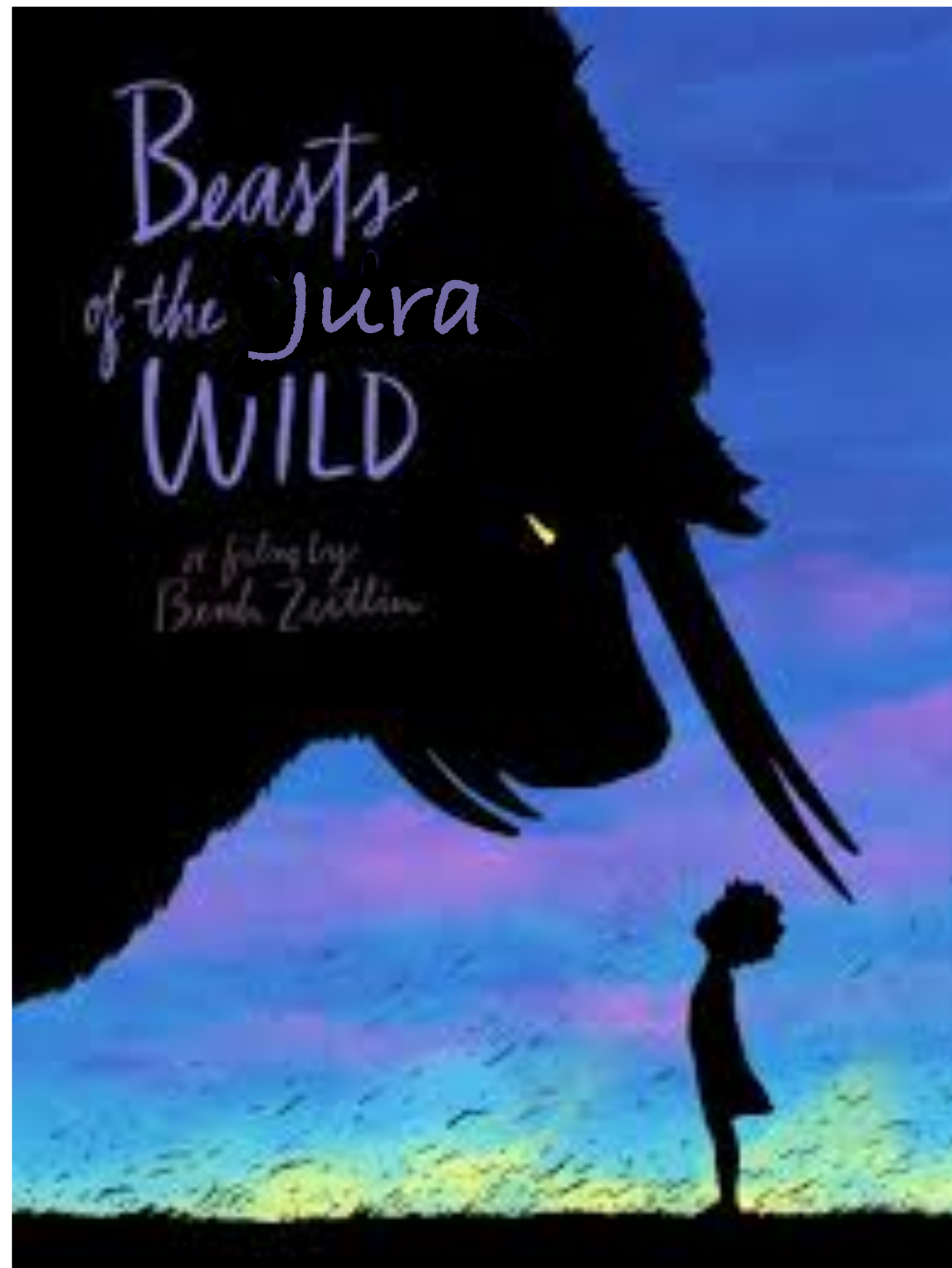


CONSISTENT INTERPRETATION OF THE PENTAQUARK STATES

BEASTS OF THE JURA WILD

Eric Swanson







Tim Burns

T.J. Burns and E.S. Swanson, Experimental Constraints on the Properties of P_c States, 2112.11527

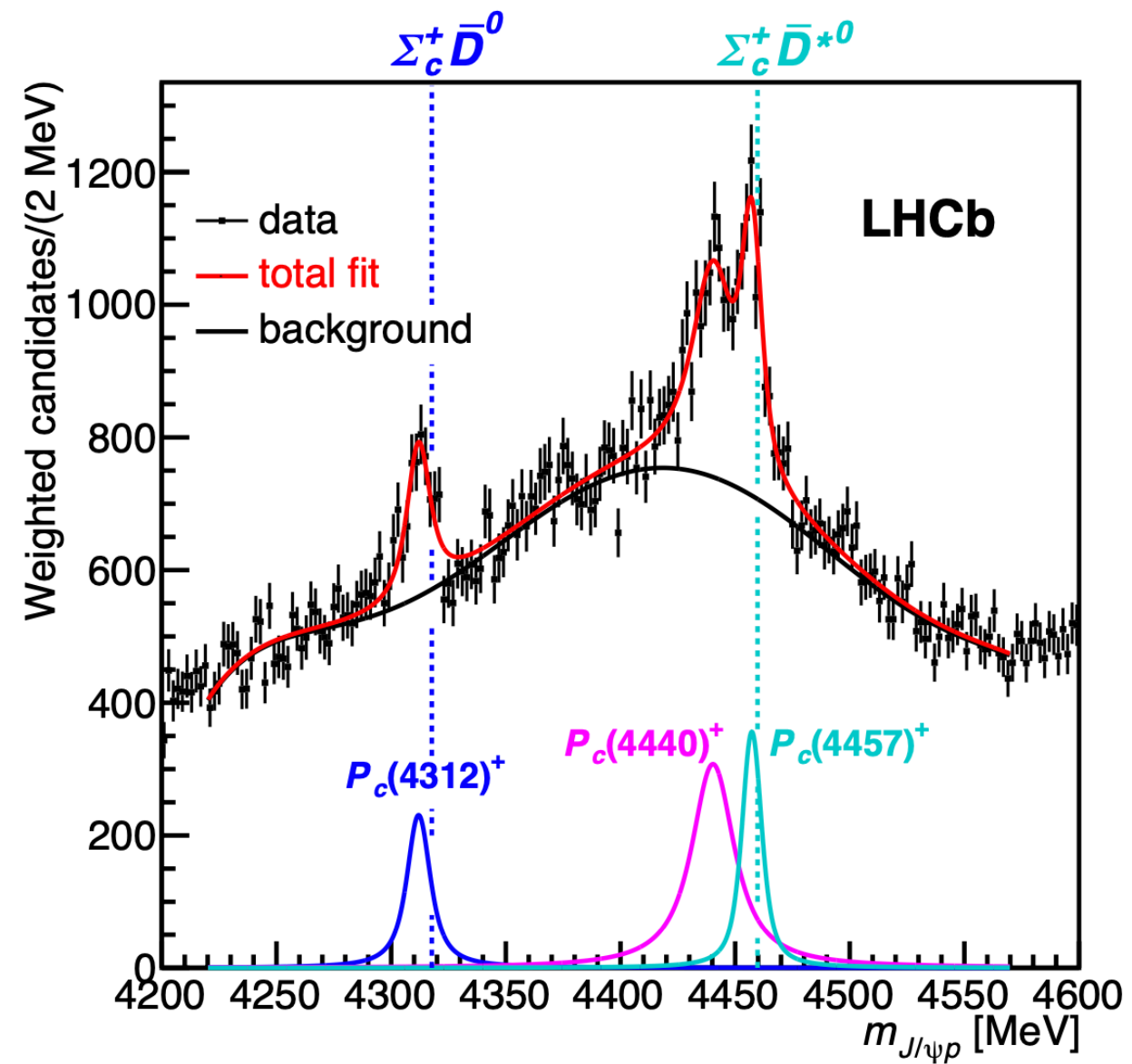
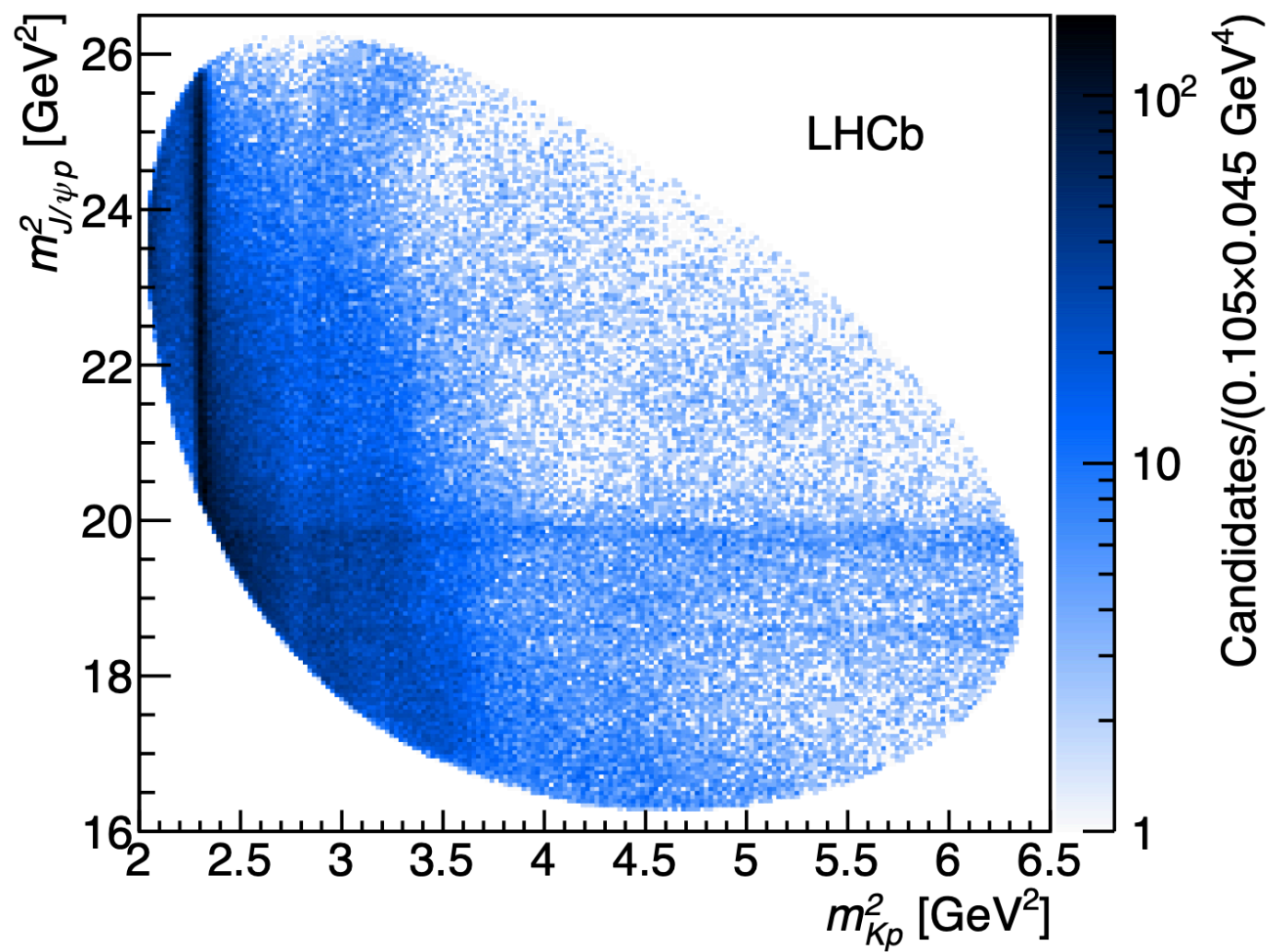
T.J. Burns and E.S. Swanson, Production of P_c States in Λ_b Decays, 2207.00511

Experimental Constraints

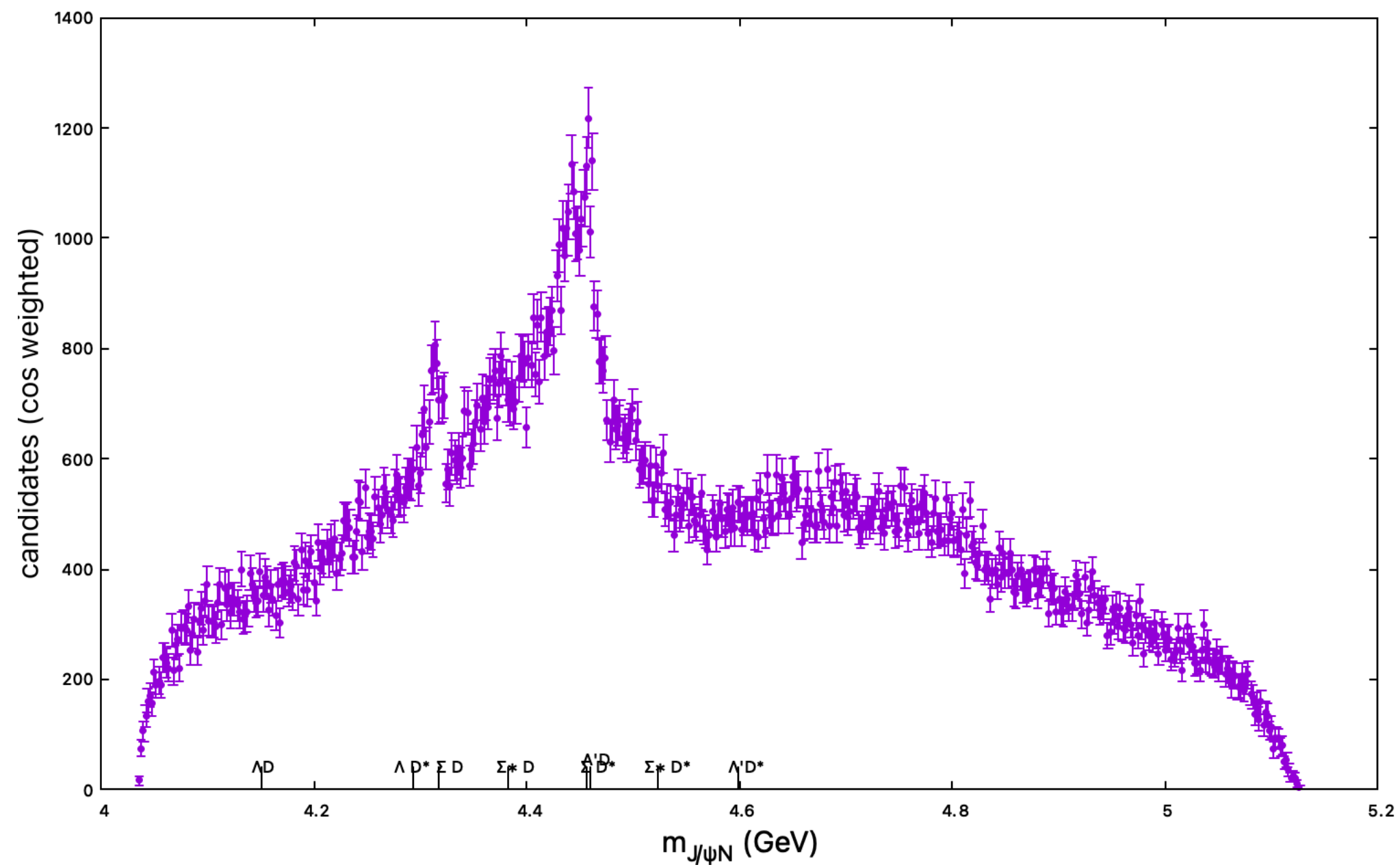


LHCb Discovery

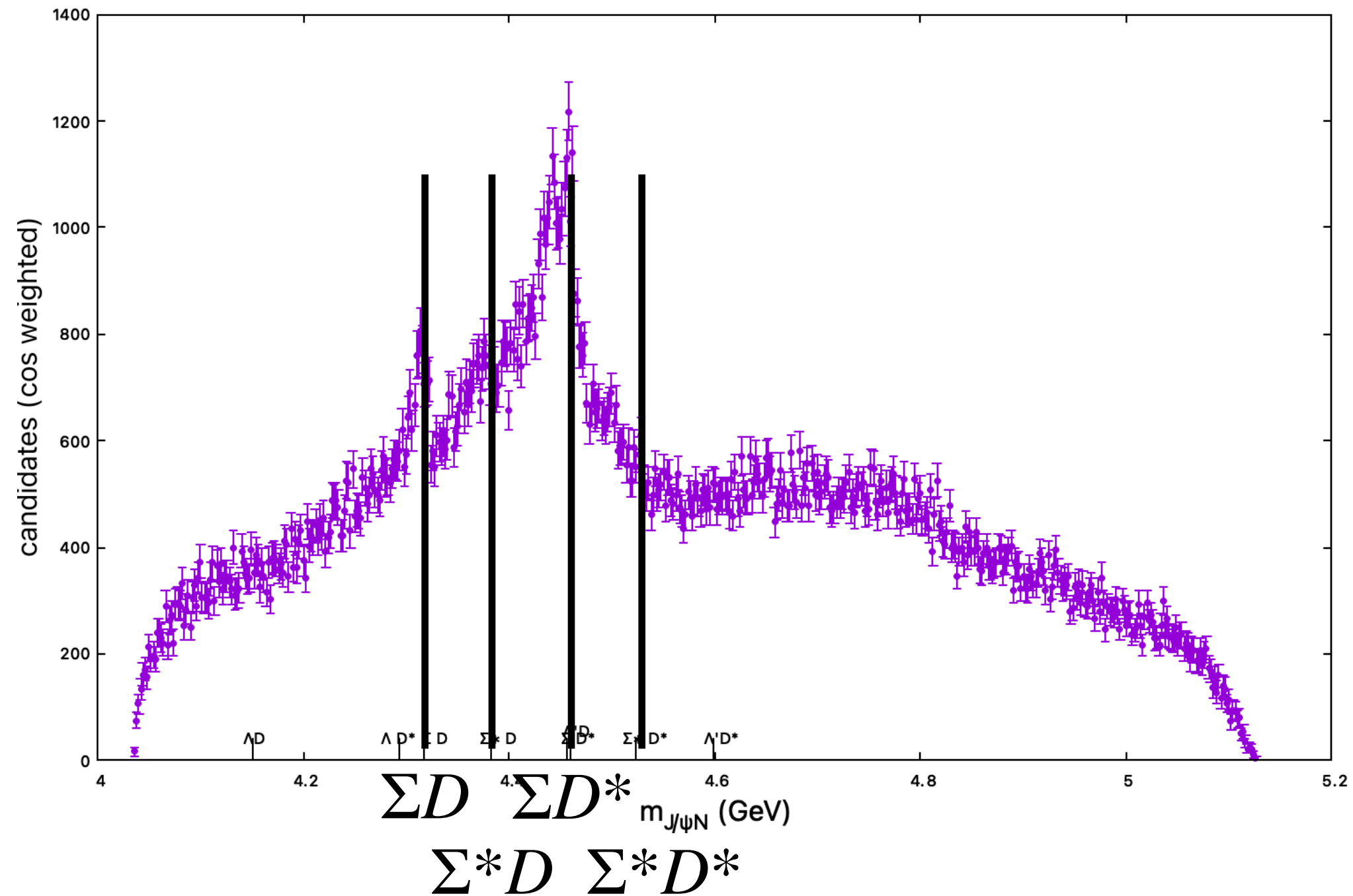
$$\Lambda_b^0 \rightarrow J/\psi p K^-$$



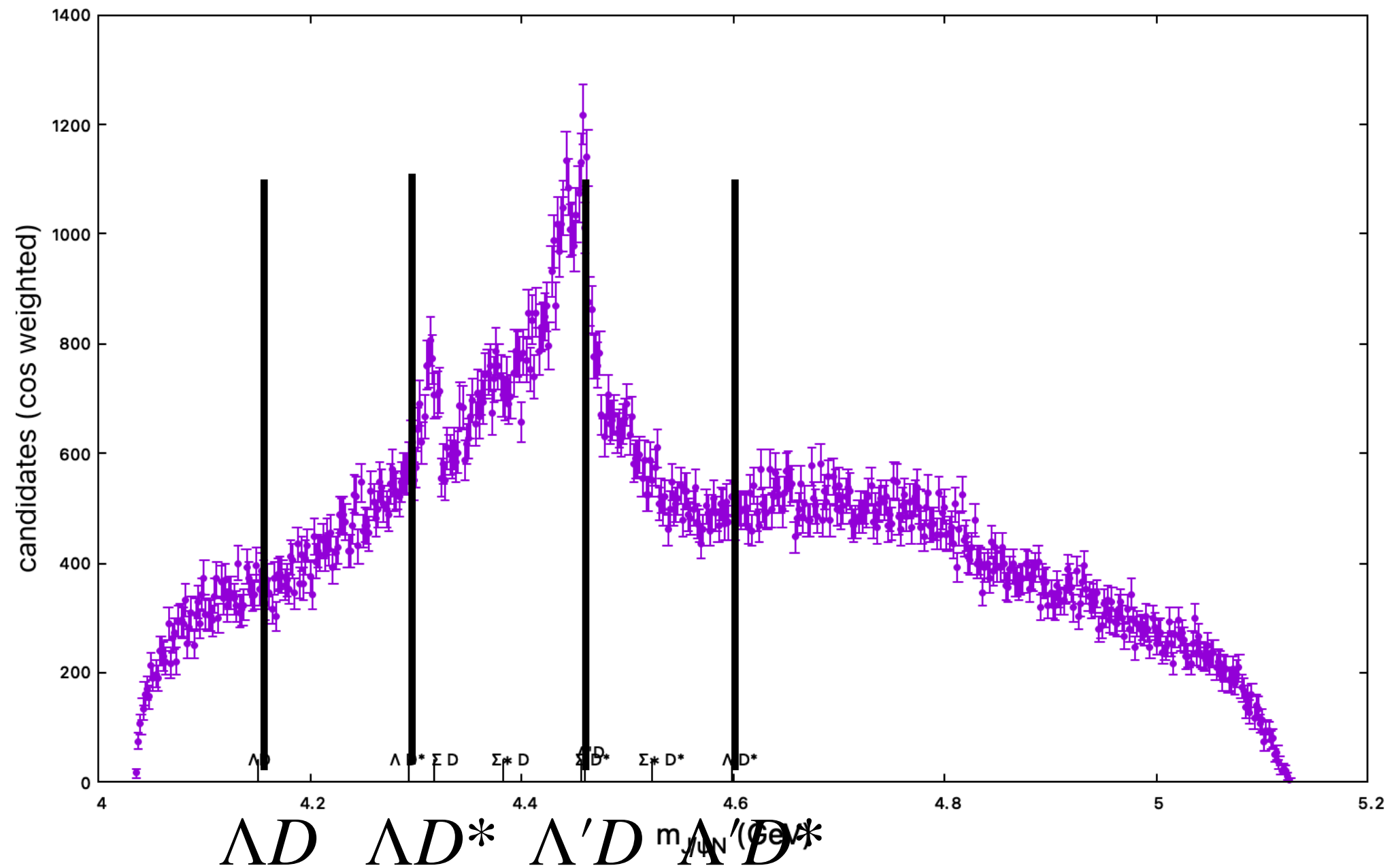
A Look at the Data (LHCb cos weighted)



A Look at the Data (LHCb cos weighted)



A Look at the Data (LHCb cos weighted)



A Look at the Data (JLab)

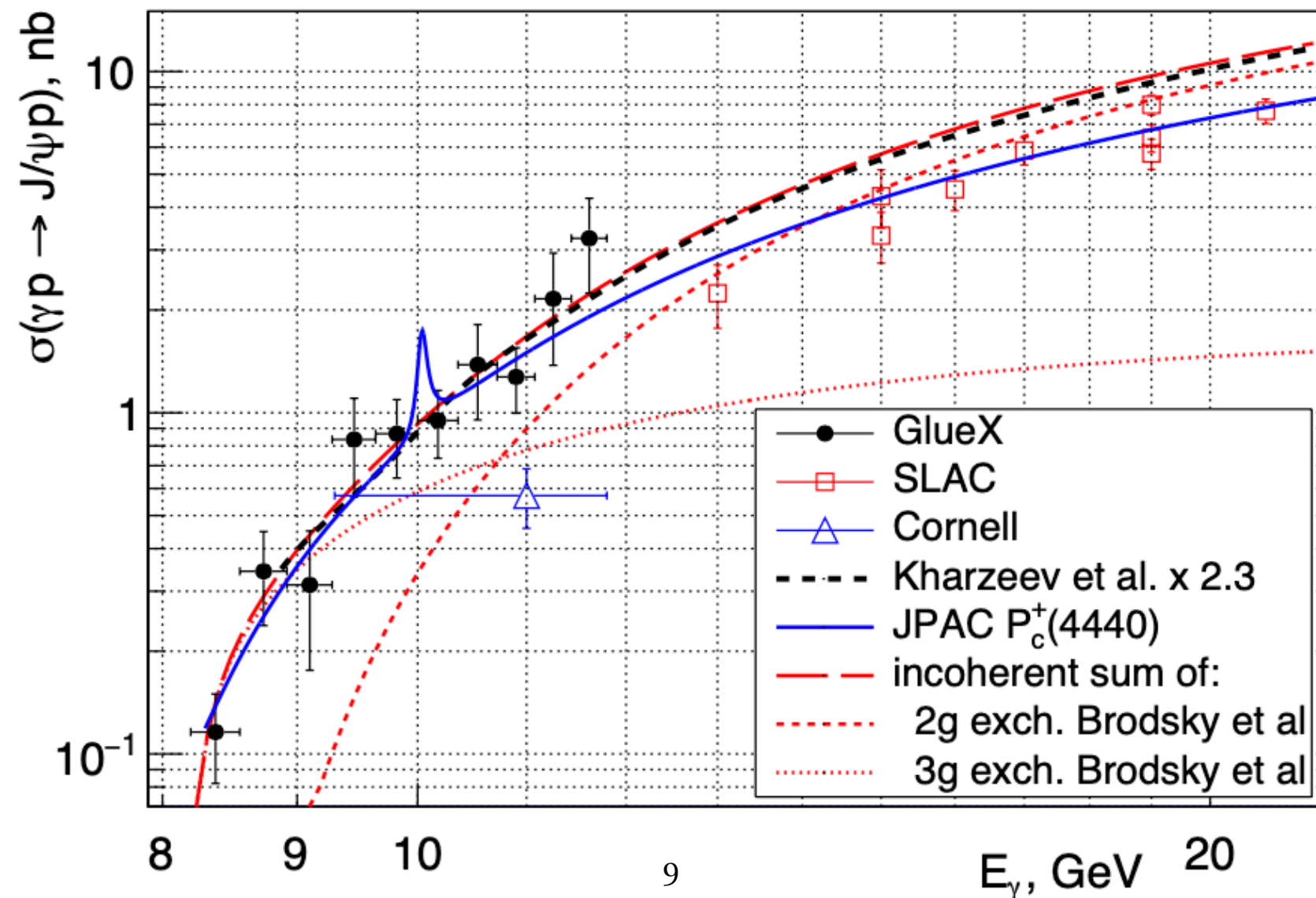
Hiller Blin et al. arXiv:1606.08912

Ali et al, arXiv:1905.10811

$$Bf(Pc(4312) \rightarrow J/\psi p) < 4.6 \% (90 \% C.L.)$$

$$Bf(Pc(4440) \rightarrow J/\psi p) < 2.3 \% (90 \% C.L.)$$

$$Bf(Pc(4457) \rightarrow J/\psi p) < 3.8 \% (90 \% C.L.)$$



A Look at the Data (JLab J ψ -007)

Sylvester Joosten, GHP21 J/ ψ -007

4% scale uncertainty on cross section limit

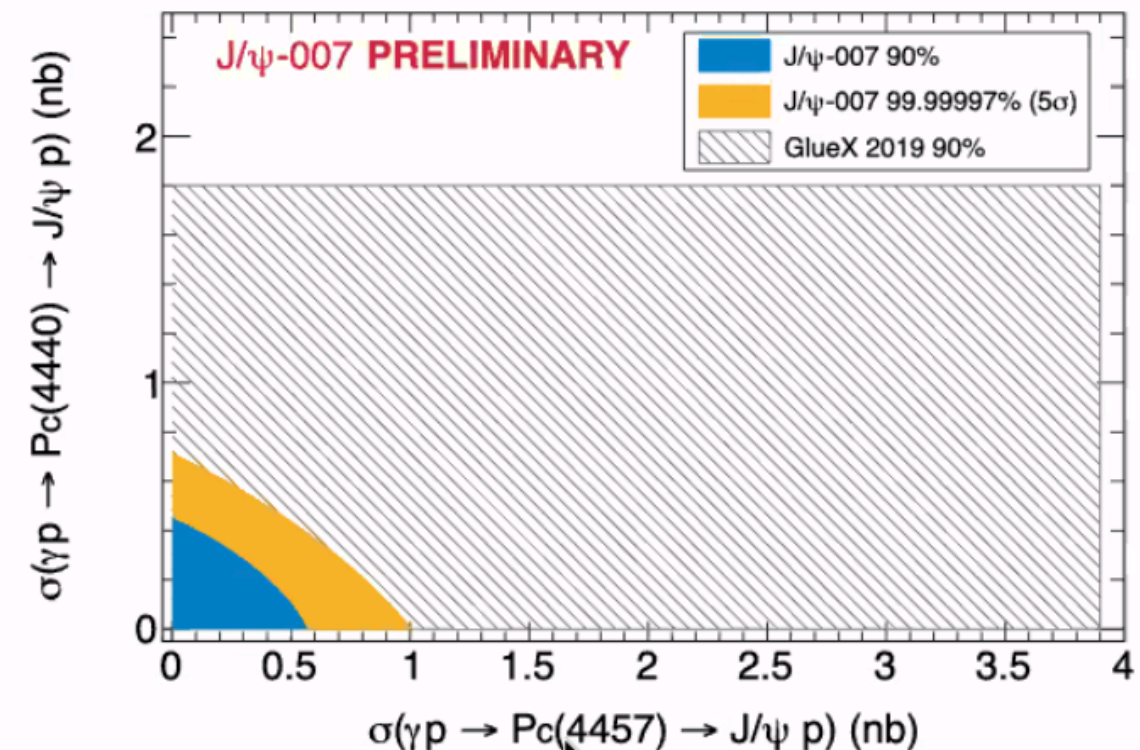
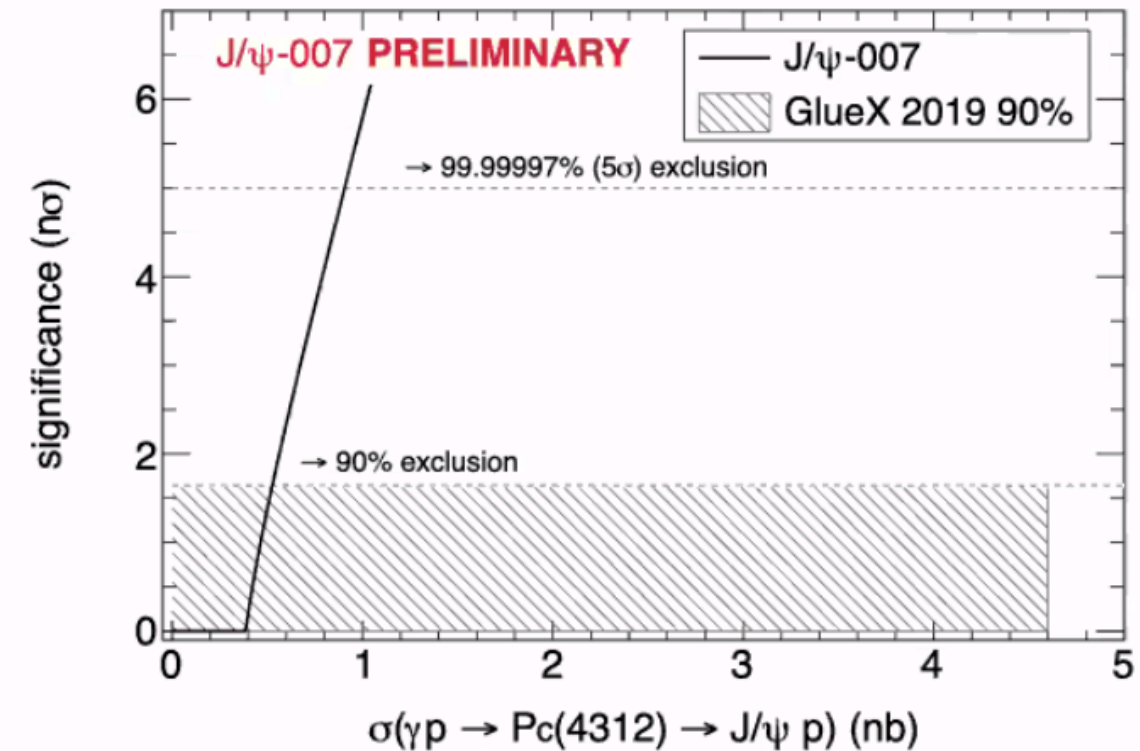
RESULTS AND IMPLICATIONS

Cross-section at the resonance peak for model-independent upper limits

Upper limit for P_c cross section almost order of magnitude below GlueX limit.

Results are inconsistent with reasonable assumptions for true 5-quark states.

Door is still open for molecular states, but will be very hard to measure in photoproduction due to small overlap with both γp initial state and $J/\psi p$ final state



A Look at the Data (Λ D modes)

Amplitude analysis of $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-$ decays
and pentaquark searches in the $\Lambda_c^+ \bar{D}^0$ system
at the LHCb experiment

Alessio Piucci

Heidelberg University, Germany

First observation of the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$ in preparation of
a pentaquark search in the $\Lambda_c^+ \bar{D}^{(*)0}$ system at the LHCb
experiment

[Marian Stahl \(Heidelberg U.\)](#)

Jul 11, 2018

139 pages

Supervisors: Stephanie Hansmann-Menzemer ([Heidelberg U.](#)), Klaus Reygers ([Heidelberg U.](#))

Thesis: PhD U. Heidelberg (main) (defense: Jul 11, 2018)

DOI: [10.11588/heidok.00025126](https://doi.org/10.11588/heidok.00025126)

Report number: CERN-THESIS-2018-176

Experiments: [CERN-LHC-LHCb](#)

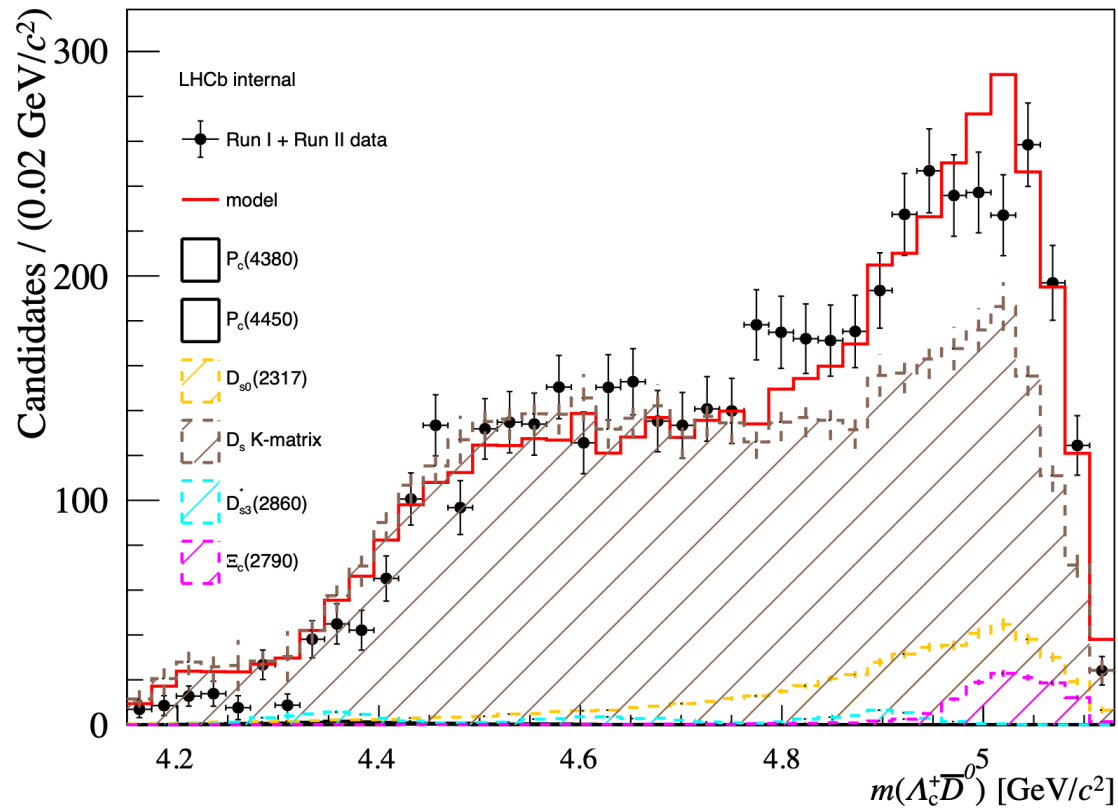
View in: [CERN Document Server](#)

<http://cds.cern.ch/record/2640677>

https://cds.cern.ch/record/2712057/files/10.11588_heidok.00027350.pdf

A Look at the Data (ΛD modes)

Piucci reports P_c fit fraction upper limits in $\Lambda_b \rightarrow \Lambda_c DK$



$P_c(4312)^+$ fit fraction < 0.004 (95%CL)

$P_c(4440)^+, J^P = \frac{1}{2}^-$ fit fraction < 0.006 (95%CL)

$P_c(4440)^+, J^P = \frac{3}{2}^-$ fit fraction < 0.0045 (95%CL)

$P_c(4457)^+, J^P = \frac{1}{2}^-$ fit fraction < 0.0045 (95%CL)

$P_c(4457)^+, J^P = \frac{3}{2}^-$ fit fraction < 0.008 (95%CL)

A Look at the Data (Λ D modes)

Combine with measurements of

$$\mathcal{R} \equiv \mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-) \mathcal{B}(P_c^+ \rightarrow J/\psi p) / \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)$$

and branching fractions

$$Bf(\Lambda_b \rightarrow J/\psi p K) = 3.2(5) \cdot 10^{-4}$$

$$Bf(\Lambda_b \rightarrow D \Lambda_c K) = 1.5 \cdot 10^{-3}$$

to obtain upper limits

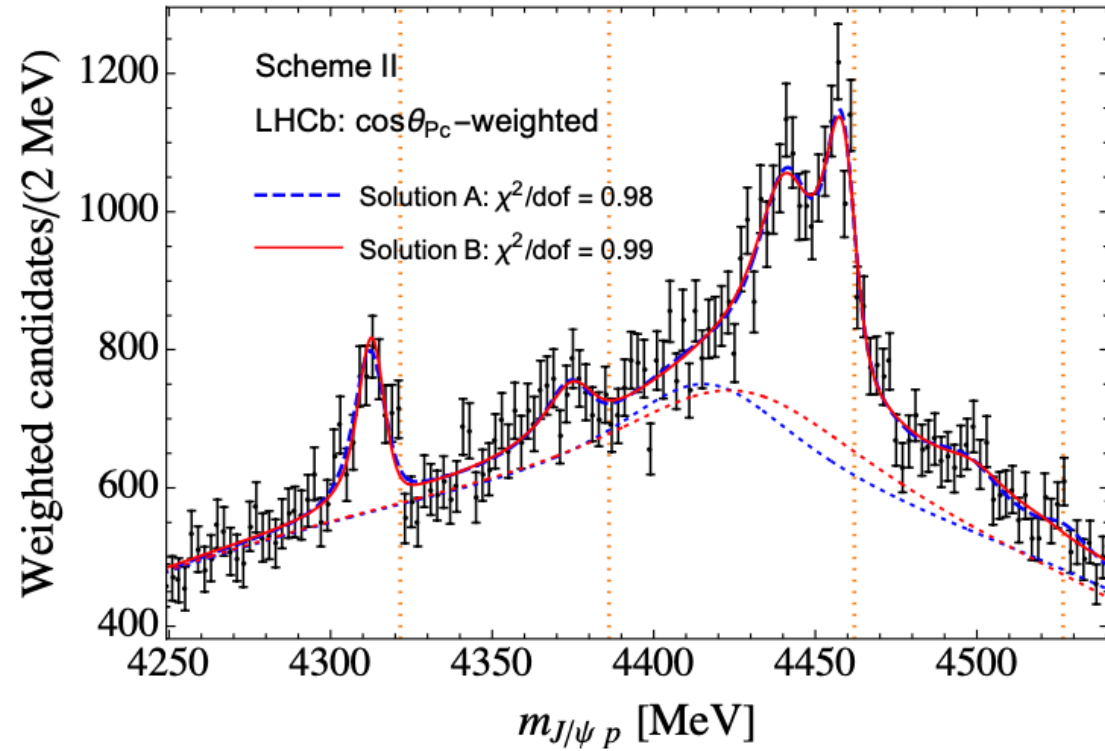
$$Bf(P_c \rightarrow \Lambda_c D) \lesssim \begin{cases} 6.3, (4312) \\ 2.5, (4440; 1/2^-) \\ 1.9, (4440; 3/2^-) \cdot Bf(P_c \rightarrow J/\psi p) \\ 4.0, (4457; 1/2^-) \\ 7.1, (4457; 3/2^-) \end{cases}$$

A Previous Model



A Recent Molecular Model

Du *et al.*, arXiv:2102.07159



- (i) 3 extraneous resonances?
- (ii) artificial production
- (iii) restricted fit range/LD?
- (iv) 4440 Λ D branching fraction?
- (v) extreme background model:

$$f_{\text{bgd}}(E) = b_0 + b_1 E^2 + b_2 E^4 + \frac{g_r^2}{(m - E)^2 + \Gamma^2/4},$$

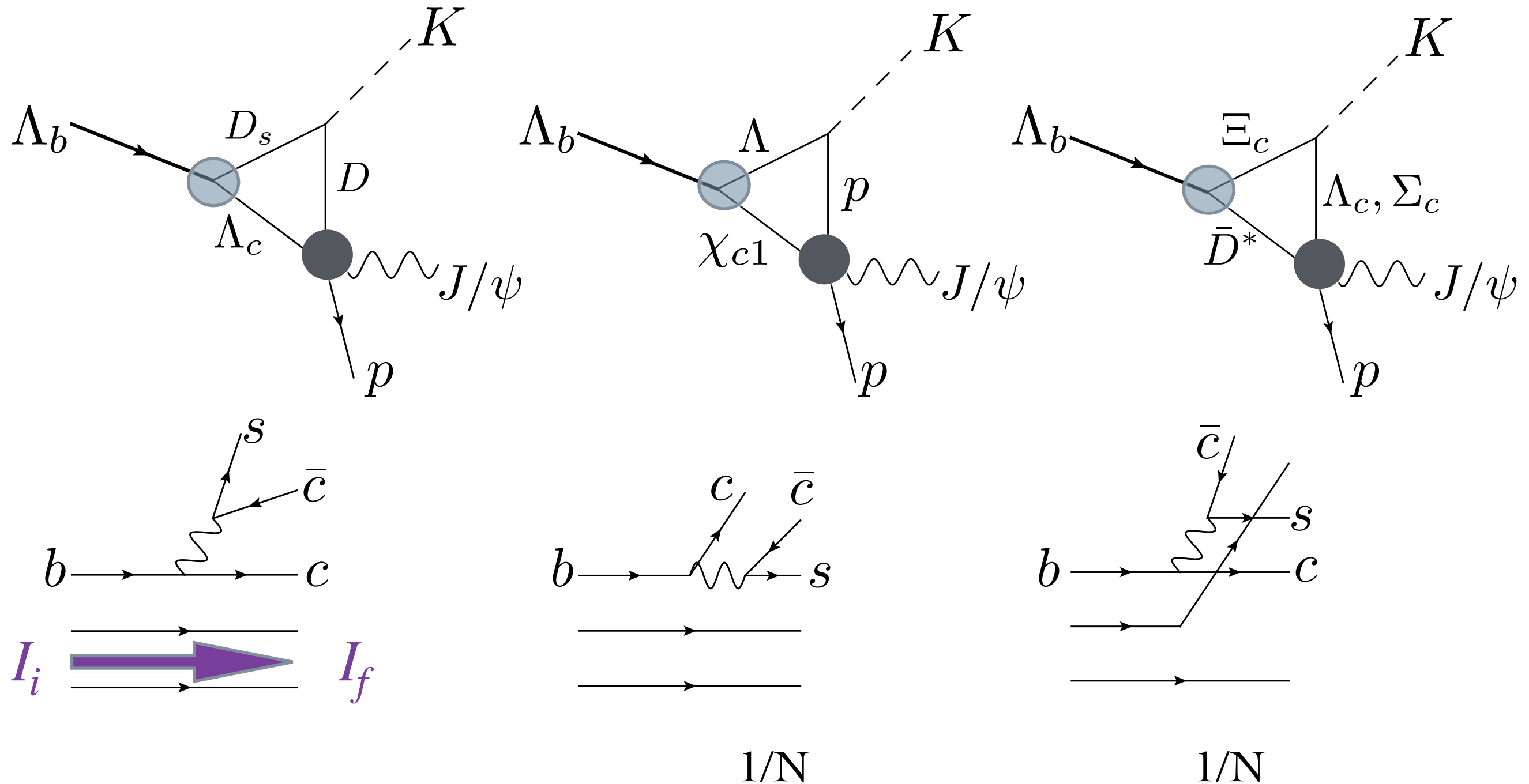
			solution A			solution B		
	DC ([MeV])	RS	J^P	Pole [MeV]	g_{DC}	J^P	Pole [MeV]	g_{DC}
$P_c(4312)$	$\Sigma_c \bar{D} (4321.6)$	I	$\frac{1}{2}^-$	4314(1) - 4(1)i	2.6(1) + 0.4(2)i	$\frac{1}{2}^-$	4312(2) - 4(2)i	2.9(1) + 0.4(2)i
$P_c(4380)$	$\Sigma_c^* \bar{D} (4386.2)$	II	$\frac{3}{2}^-$	4377(1) - 7(1)i	2.8(1) + 0.1(1)i	$\frac{3}{2}^-$	4375(2) - 6(1)i	3.0(1) + 0.1(1)i
$P_c(4440)$	$\Sigma_c \bar{D}^* (4462.1)$	III	$\frac{1}{2}^-$	4440(1) - 9(2)i	3.7(2) + 0.6(1)i	$\frac{3}{2}^-$	4441(3) - 5(2)i	3.6(1) + 0.3(1)i
$P_c(4457)$	$\Sigma_c \bar{D}^* (4462.1)$	III	$\frac{3}{2}^-$	4458(2) - 3(1)i	2.1(2) + 0.3(1)i	$\frac{1}{2}^-$	4462(4) - 5(3)i	2.0(2) + 1.2(3)i
P_c	$\Sigma_c^* \bar{D}^* (4526.7)$	IV	$\frac{1}{2}^-$	4498(2) - 9(3)i	4.0(1) + 0.4(2)i	$\frac{1}{2}^-$	4526(3) - 9(2)i	1.5(2) + 1.1(4)i
P_c	$\Sigma_c^* \bar{D}^* (4526.7)$	IV	$\frac{3}{2}^-$	4510(2) - 14(3)i	3.3(2) + 0.6(2)i	$\frac{3}{2}^-$	4521(2) - 12(3)i	2.5(2) + 0.9(2)i
P_c	$\Sigma_c^* \bar{D}^* (4526.7)$	IV	$\frac{5}{2}^-$	4525(2) - 9(3)i	1.9(2) + 0.6(7)i	$\frac{5}{2}^-$	4501(3) - 6(4)i	3.9(2) + 0.1(2)i

?

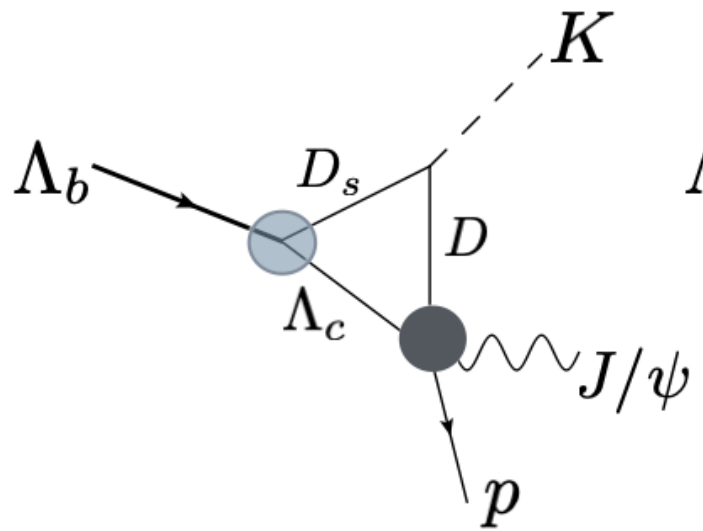
Our Model



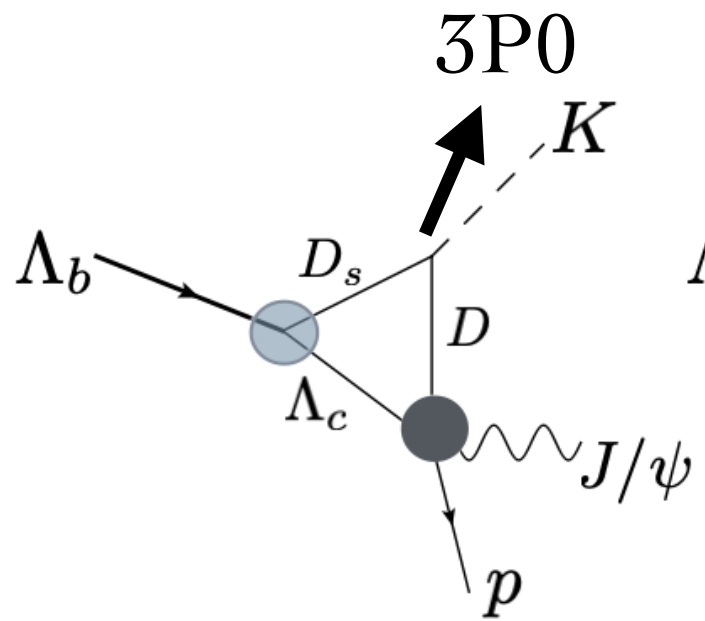
A Production/ Rescattering Model for Pentaquarks



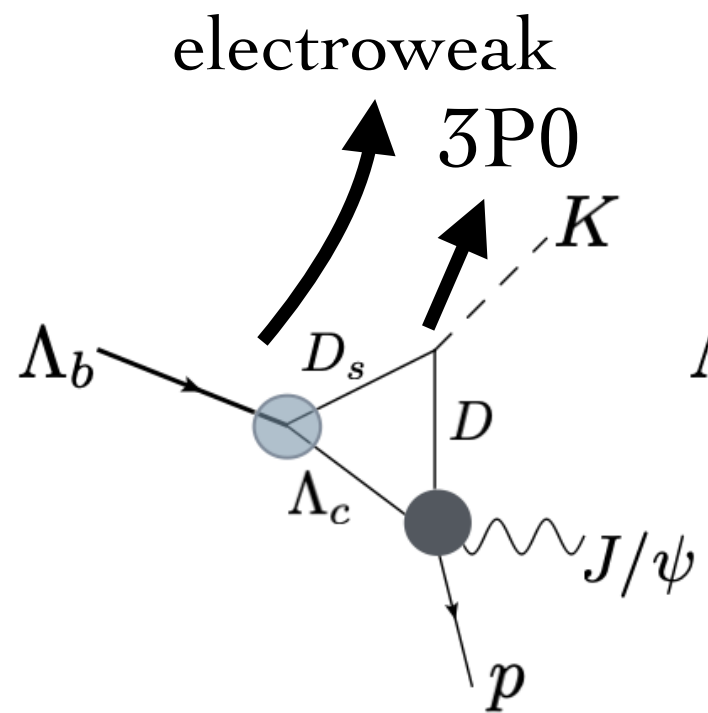
A Production/ Rescattering Model for Pentaquarks



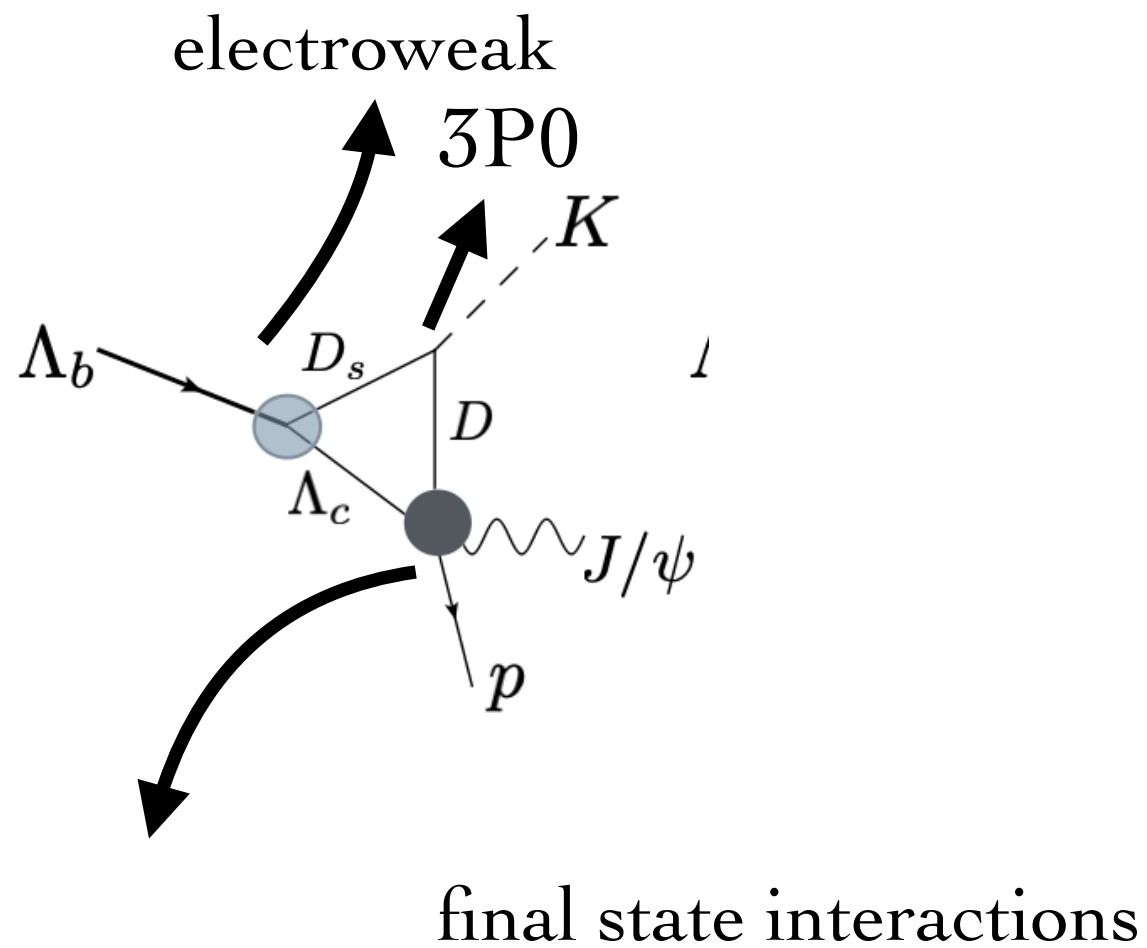
A Production/ Rescattering Model for Pentaquarks



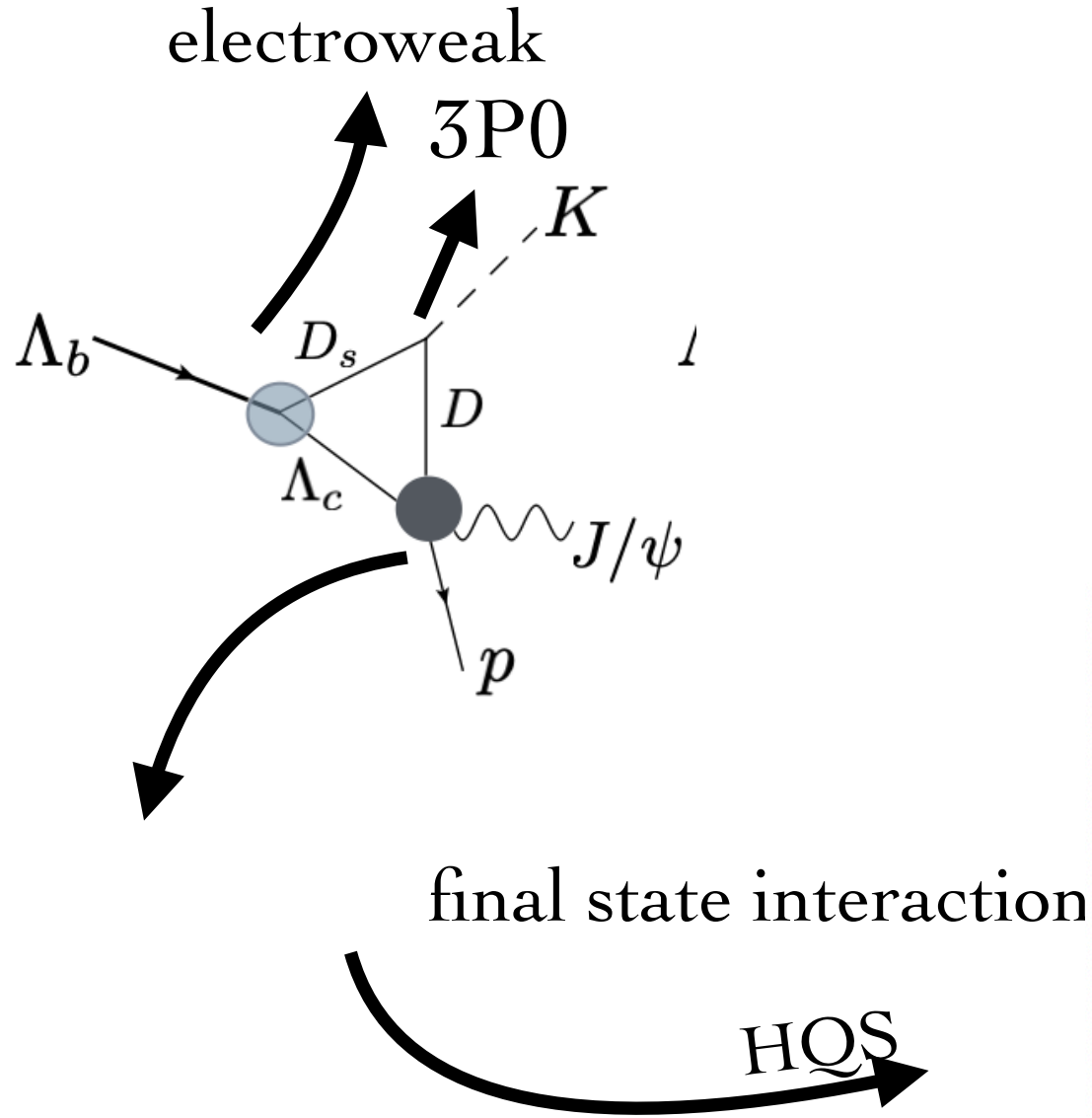
A Production/ Rescattering Model for Pentaquarks



A Production/ Rescattering Model for Pentaquarks



A Production/ Rescattering Model for Pentaquarks

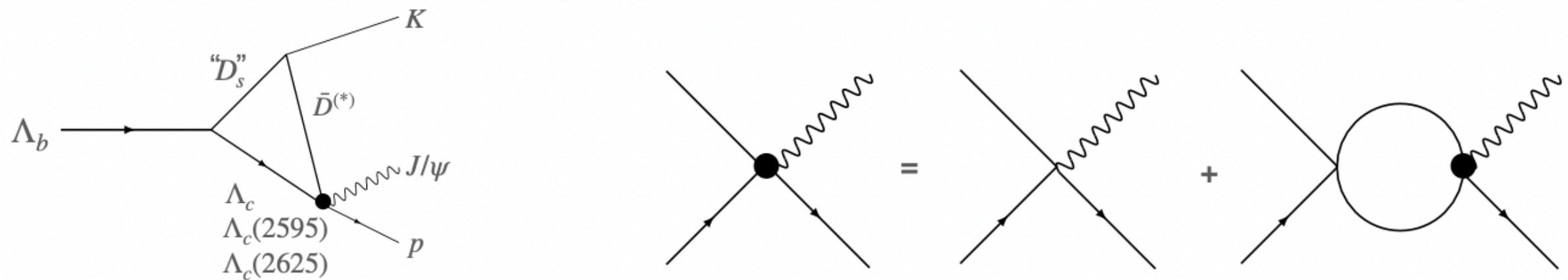


$1/2^-$	$\Lambda_c D$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$	NJ/ψ	$N\eta_c$
$\Lambda_c \bar{D}$	A	0	0	$\sqrt{3}B$	$\sqrt{6}B$	$\frac{\sqrt{3}}{2}D$	$\frac{1}{2}D$
$\Lambda_c \bar{D}^*$		A	$\sqrt{3}B$	$-2B$	$\sqrt{2}B$	$-\frac{D}{2}$	$\frac{\sqrt{3}}{2}D$
$\Sigma_c \bar{D}$			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/ψ						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/ψ
$\Lambda_c \bar{D}^*$	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/ψ					0

$1/2^+$	$\Lambda_c(2595)\bar{D}$	$\Lambda_c(2595)\bar{D}^*$	$\Lambda_c(2625)\bar{D}^*$	$NJ/\psi(^2P_{1/2})$	$NJ/\psi(^4P_{1/2})$	$N\eta_c(^2P_{1/2})$
$\Lambda_c(2595)\bar{D}$	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

A Production/ Rescattering Model for Pentaquarks



- bound/resonance states
- threshold cusps
- triangle singularities

A Production/ Rescattering Model for Pentaquarks

- (i) employs the preferred production mechanism
- (ii) $\eta_c N$ predictions possible
- (iii) other decay mode predictions possible
- (iv) fitting the full energy range constrains the model
- (v) $J/\psi N$ branching fractions are controlled by D & E
- (vi) 4312 ($1/2^-$) : $\Lambda_c D$ has zero coupling
- (vii) 4440 ($3/2^-$) : $\Lambda_c D$ has D-wave coupling
- (viii) 4457 ($1/2^\pm$) : cusp(s) explanation
- (ix) $1/2^-$ and $3/2^-$ $\Sigma_c^* D^*$ resonances are eliminated by -Cb
- (x) shoulder and 4450 hump is due to $1/2^- \Sigma_c D - \Sigma_c D^*$ interactions + threshold cusp

A Production/ Rescattering Model for Pentaquarks

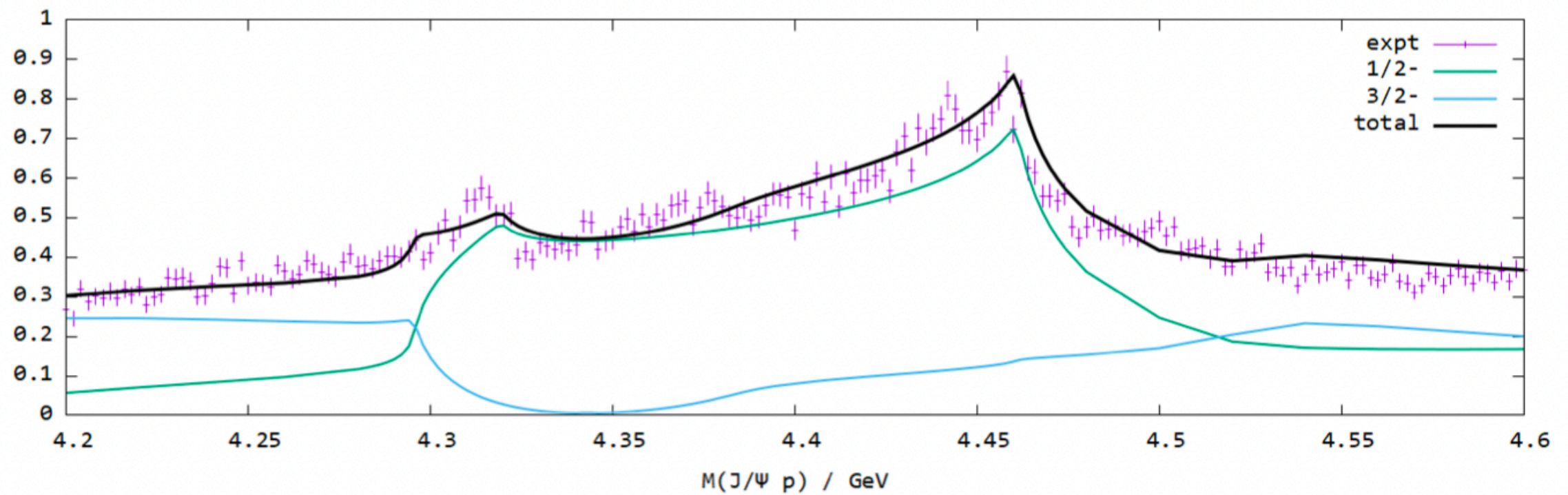
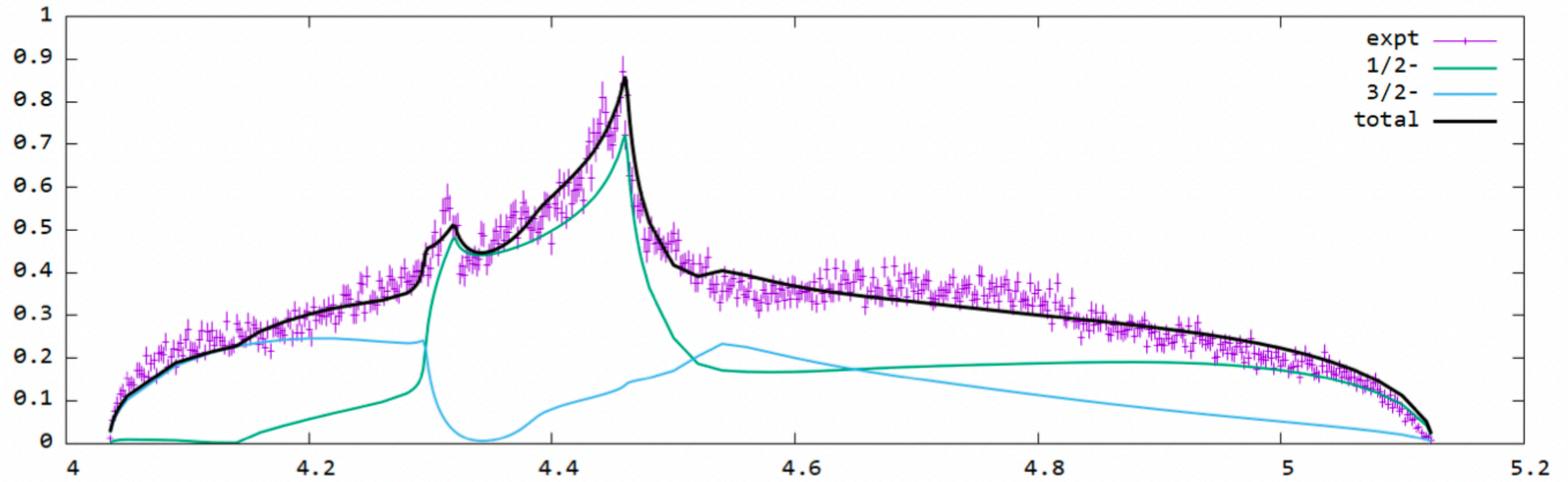
Develop models with increasing complexity:

- i triangles+thresholds only
- ii add C_a , C_b to generate resonances
- iii add $J^P = 1/2^+$ channel,
- iv tune D_s mass
- v add 4457 $1/2^+$ resonance

Constant background term added *coherently*.

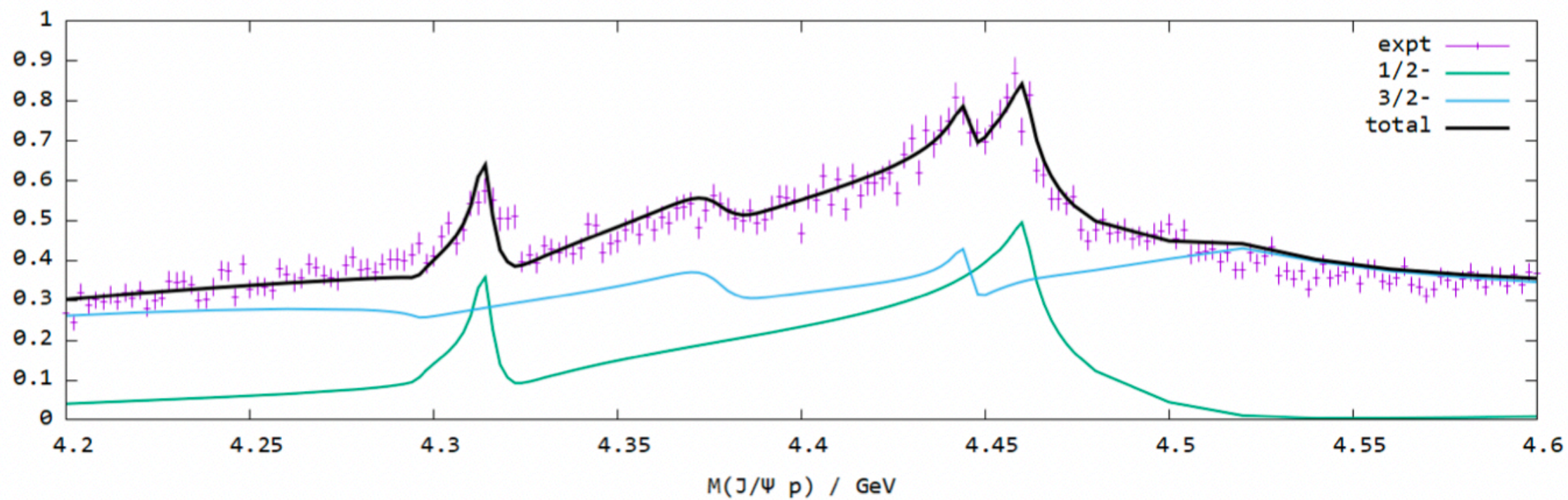
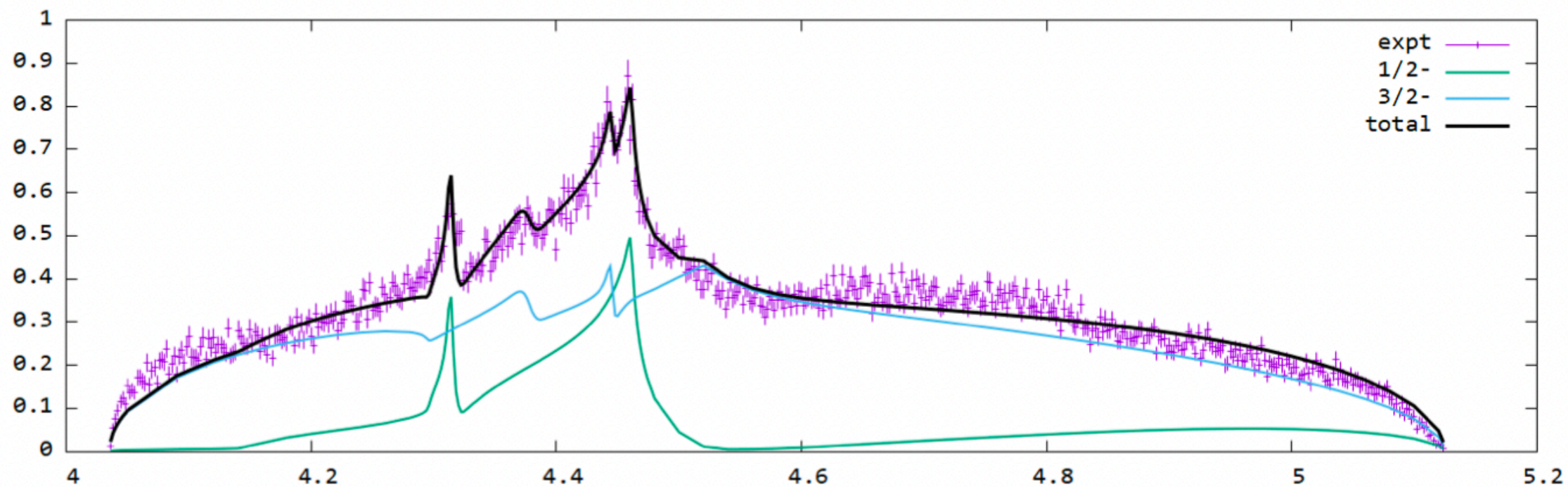
Case I

triangles+thresholds only



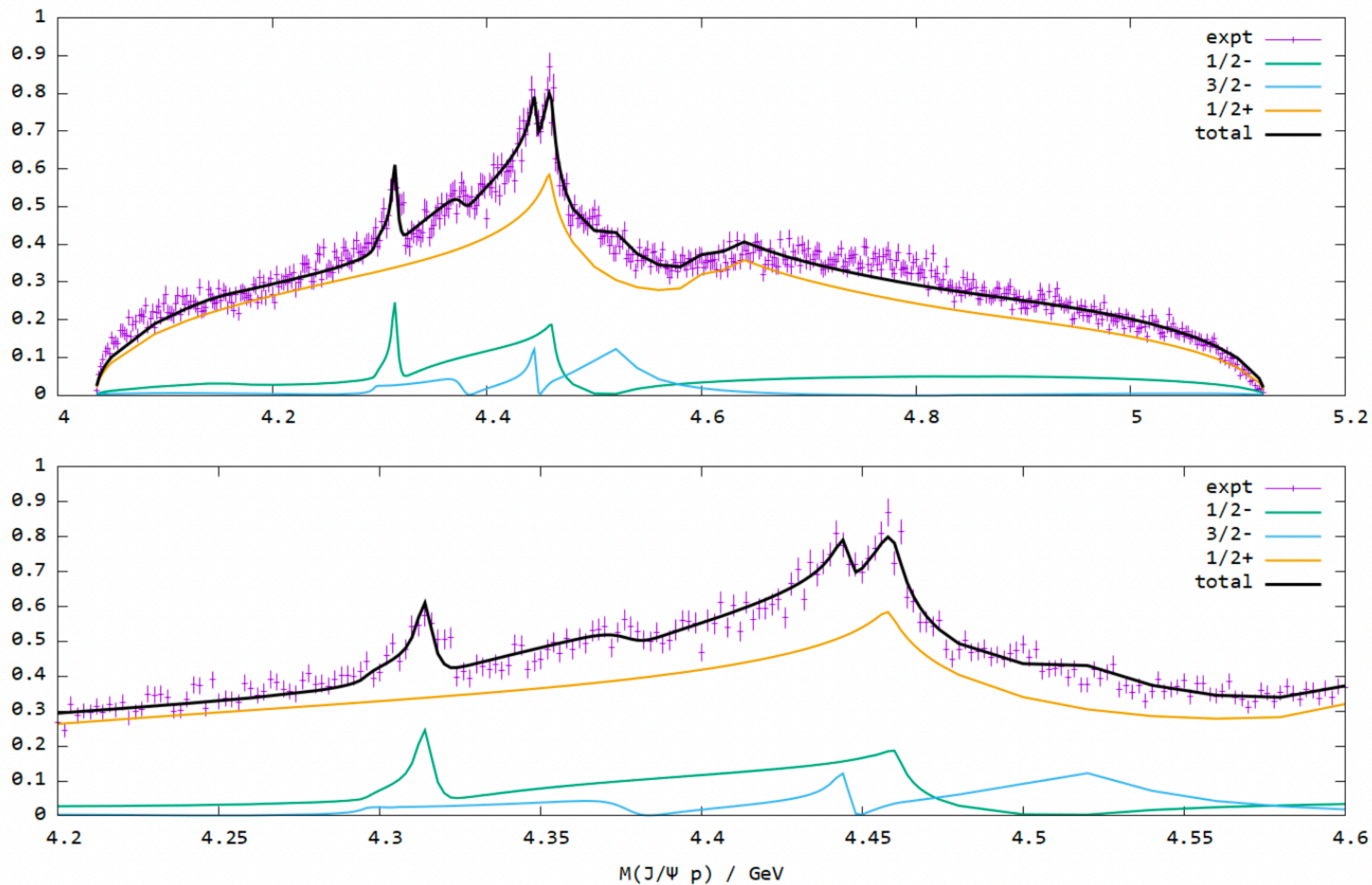
Case II

add Ca, Cb to generate resonances



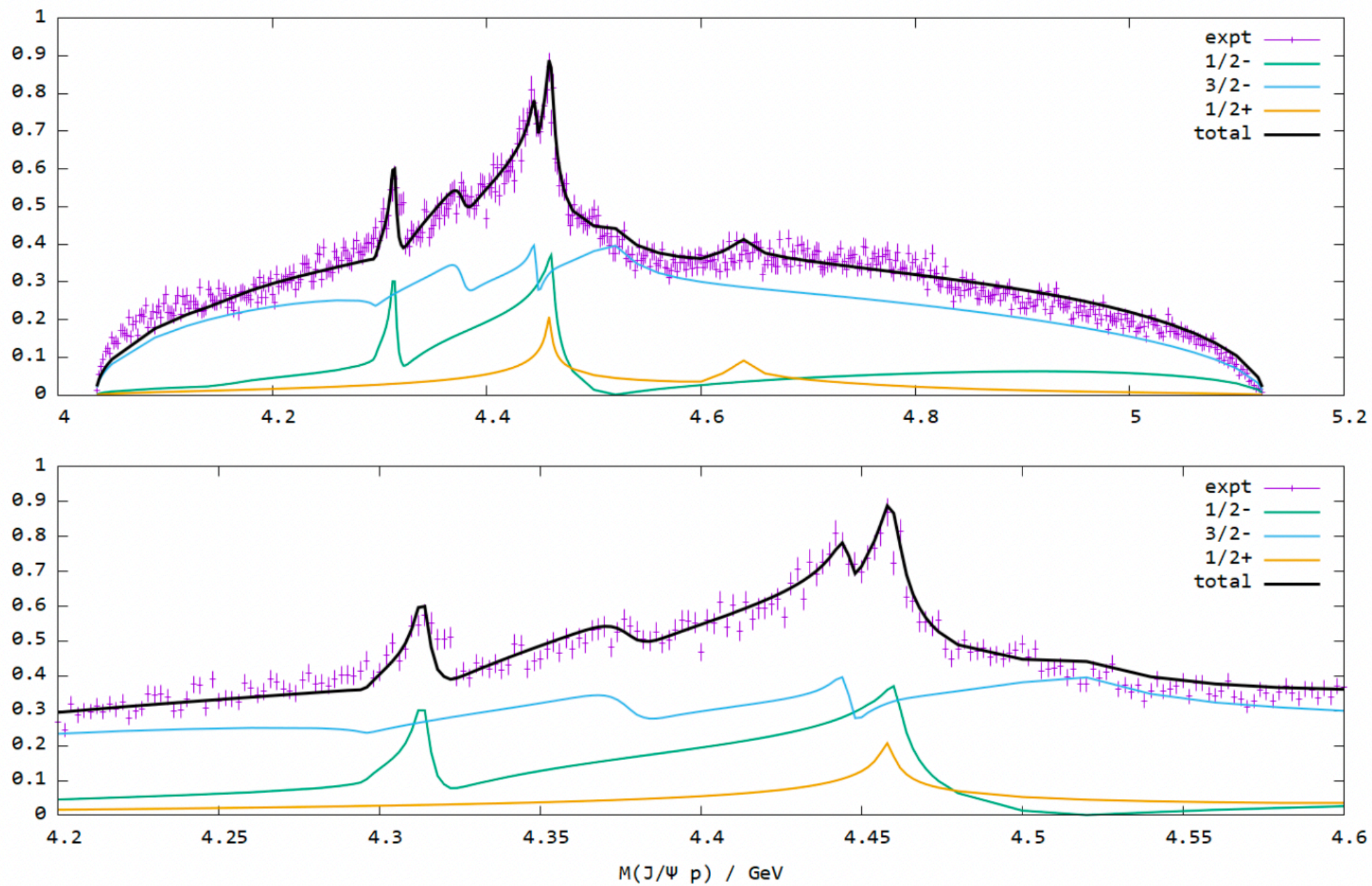
Case III

add $J^P = 1/2^+$ channel



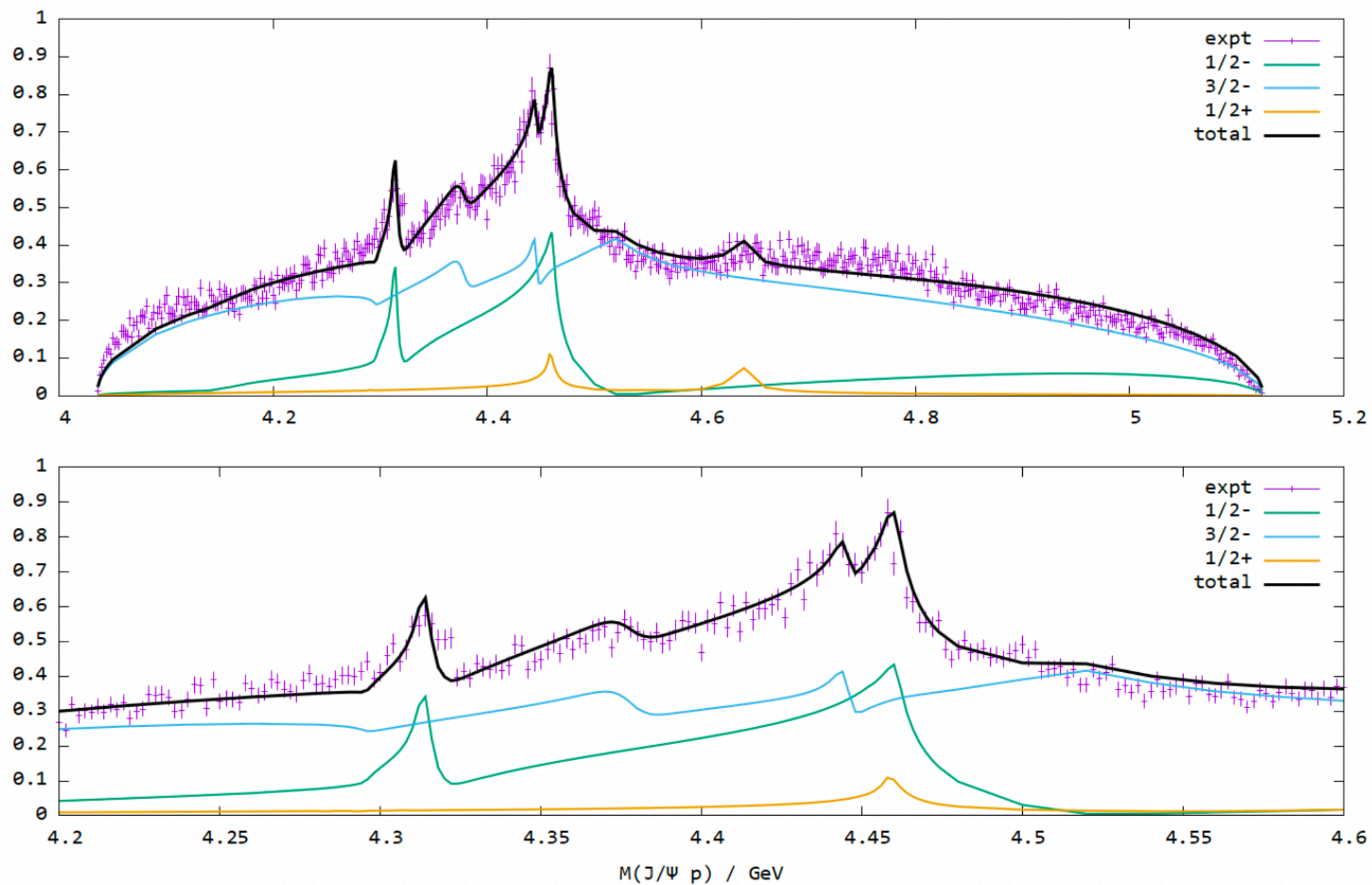
CaseIV

tune D_s mass



Case V

add 4457 $1/2^+$ resonance



$\Sigma_c \bar{D}$

	Case 2a/3	Case 2b	Case 4	Case 5
1/2 ⁻ pole	4312 − 2.4 <i>i</i>	4308 − 5.2 <i>i</i>	4312 − 2.6 <i>i</i>	4312 − 2.4 <i>i</i>
residue $\Lambda_c \bar{D}$	0.0086	0.0194	0.0080	0.0086
residue $\Lambda_c \bar{D}^*$	3.10	9.8	3.4	3.1
residue NJ/ψ	0.0015	0.0011	0.0017	0.0015
residue $N\eta_c$	0.0055	0.0041	0.0060	0.0055
three body	1.86	1.86	1.86	1.86

 $\Sigma_c^* \bar{D}$

3/2 ⁻ pole	4376.5 − 9.0 <i>i</i>	4375 − 10.7 <i>i</i>	4376.5 − 9.1 <i>i</i>	4376.5 − 8.9 <i>i</i>
residue $\Lambda_c \bar{D}^*$	3.11	7.2	3.41	3.12
residue NJ/ψ	0.0088	0.0085	0.0097	0.0088
three body	15	15	15	15

 $\Sigma_c \bar{D}^*$

3/2 ⁻ pole	4444 − 2.56 <i>i</i>	4440 − 3.3 <i>i</i>	4444.5 − 2.56 <i>i</i>	4444 − 2.56 <i>i</i>
residue $\Lambda_c \bar{D}^*$	1.16	2.2	1.25	1.16
residue $\Sigma_c^* \bar{D}$	1.7	2.1	1.58	1.70
residue NJ/ψ	0.0041	0.0036	0.0045	0.0041
three body	1.86	1.86	1.86	1.86

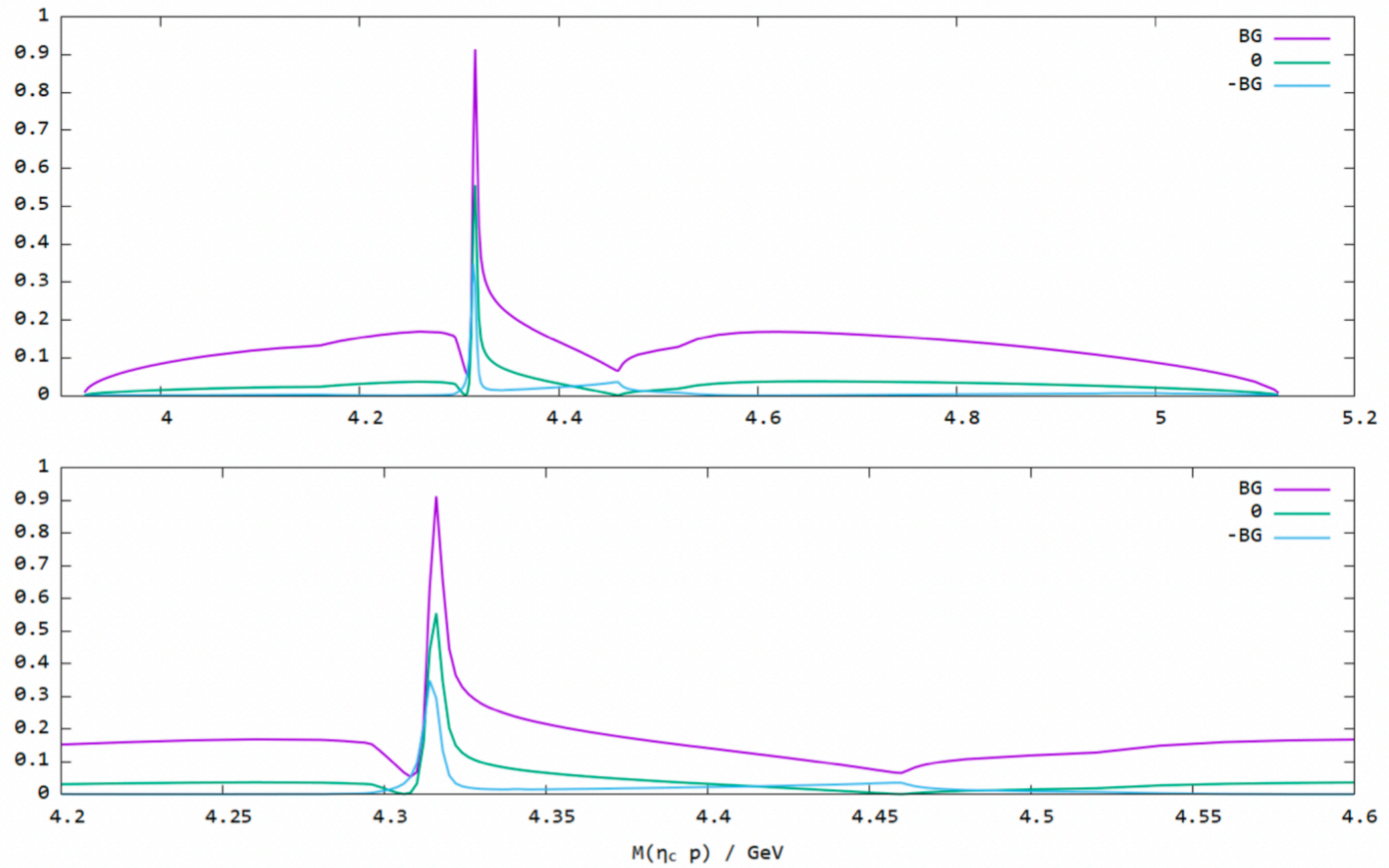
 $\Lambda_c(2595)D$

1/2 ⁺ pole	4458 − 0 <i>i</i>			
-----------------------	-------------------	--	--	--

	$\Sigma_c \bar{D}$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$
channel	$1/2^-(4312.0 - 2.4375i)$	$3/2^-(4376.5 - 8.88i)$	$3/2^-(4444.0 - 2.56i)$
$\Lambda_c \bar{D}$	$(11.17 - 1.28i) \cdot 10^{-5}$		
$\Lambda_c \bar{D}^*$	$(4.91 + 1.45i) \cdot 10^{-2}$	$(3.30 + 1.42i) \cdot 10^{-2}$	$(13.89 - 1.38i) \cdot 10^{-3}$
$\Sigma_c \bar{D}$	$0.888 + 0.162i$		
$\Sigma_c^* \bar{D}$		$0.865 + 0.151i$	$(-1.012 + 1.74i) \cdot 10^{-2}$
$\Sigma_c \bar{D}^*$	$0.186 - 0.0377i$	$0.108 - 0.035i$	$1.74 + 0.172i$
$\Sigma_c^* \bar{D}^*$	$(9.71 - 2.25i) \cdot 10^{-2}$	$0.285 - 0.054i$	$0.248 - 0.151i$
$J/\psi N$	$(27.1 - 8.87i) \cdot 10^{-6}$	$(16.8 - 5.44i) \cdot 10^{-5}$	$(6.27 - 5.89i) \cdot 10^{-5}$
$\eta_c N$	$(10.9 - 4.42i) \cdot 10^{-5}$		

.. Residues for Case 2a (GeV^{-1}).

prediction for $\Lambda_b \rightarrow \eta_c p K^-$



Conclusions & Observations



- Data exclude many models.
- Good fits obtained by insufficiently constrained models should not be taken as evidence in favour of the model assumptions.
- $\Lambda_c^{(*)}\bar{D}^{(*)}$ degrees of freedom are natural & important.
- our model incorporates all known experimental constraints, EW phenomenology, and heavy quark symmetry, fits the entire spectrum, and does not predict unseen states.
- “Triangles” explain ‘kinks’ at $\Lambda_c D$, $\Lambda'_c D^*$ and possibly the 4457 peak ($\Lambda'_c D$).
- Current experiments are at the threshold for observing Pc's

- Strong evidence for exotic pentaquark states:
 - 4312 ($\Sigma_c D$, 1/2-)
 - 4380 ($\Sigma_c^* D$, 3/2-)
 - 4440 ($\Sigma_c D^*$, 3/2-)
 - 4457 (1/2- $\Sigma_c D^*$ threshold cusp / 1/2+ triangle)
 - 4508 ($\Sigma_c^* D^*$, 5/2-)

Pcs



T.J. Burns and E.S. Swanson, the LHCb State $P_{\psi S}^{\Lambda}(4338)$ as a Triangle Singularity, 2208.05015

Observation of a $J/\psi\Lambda$ resonance in $B^- \rightarrow J/\psi\Lambda\bar{p}$ decays

LHCb-PAPER-2022-031 in preparation

Discussion on the new $J/\psi\Lambda$ state

For theoretical interpretation

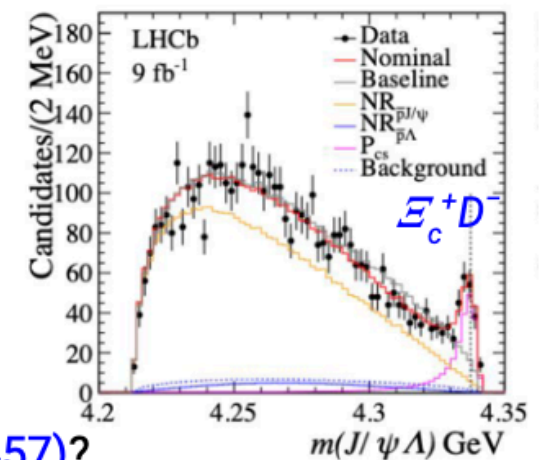
First pentaquark candidate $P_{\psi s}^{\Lambda}(4338)$
with strange quark content $c\bar{c}uds$,

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

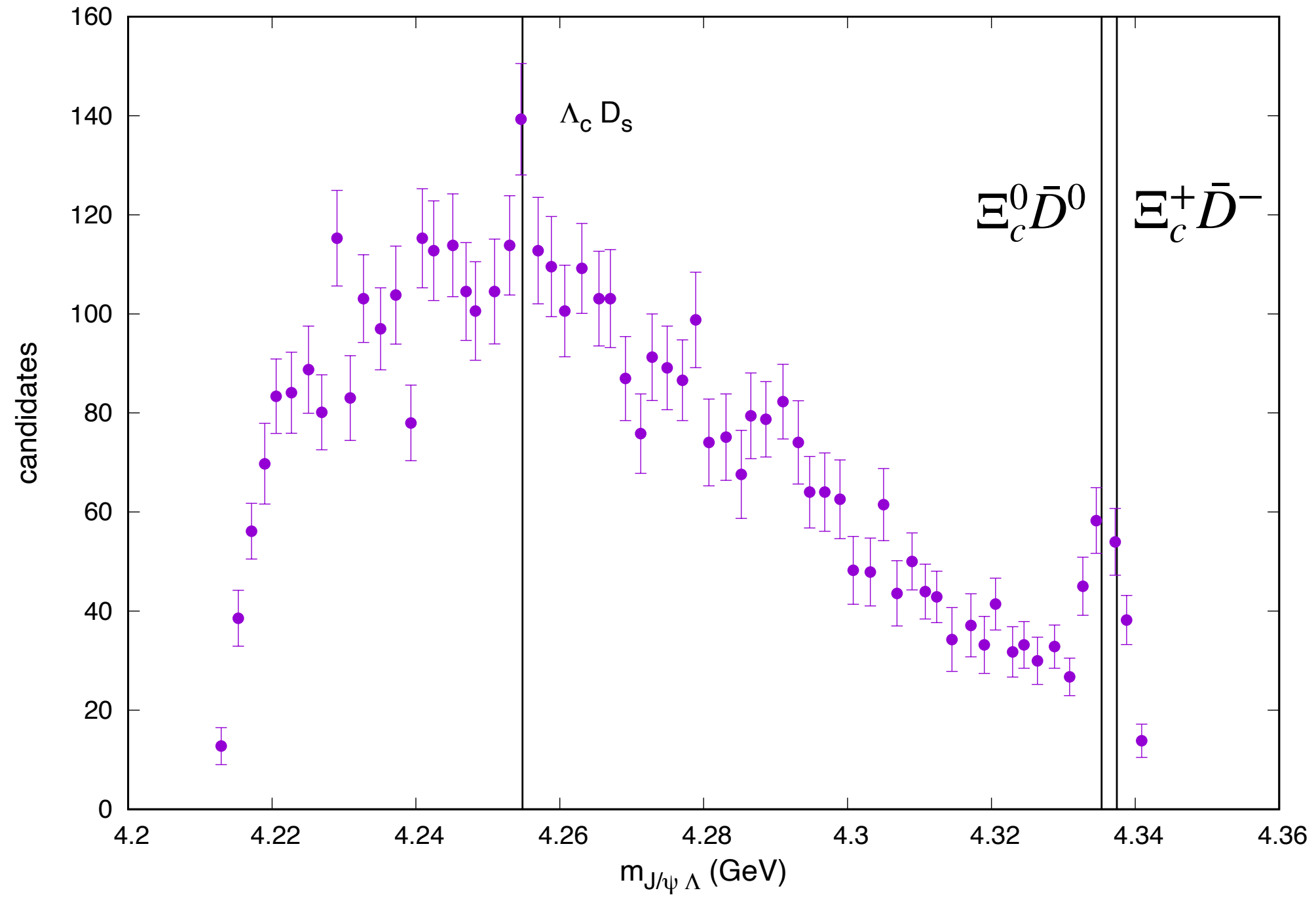
$\Rightarrow$ first pentaquark with spin assigned $J^P = \frac{1}{2}^-$

- ✓ narrow, close to $\Xi_c^+ D^-$ threshold and in S-wave
- ✓ pentaquark with strangeness, due to SU(3) symmetry
- ✓ at same mass of $P_{\psi}^N(4337)$: analogy to $P_{\psi s}^{\Lambda}(4459)$ & $P_{\psi}^N(4457)$?

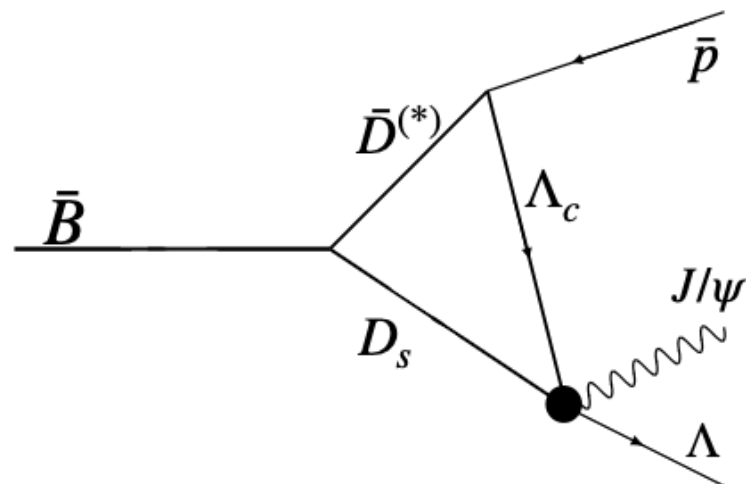


Can fit in SU(3) multiplets or are more likely molecular states?

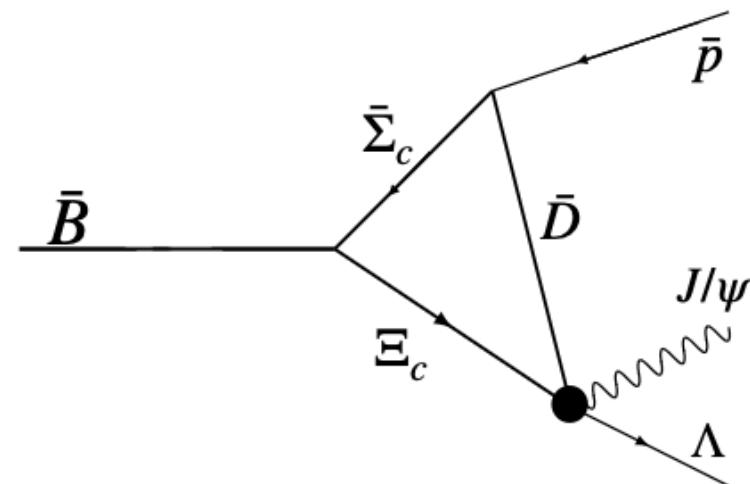
Relevant Thresholds



dominant production mechanism



subdominant production



but this can be comparable if the Landau conditions are $\sim$ satisfied $\rightarrow \Sigma_c(2800)$!

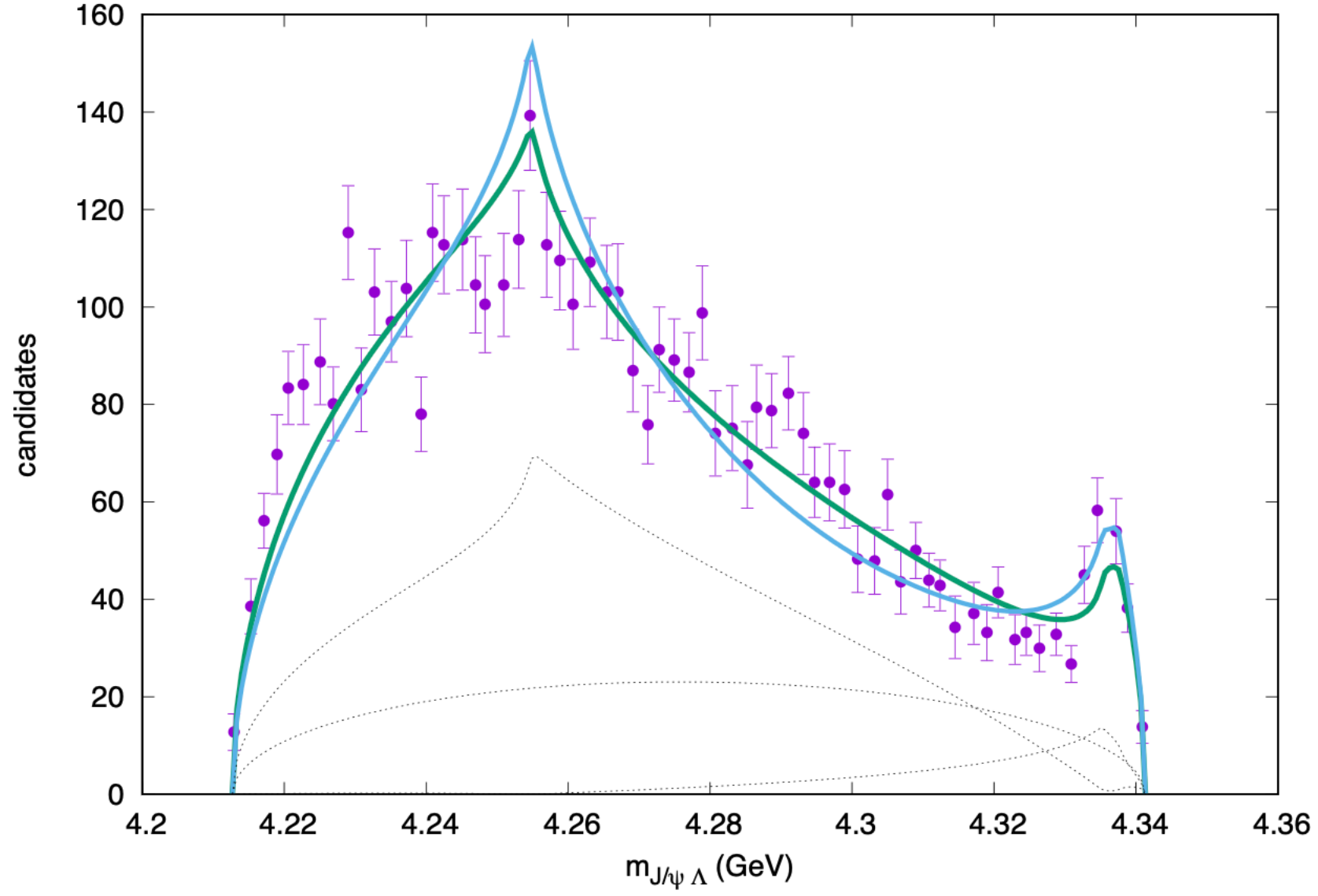
$$\langle \mathbf{8}, \mathbf{1} | V | \mathbf{8}, \mathbf{1} \rangle = \langle \mathbf{8}, \mathbf{3} | V | \mathbf{8}, \mathbf{3} \rangle = A,$$

$$\langle \mathbf{8}, \mathbf{1} | V | \Lambda J/\psi \rangle = \langle \mathbf{8}, \mathbf{3} | V | \Sigma J/\psi \rangle = \frac{\sqrt{3}}{2} D,$$

$$\langle \mathbf{8}, \mathbf{1} | V | \Lambda \eta_c \rangle = \langle \mathbf{8}, \mathbf{3} | V | \Sigma \eta_c \rangle = \frac{1}{2} D,$$

$$\langle \mathbf{1}, \mathbf{1} | V | \mathbf{1}, \mathbf{1} \rangle = A'.$$

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



	$\Gamma(\bar{\Sigma}_c) / \text{MeV}$	A / GeV^{-2}	Δ / GeV^{-2}
Set A	70	6	-7
Set B	15	0	-1

TABLE II. Parameter sets A (green) and B (blue) in Fig 2.

~thank you~