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The LHCb State $P_{\psi s}^{\Lambda}(4338)$ as a Triangle Singularity

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

LHCb-PAPER-2022-031 in preparation

Discussion on the new J/ψΛ state

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

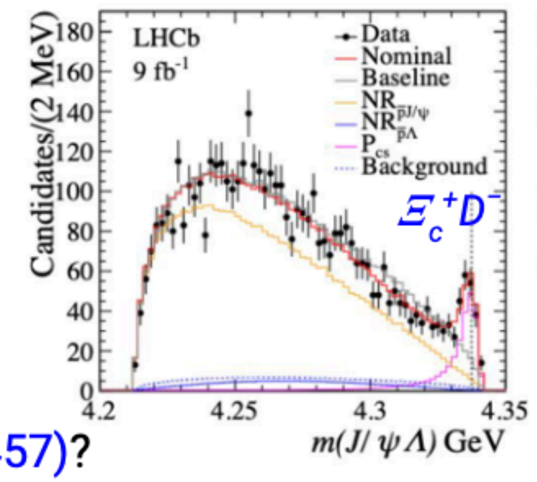
$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$

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

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

For theoretical interpretation

- ✓ 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?

Is a $\Xi_c D$ bound state plausible?

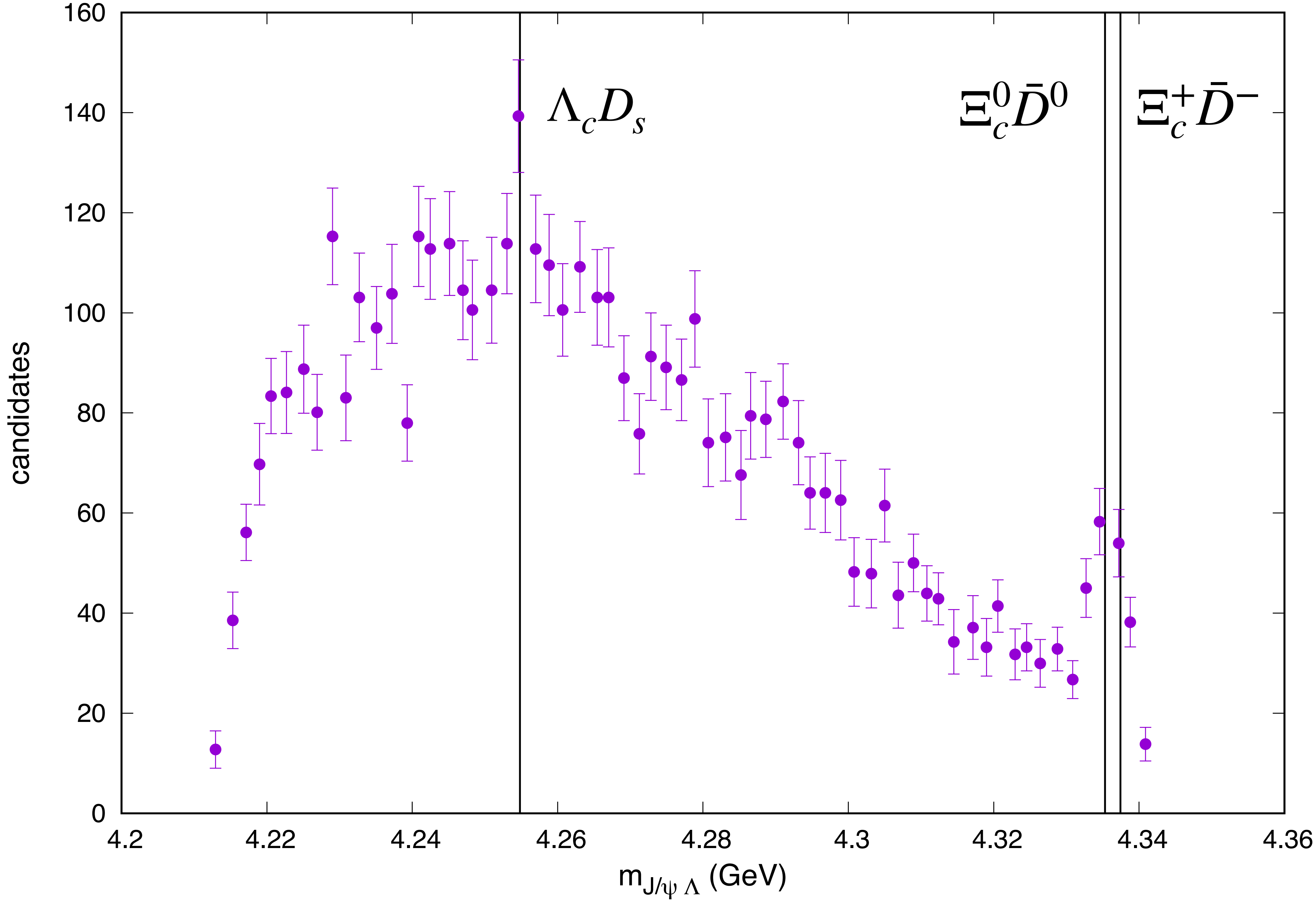
Heavy quark symmetry implies $\Xi_c D^*$ partners

$$V(\Xi_c \bar{D}, 1/2^-) = V(\Xi_c \bar{D}^*, 1/2^-) = V(\Xi_c \bar{D}^*, 3/2^-),$$

Possible partner state is the $P_{cs}(4459)$, but the binding energy is ~19 MeV, not ~0.

The $P_{\psi s}^{\Lambda}$ is 1-3 MeV *above* threshold.

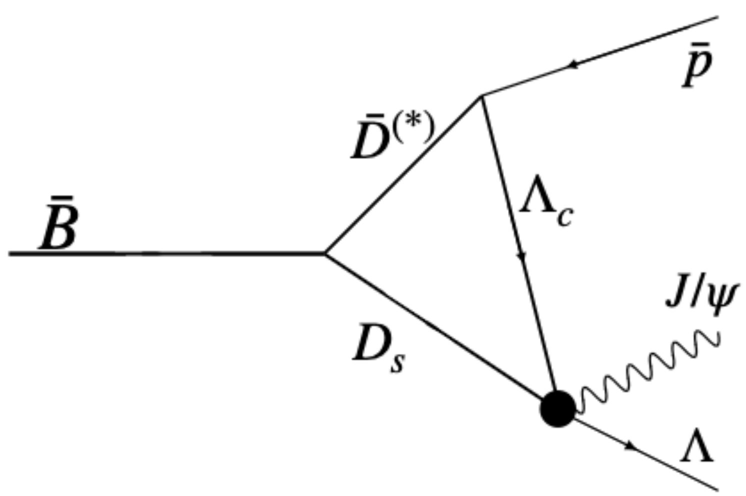
Relevant Thresholds



Production

the tree-level diagrams for the J/ψ Λ p̄ final state are color-suppressed; hence it is natural to assume that the color-favored triangle diagram is a dominant contribution.

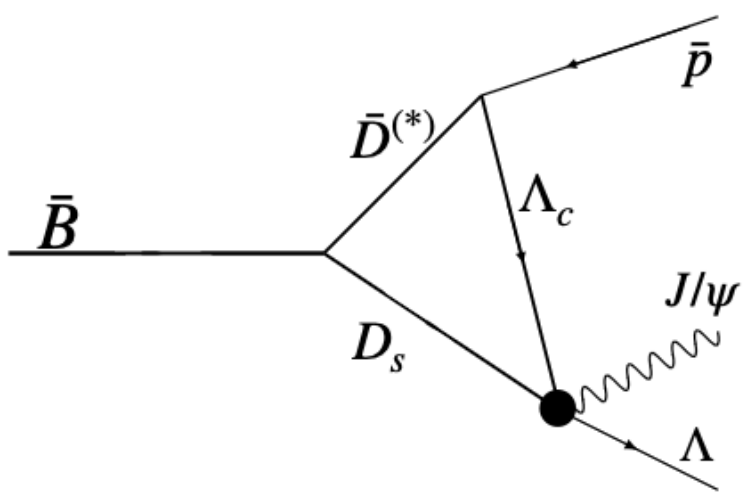
dominant mechanism

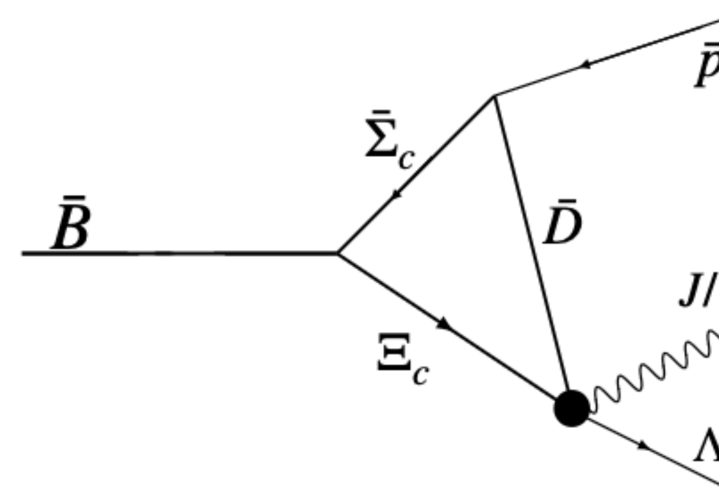


Production

the tree-level diagrams for the J/ψ Λ p^- final state are color-suppressed; hence it is natural to assume that the color-favored triangle diagram is a dominant contribution.

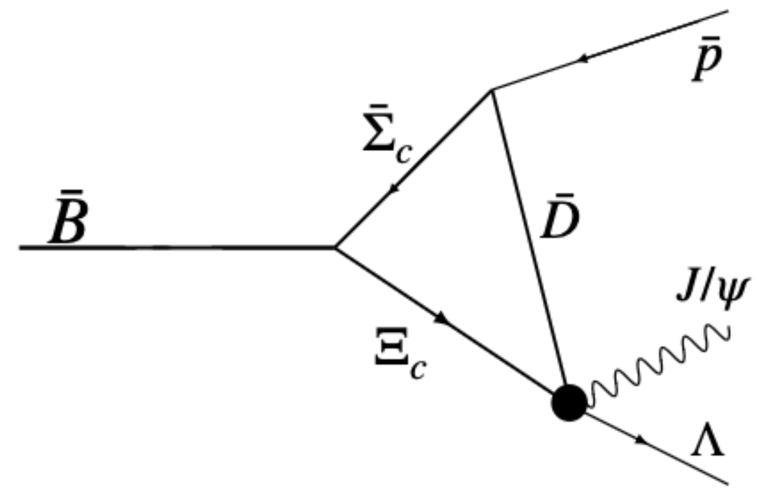
dominant mechanism





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

Production



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

And they are for $m(\Sigma_c) \approx 2800$ MeV.

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***

Model

$\Lambda_c D_s$ $\Xi_c^+ \bar{D}^-$ $\Xi_c^0 \bar{D}^0$

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

constant background

Substantial isospin breaking!

Model

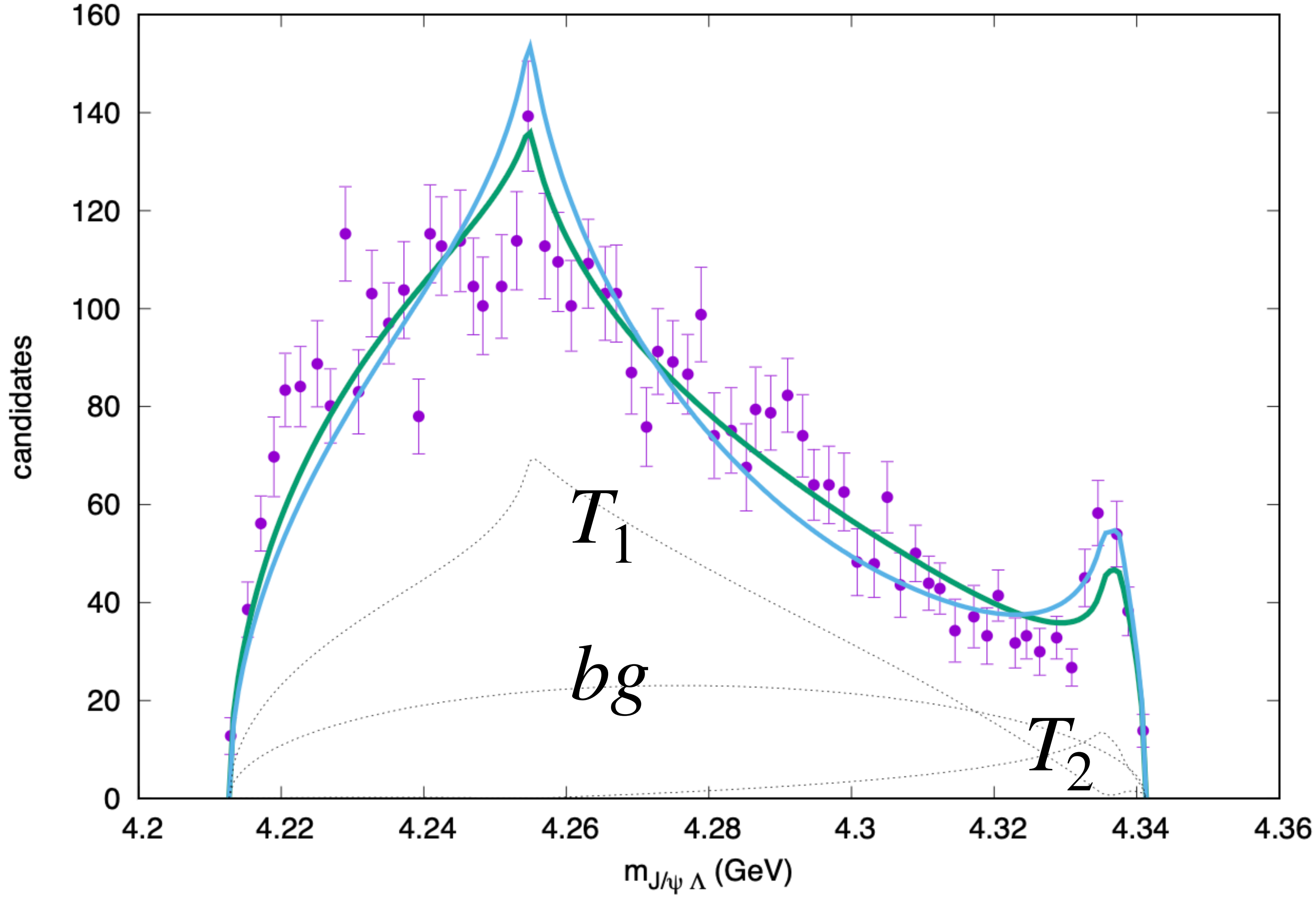
$$\langle \mathbf{8},\mathbf{1}|V|\mathbf{8},\mathbf{1}\rangle = \langle \mathbf{8},\mathbf{3}|V|\mathbf{8},\mathbf{3}\rangle = A, \qquad \langle \mathbf{1},\mathbf{1}|V|\mathbf{1},\mathbf{1}\rangle = A'.$$

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

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

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

Fit Results



$g_2 \ll g_1$ ✓

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

Fit Results

A comparable $P_{\psi s}^{\Lambda}$ signal is predicted in $\eta_c \Lambda$.

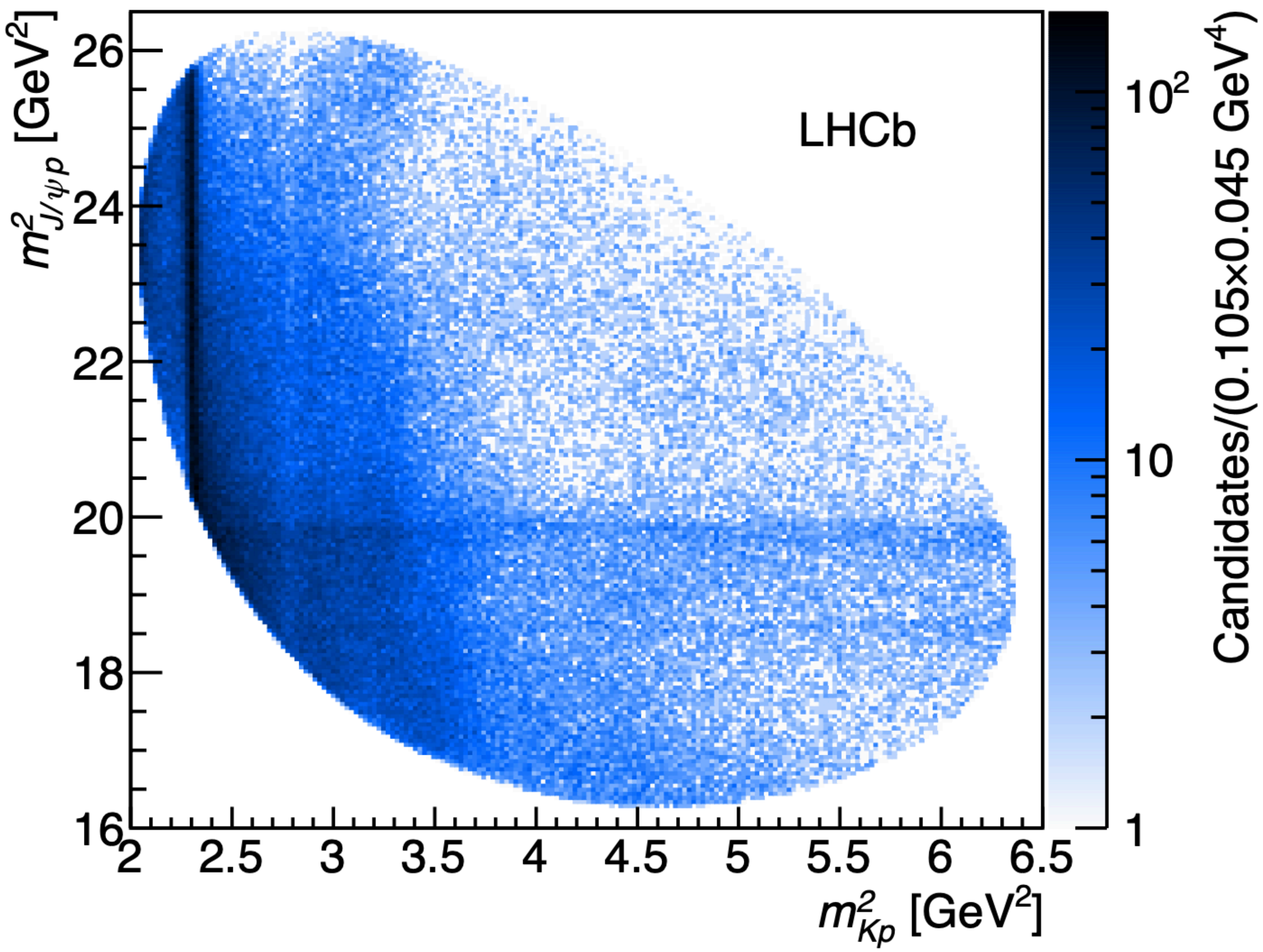
Possible isospin violation observable in $\eta_c \Sigma^0$ or $J/\psi \Sigma^0$

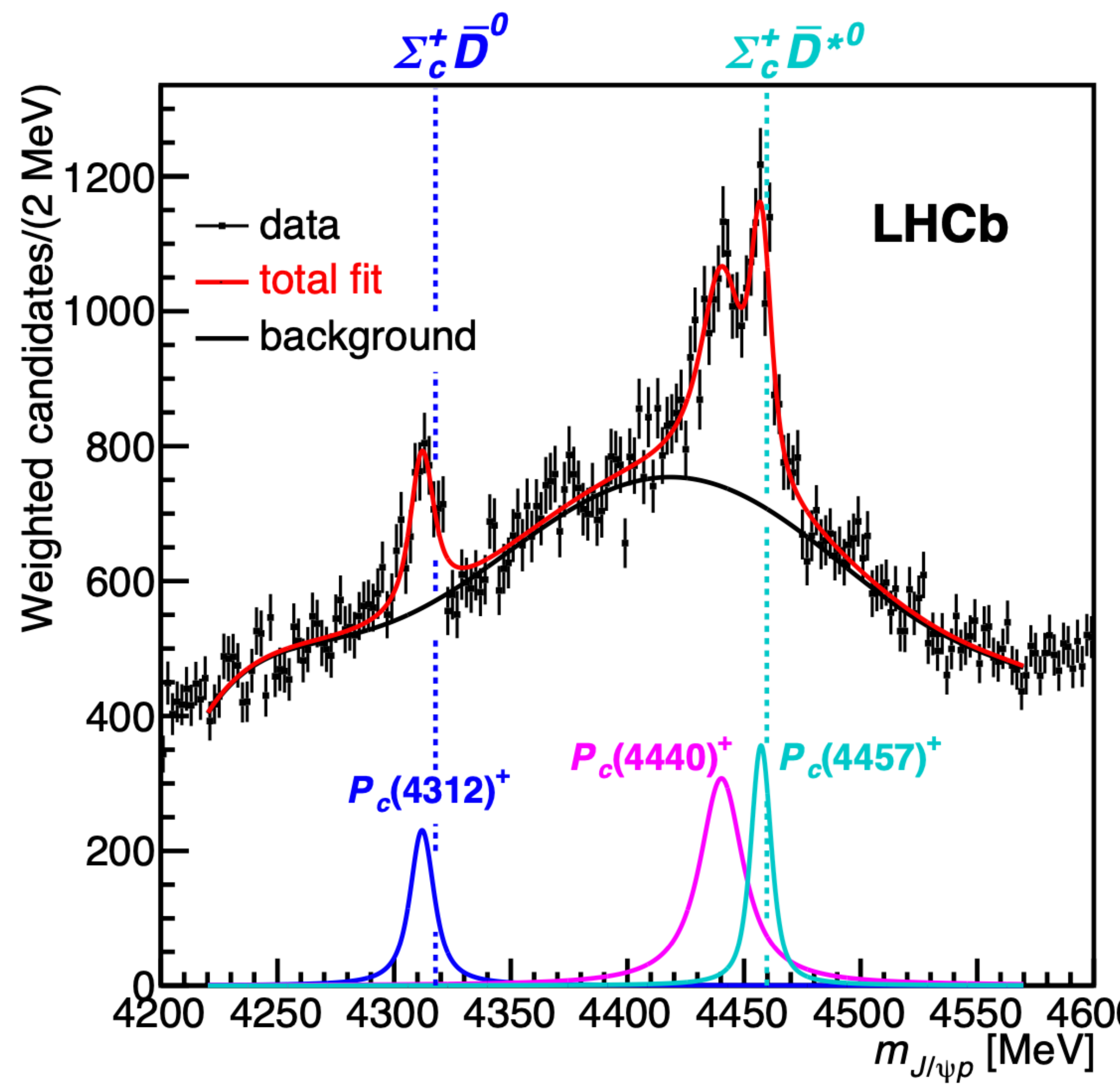
Related States

"Vi har nu en model, der på smukke ste vis forklarer data og for første gang indeholder alle de begrænsninger, data giver," sagde fysikeren Tim Burns fra Swansea University ved offentliggørelsen.

Pc(4312), Pc(4440), Pc(4357)

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

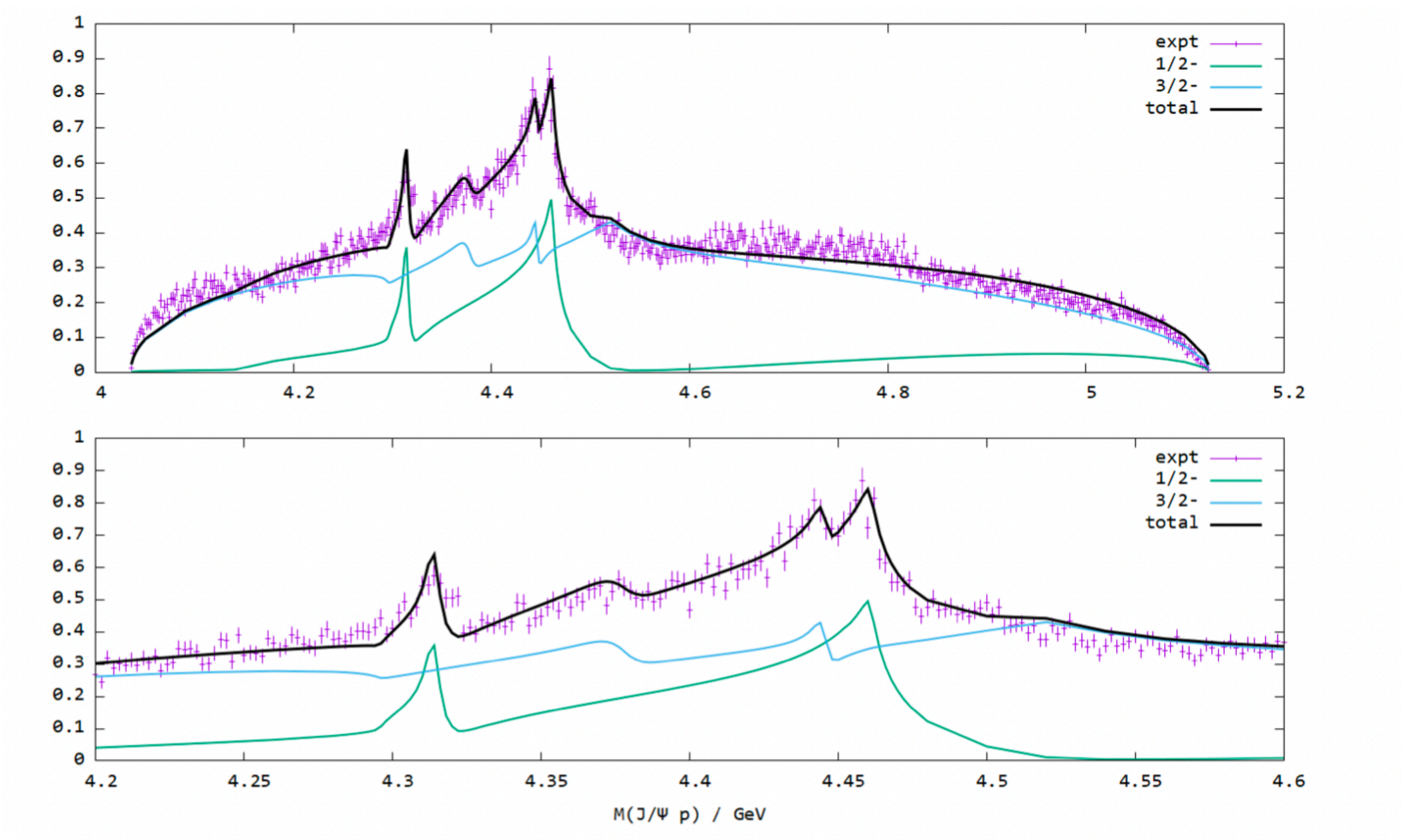




T.J. Burns and E.S. Swanson, Experimental Constraints on the Properties of P_c States, 2112.11527

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

Triangle + FSI model fit



- 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 ($\Lambda_c' D$).

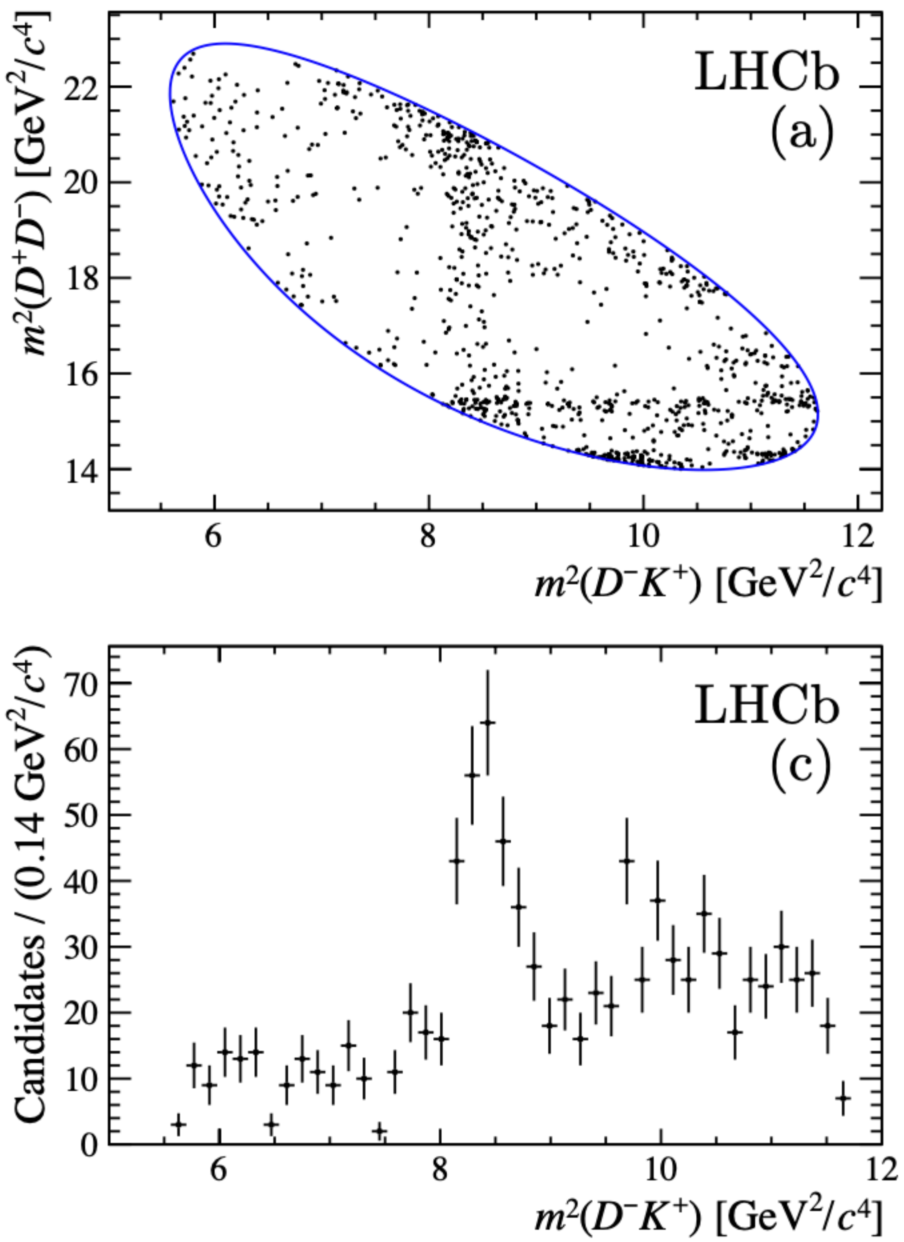
- Current experiments are at the threshold for observing Pc's

- 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-)

X(2900)

$B^+ \to D^+ D^- K^+$



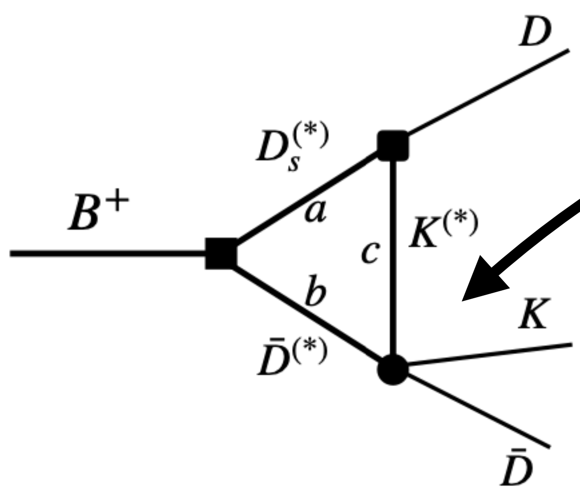
X_0 $M = 2.866 \pm 0.007 \pm 0.002$ GeV, $\Gamma = 57 \pm 12 \pm 4$ MeV,

X_1 $M = 2.904 \pm 0.005 \pm 0.001$ GeV, $\Gamma = 110 \pm 11 \pm 4$ MeV.

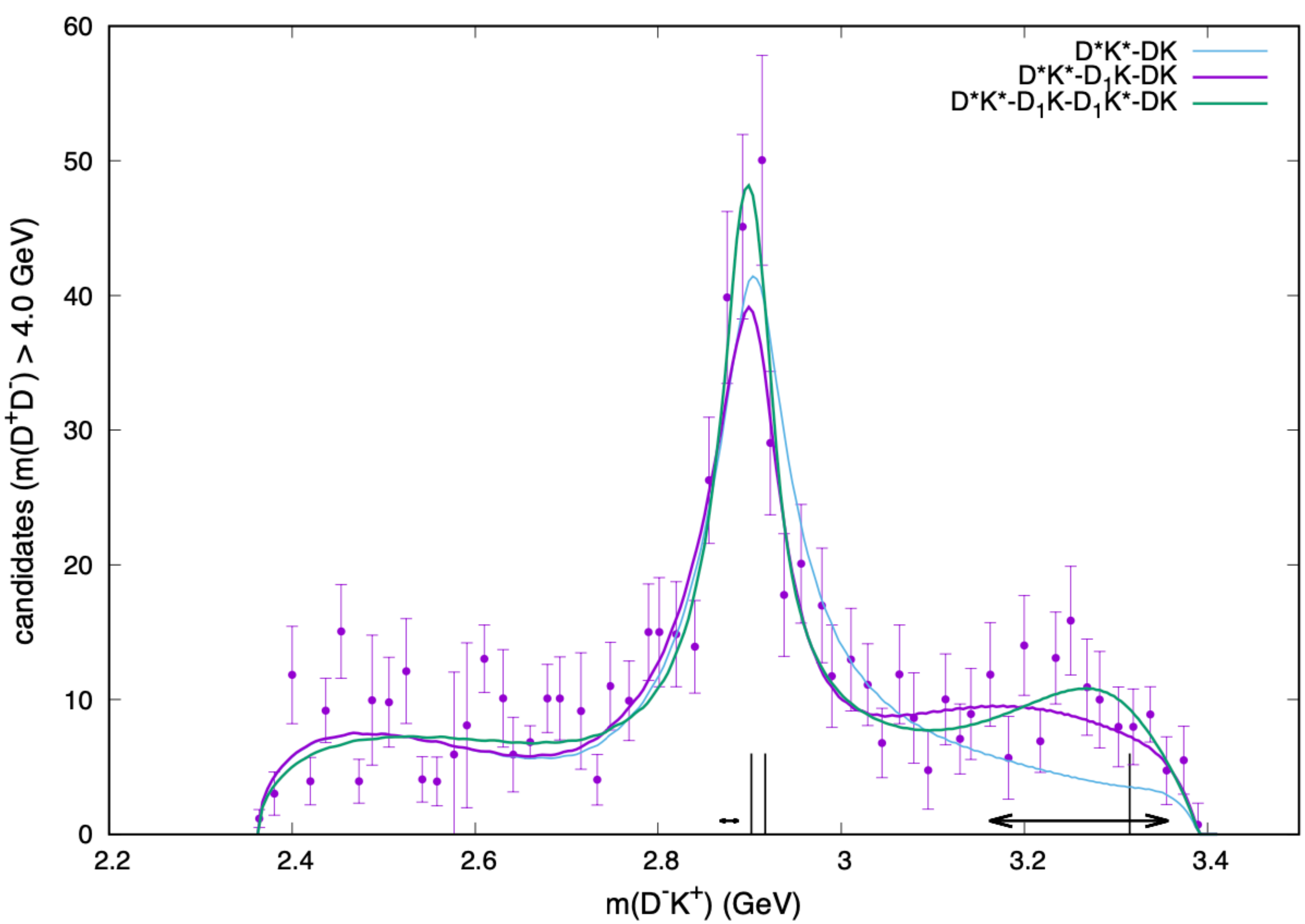
manifestly exotic channel $ud\bar{s}\bar{c}$

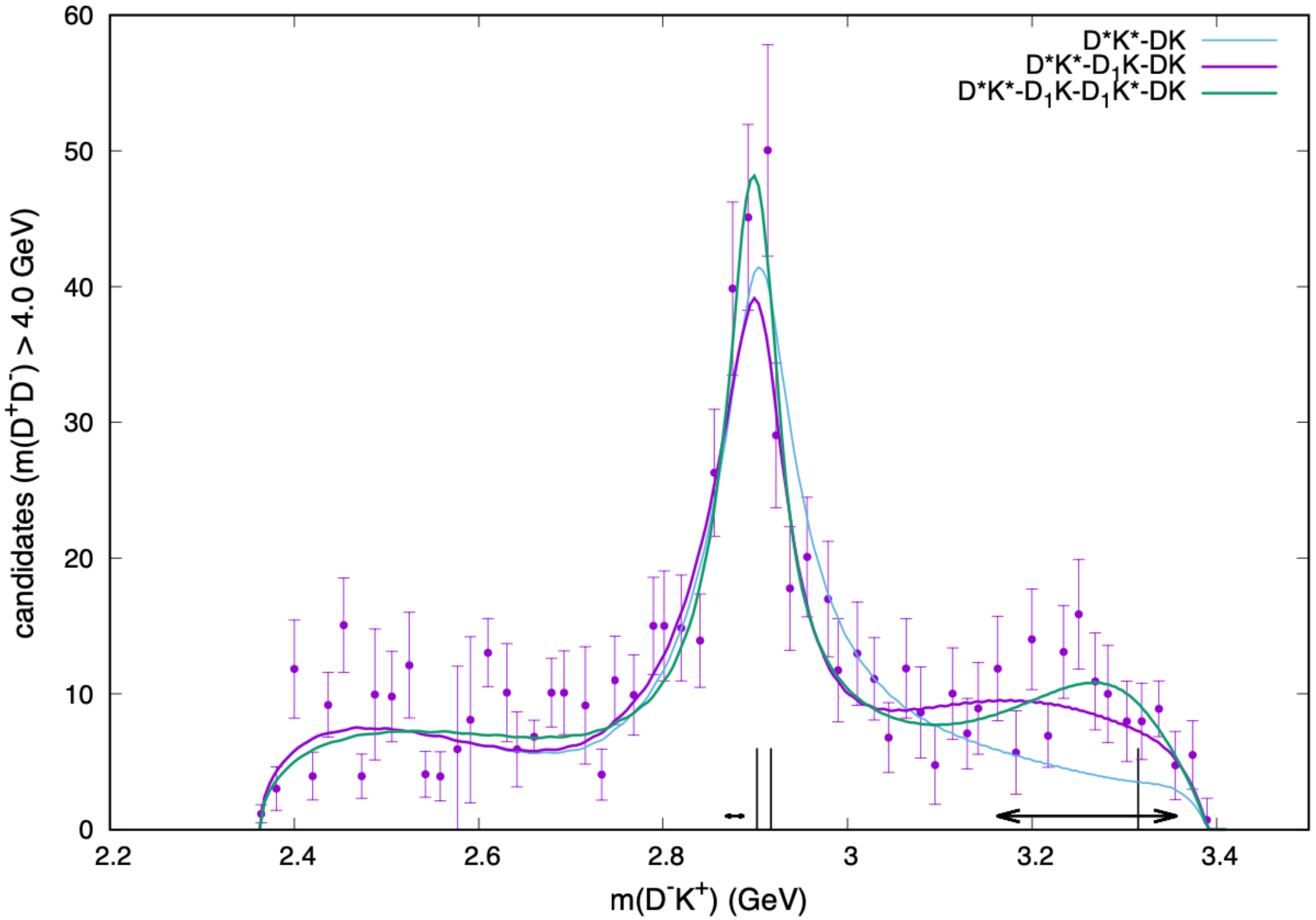
T.J. Burns and E.S. Swanson, Kinematical cusp and resonance interpretations of the X(2900),2008.12838.

T.J. Burns and E.S. Swanson, Discriminating among interpretations for the X(2900),2009.05352.



$\boldsymbol{\lambda}(1^-)$	$\bar{D}^*K^*\vert_P$	$\bar{D}_1K\vert_S$	$\bar{D}_1K^*\vert_S$	$\bar{D}K\vert_P$
$\bar{D}^*K^*\vert_P$	C_1	C_2	C_3	C_4
$\bar{D}_1K\vert_S$		0	C_5	0
$\bar{D}_1K^*\vert_S$			C_6	0
$\bar{D}K\vert_P$				0





thresholds: $\bar{D}^*K^*$, $\bar{D}_1K$ $\bar{D}_1K^*$

resonances: 2849 - i 23 MeV 3173 - i 236 MeV
$\bar{D}^*K^* - \bar{D}_1K$ $\bar{D}_1K^*$

a resonance interpretation is possible, but has weak evidence

Conclusions

$P_{\psi s}^{\Lambda}(4338) \to \triangle$
$P_c(4312) \to \Sigma_c D(1/2^-)$
$P_c(4380) \to \Sigma_c^* D(3/2^-)$
$P_c(4440) \to \Sigma_c D^*(3/2^-)$
$P_c(4457) \to \triangle$, cusp
$P_c(4508) \to \Sigma_c^* D^*(5/2^-)$
$X(2900) \to \triangle$

Consideration of production in EW decays leads naturally to triangle diagrams.

These kinematical structures can give rise to signifcanct enhancements, that are not always resonances.

~thank you~