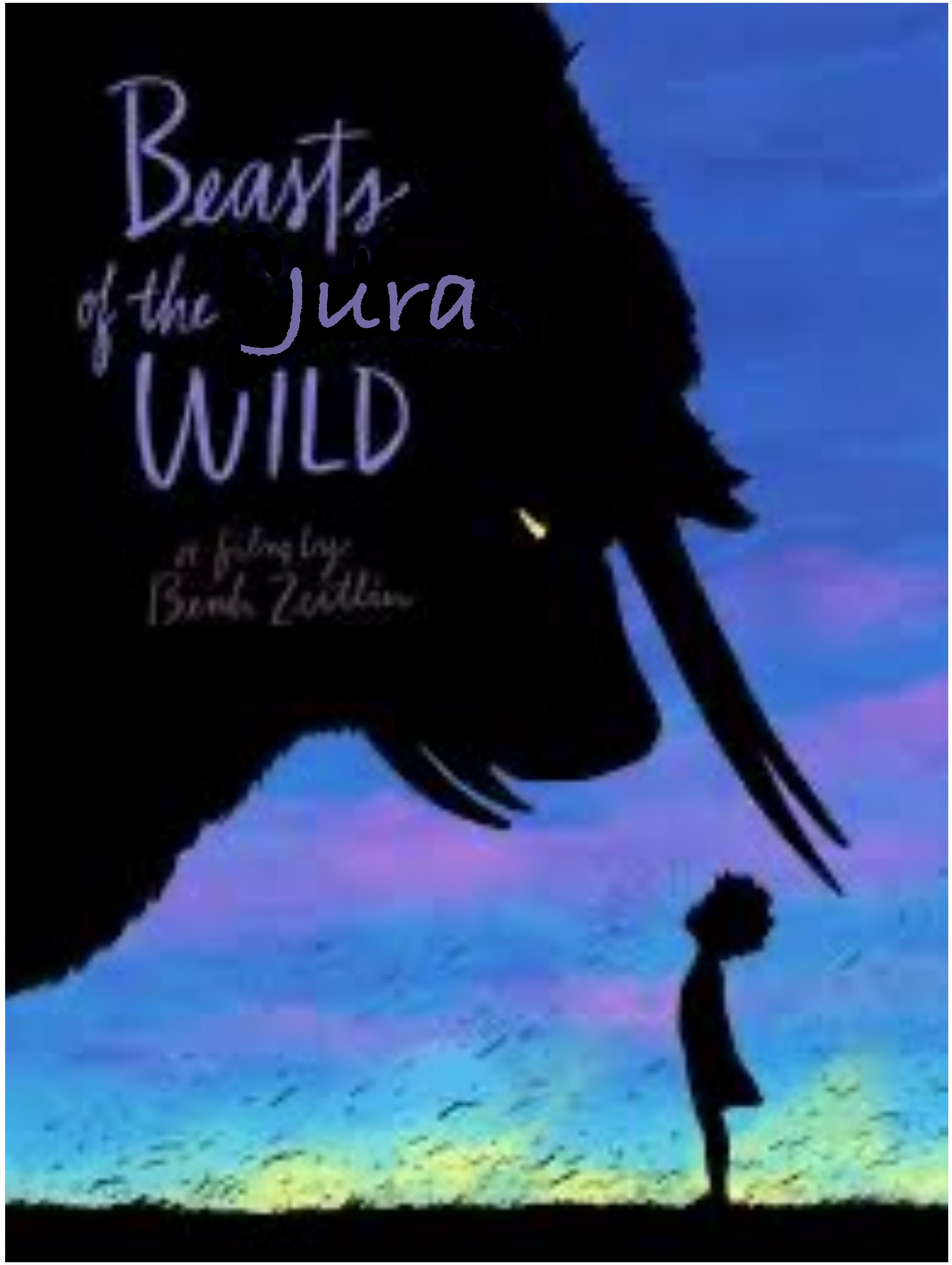
Aug, 2022

Beasts of the Jura Wild

Consistent interpretation of the Pentaquark States in Λ_b decays

Eric Swanson

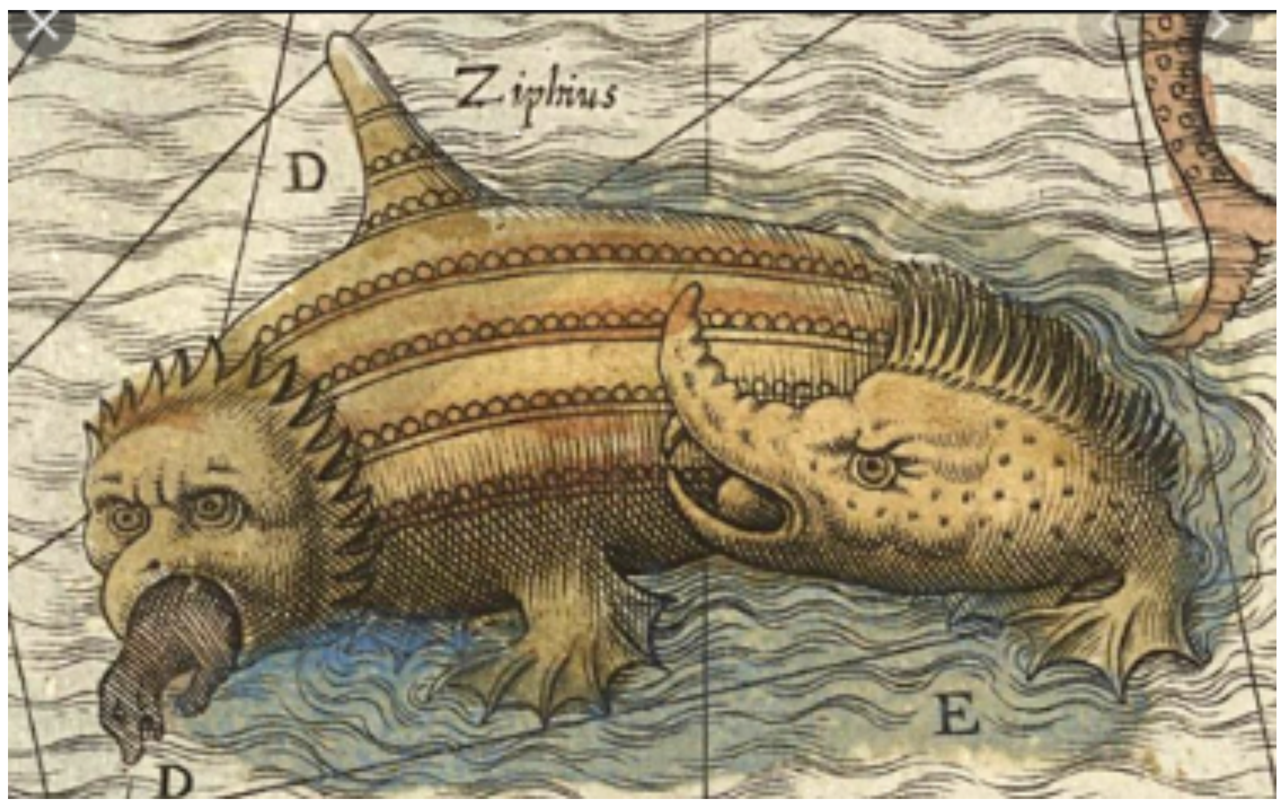

Beasts
of the Jura
WILD

Tim Burns

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

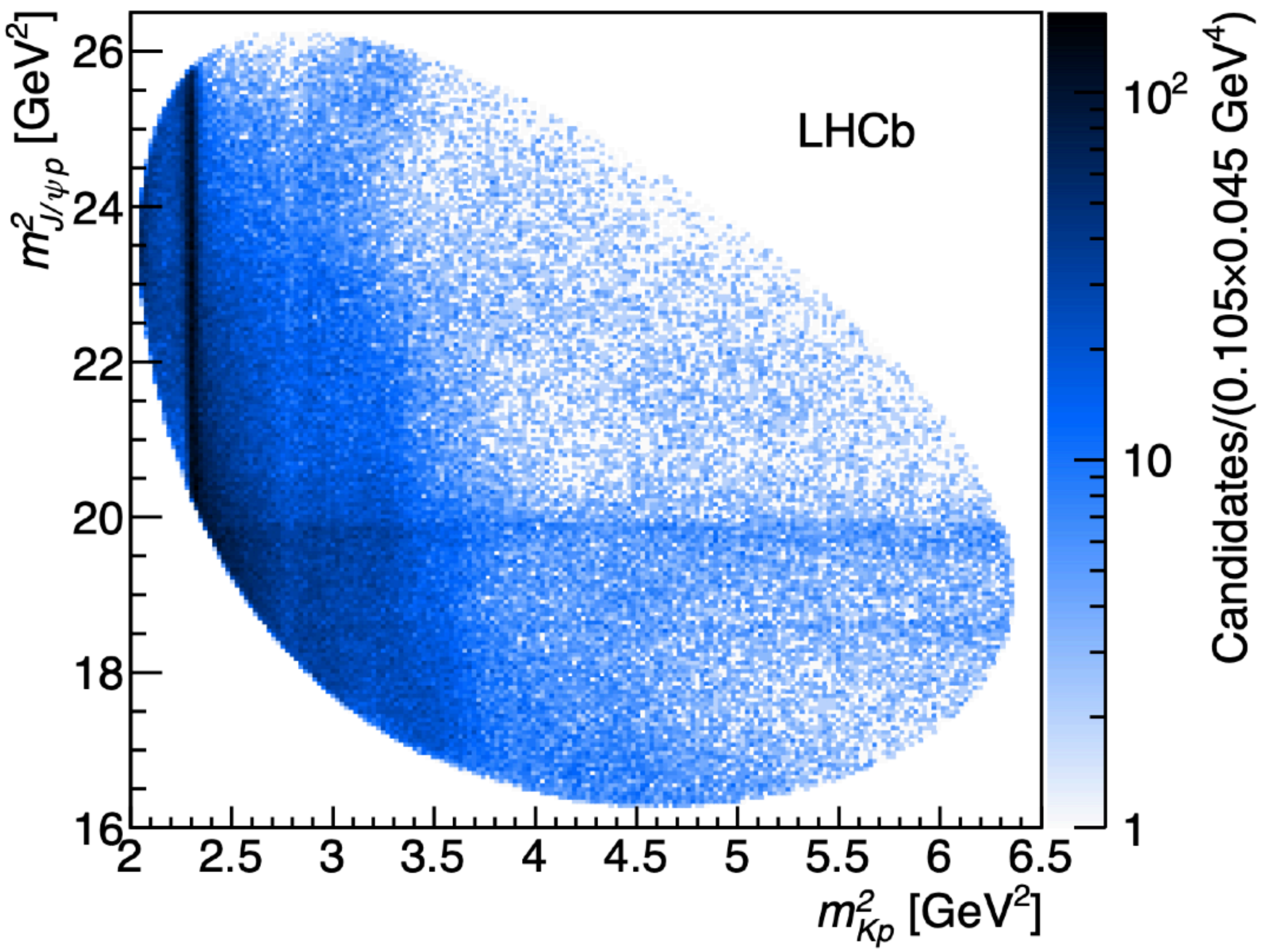
T.J. Burns and E.S. Swanson, Production of P_c States in Λ_b Decays, 2207.00511

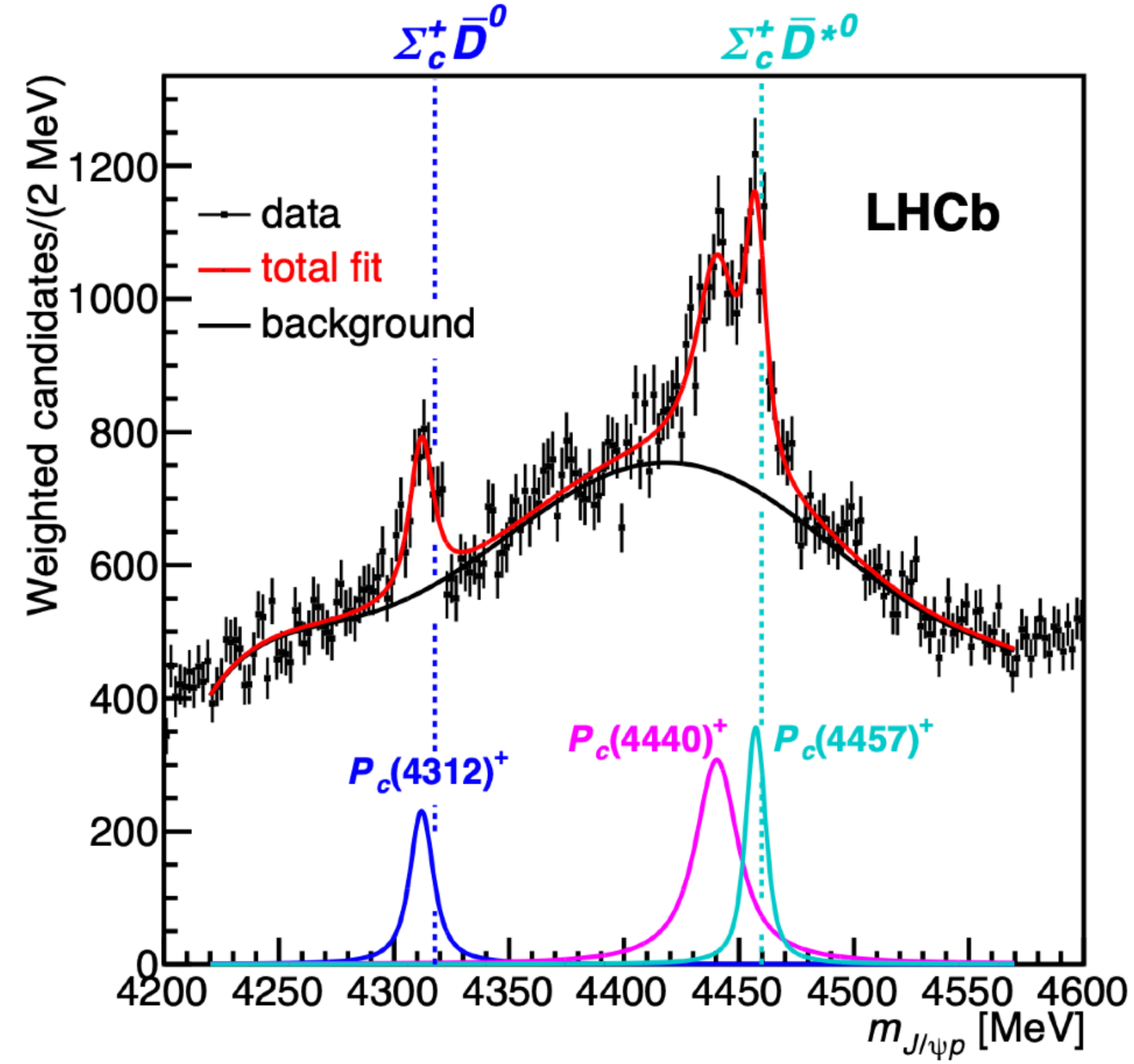
Experimental Constraints



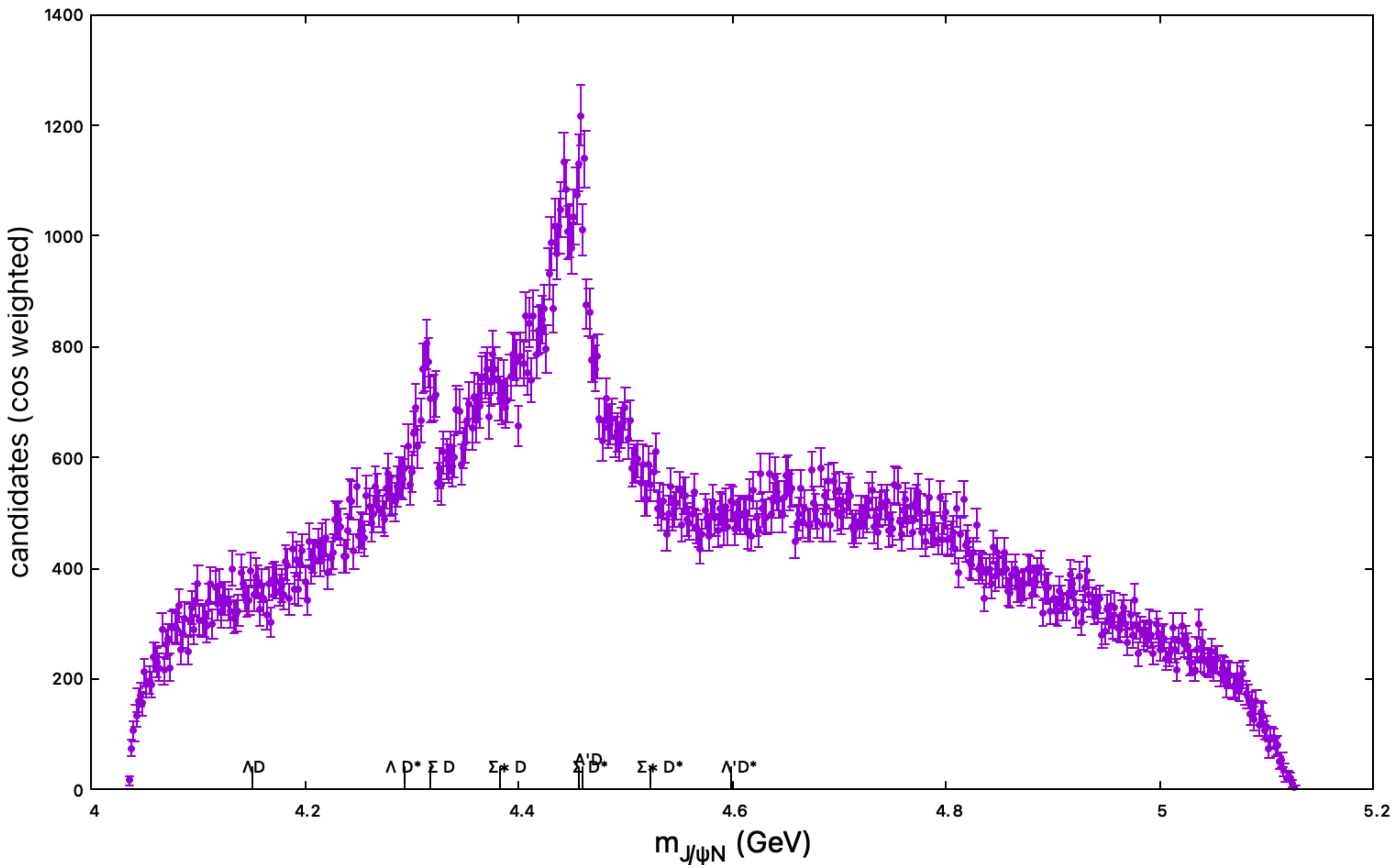
LHCb Discovery

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

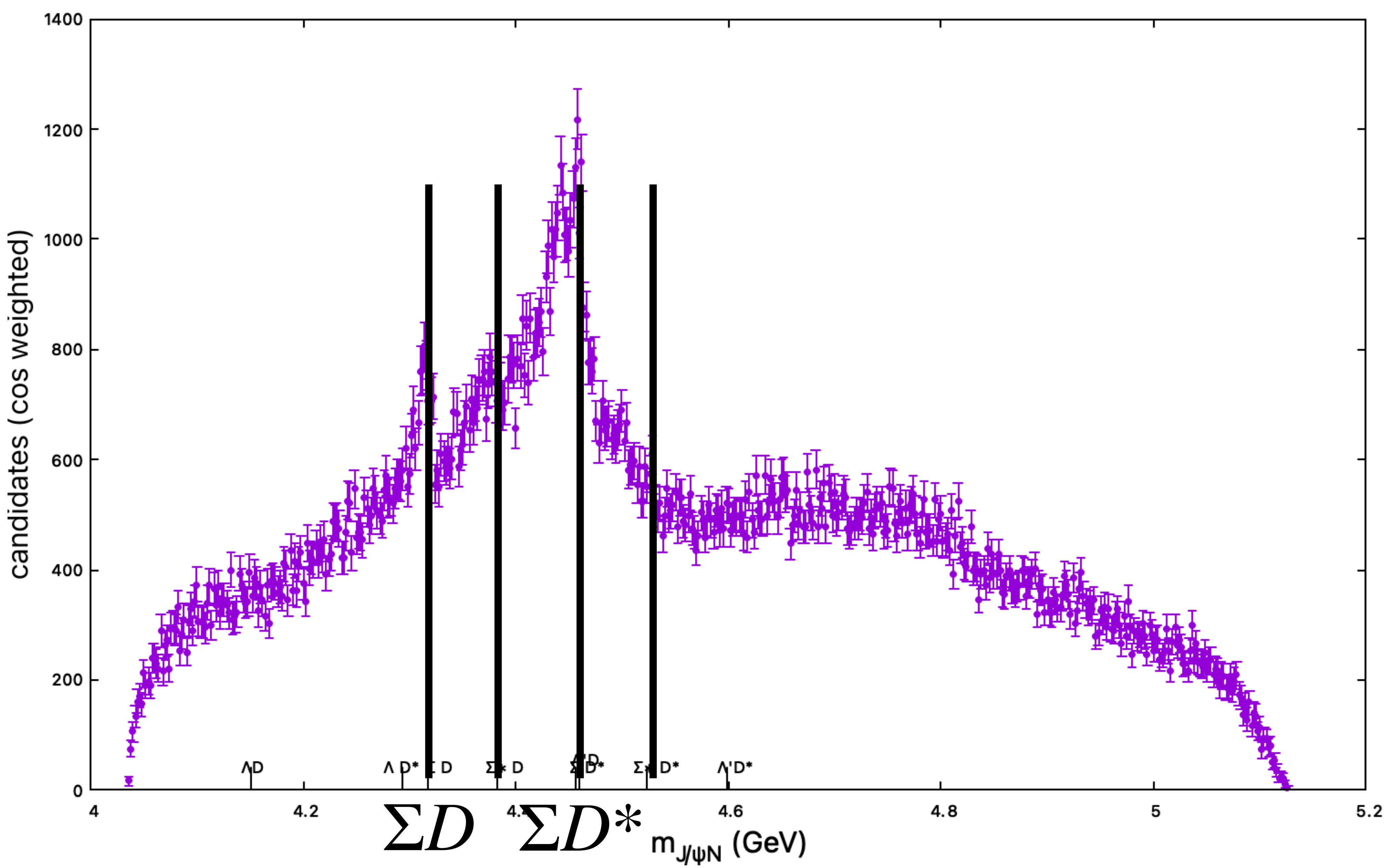




A Look at the Data (LHCb cos weighted)



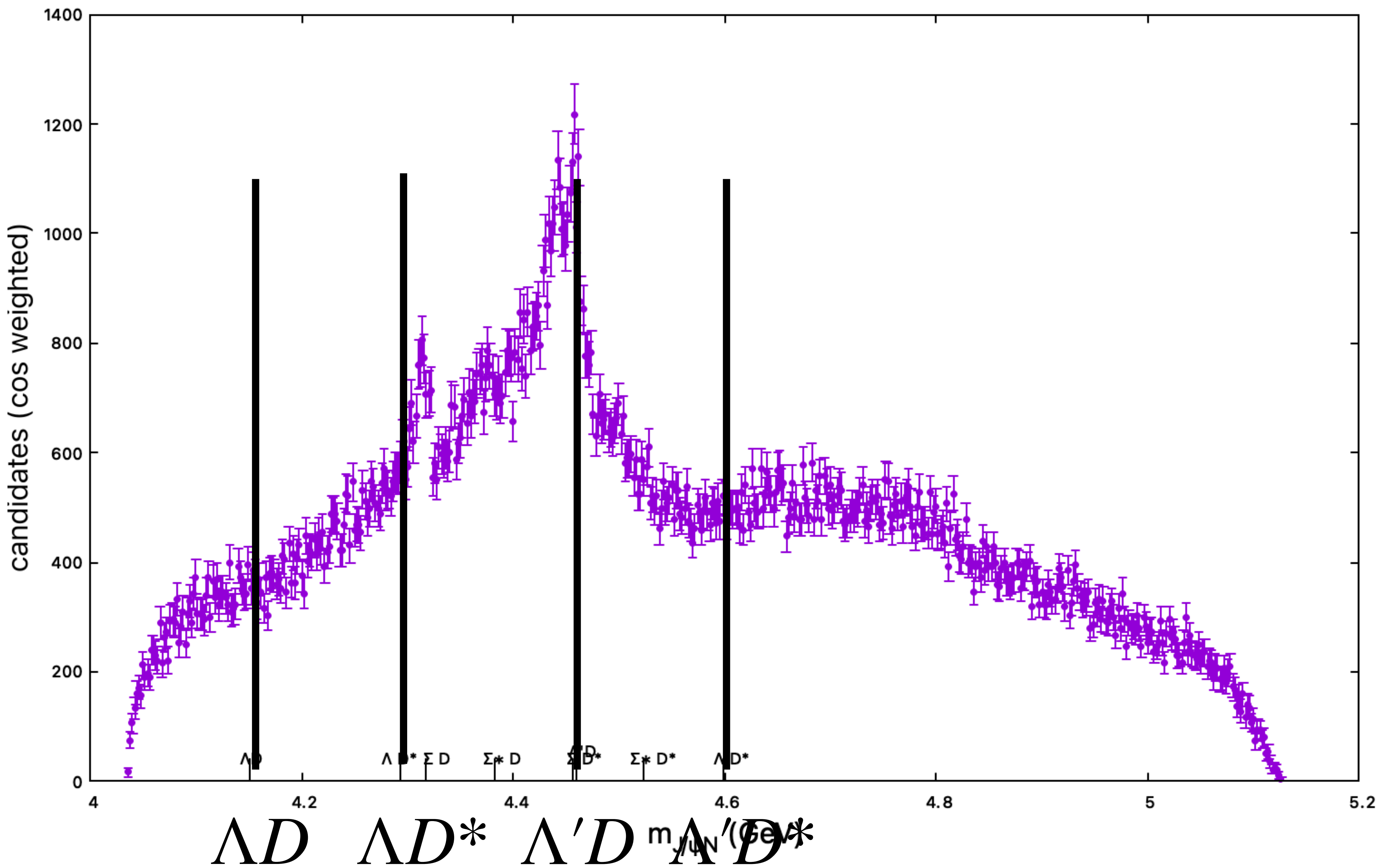
A Look at the Data (LHCb cos weighted)



ΣD ΣD^*

$\Sigma^* D$ $\Sigma^* D^*$

A Look at the Data (LHCb cos weighted)



A Look at the Data (JLab)

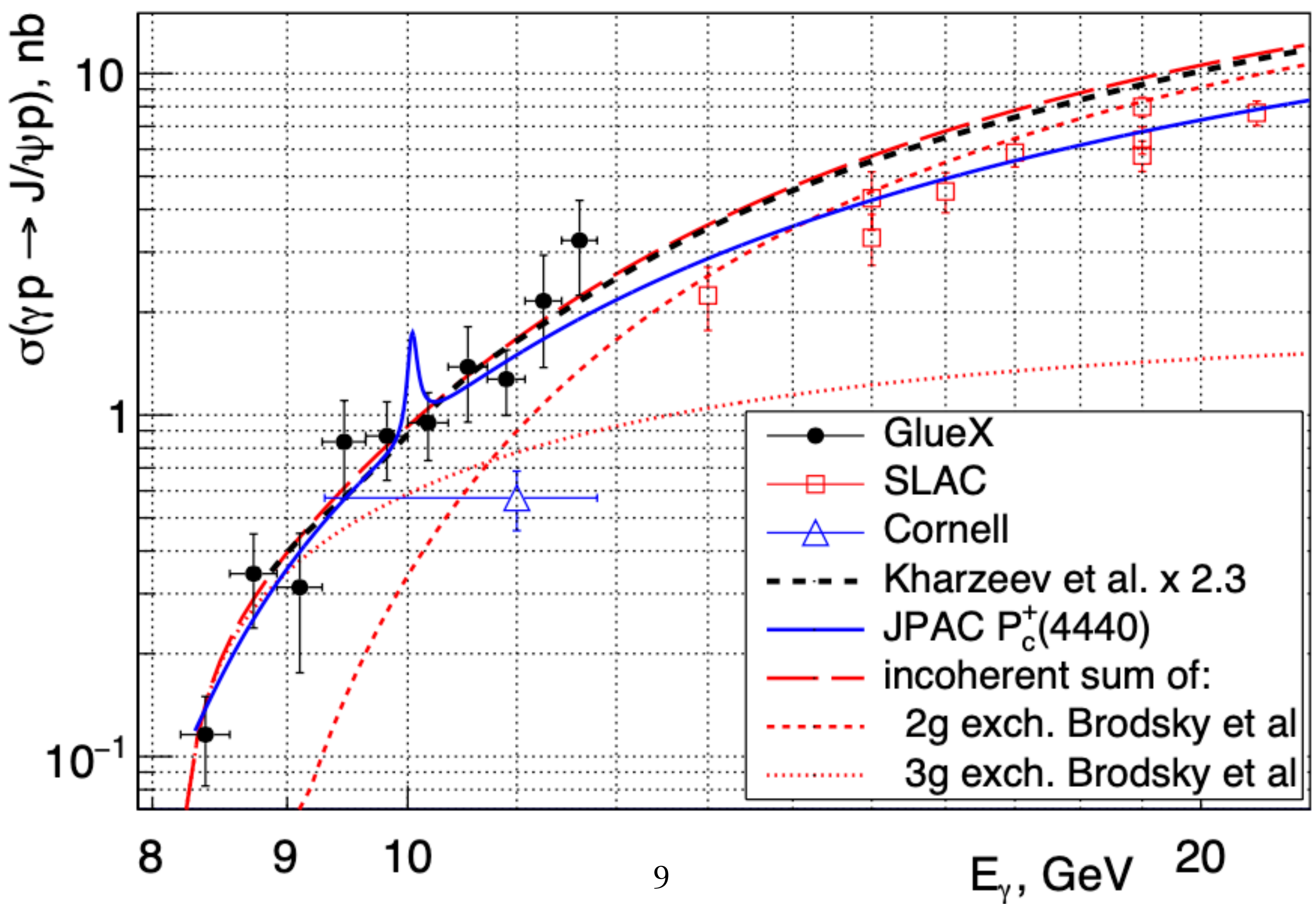
Hiller Blin et al. arXiv:1606.08912

Ali et al, arXiv:1905.10811

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

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

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



A Look at the Data (JLab Jψ-007)

Sylvester Joosten, GHP21 J/ψ-007

4% scale uncertainty on cross section limit

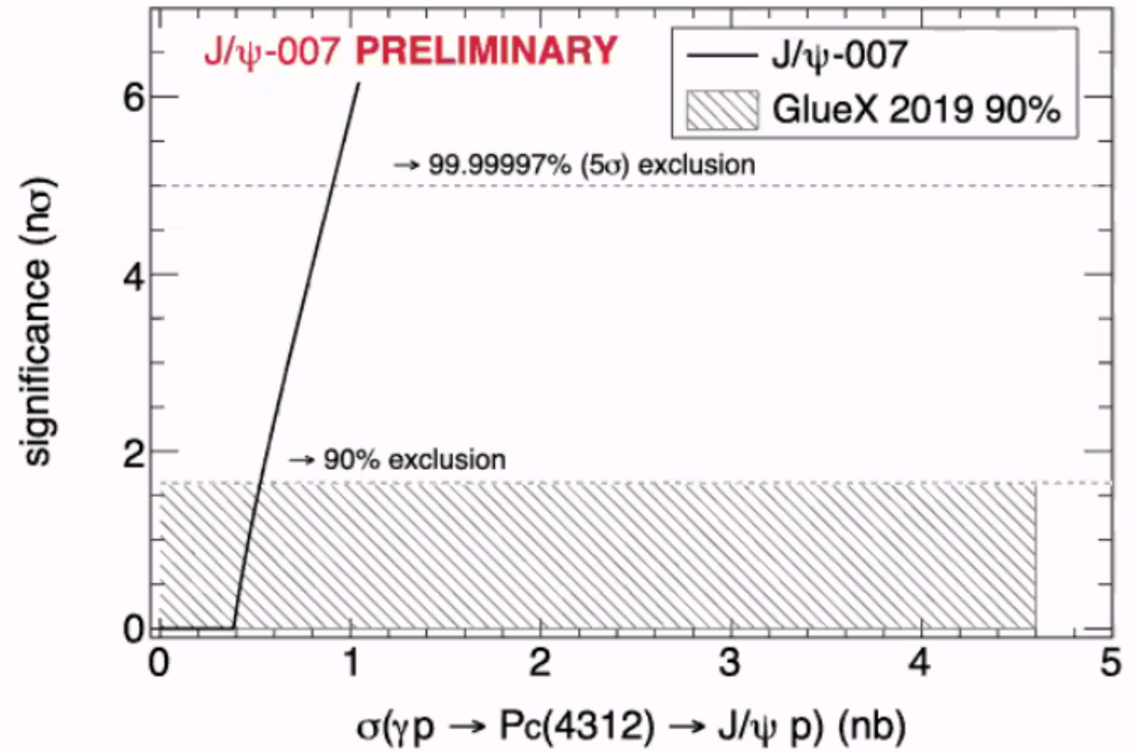
RESULTS AND IMPLICATIONS

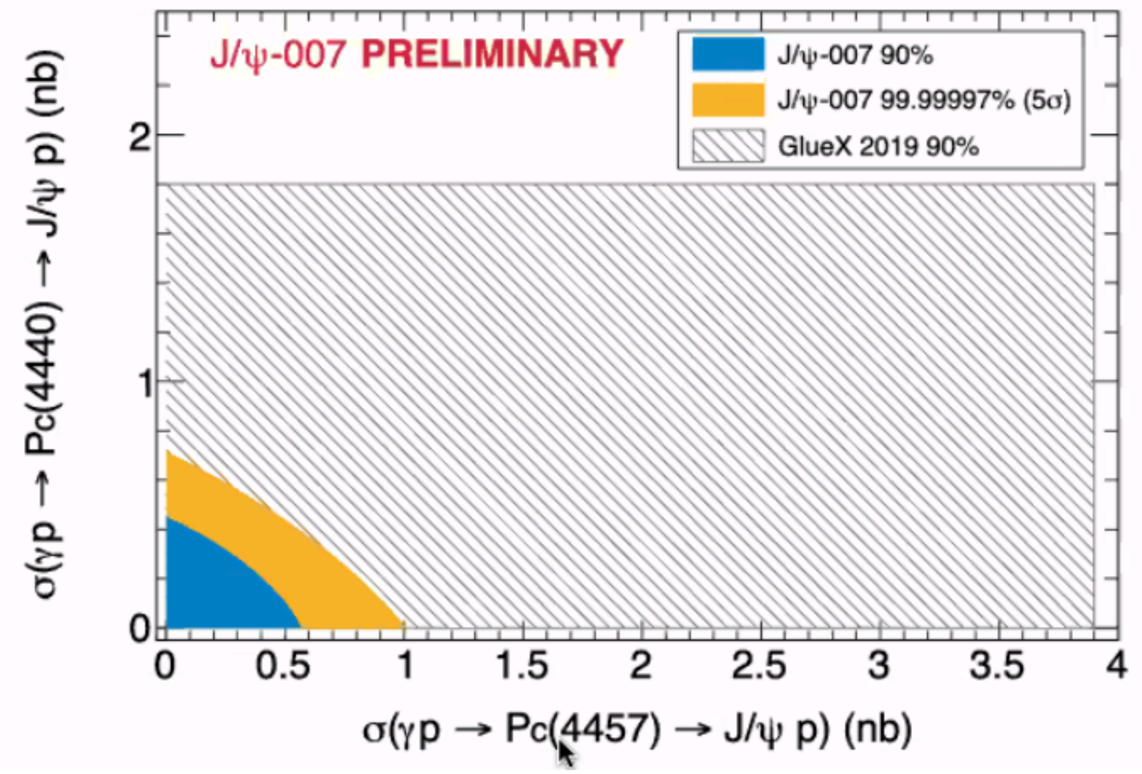
Cross-section at the resonance peak for model-independent upper limits

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/ψp final state





U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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A Look at the Data (ΛD modes)

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

Alessio Piucci

Heidelberg University, Germany

First observation of the decay $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ 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

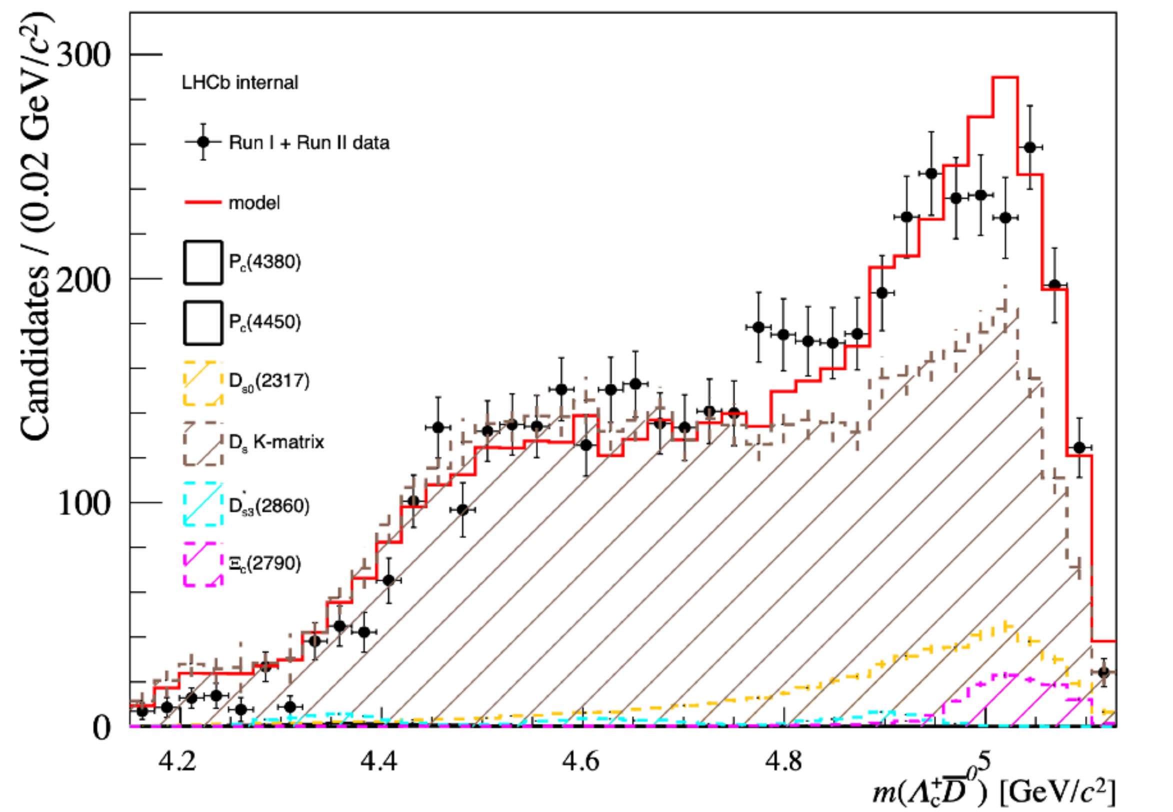
139 pages
Supervisors: Stephanie Hansmann-Menzemer (Heidelberg U.), Klaus Reygers (Heidelberg U.)
Thesis: PhD U. Heidelberg (main) (defense: Jul 11, 2018)
DOI: 10.11588/heidok.00025126
Report number: CERN-THESIS-2018-176
Experiments: CERN-LHC-LHCb
View in: CERN Document Server

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 Pc fit fraction upper limits in $\Lambda_b \to \Lambda_c DK$



$P_c(4312)^+$ 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 (ΛD modes)

Combine with measurements of

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

and branching fractions

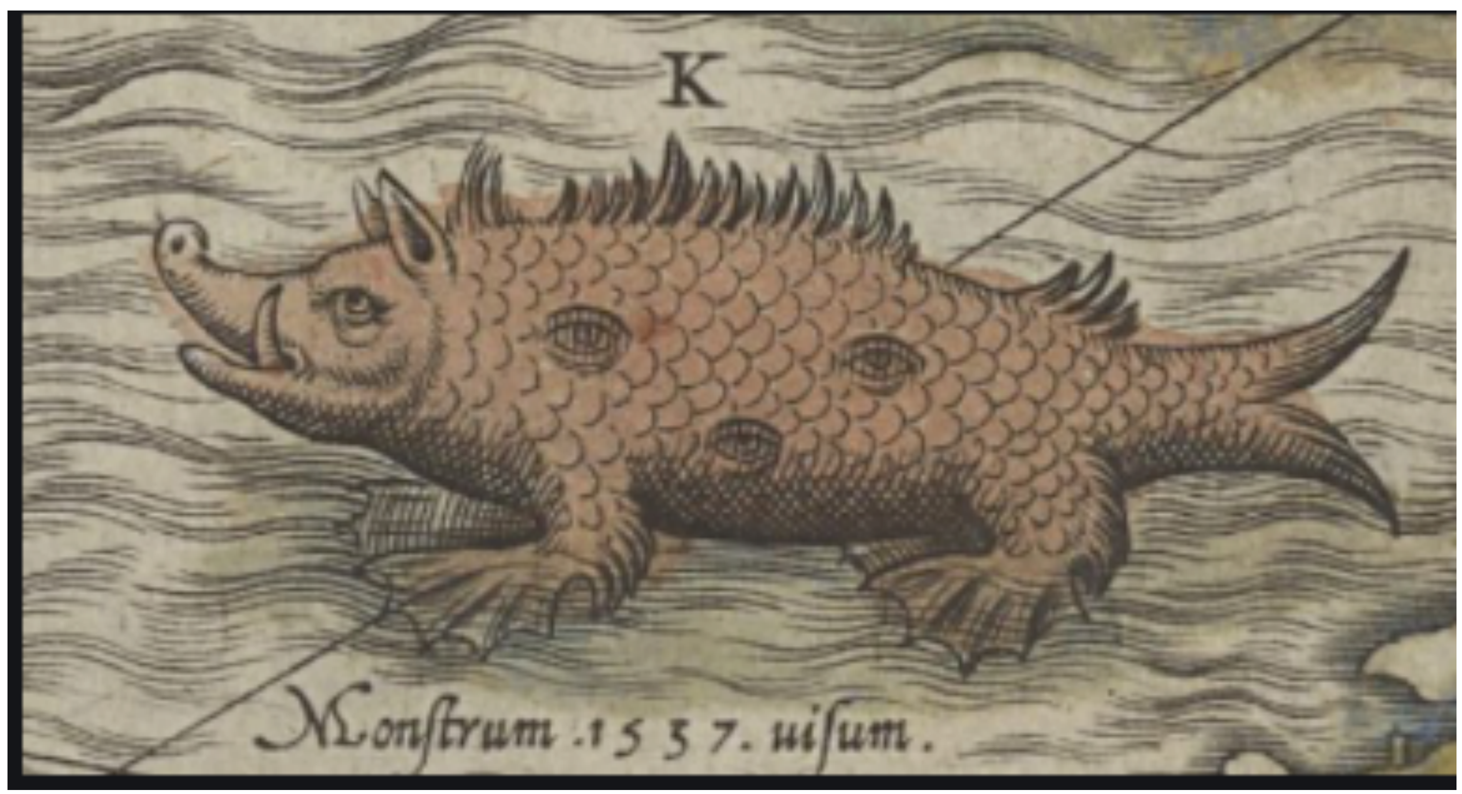
$$Bf(\Lambda_b \to J/\psi pK) = 3.2(5) \cdot 10^{-4}$$

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

to obtain upper limits

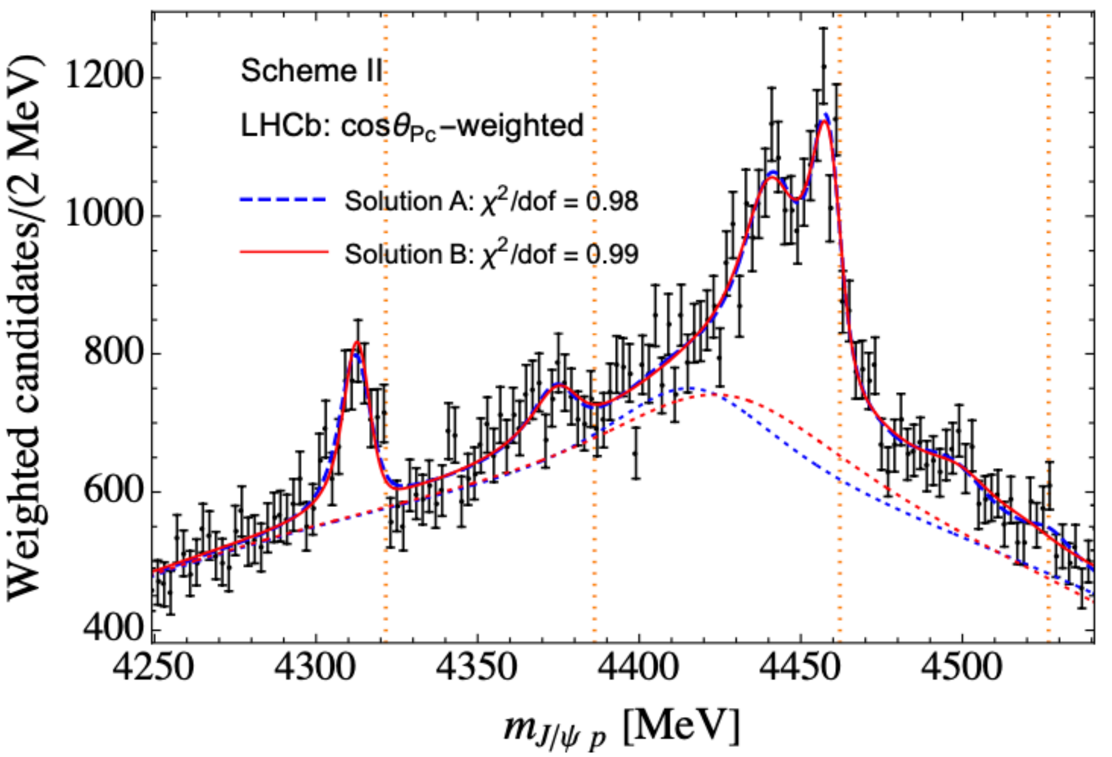
$$Bf(P_c \to \Lambda_c D) \lesssim \begin{cases} 6.3, & (4312) \\ 2.5, & (4440; 1/2^-) \\ 1.9, & (4440; 3/2^-) \\ 4.0, & (4457; 1/2^-) \\ 7.1, & (4457; 3/2^-) \end{cases} \cdot Bf(P_c \to J/\psi p)$$

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 ΛD branching fraction?

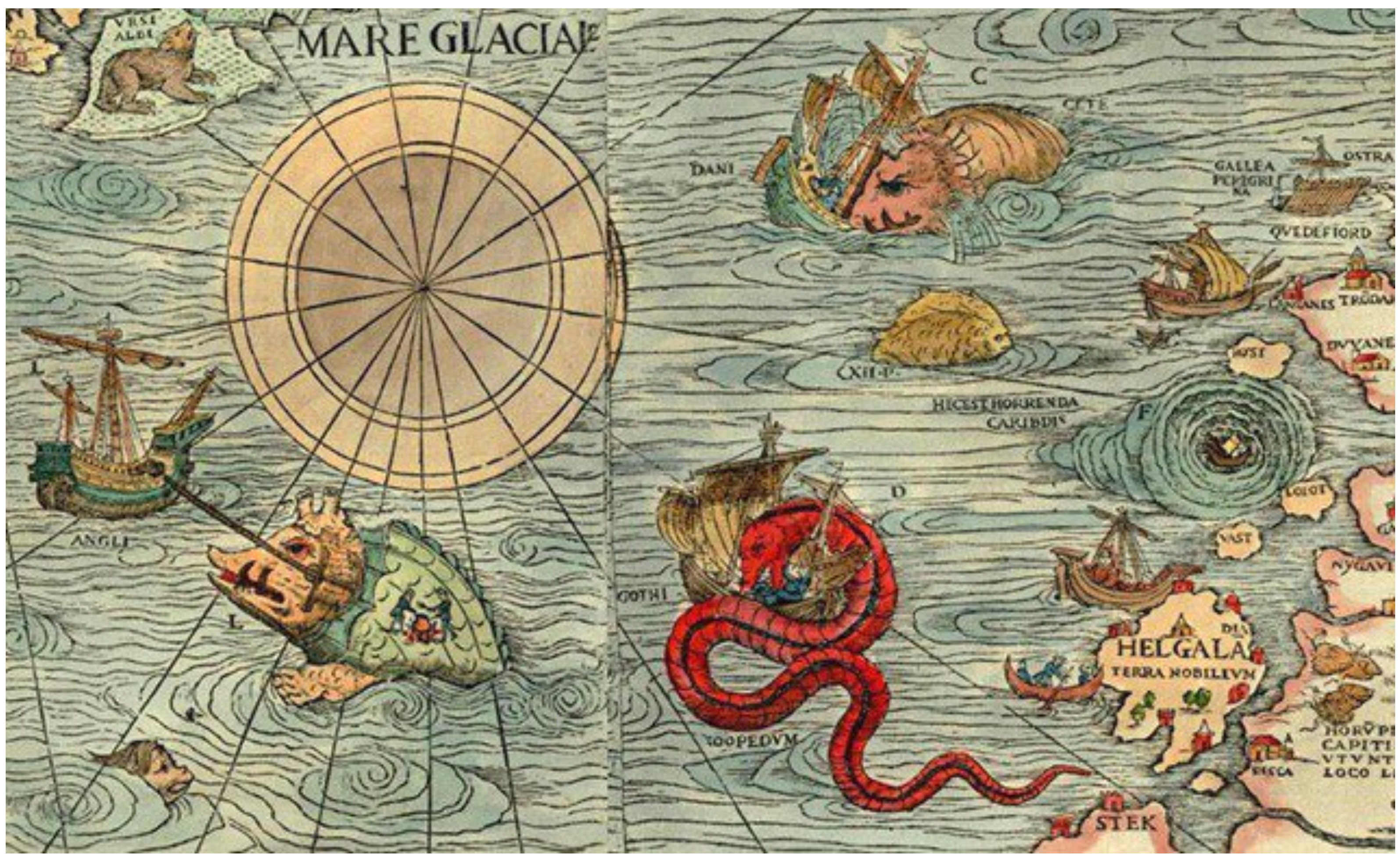
(v) extreme background model:

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

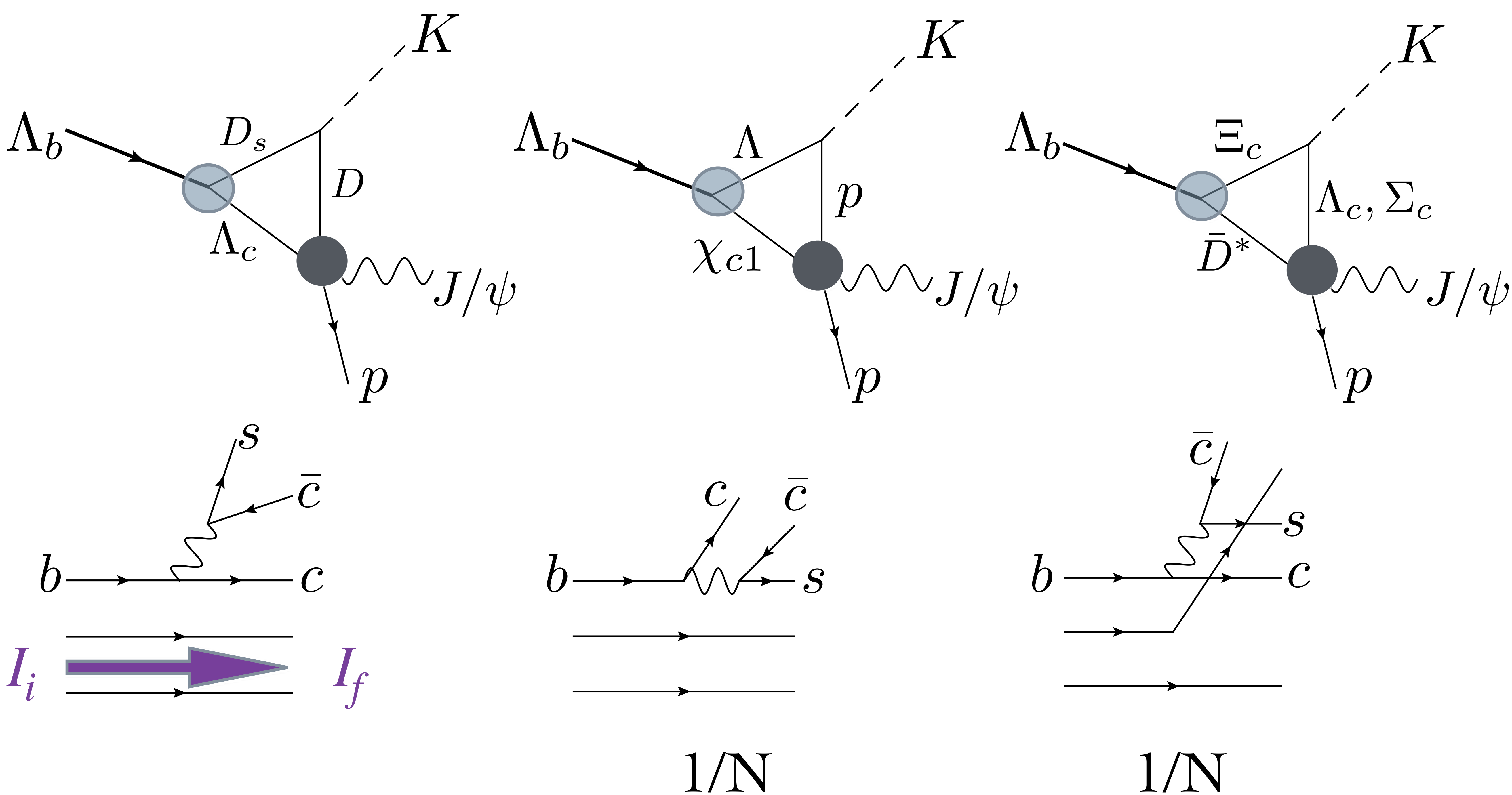
			solution		A	solution		B
	DC ([MeV])	RS	J^P	Pole [MeV]	g_{DC}	J^P	Pole [MeV]	g_{DC}
$P_c(4312)$	$\Sigma_c\bar{D}$ (4321.6)	I	$\frac{1}{2}^-$	$4314(1) - 4(1)i$	$2.6(1) + 0.4(2)i$	$\frac{1}{2}^-$	$4312(2) - 4(2)i$	$2.9(1) + 0.4(2)i$
$P_c(4380)$	$\Sigma_c^*\bar{D}$ (4386.2)	II	$\frac{3}{2}^-$	$4377(1) - 7(1)i$	$2.8(1) + 0.1(1)i$	$\frac{3}{2}^-$	$4375(2) - 6(1)i$	$3.0(1) + 0.1(1)i$
$P_c(4440)$	$\Sigma_c\bar{D}^*$ (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	$\frac{5}{2}^-$	$4525(2) - 9(3)i$	$1.9(2) + 0.6(7)i$	$\frac{5}{2}^-$	$4501(3) - 6(4)i$	$3.9(2) + 0.1(2)i$

?

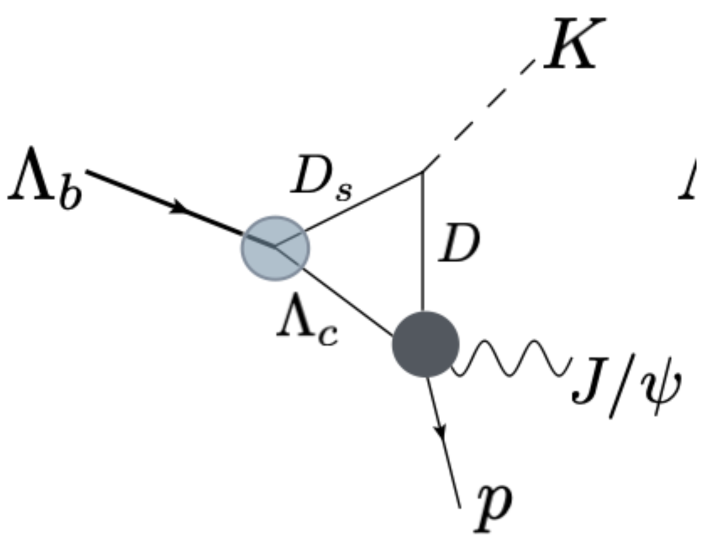
Our Model



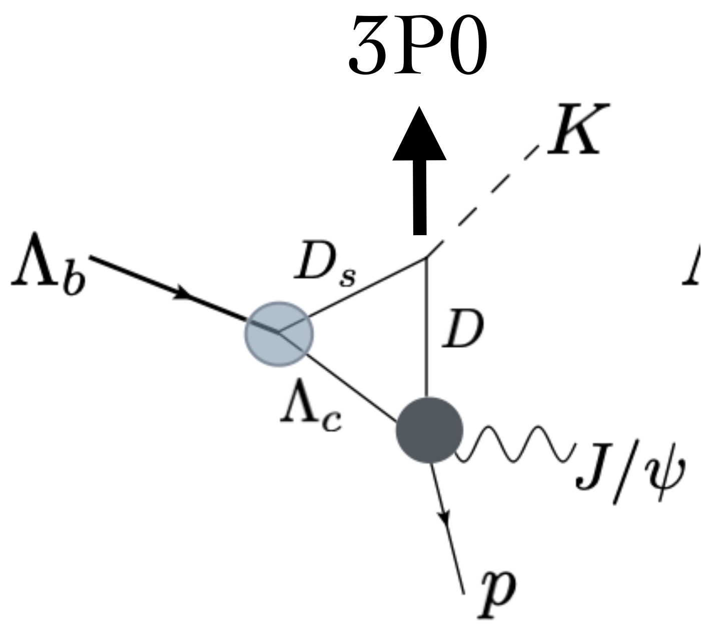
A Production/ Rescattering Model for Pentaquarks



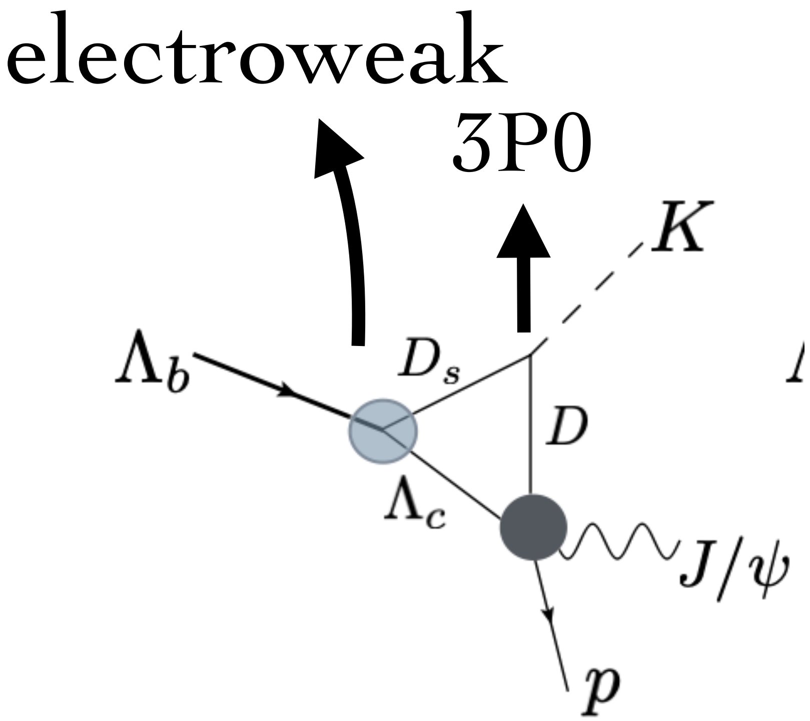
A Production/ Rescattering Model for Pentaquarks



A Production/ Rescattering Model for Pentaquarks

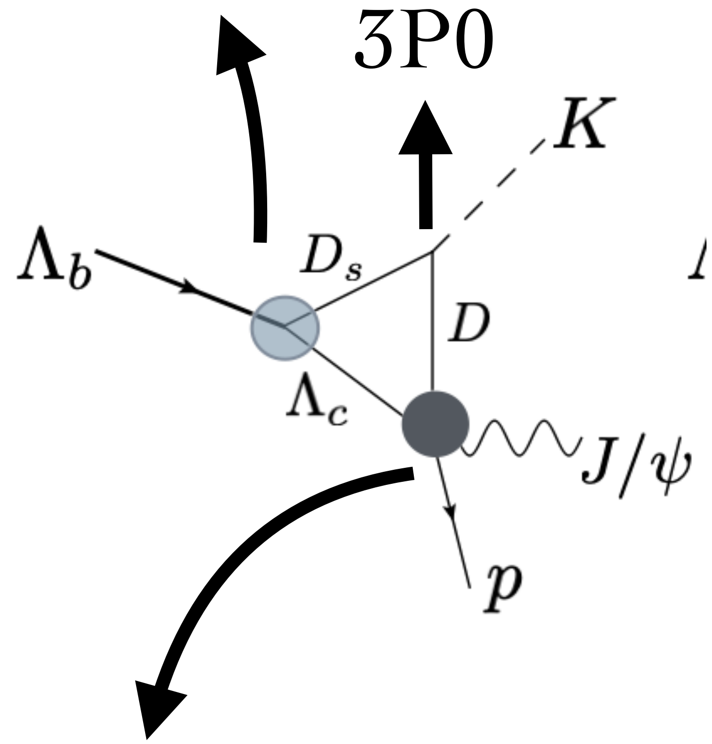


A Production/ Rescattering Model for Pentaquarks



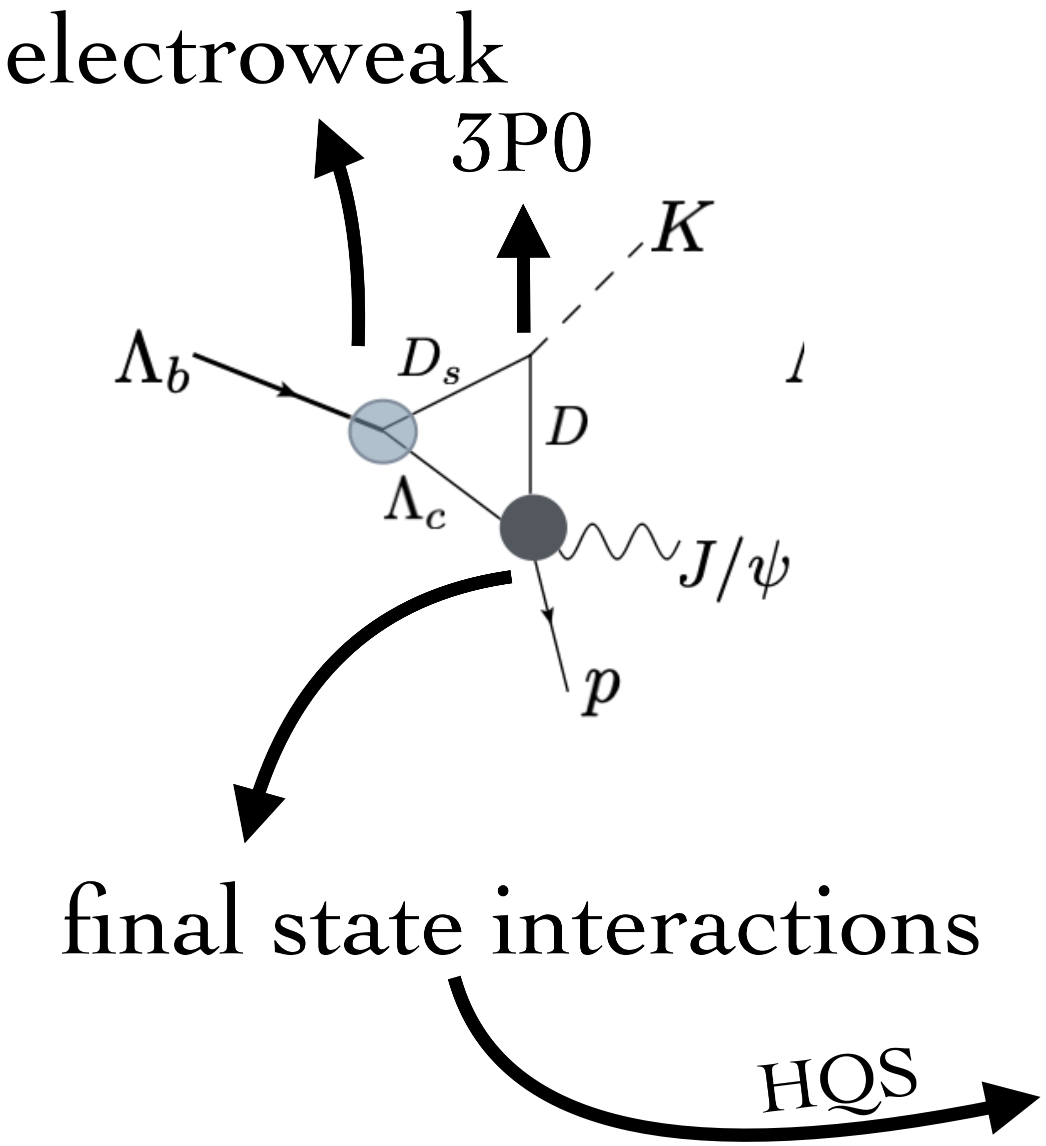
A Production/ Rescattering Model for Pentaquarks

electroweak



final state interactions

A Production/ Rescattering Model for Pentaquarks

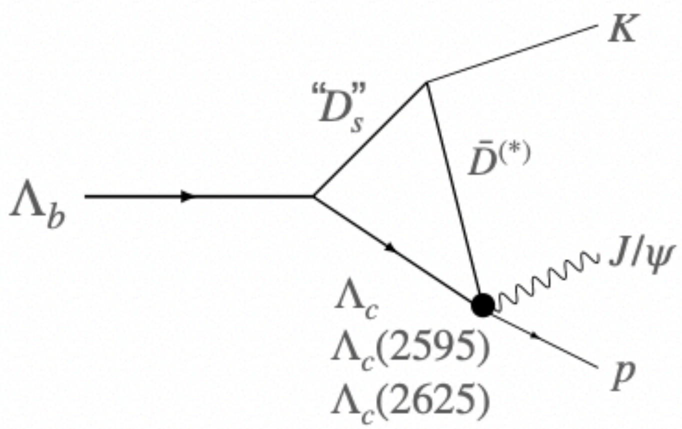


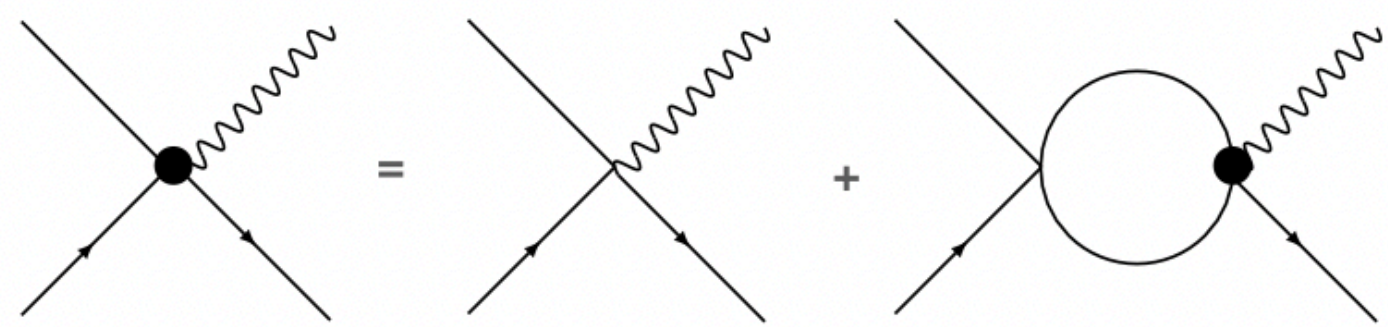
$1/2^-$	$\Lambda_c D$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$	NJ/ψ	$N\eta_c$
$\Lambda_c \bar{D}$	A	0	0	$\sqrt{3}B$	$\sqrt{6}B$	$\frac{\sqrt{3}}{2}D$	$\frac{1}{2}D$
$\Lambda_c \bar{D}^*$		A	$\sqrt{3}B$	$-2B$	$\sqrt{2}B$	$-\frac{D}{2}$	$\frac{\sqrt{3}}{2}D$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





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

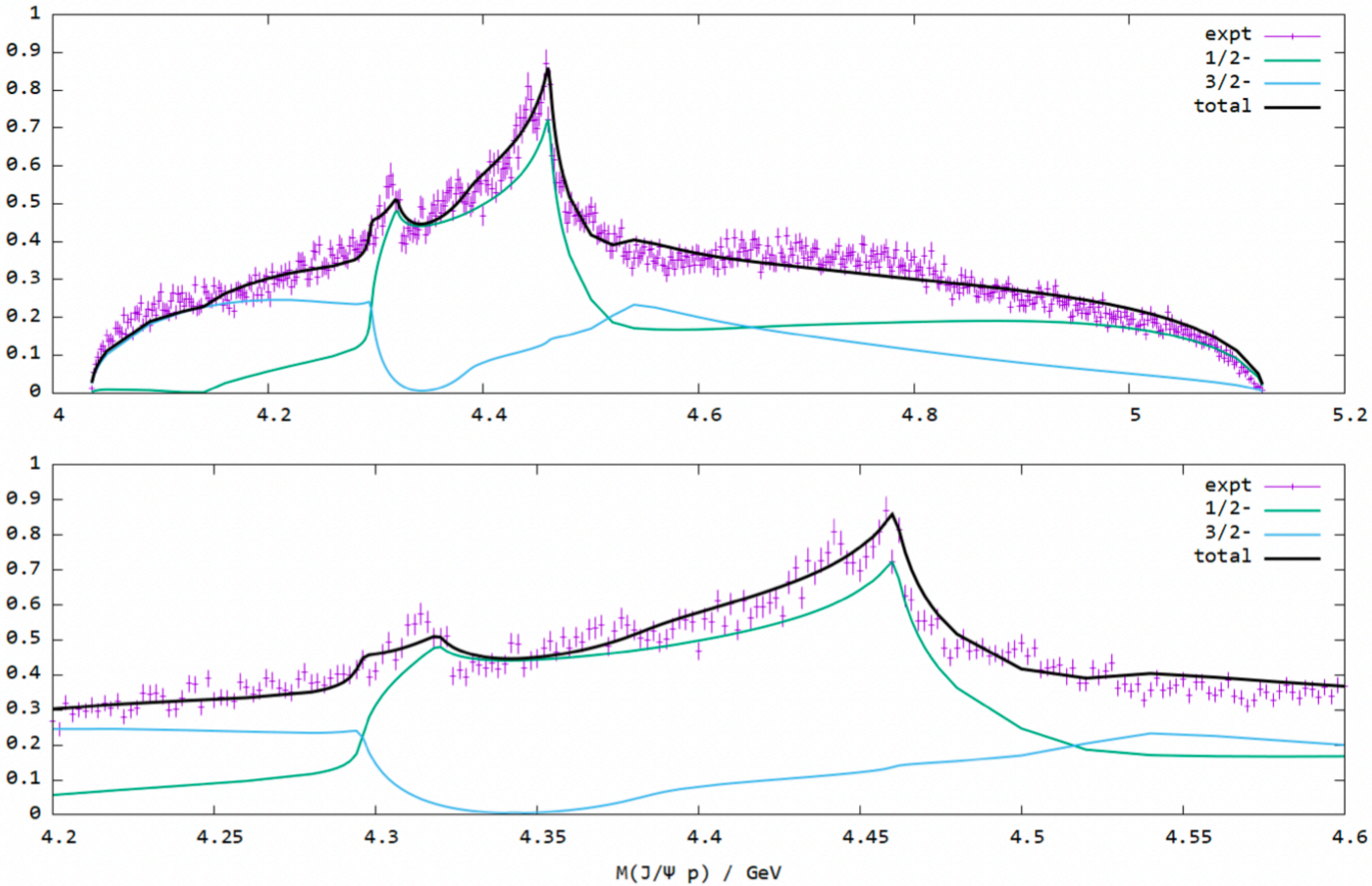
A Production/ Rescattering Model for Pentaquarks

Develop models with increasing complexity:

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

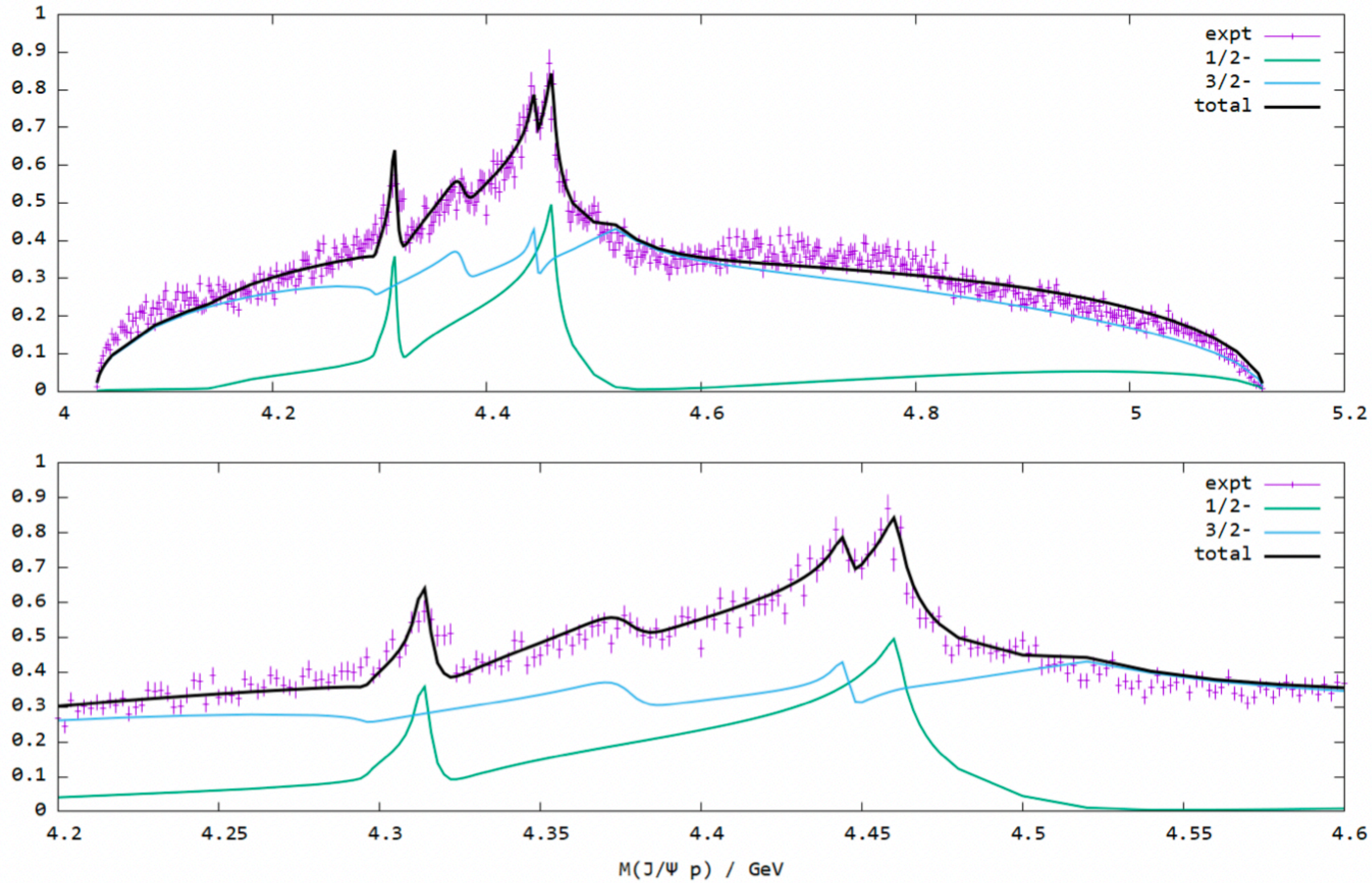
Constant background term added coherently.

Case I

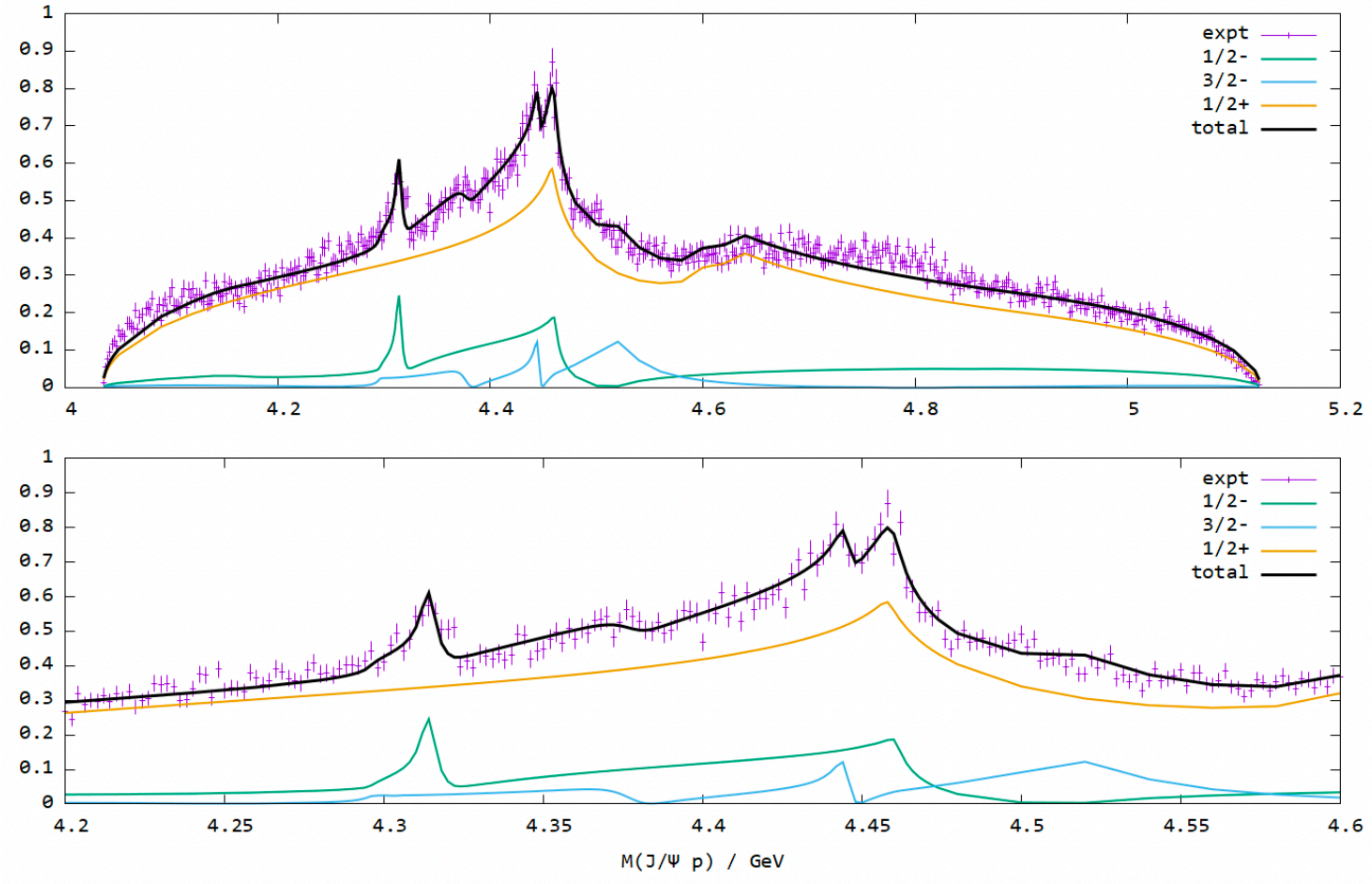


expt
1/2-
3/2-
total
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
4.2
4.4
4.6
4.8
5
5.2
expt
1/2-
3/2-
total
4.2
4.25
4.3
4.35
4.4
4.45
4.5
4.55
4.6
M(J/Ψ p) / GeV

Case II

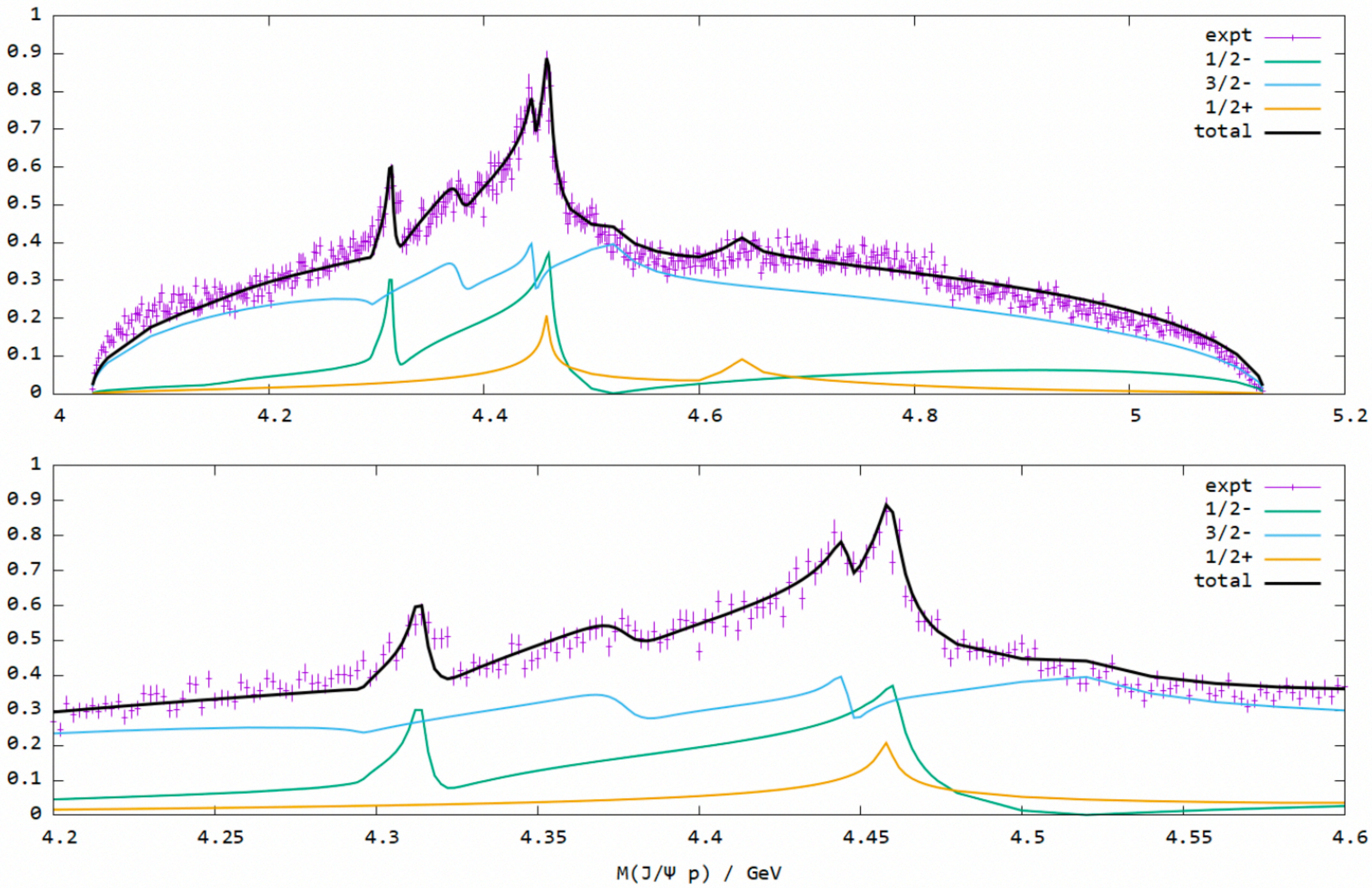


Case III



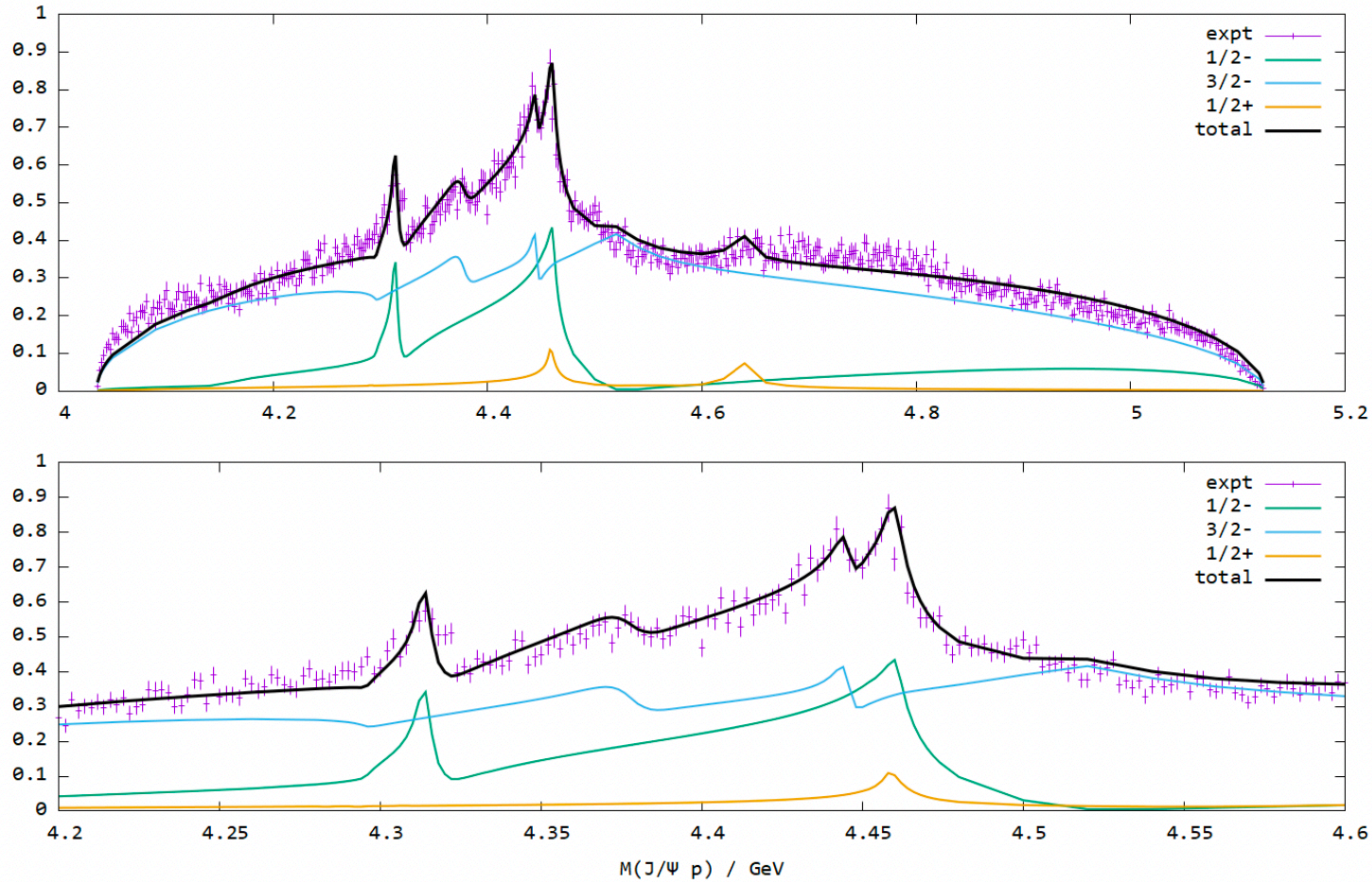
expt
1/2-
3/2-
1/2+
total
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
4.2
4.4
4.6
4.8
5
5.2
4.25
4.3
4.35
4.45
4.5
4.55
M(J/Ψ p) / GeV

CaseIV



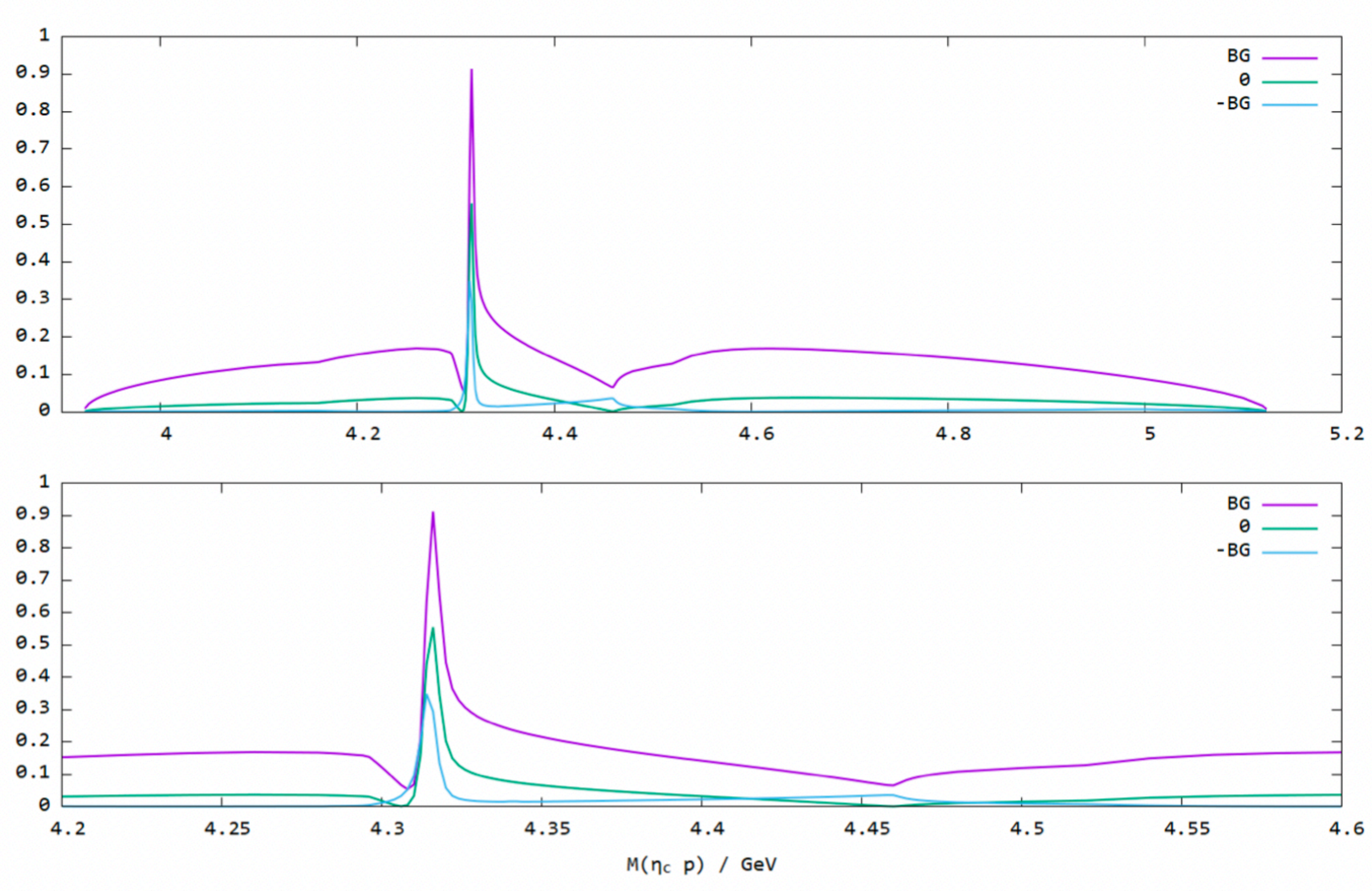
expt
1/2-
3/2-
1/2+
total
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
4.2
4.4
4.6
4.8
5
5.2
4.25
4.3
4.35
4.4
4.45
4.5
4.55
4.6
M(J/Ψ p) / GeV

Case V

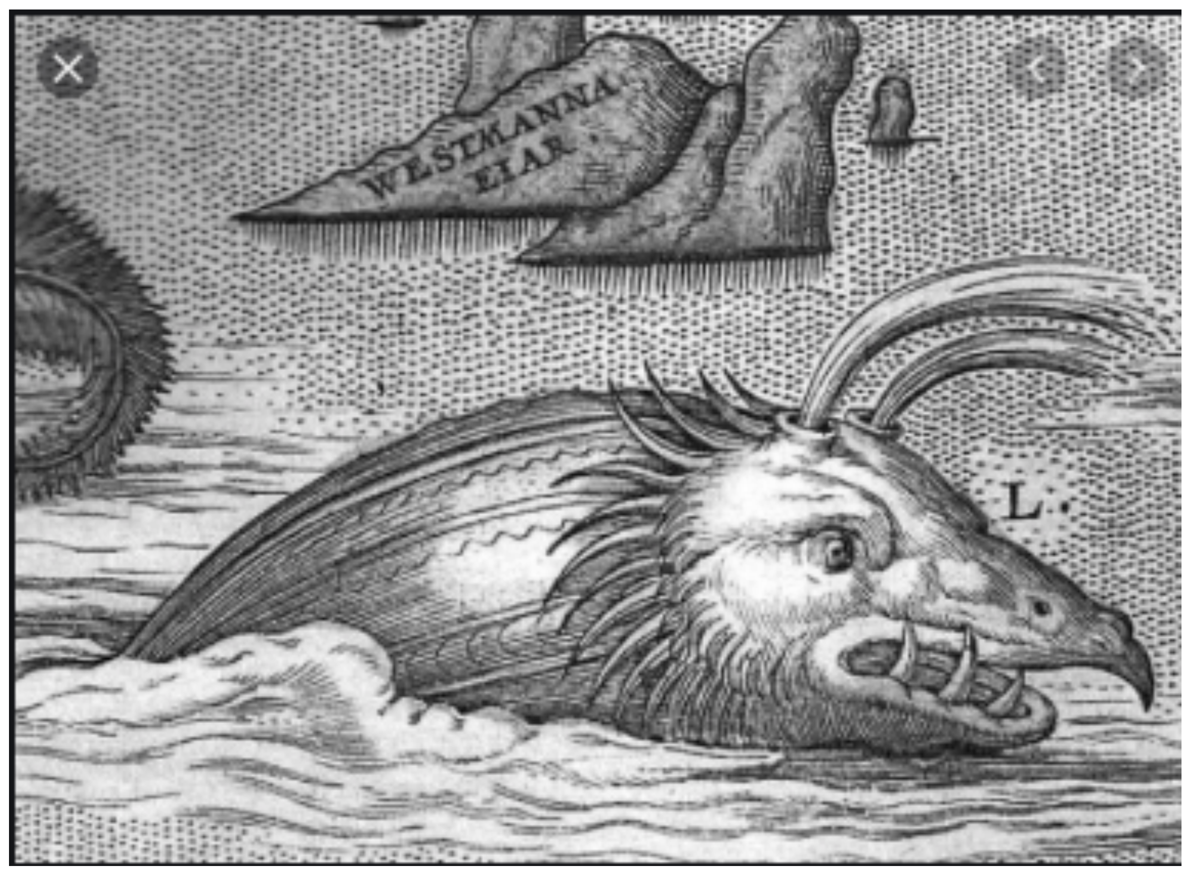


		Case 2a/3	Case 2b	Case 4	Case 5
$\Sigma_c \bar{D}$	$1/2^-$ pole	$4312 - 2.4i$	$4308 - 5.2i$	$4312 - 2.6i$	$4312 - 2.4i$
	residue $\Lambda_c \bar{D}$	0.0086	0.0194	0.0080	0.0086
	residue $\Lambda_c \bar{D}^*$	3.10	9.8	3.4	3.1
	residue NJ/ψ	0.0015	0.0011	0.0017	0.0015
	residue $N\eta_c$	0.0055	0.0041	0.0060	0.0055
	three body	1.86	1.86	1.86	1.86
$\Sigma_c^* \bar{D}$	$3/2^-$ pole	$4376.5 - 9.0i$	$4375 - 10.7i$	$4376.5 - 9.1i$	$4376.5 - 8.9i$
	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	$4444 - 2.56i$	$4440 - 3.3i$	$4444.5 - 2.56i$	$4444 - 2.56i$
	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				$4458 - 0i$

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



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

LHCb-PAPER-2022-031 in preparation

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

For theoretical interpretation

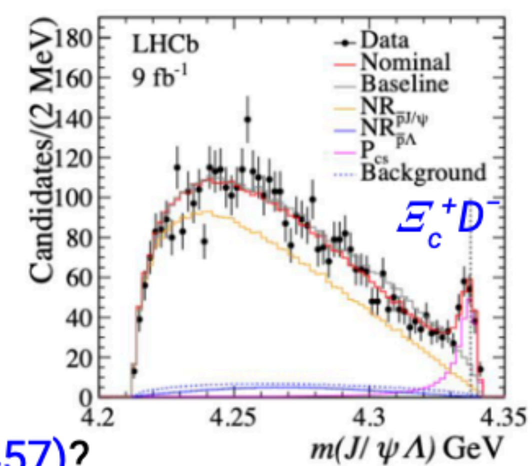
First pentaquark candidate $P^{\Lambda}_{\psi s}(4338)$ with strange quark content : $c\bar{c}uds$,

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

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

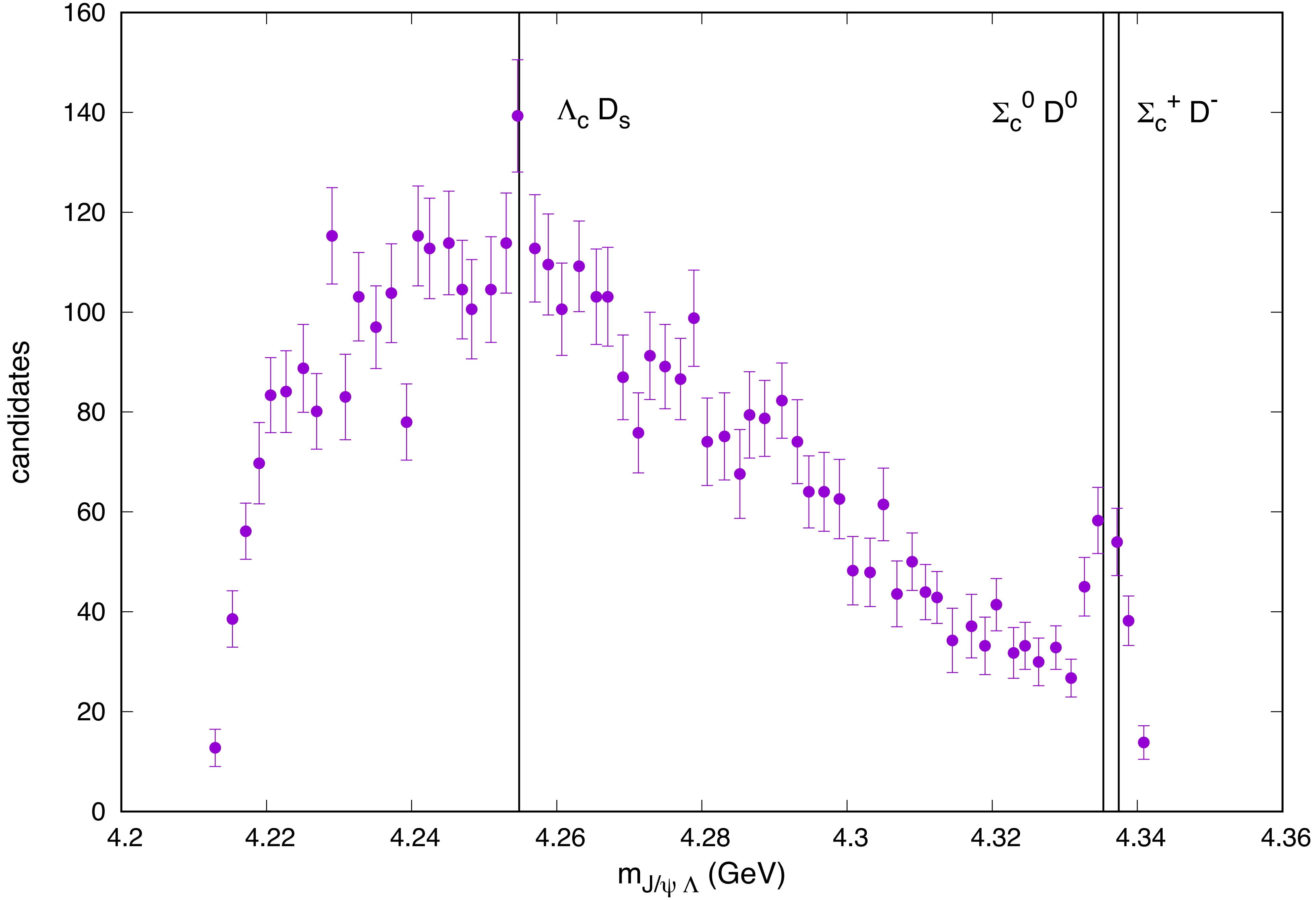
⇒ first pentaquark with spin assigned $J^P = \frac{1}{2}^-$

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

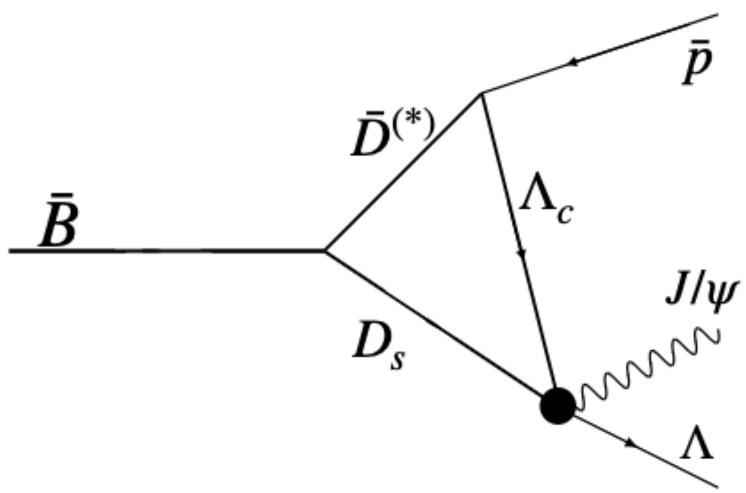


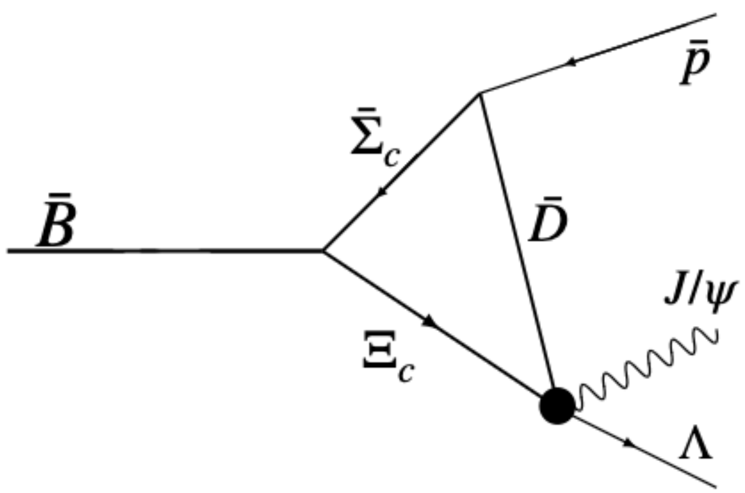
Can fit in SU(3) multiplets or are more likely molecular states?

Relevant Thresholds

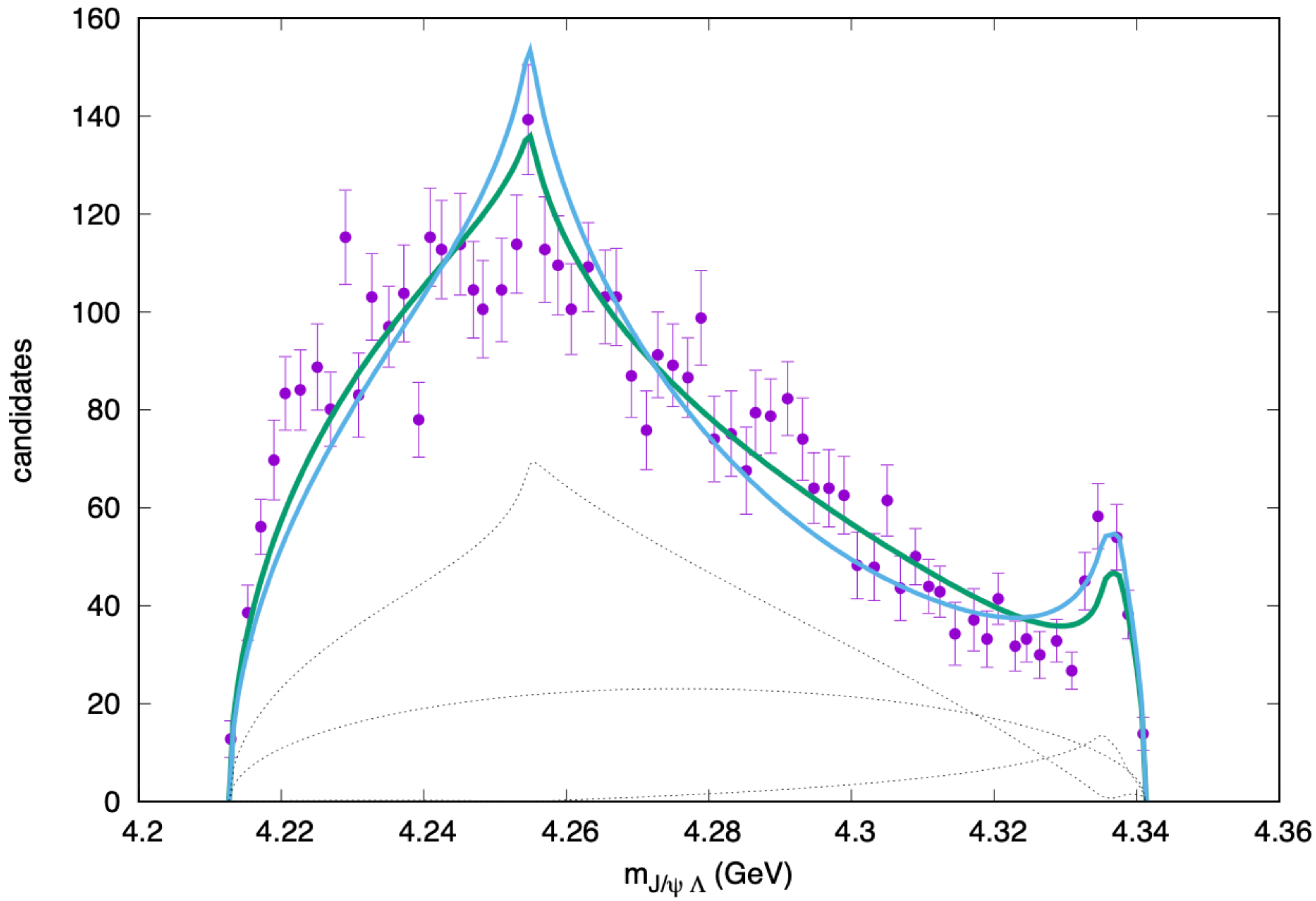


dominant production mechanism





but this can be comparable if the Landau conditions are ~ satisfied



	$\Gamma(\bar{\Sigma}_c)$ / 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~