# Production of $P_c$ states in $\Lambda_b$ decays (and related)

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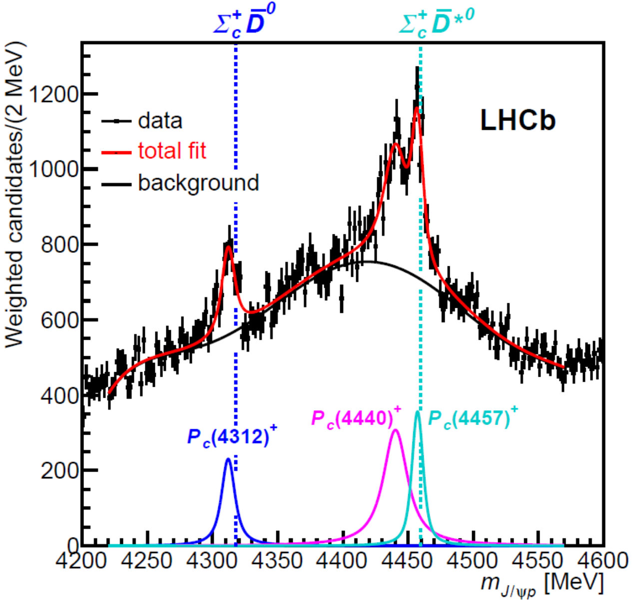
[T.B. & E.Swanson, 2112.11527 (EPJA)]
[T.B. & E.Swanson, 2207.00511 (PRD)]
[T.B. & E.Swanson, 2208.05106]

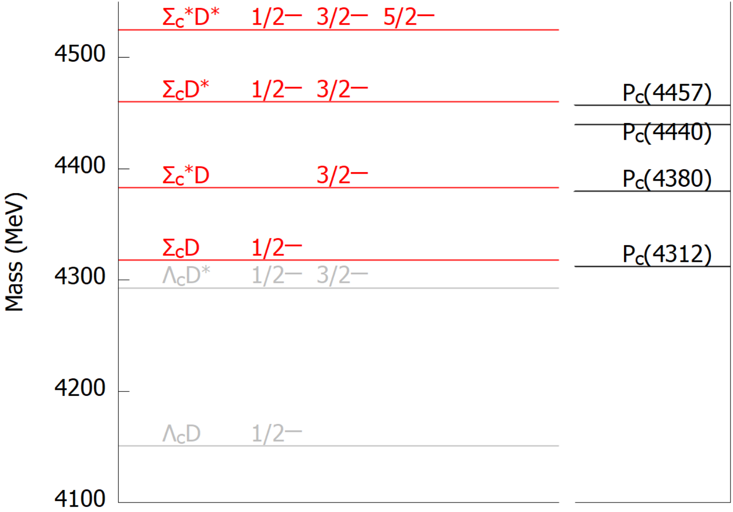
# Experimental constraints on the properties of $P_c$ states

[T.B. & E.Swanson, 2112.11527 (EPJA)]

# $\Lambda_b \to J/\psi\, p\, K^-$ at LHCb



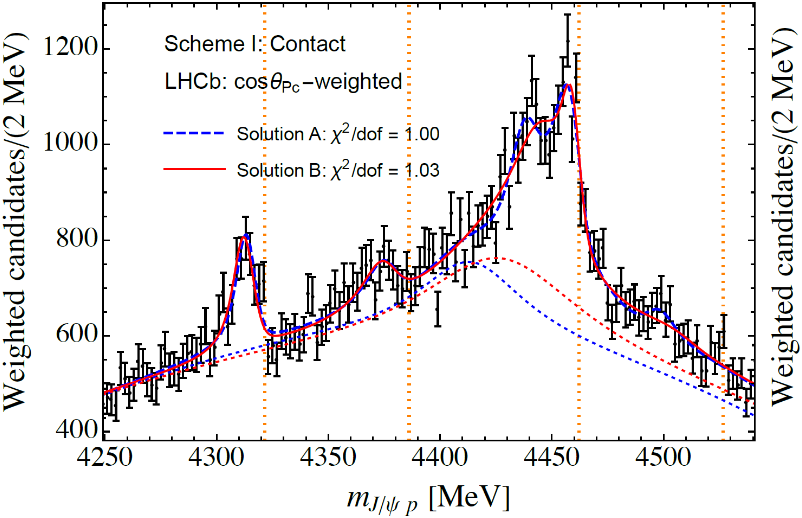
# Typically heavy quark symmetry implies many states




Xiao, Nieves, Oset et al., Du, Baru, Guo et al.

But there is no evidence for $\Sigma_c^* \bar{D}^*$ states in the data

# Model works if production of $\Sigma_c^*\bar{D}^*$ states is suppressed




Du, Baru, **Guo**, Hanhart, Meißner, Oller, Wang 1910.11846 (PRL), 2102.07159 (JHEP)

# But there is a problem with the $1/2^-$ states

$$\mathcal{R}(J/\psi\, p) = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\, \mathcal{B}(P_c^+ \to J/\psi\, p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\, K^-)} \quad (LHCb)$$

$$\mathcal{R}(\Lambda_c^+ \bar{D}^0) = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\, \mathcal{B}(P_c^+ \to \Lambda_c^+ \bar{D}^0)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)} \quad (Piucci\ limits)$$

imply limits on

$$\frac{\mathcal{B}(P_c^+ \to \Lambda_c^+ \bar{D}^0)}{\mathcal{B}(P_c^+ \to J/\psi\, p)} = \frac{\mathcal{R}(\Lambda_c^+ \bar{D}^0)}{\mathcal{R}(J/\psi\, p)} \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\, K^-)}$$

With the $J/\psi$-007 result (updating GlueX, JPAC):

$$\mathcal{B}(P_c^+ \to J/\psi\, p) < (few) \times 10^{-3}$$

we get

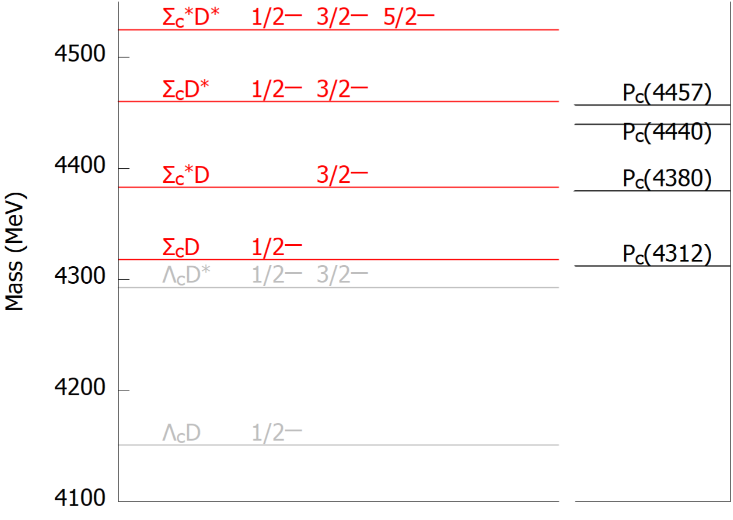
$$\mathcal{B}(P_c^+ \to \Lambda_c^+ \bar{D}^0) \lesssim \mathcal{O}(1\%)$$

But we estimate (e.g.)

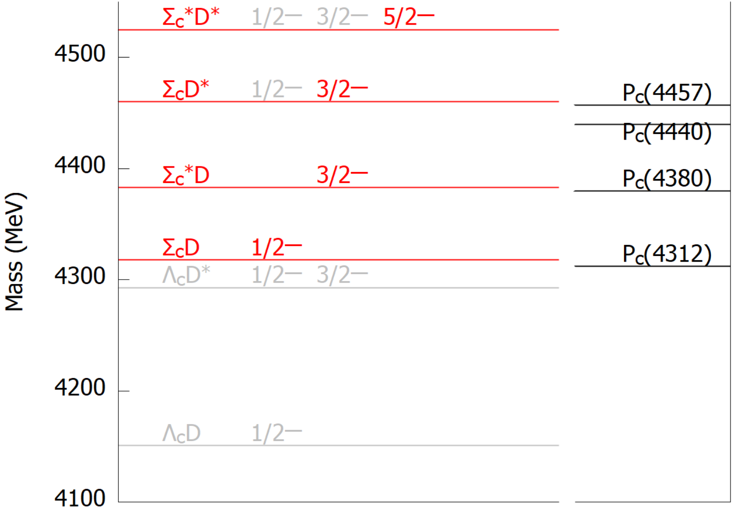
$$\mathcal{B}[P_c^+(4312) \to \Lambda_c^+ \bar{D}^{*0}] = 59\% \div 87\%$$

OK for $P_c(4312)$ (Voloshin selection rule), not other $1/2^-$ states.

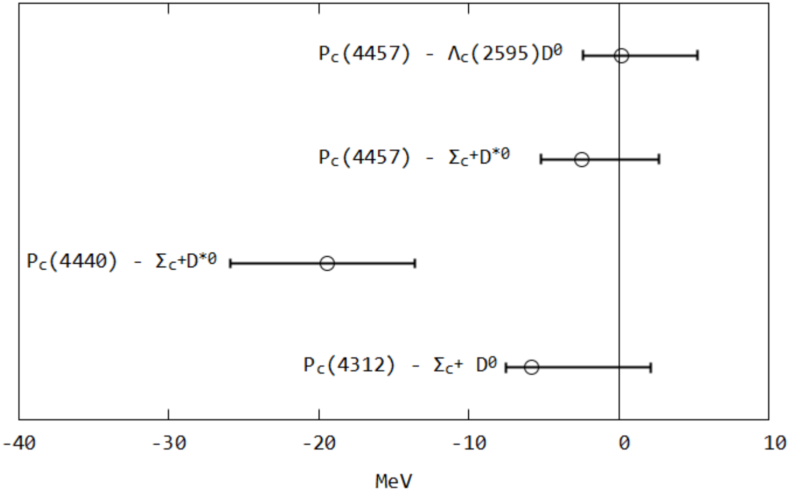
# Adjusting contact terms fixes both problems



# Adjusting contact terms fixes both problems



# Closer look at masses

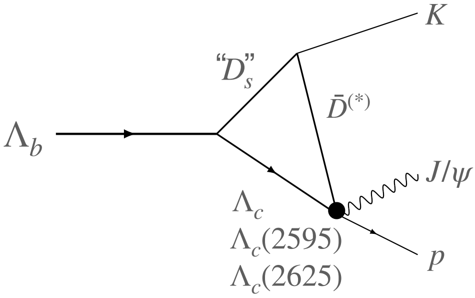


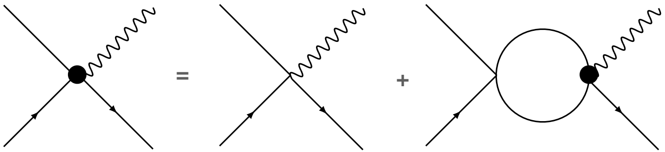

Clearly, $P_c(4457)$ is not necessarily a $\Sigma_c \bar{D}^*$ bound state...

# Production of $P_c$ states in $\Lambda_b$ decays

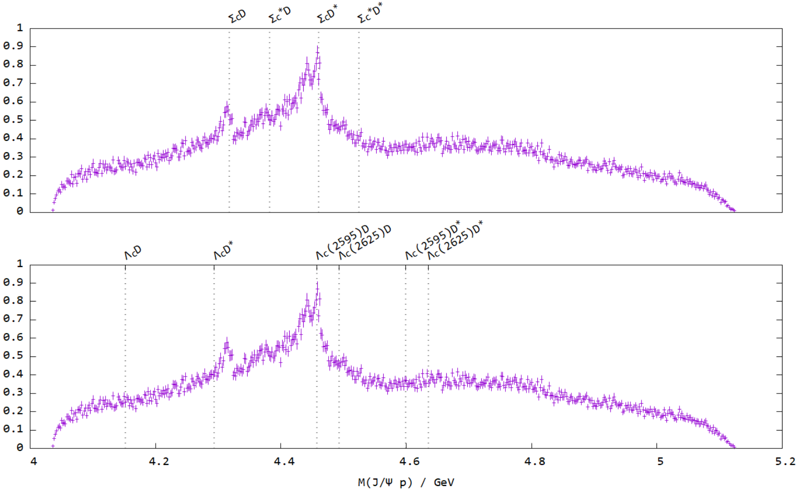
[T.B. & E.Swanson, 2207.00511 (PRD)]

# Model



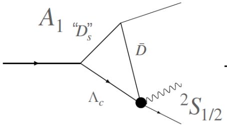
# Thresholds

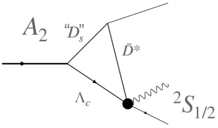


ΣcD
Σc*D
ΣcD*
Σc*D*
ΛcD
ΛcD*
Λc(2595)D
Λc(2625)D
Λc(2595)D*
Λc(2625)D*
M(J/Ψ p) / GeV

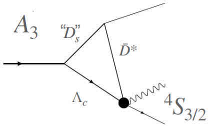
# $1/2^-$ and $3/2^-$ channels

$$\mathcal{A}(^2S_{1/2}) = b_1 + g_1 A_1 + g_2 A_2$$



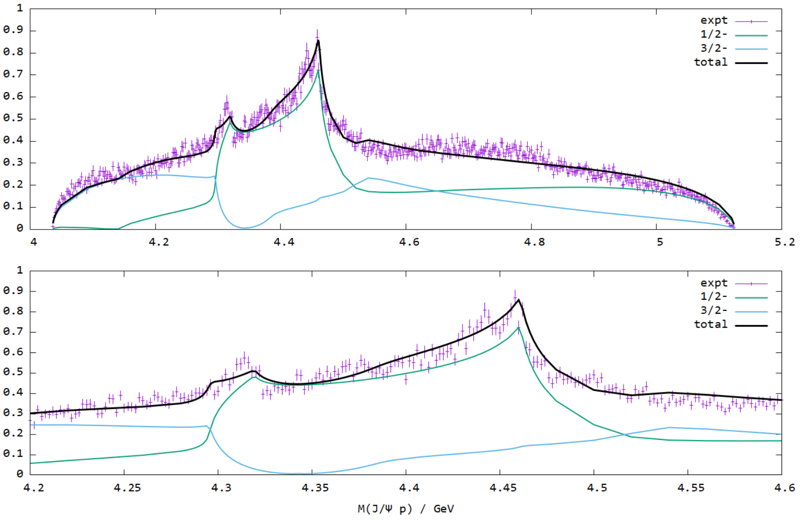

$$\mathcal{A}(^4S_{3/2}) = b_2 + g_3 A_3$$



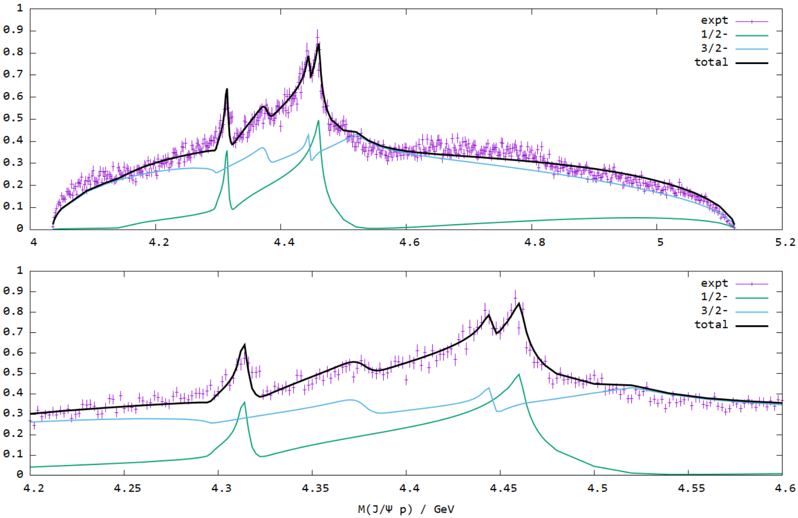

| $1/2^-$ | $\Lambda_c D$ | $\Lambda_c\bar{D}^*$ | $\Sigma_c\bar{D}$ | $\Sigma_c\bar{D}^*$ | $\Sigma_c^*\bar{D}^*$ | $NJ/\psi$ | $N\eta_c$ |
|---|---|---|---|---|---|---|---|
| $\Lambda_c\bar{D}$ | A | 0 | 0 | $\sqrt{3}B$ | $\sqrt{6}B$ | $\frac{\sqrt{3}}{2}D$ | $\frac{1}{2}D$ |
| $\Lambda_c\bar{D}^*$ | | A | $\sqrt{3}B$ | $-2B$ | $\sqrt{2}B$ | $-\frac{D}{2}$ | $\frac{\sqrt{3}}{2}D$ |
| $\Sigma_c\bar{D}$ | | | $C_a$ | $\frac{2}{\sqrt{3}}C_b$ | $-\sqrt{\frac{2}{3}}C_b$ | $-\frac{1}{2\sqrt{3}}E$ | $\frac{1}{2}E$ |
| $\Sigma_c\bar{D}^*$ | | | | $C_a - \frac{4}{3}C_b$ | $-\frac{\sqrt{2}}{3}C_b$ | $\frac{5}{6}E$ | $-\frac{1}{2\sqrt{3}}E$ |
| $\Sigma_c^*\bar{D}^*$ | | | | | $C_a - \frac{5}{3}C_b$ | $\frac{\sqrt{2}}{3}E$ | $\sqrt{\frac{2}{3}}E$ |
| $NJ/\psi$ | | | | | | 0 | 0 |
| $N\eta_c$ | | | | | | | 0 |

| $3/2^-$ | $\Lambda_c\bar{D}^*$ | $\Sigma_c^*\bar{D}$ | $\Sigma_c\bar{D}^*$ | $\Sigma_c^*\bar{D}^*$ | $NJ/\psi$ |
|---|---|---|---|---|---|
| $\Lambda_c\bar{D}^*$ | $A$ | $-\sqrt{3}B$ | $B$ | $\sqrt{5}B$ | $D$ |
| $\Sigma_c^*\bar{D}$ | | $C_a$ | $\frac{C_b}{\sqrt{3}}$ | $\sqrt{\frac{5}{3}}C_b$ | $-\frac{E}{\sqrt{3}}$ |
| $\Sigma_c\bar{D}^*$ | | | $C_a + \frac{2}{3}C_b$ | $-\frac{\sqrt{5}}{3}C_b$ | $\frac{E}{3}$ |
| $\Sigma_c^*\bar{D}^*$ | | | | $C_a - \frac{2}{3}C_b$ | $\frac{\sqrt{5}}{3}E$ |
| $NJ/\psi$ | | | | | 0 |

# Case 1: $P_c(4457)$ as a $\Sigma_c \bar{D}^*$ cusp



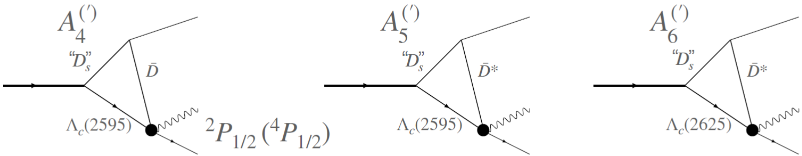
# Case 2: $P_c(4312)$, "$P_c(4380)$" and $P_c(4440)$ bind



# $1/2^+$ channels

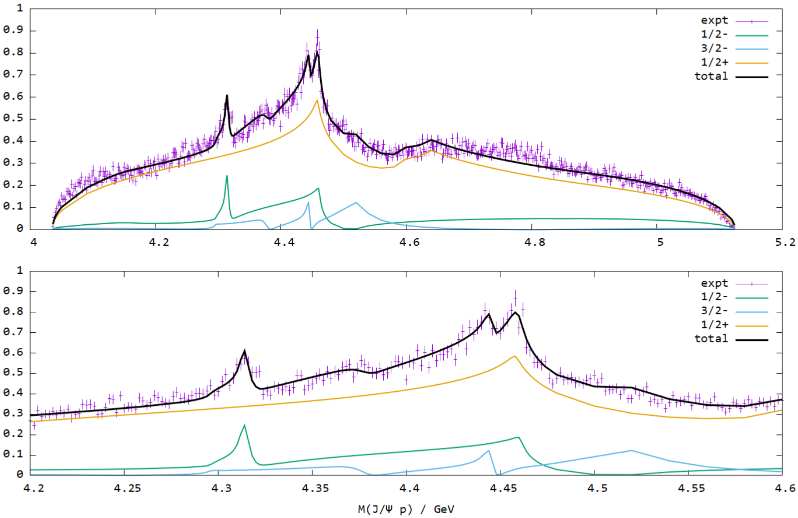
$$\mathcal{A}(^2P_{1/2}) = b_3 + g_4 A_4 + g_5 A_5 + g_6 A_6$$

$$\mathcal{A}(^4P_{1/2}) = b_4 + g_4 A'_4 + g_5 A'_5 + g_6 A'_6.$$

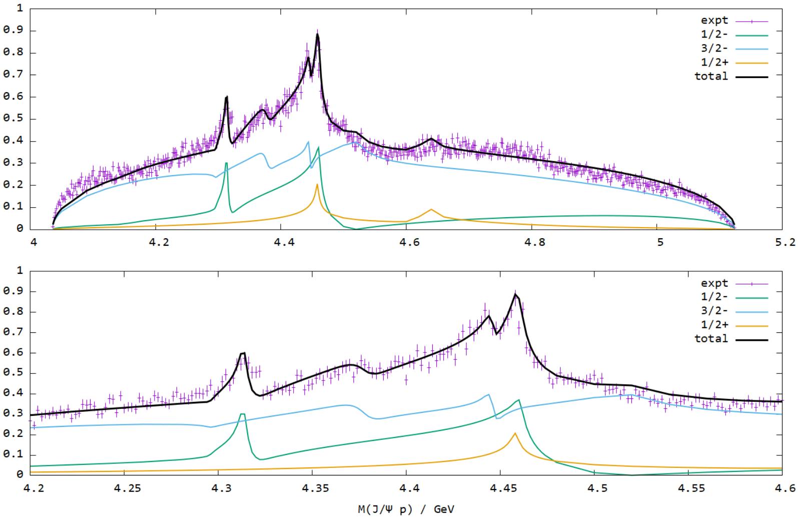



| $1/2^+$ | $\Lambda_c(2595)\bar{D}$ | $\Lambda_c(2595)\bar{D}^*$ | $\Lambda_c(2625)\bar{D}^*$ | $NJ/\psi(^2P_{1/2})$ | $NJ/\psi(^4P_{1/2})$ | $N\eta_c(^2P_{1/2})$ |
|---|---|---|---|---|---|---|
| $\Lambda_c(2595)\bar{D}$ | $F_a$ | $\frac{2}{\sqrt{3}}F_b$ | $-\sqrt{\frac{2}{3}}F_b$ | $\frac{1}{6\sqrt{3}}G_a - \frac{4}{3\sqrt{3}}G_b$ | $\frac{1}{3}\sqrt{\frac{2}{3}}\,(G_a + G_b)$ | $\frac{1}{2}G_a$ |
| $\Lambda_c(2595)\bar{D}^*$ | | $F_a - \frac{4}{3}F_b$ | $-\frac{\sqrt{2}}{3}F_b$ | $-\frac{5}{18}G_a - \frac{4}{9}G_b$ | $-\frac{10\sqrt{2}}{18}G_a + \frac{\sqrt{2}}{9}G_b$ | $-\frac{1}{2\sqrt{3}}G_a$ |
| $\Lambda_c(2625)\bar{D}^*$ | | | $F_a - \frac{5}{3}F_b$ | $-\frac{\sqrt{2}}{9}G_a + \frac{2\sqrt{2}}{9}G_b$ | $-\frac{4}{9}G_a - \frac{1}{9}G_b$ | $\sqrt{\frac{2}{3}}G_a$ |
| $NJ/\psi(^2P_{1/2})$ | | | | 0 | 0 | 0 |
| $NJ/\psi(^4P_{1/2})$ | | | | | 0 | 0 |
| $N\eta_c(^2P_{1/2})$ | | | | | | 0 |

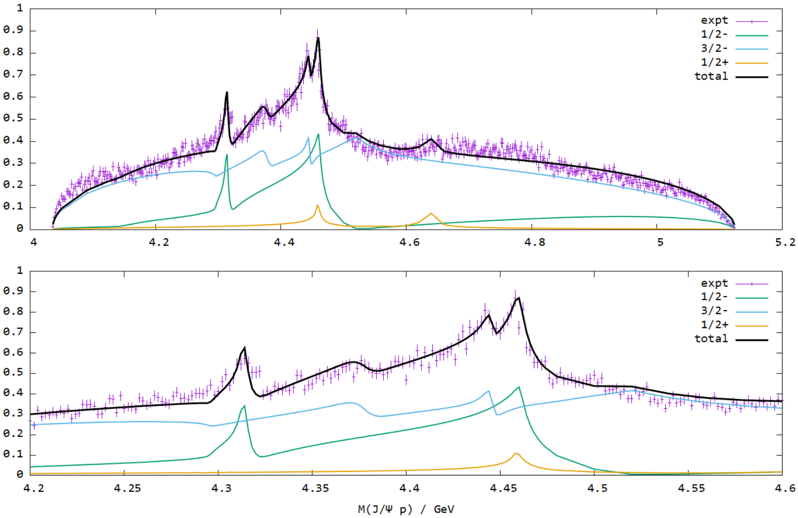
# Case 3: great fit, but too much $1/2^+$ background



# Case 4: $P_c(4457)$ as a triangle singularity



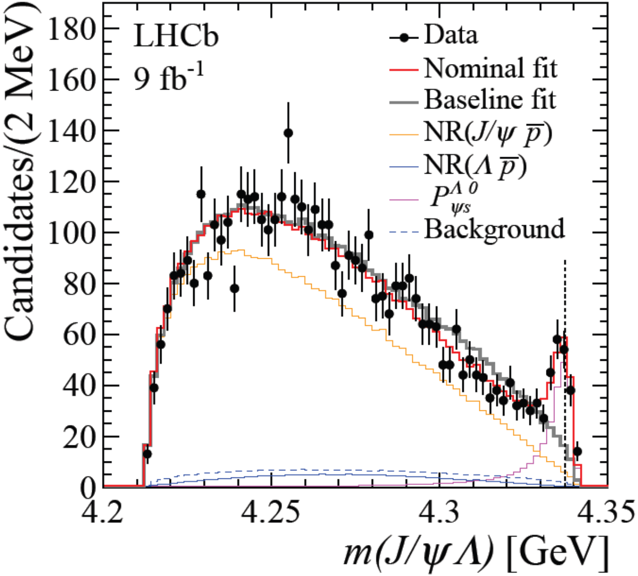
# Case 5: $P_c(4457)$ as a $1/2^+$ $\Lambda_c(2595)\bar{D}$ resonance



# $P_{\psi s}^{\Lambda}(4338)$ as a triangle singularity

[T.B. & E.Swanson, 2208.05106]

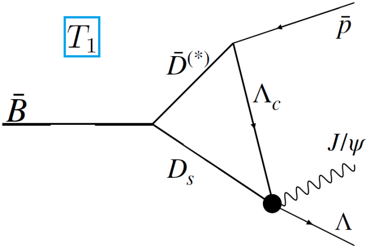
## $B^- \to J/\psi \Lambda \bar{p}$ LHCb

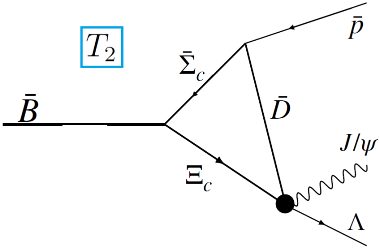



$\Xi_c \bar{D}$ molecule? Karliner/Rosner, Wang/Liu, **Ortega** et al.
But note it is not bound.

# Our model

$$\mathcal{A} = b + g_1 T_1 + g_2 \frac{1}{\sqrt{6}} \left[ 2T_2^{(--)} - T_2^{(-)} \right]$$

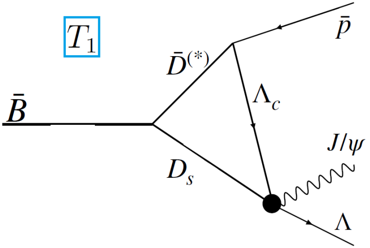


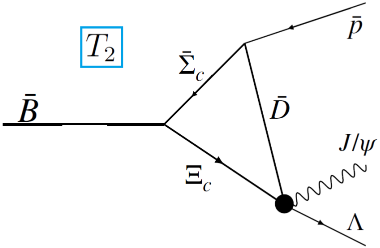




| | $\Lambda_c^+ D_s^-$ | $\Xi_c^+ D^-$ | $\Xi_c^0 \bar{D}^0$ | $\Lambda J/\psi$ | $\Lambda\eta_c$ | $\Sigma J/\psi$ | $\Sigma\eta_c$ |
|---|---|---|---|---|---|---|---|
| $\Lambda_c^+ D_s^-$ | $A+\Delta$ | $\Delta$ | $-\Delta$ | $\frac{D}{\sqrt{2}}$ | $\frac{D}{\sqrt{6}}$ | $0$ | $0$ |
| $\Xi_c^+ \bar{D}^-$ | | $A+\Delta$ | $-\Delta$ | $-\frac{D}{2\sqrt{2}}$ | $-\frac{D}{2\sqrt{6}}$ | $\frac{\sqrt{3}D}{2\sqrt{2}}$ | $\frac{D}{2\sqrt{2}}$ |
| $\Xi_c^0 \bar{D}^0$ | | | $A+\Delta$ | $\frac{D}{2\sqrt{2}}$ | $\frac{D}{2\sqrt{6}}$ | $\frac{\sqrt{3}D}{2\sqrt{2}}$ | $\frac{D}{2\sqrt{2}}$ |
| $\Lambda J/\psi$ | | | | $0$ | $0$ | $0$ | $0$ |
| $\Lambda\eta_c$ | | | | | $0$ | $0$ | $0$ |
| $\Sigma J/\psi$ | | | | | | $0$ | $0$ |
| $\Sigma\eta_c$ | | | | | | | $0$ |

# Our model

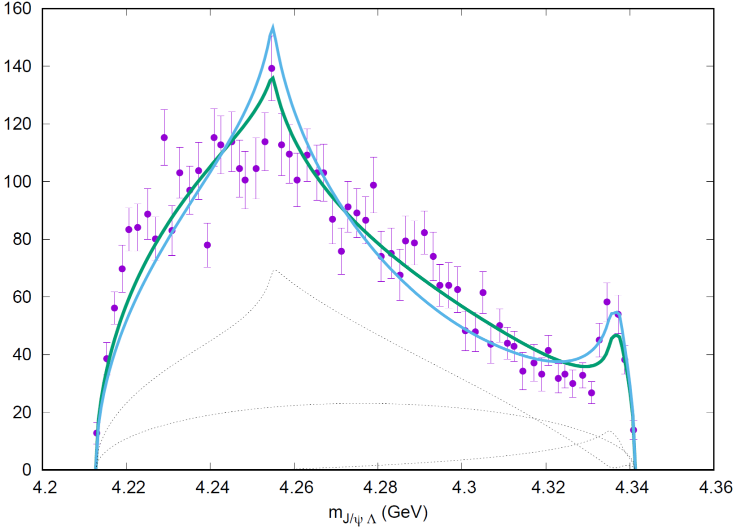
$$\mathcal{A} = b + g_1 T_1 + g_2 \frac{1}{\sqrt{6}} \left[ 2T_2^{(--)} - T_2^{(-)} \right]$$




| | $\Lambda_c^+ D_s^-$ | $\Xi_c^+ D^-$ | $\Xi_c^0 \bar{D}^0$ | $\Lambda J/\psi$ | $\Lambda\eta_c$ | $\Sigma J/\psi$ | $\Sigma\eta_c$ |
|---|---|---|---|---|---|---|---|
| $\Lambda_c^+ D_s^-$ | $A+\Delta$ | $\Delta$ | $-\Delta$ | $\frac{D}{\sqrt{2}}$ | $\frac{D}{\sqrt{6}}$ | 0 | 0 |
| $\Xi_c^+ \bar{D}^-$ | | $A+\Delta$ | $-\Delta$ | $-\frac{D}{2\sqrt{2}}$ | $-\frac{D}{2\sqrt{6}}$ | $\frac{\sqrt{3}D}{2\sqrt{2}}$ | $\frac{D}{2\sqrt{2}}$ |
| $\Xi_c^0 \bar{D}^0$ | | | $A+\Delta$ | $\frac{D}{2\sqrt{2}}$ | $\frac{D}{2\sqrt{6}}$ | $\frac{\sqrt{3}D}{2\sqrt{2}}$ | $\frac{D}{2\sqrt{2}}$ |
| $\Lambda J/\psi$ | | | | 0 | 0 | 0 | 0 |
| $\Lambda\eta_c$ | | | | | 0 | 0 | 0 |
| $\Sigma J/\psi$ | | | | | | 0 | 0 |
| $\Sigma\eta_c$ | | | | | | | 0 |

# Result

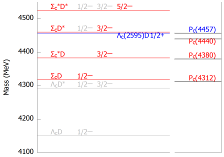


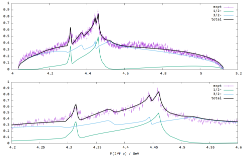

$T_1$ peaks at $\Lambda_c^+ D_s^-$ threshold (cusp)

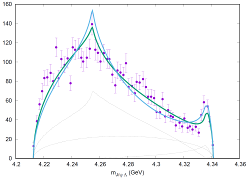
$T_2$ has a $P_{\psi s}^{\Lambda}(4338)$ peak at $\Xi_c \bar{D}$ (triangle singularity)

Fit has $|g_1| >> |g_2|$, as required.

# Thanks to the organisers






- Experimental data imply that $P_c(4457)$ is not a $\Sigma_c \bar{D}^*$ molecule, but could be $\Sigma_c \bar{D}^*$ cusp, $\Lambda_c(2595)\bar{D}$ molecule, or triangle singularity.

- A model with colour-favoured production and heavy-quark symmetry nicely describes the $\Lambda_b \to J/\psi\, p\, K^-$ data.

- The same ideas describe $B^- \to J/\psi \Lambda \bar{p}$ data, where $P^{\Lambda}_{\psi s}(4338)$ is due to the triangle singularity.