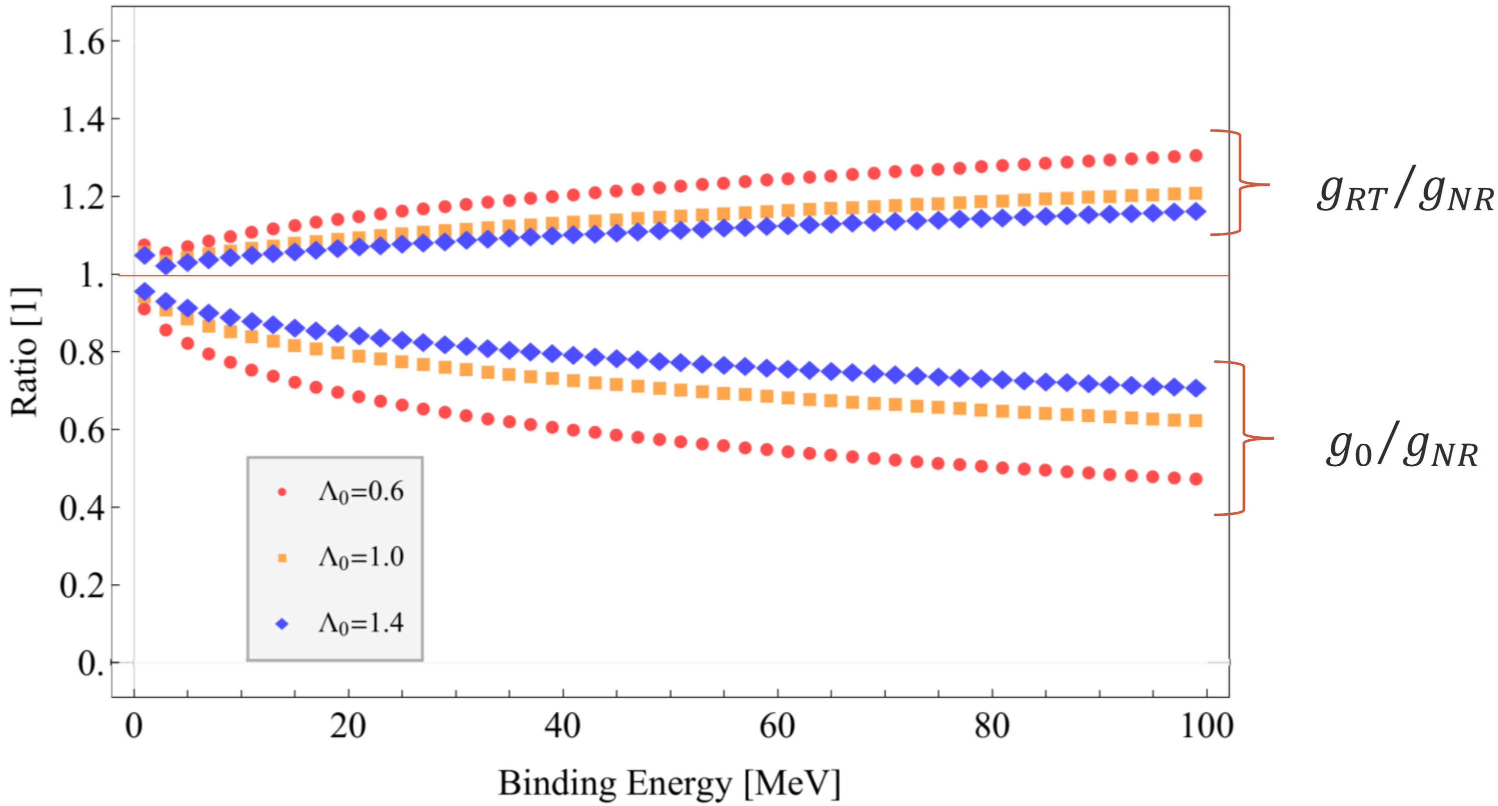
$$F_T = \begin{cases} 1 & \text{for spin-1/2 molecule,} \\ 3/2 & \text{for spin-3/2 molecule,} \\ 5/3 & \text{for spin-5/2 molecule.} \end{cases}$$

$$g_0 = \sqrt{\frac{8\sqrt{2}\sqrt{E_B}m_1 m_2 \pi}{(m_1 m_2/(m_1+m_2))^{3/2}}}\sqrt{\frac{1}{\mathcal{M}_N F_T}}$$

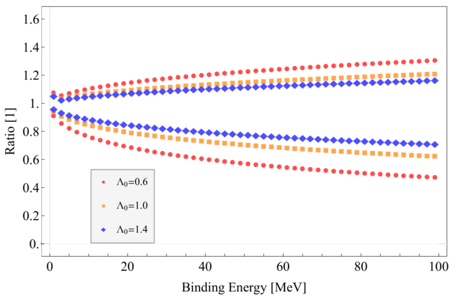
$$\mathcal{M}_N = \begin{cases} 2\,m_1 & \text{for spin-1/2 } \bar{D}\Sigma_c \text{ molecule,} \\ 6\,m_1 & \text{for spin-1/2 } \bar{D}^*\Sigma_c \text{ molecule,} \\ 4/3\,m_1 & \text{for spin-3/2 } \bar{D}\Sigma_c^* \text{ or } \bar{D}^*\Sigma_c \text{ molecule,} \\ 4\,m_1 & \text{for spin-1/2 } \bar{D}^*\Sigma_c^* \text{ molecule,} \\ 20/9\,m_1 & \text{for spin-3/2 } \bar{D}^*\Sigma_c^* \text{ molecule,} \\ 6/5\,m_1 & \text{for spin-5/2 } \bar{D}^*\Sigma_c \text{ molecule.} \end{cases}$$

Couplings $g_{\bar{D}^{(*)}\Sigma_c^{(*)}P_c}$

- Difference among three strategies, g_{RT}, g_{NR}, g_0, for the determinations of $g_{P_c\bar{D}\Sigma_c}$



Comparations of g_{RT}, g_{NR}, g_0



1. The larger difference comes with the lager binding energy. The same coupling $g_{P_c \bar{D} \Sigma_c}$ will be obtained in the zero-binding-energy limit.
2. $g_{RT} \geq g_{NR} \geq g_0$.
3. g_{RT} and g_{NR} decrease with the increasing of Λ_0.

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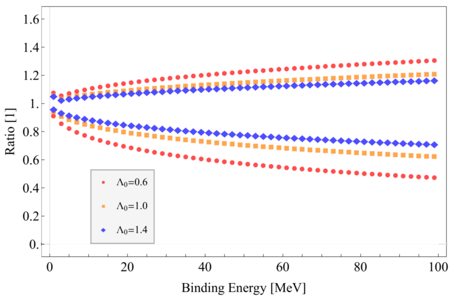
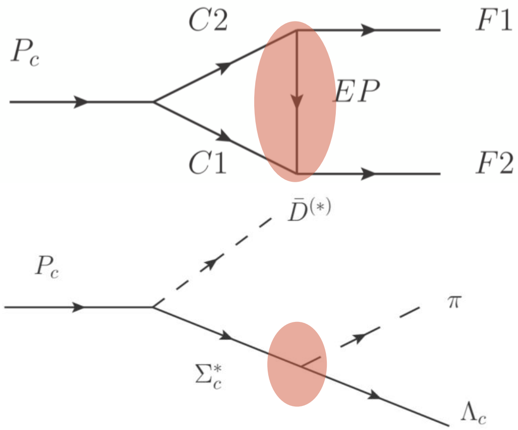


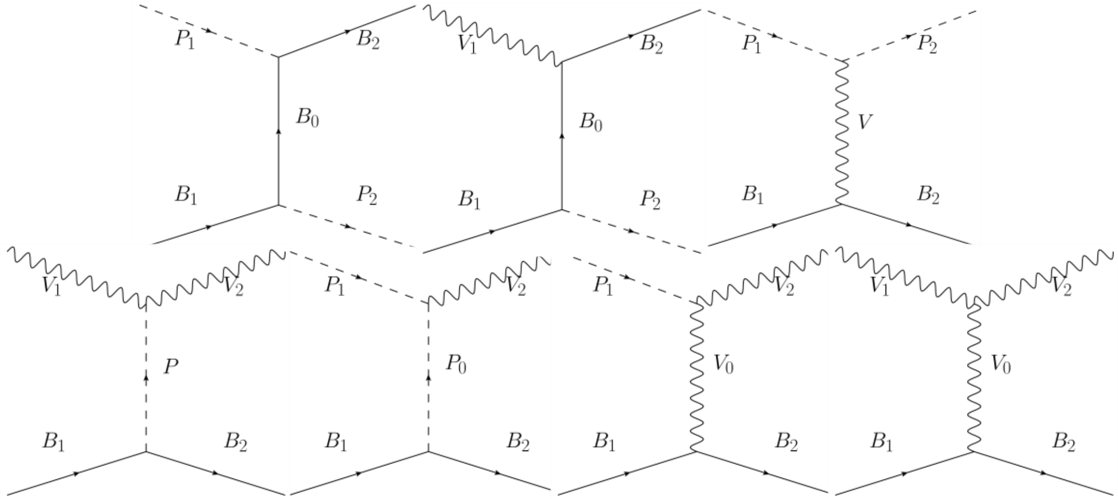
1. The larger difference comes with the lager binding energy. The same coupling $g_{P_c\bar{D}\Sigma_c}$ will be obtained in the zero-binding-energy limit.
2. $g_{RT} \geq g_{NR} \geq g_0$.
3. g_{RT} and g_{NR} decrease with the increasing of Λ_0.

- g_{RT} is adopted for the these P_c molecules with the binding energy larger than10 MeV.
- For $P_c(4312)$, $P_c(4457)$, $P_c(4376)$ and $P_c(4523)$ that have small binding energy, g_0 is used for simplicity.

Effective Lagrangian Approach

- Conventional effective Lagrangians are adopted for the vertices in t-channel, e.g., $\mathcal{L}_{VPP}$, $\mathcal{L}_{VVV}$, $\mathcal{L}_{BBP}$,…





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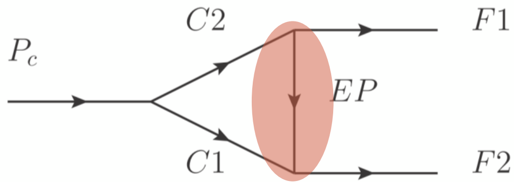
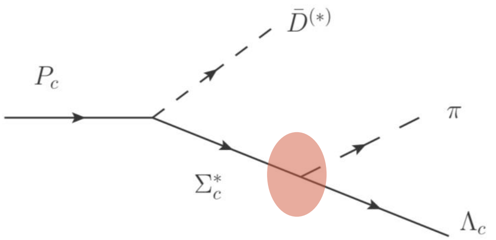
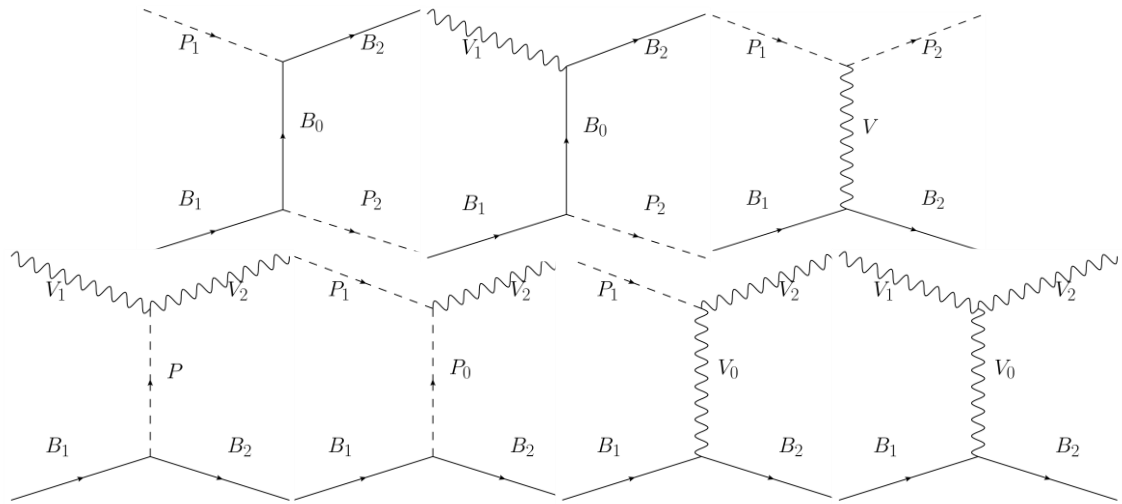


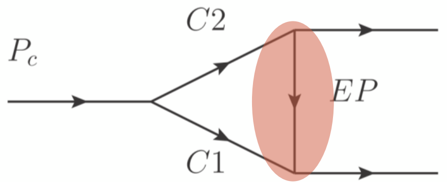


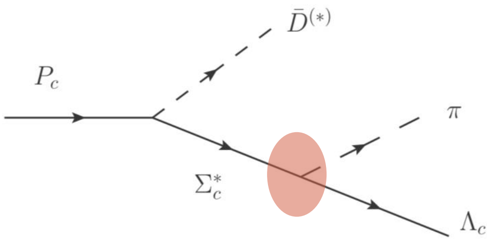


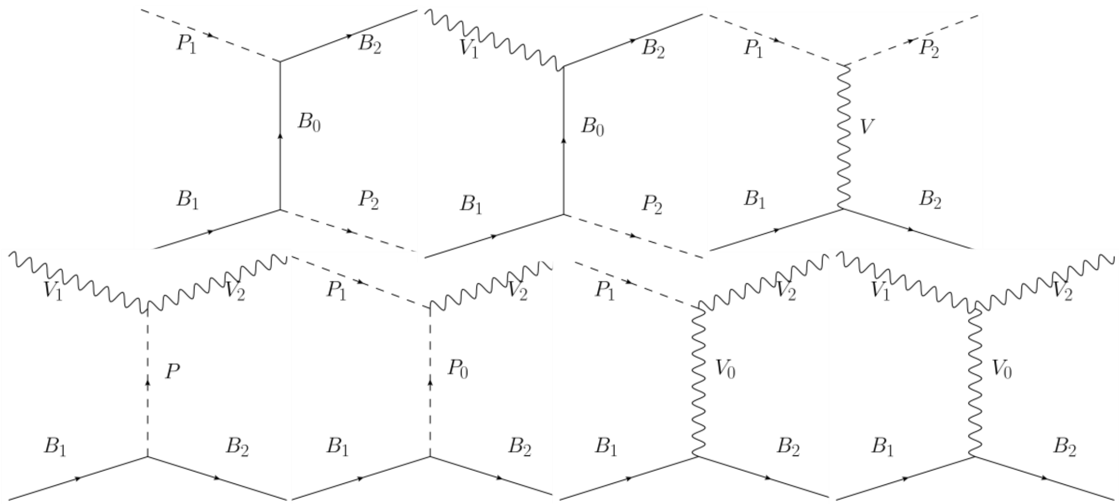
- Effective coupling constants
  - Inferred from experimental decay widths, $g_{\pi\Sigma_c\Lambda_c}$, $g_{D^*D\pi}$, …
  - Heavy quark spin symmetry, such as $g_{\pi\Sigma_c\Sigma_c^*} = \frac{\sqrt{3}}{2} g_{\pi\Sigma_c\Sigma_c}$, …
  - The simplest approximation that $c = s$, namely $g_{\pi\Sigma_c\Sigma_c} = g_{\pi\Sigma\Sigma}$, …
  - SU(3) relations, like $g_{\pi\Sigma\Sigma} = g_{BBP} 2\alpha_{BBP}$, …
  - Vector meson dominant (VMD) model is used for $g_{DD\rho}$, $g_{DD\omega}$

Effective Lagrangian Approach

- Conventional effective Lagrangians are adopted for the vertices in t-channel, e.g., $\mathcal{L}_{VPP}$, $\mathcal{L}_{VVV}$, $\mathcal{L}_{BBP}$,…



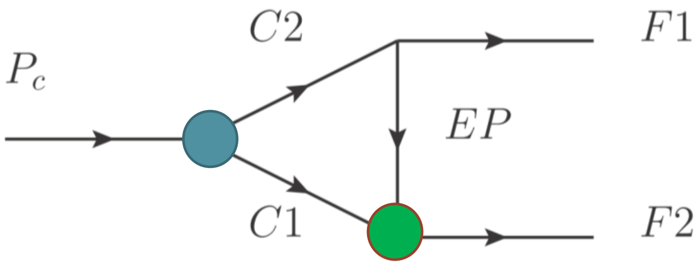




- Effective coupling constants

$g_{\pi\Sigma_c\Sigma_c}$	$g_{DN\Sigma_c}$	$g_{DN\Lambda_c}$	$g_{\rho\Sigma_c\Sigma_c}$	$g_{\rho\Sigma_c\Lambda_c}$	$g_{D^*N\Sigma_c}$	$g_{D^*N\Lambda_c}$	$g_{D^*N\Sigma_c^*}$	$g_{DN\Sigma_c^*}$	$g_{D^*D^*\eta_c}$ (GeV^{-1})	$g_{D^*D\eta_c}$
10.8	2.7	14.03	7.48	0.56	4.2	6.19	8.44	6.2	3.52	6.82
$g_{\pi\Lambda_c\Sigma_c}$	$g_{\pi\Lambda_c\Sigma_c^*}$ (GeV^{-1})	$g_{D^*D\pi}$	$g_{D^*D^*\pi}$ (GeV^{-1})	$g_{D^*D\rho}$ (GeV^{-1})	$g_{D^*D^*\rho}$	$g_{DD\rho}$	$g_{D^*D\omega}$ (GeV^{-1})	$g_{D^*D^*\omega}$	$g_{DD\omega}$	$g_{D^*DJ/\psi}$ (GeV^{-1})
19.31	7.46	6.0	6.2	2.51	2.52	2.52	2.83	2.84	2.84	7.94
$g_{D^*D^*J/\psi}$	$g_{DDJ/\psi}$	$g_{DD\chi_{c0}}$	$g_{D^*D^*\chi_{c0}}$ (GeV^{-1})							
7.44	7.44	32.24	11.57							

Form factors



- Gaussian regulators

$$f_1(p_E^2/\Lambda_0^2) = \exp(-p_E^2/\Lambda_0^2), \qquad f_2(\boldsymbol{p}^2/\Lambda_0^2) = \exp(-\boldsymbol{p}^2/\Lambda_0^2),$$

$$p_E \equiv \frac{m_1}{m_1+m_2} p_2 - \frac{m_2}{m_1+m_2} p_1 = (p_2^0 - \frac{m_2}{m_1+m_2} M, \boldsymbol{p}),\ p_E^2 = \left(p_E^0\right)^2 + \boldsymbol{p}^2$$

- multipolar regulators

$$f_3(q^2) = \frac{\Lambda_1^4}{(m^2 - q^2)^2 + \Lambda_1^4},$$

(f_1, f_3) for RT, (f_2, f_3) for NR

Decay pattern of $\bar{D}^{(*)}\Sigma_c$ molecules

- The numerical results on partial decay widths with $\Lambda_0 = 1.0$ GeV and $\Lambda_1 = 0.6$ GeV.

Mode	Widths (MeV) with (f_1, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	3.8	13.9	6.2	12.5	6.1
$J/\psi p$	0.001	0.03	0.02	0.02	0.01
$\bar{D}\Lambda_c$	0.06	5.6	1.7	3.8	1.5
πN	0.004	0.002	~ 0	0.001	~ 0
$\chi_{c0}p$	-	~ 0	~ 0	~ 0	~ 0
$\eta_c p$	0.01	~ 0	~ 0	~ 0	~ 0
ρN	~ 0	~ 0	~ 0	~ 0	~ 0
ωp	~ 0	0.001	~ 0	~ 0	~ 0
$\bar{D}\Sigma_c$	-	3.4	0.5	2.6	1.0
$\bar{D}\Sigma_c^*$	-	0.8	5.4	1.9	6.2
Total	3.9	23.7	13.9	20.7	14.7

Mode	Widths (MeV) with (f_2, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	10.7	12.5	6.8	10.8	6.9
$J/\psi p$	0.1	0.6	1.8	0.2	0.6
$\bar{D}\Lambda_c$	0.3	2.7	1.2	2.0	1.2
πN	1.7	0.2	1.9	0.07	0.6
$\chi_{c0}p$	-	0.1	0.009	0.05	0.003
$\eta_c p$	0.4	0.07	0.008	0.02	0.003
ρN	0.0008	0.4	0.3	0.1	0.1
ωp	0.003	1.5	1.2	0.5	0.4
$\bar{D}\Sigma_c$	-	3.4	0.6	2.8	0.9
$\bar{D}\Sigma_c^*$	-	0.9	7.3	2.3	7.2
Total	13.2	22.4	21.0	18.8	17.9

States	Width (MeV)
$P_c(4312)^+$	$2.6 \sim 9.8 \sim 16.2$
$P_c(4440)^+$	$5.6 \sim 20.6 \sim 34.2$
$P_c(4457)^+$	$2.5 \sim 6.4 \sim 14.1$

Model-dependent upper limits at 90% CL (assuming $J^P=3/2^-$):

- Br($P_c(4312)$ → J/ψ p) < 4.6%
- Br($P_c(4440)$ → J/ψ p) < 2.3%
- Br($P_c(4457)$ → J/ψ p) < 3.8%

$\Gamma_{J/\psi p}/\Gamma_{\eta_c p}$

$\Gamma_{\bar{D}\Sigma_c}/\Gamma_{\bar{D}\Sigma_c^*}$

Decay pattern of $\bar{D}^{(*)}\Sigma_c^*$ molecules

- For $P_c(4376)$, $P_c(4500)$, $P_c(4511)$, $P_c(4523)$, partial widths with $\Lambda_0 = 1.0$ GeV and $\Lambda_1 = 0.6$ GeV.

Mode	Widths (MeV) with (f_1, f_3)			
	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$		
	$P_c(4376)$	$P_c(4500)$	$P_c(4511)$	$P_c(4523)$
	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$\boxed{\bar{D}^*\Lambda_c}$	12.4	7.1	17.0	4.5
$J/\psi p$	0.01	0.006	0.02	0.006
$\boxed{\bar{D}\Lambda_c}$	~ 0	10.0	0.3	1.5
πN	~ 0	0.003	~ 0	~ 0
$\chi_{c0}p$	0.003	0.01	0.002	~ 0
$\eta_c p$	0.001	0.01	~ 0	~ 0
ρN	~ 0	0.001	0.01	~ 0
ωp	0.002	0.004	0.005	~ 0
$\bar{D}\Sigma_c$	~ 0	10.6	0.2	1.3
$\bar{D}\Sigma_c^*$	-	1.0	33.8	6.2
$\bar{D}^*\Sigma_c$	-	10.6	0.07	1.2
$\bar{D}\Lambda_c\pi$	5.0	-	-	-
$\bar{D}^*\Lambda_c\pi$	-	4.0	7.7	7.8
Total	17.5	43.3	59.1	22.5

Mode	Widths (MeV) with (f_2, f_3)			
	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$		
	$P_c(4376)$	$P_c(4500)$	$P_c(4511)$	$P_c(4523)$
	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$\bar{D}^*\Lambda_c$	21.6	6.4	16.7	3.1
$J/\psi p$	0.7	36.7	4.4	0.2
$\bar{D}\Lambda_c$	~ 0	2.0	0.09	0.7
πN	0.6	49.9	6.0	0.5
$\chi_{c0}p$	0.1	4.7	0.5	~ 0
$\eta_c p$	~ 0	13.5	0.1	0.04
ρN	0.2	11.6	0.6	0.1
ωp	0.8	44.0	2.3	0.4
$\bar{D}\Sigma_c$	~ 0	6.7	0.2	1.0
$\bar{D}\Sigma_c^*$	-	1.2	35.0	4.1
$\bar{D}^*\Sigma_c$	-	13.6	0.08	0.7
$\bar{D}\Lambda_c\pi$	5.0	-	-	-
$\bar{D}^*\Lambda_c\pi$	-	4.0	7.7	7.8
Total	29.0	194.5	73.7	18.7

Summary

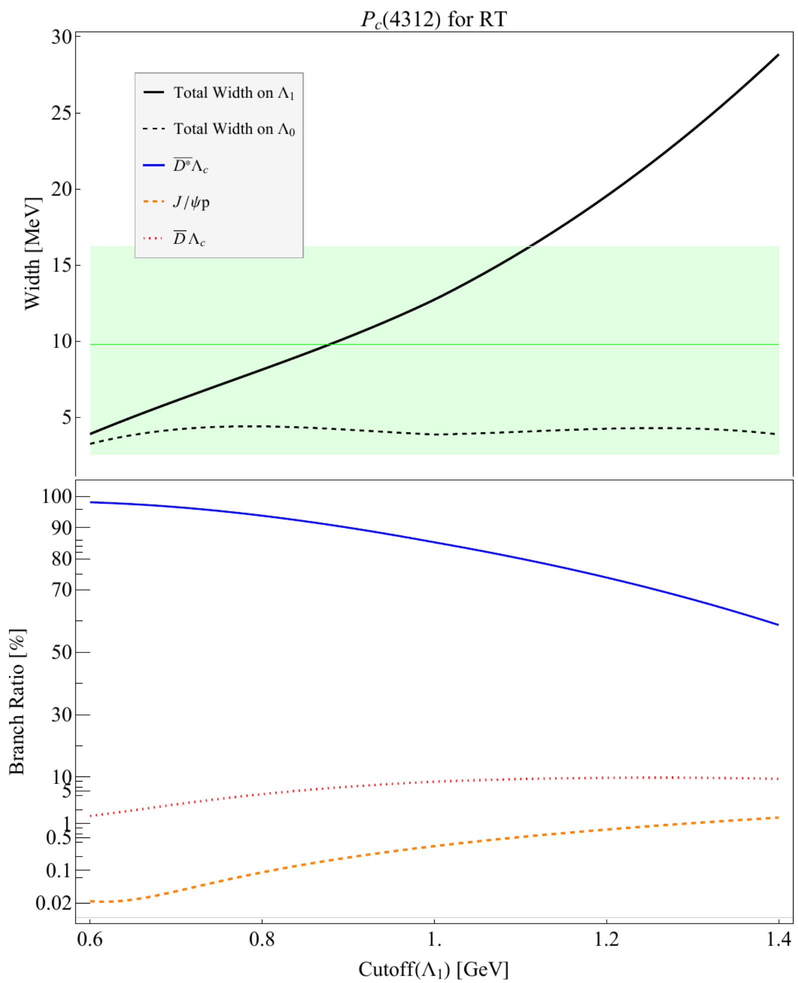
- The experimental data on $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ can be described well with the $1/2^{-}$-$\bar{D}\Sigma_c$, $1/2^{-}$-$\bar{D}^*\Sigma_c$, $3/2^{-}$-$\bar{D}^*\Sigma_c$ hadronic molecule scenarios, respectively.
- The determination of the spin parities for two higher P_c states requires further experimental investigation, especially on the decay behaviors, such as $\Gamma_{\bar{D}\Sigma_c}/\Gamma_{\bar{D}\Sigma_c^*}$, $\Gamma_{J/\psi p}/\Gamma_{\eta_c p}$.
- Four additional heavy quark spin partners ($\Gamma \sim 20$-60 MeV) that strongly couple to $\bar{D}^*\Lambda_c$, $\bar{D}\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ channels are expected to be confirmed in the future.

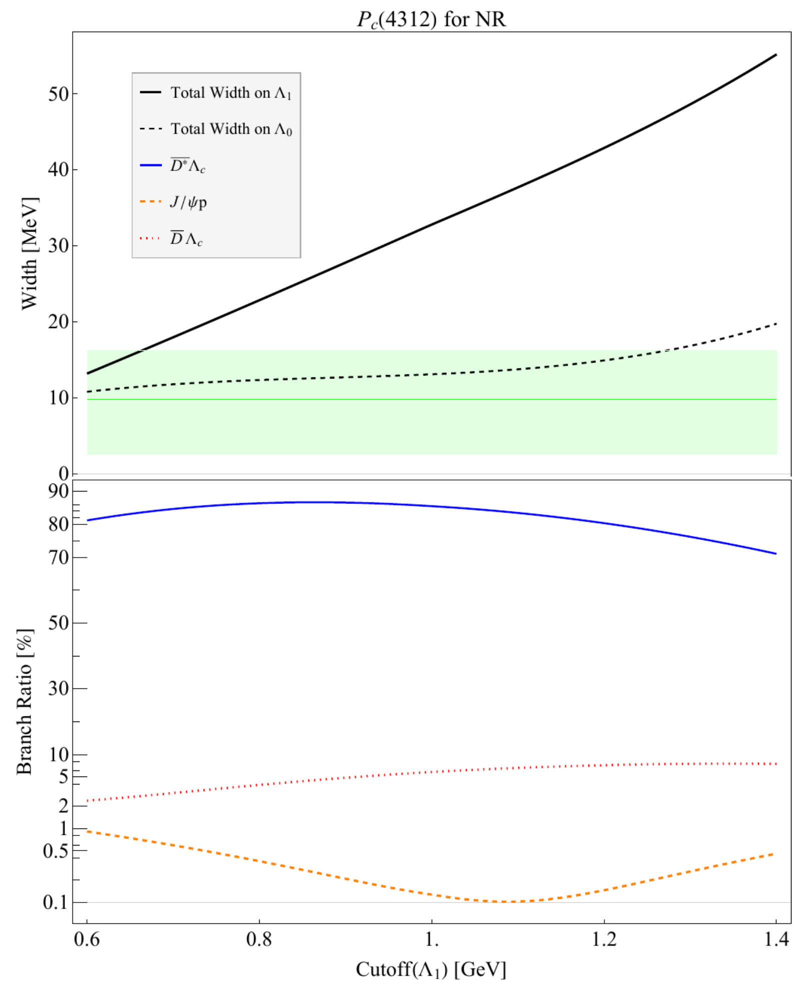
Thank you!

Back up slides

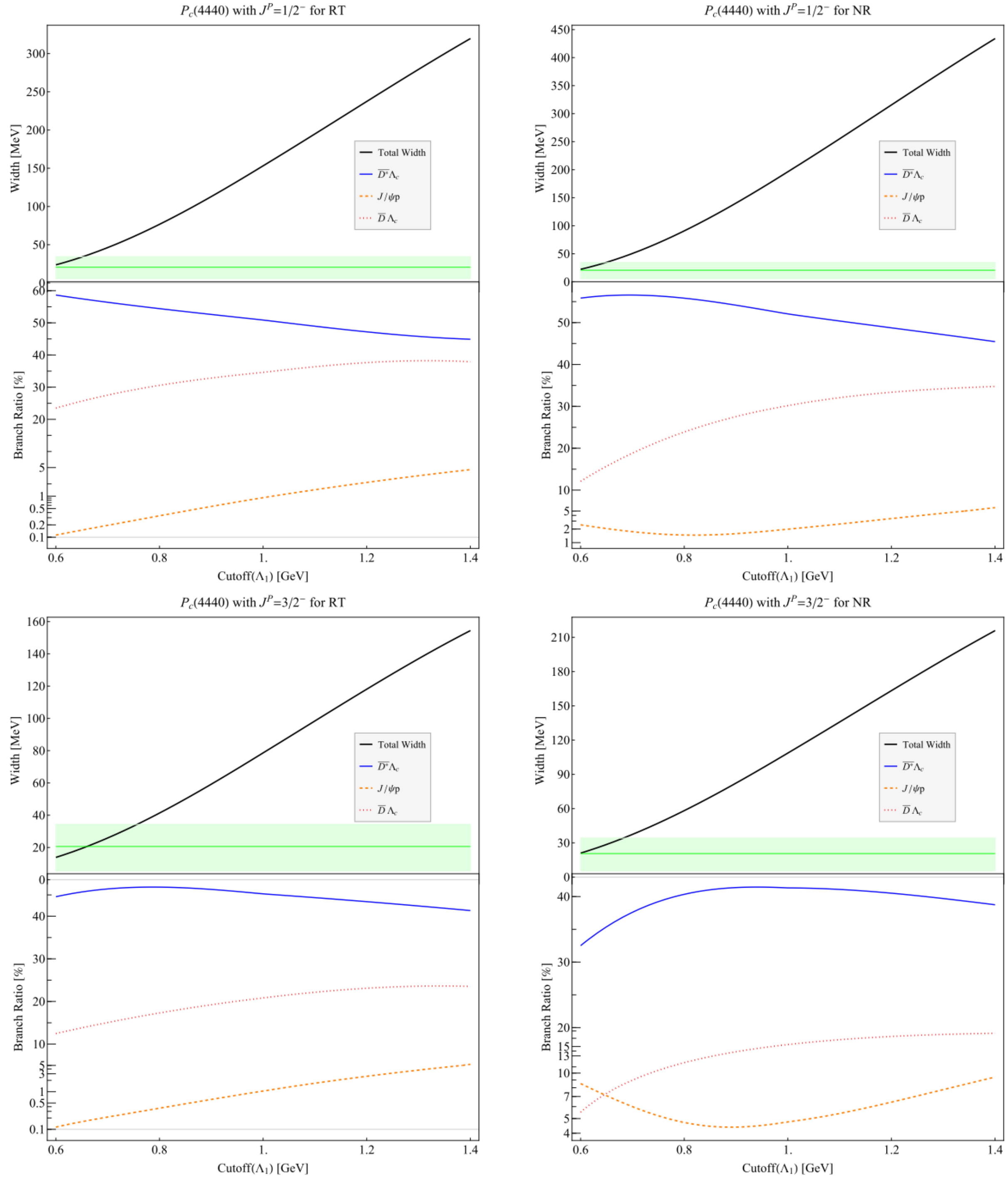
Cut-off dependence $P_c(4312)$

- The total widths and branching fractions of $\bar{D}^*\Lambda_c$, $J/\psi p$, $\bar{D}\Lambda_c$





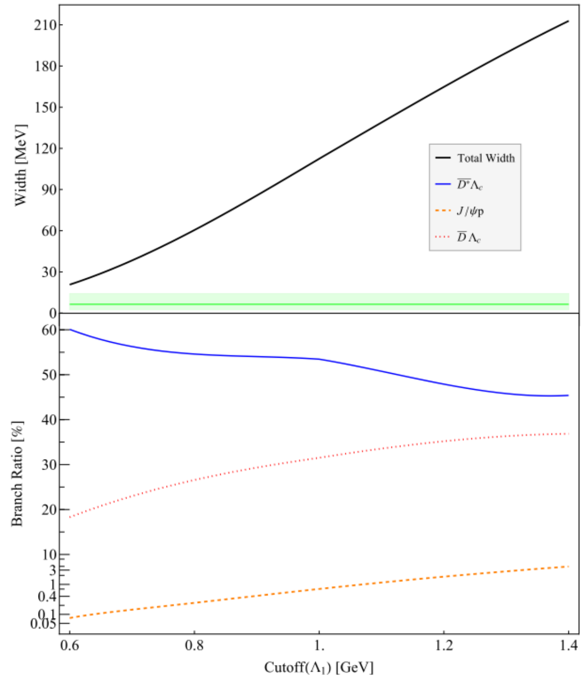
$P_c(4440)$



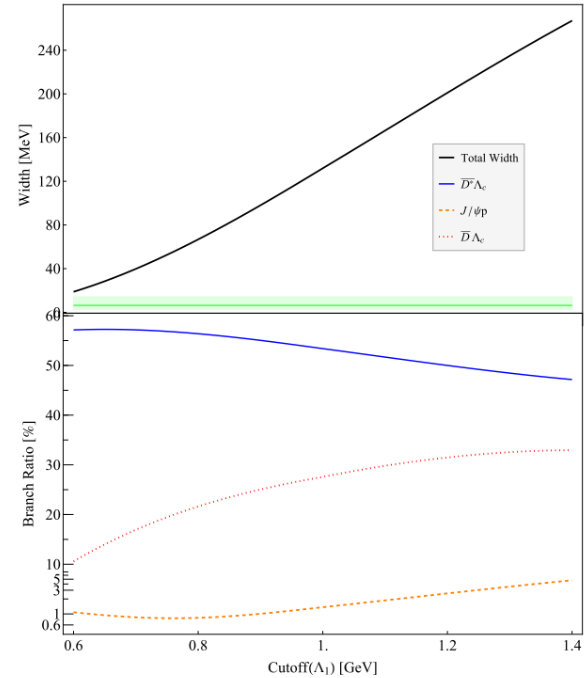
$P_c(4440)$ with $J^P=1/2^-$ for RT
$P_c(4440)$ with $J^P=1/2^-$ for NR
$P_c(4440)$ with $J^P=3/2^-$ for RT
$P_c(4440)$ with $J^P=3/2^-$ for NR
Width [MeV]
Branch Ratio [%]
Cutoff(Λ_1) [GeV]
Total Width
$\bar{D}^*\Lambda_c$
$J/\psi p$
$\bar{D}\Lambda_c$

$P_c(4457)$

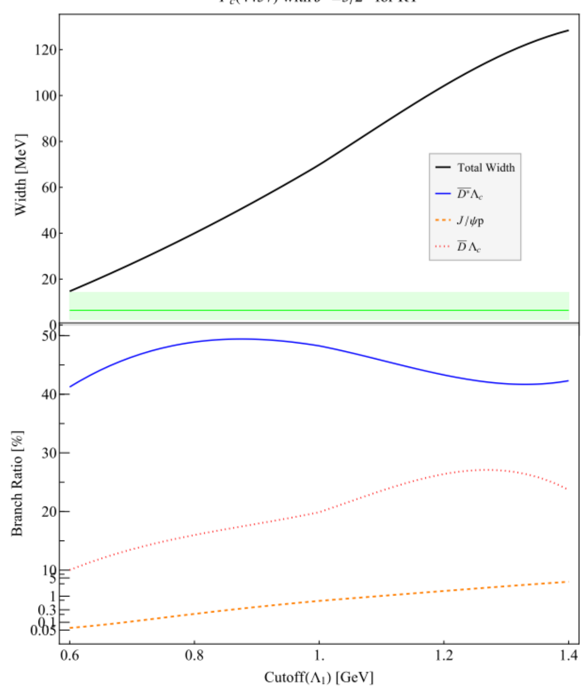
$P_c(4457)$ with $J^P=1/2^-$ for RT



$P_c(4457)$ with $J^P=1/2^-$ for NR



$P_c(4457)$ with $J^P=3/2^-$ for RT



$P_c(4457)$ with $J^P=3/2^-$ for NR