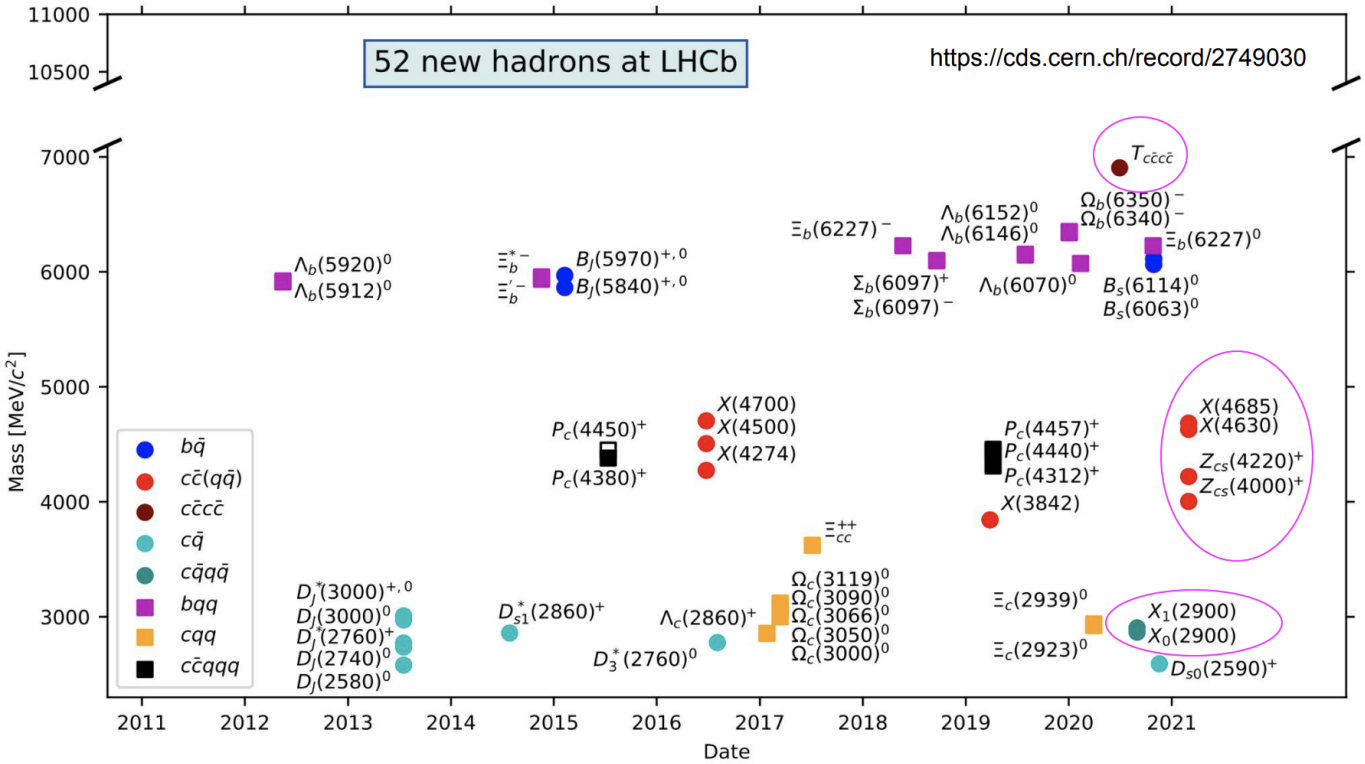
PWA/ATHOS 2021
LHCb: Exotic hadrons

N. Skidmore on behalf of LHCb

September 2021

Results shown today...

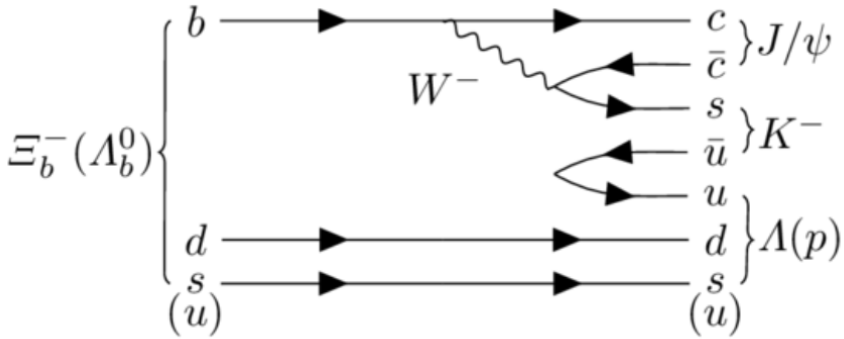
- Try to cover LHCb exotic results since last PWA/ATHOS workshop (2019)
- All results use full run 1+2 LHCb dataset $= 9\,\text{fb}^{-1}$

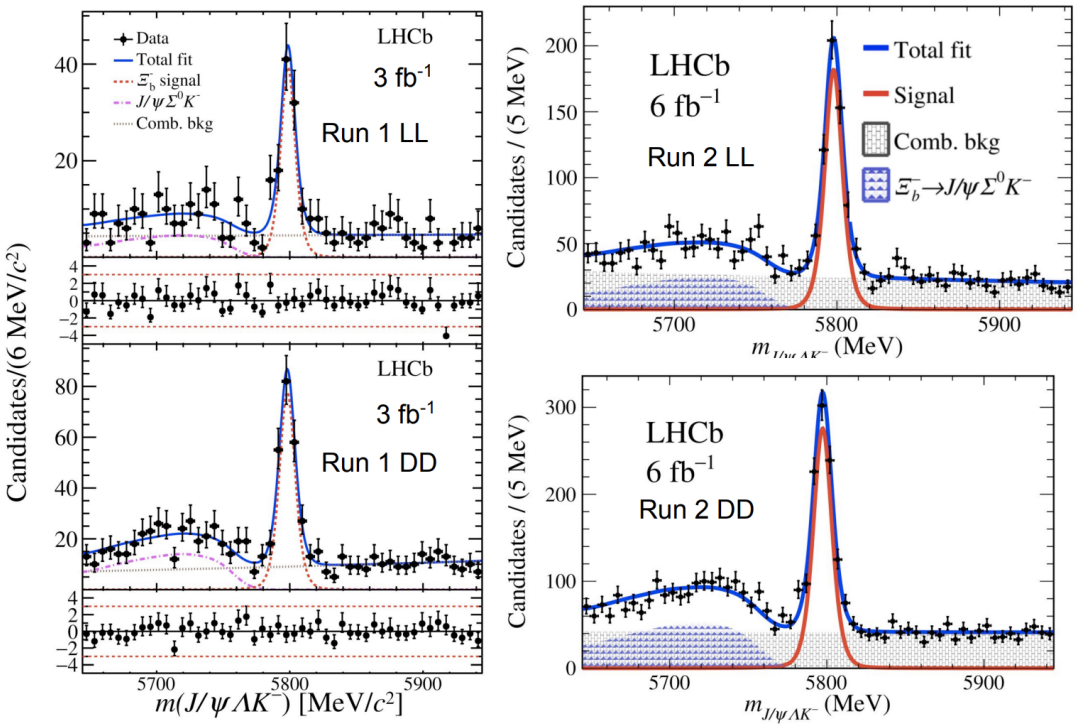


- P_{cs}^0 in $\Xi_b^- \to J/\psi\,\Lambda K^-$
- Exotic states in $B_s^0 \to J/\psi\,p\bar{p}$
- X and Z_{cs}^+ states in $B^+ \to J/\psi\,\phi K^+$
- Tetraquarks in $B^+ \to D^+ D^- K^+$
- $T_{cc\bar{c}\bar{c}}$ in prompt-J/ψ pairs
- T_{cc}^+ in $D^0 D^0 \pi^+$

Exotic states in $\Xi_b^- \to J/\psi \Lambda K^-$

- Change in spectator quark relative to P_c^+ discovery channel, $\Lambda_b^0 \to J/\psi\, pK^-$
- Search for strange counter-parts, P_{cs}^0



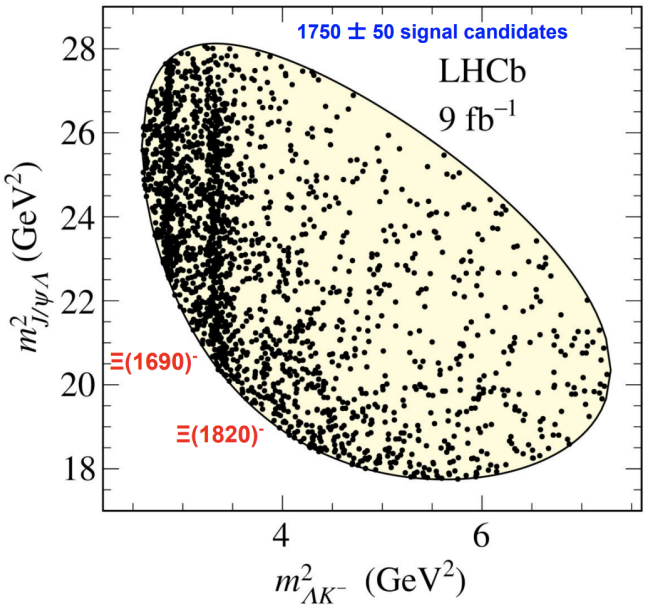


Sci.Bull. 66 (2021) 1278-1287

- Two reconstruction categories: long Λ (better resolution) and downstream Λ
- 1750 ± 50 candidates

Conventional $\Xi^{*-} \to \Lambda K^-$ decay chain

Ξ^{*-} spectrum poorly known - opportunity to study these resonances



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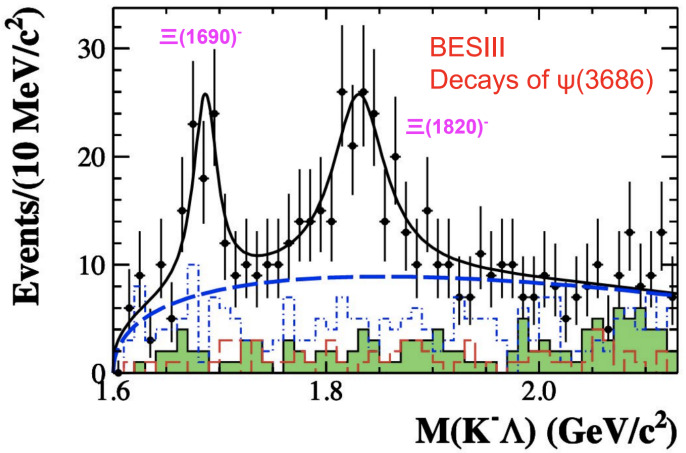


Phys. Rev. D 91, 092006

Recent studies by BESIII

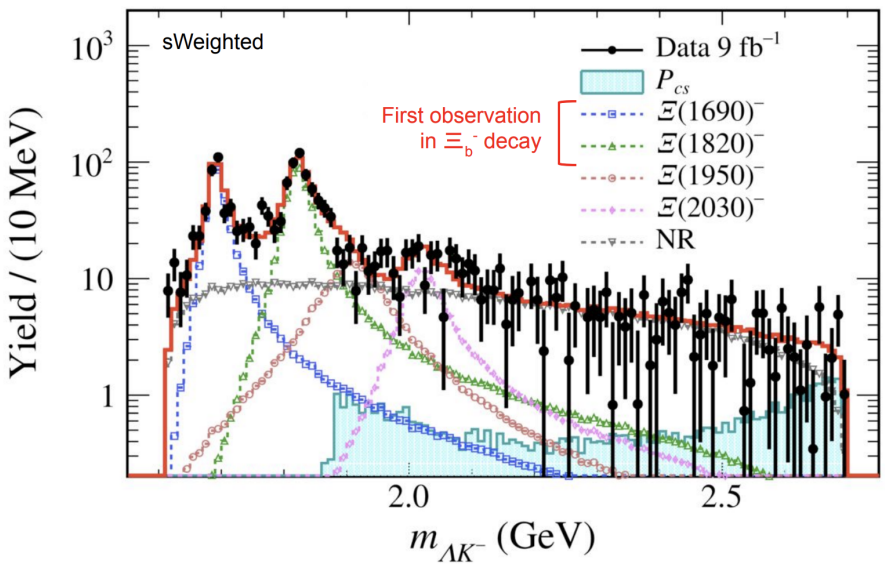
Initial amplitude model established with ΛK^- contributions only

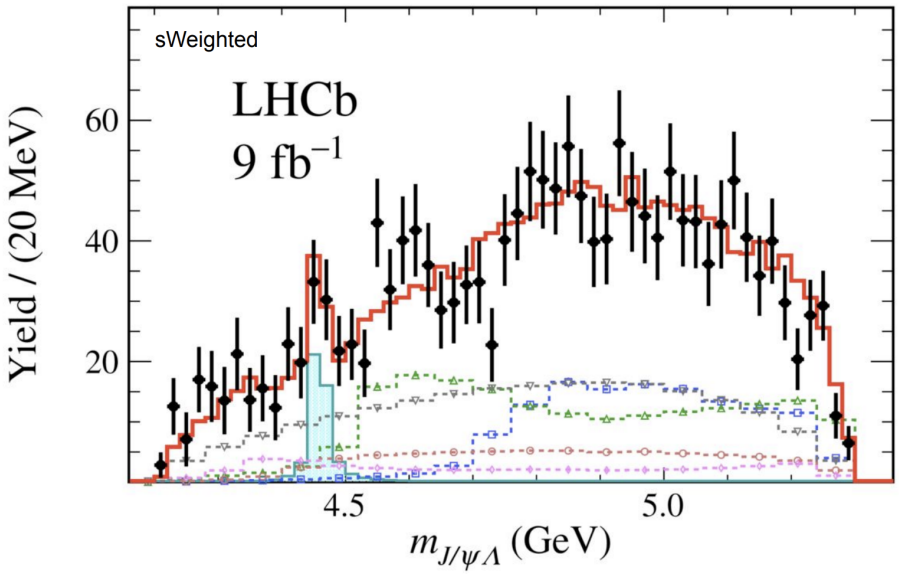
Default description of ΛK spectrum

State	M_0 (MeV)	Γ_0 (MeV)	LS couplings		J^P examined
$\Xi(1690)^-$	1690 ± 10	< 30	Free in fit	4 (6)	$(1/2, 3/2)^\pm$
$\Xi(1820)^-$	1823 ± 5	24^{+15}_{-10}		3 (6)	$3/2^-$
$\Xi(1950)^-$	1950 ± 15	60 ± 20		3 (6)	$(1/2, 3/2, 5/2)^\pm$
$\Xi(2030)^-$	2025 ± 5	20^{+15}_{-5}		3 (6)	$5/2^\pm$
NR ΛK^-	-	-		4 (4)	$1/2^-$

Combinations of J^P examined

Exotic $P_{cs}^0 \to J/\psi\,\Lambda$ decay chain



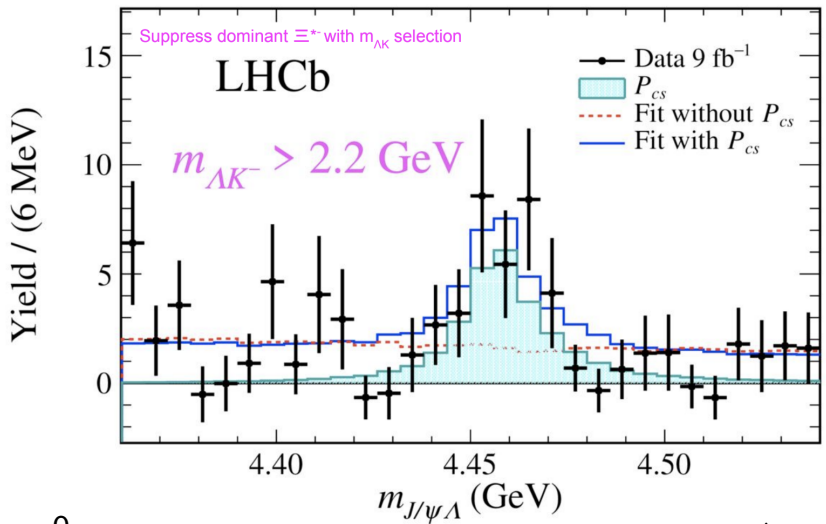


Sci.Bull. 66 (2021) 1278-1287

- P_{cs}^0 state added with $J^P = 1/2^\pm - 5/2^\pm$
- New $P_{cs}^0(4459)$ state observed at (3.1σ) (No J^P determination)

Mass (MeV)	Width (MeV)
$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$

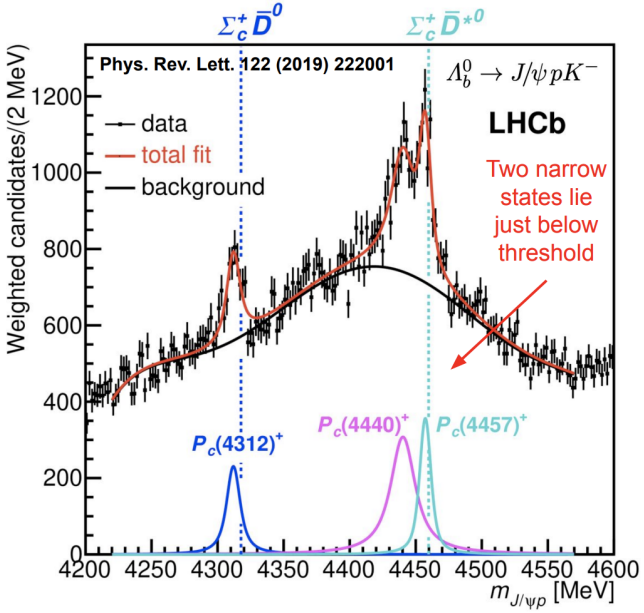
- $\Xi^-(1690)$, $\Xi^-(1820)$ consistent with PDG and BESIII results



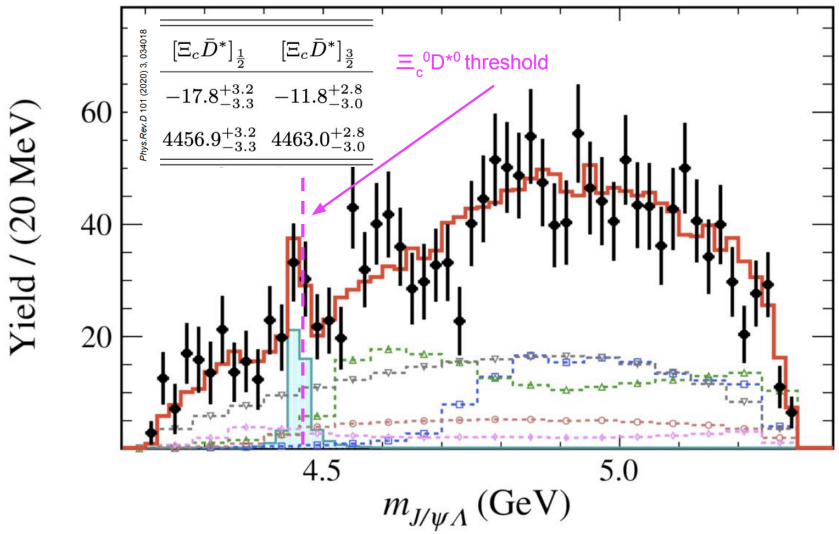
P_{cs}^0 clear with veto on dominant Ξ^{*-}

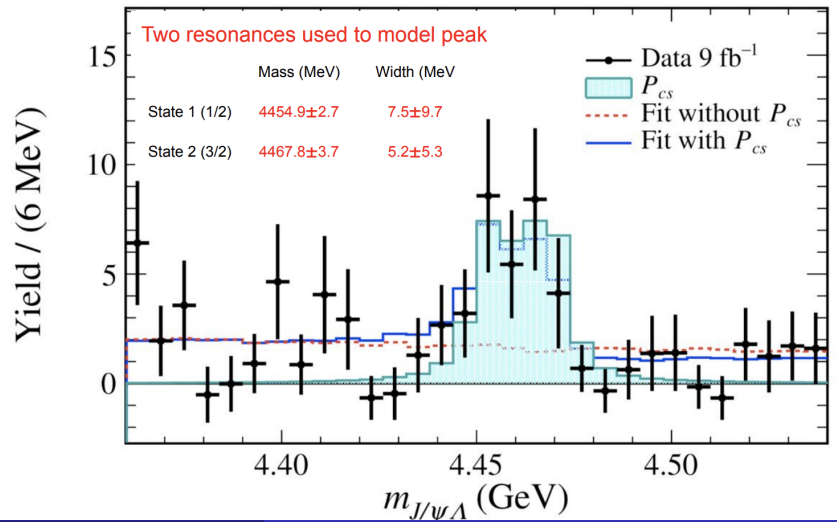
Exotic $P^0_{cs} \to J/\psi\,\Lambda$ decay chain

$P^0_{cs}(4459)$ is narrow and lies 19 MeV below $\Xi^0_c \bar{D}^{*0}$ threshold where two P_c states are predicted [Phys. Rev. D 101, 034018] Recall $\Lambda^0_b \to J/\psi\, pK^-$ discovery channel



Phys. Rev. Lett. 122 (2019) 222001



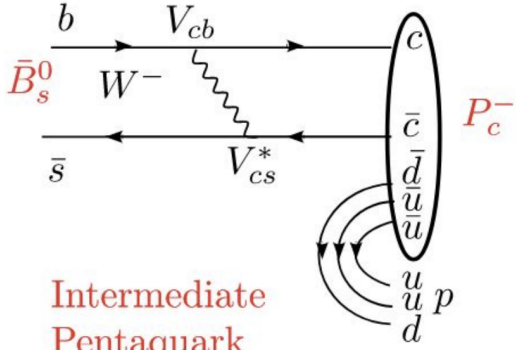


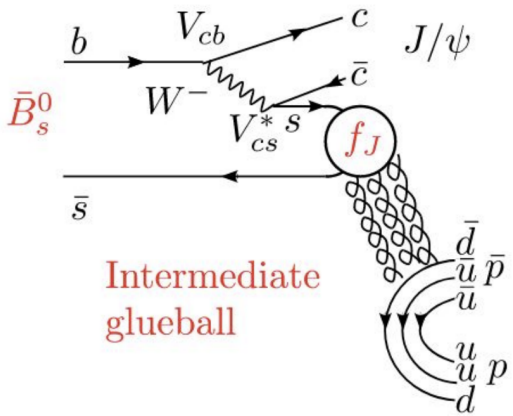
- Hypothesis of 2 peak structure with J^P values from [Phys. Rev. D 101, 034018]
- Cannot confirm or deny this description

Exotic states in $B_s^0 \to J/\psi\, p\bar{p}$

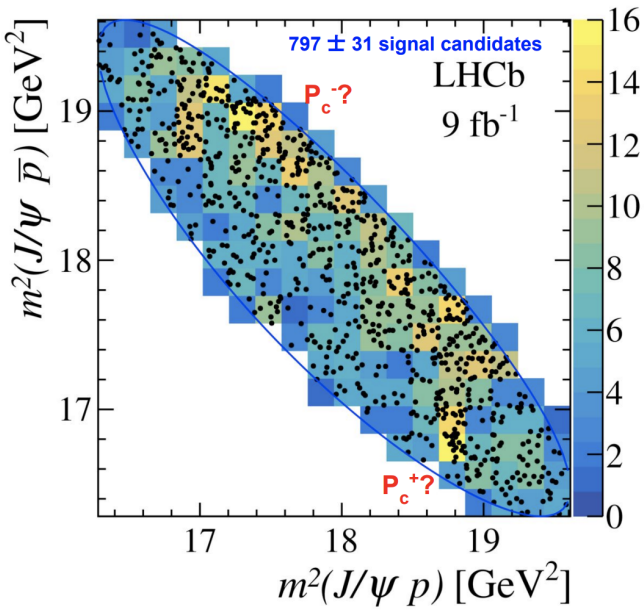
No conventional states in $B_s^0 \to J/\psi\, p\bar{p}$

- Sensitive to $P_c^+[c\bar{c}uud]$ discovered in $\Lambda_b^0 \to J/\psi\, pK^-$ as well as glueballs





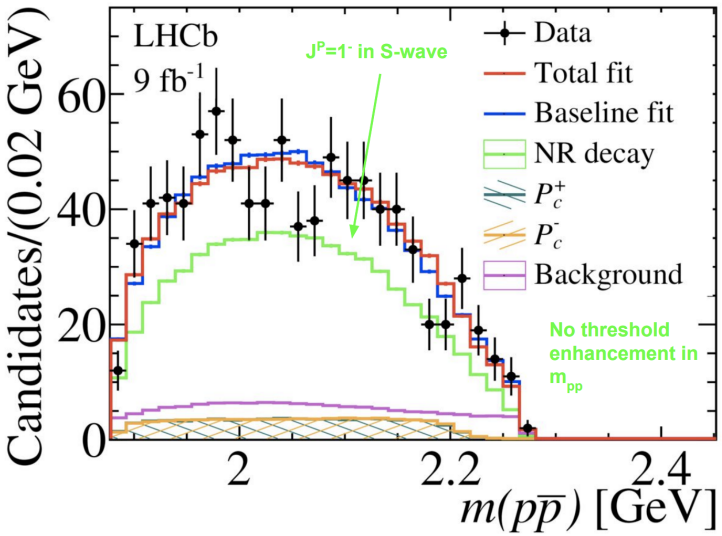
- 797 ± 31 candidates in run 1+2 data set
- Perform flavour - untagged amplitude fit where B_s^0, $\bar{B}_s^0$ analysed together

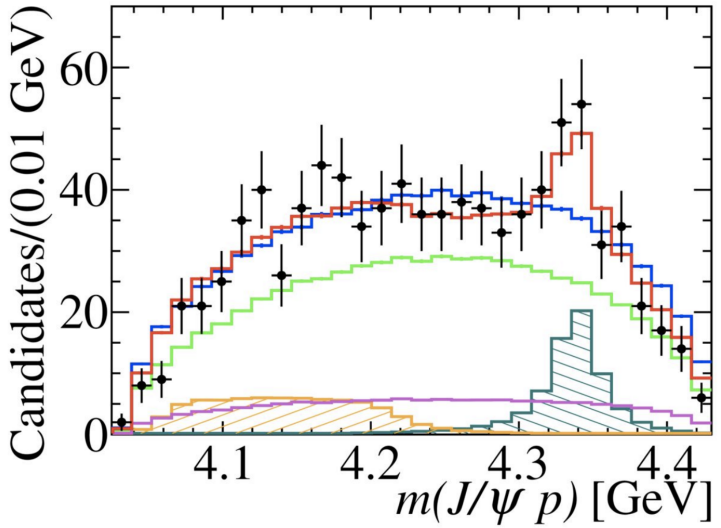


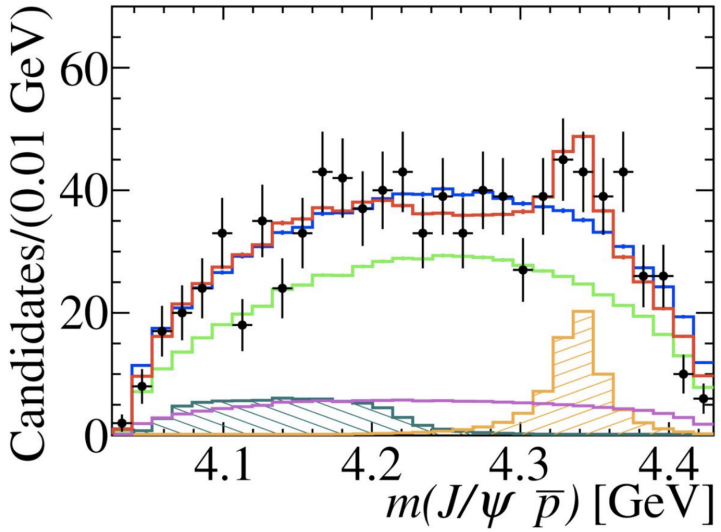
arxiv: 2108.04720, submitted to PRL

Exotic $P_c \to J/\psi\, p$ and $f \to p\bar{p}$ decay chains

Fit with non resonant contributions (green) gives poor description of data







- Add new P_c^+ and P_c^- with shared, free mass/width, same couplings and $J^P = 1/2^\pm$ or $3/2^\pm$
- Evidence of new P_c state at $3.1 - 3.7\sigma$ depending on J^P assignment

Mass (MeV)	Width (MeV)	Fit fraction
$4337^{+7}_{-4} \pm 2$	$29^{+26}_{-12} \pm 14$	$(22^{+8.5}_{-4.0} \pm 8.6)\%$

arxiv: 2108.04720, submitted to PRL

Exotic states in $B_s^0 \to J/\psi\, p\bar{p}$

- New P_c^+ compatible with state predicted in $\bar{D}\Lambda_c - \bar{D}\Sigma_c$ coupled-channel interactions [Chin. Phys. C 42 (2018) 023106]

J^P	A		
	z_R [MeV]	Couplings [10^{-3} MeV$^{-\frac{1}{2}}$]	
		$g_{\bar{D}\Lambda_c}$	$g_{\bar{D}\Sigma_c}$
$\frac{1}{2}^-$	$4295 - i\,3.7$	$1.4 + i\,0.2$	$13.2 + i\,0.8$
$\frac{1}{2}^+$	$4334 - i\,28$	$1.1 - i\,1.1$	$-1.9 + i\,3.6$
$\frac{3}{2}^+$	$4325 - i\,54$	$0.3 - i\,1.1$	$0.8 - i\,4.5$
$\frac{3}{2}^-$	$4380 - i\,147$	$0.5 - i\,1.9$	$-1.4 + i\,5.6$

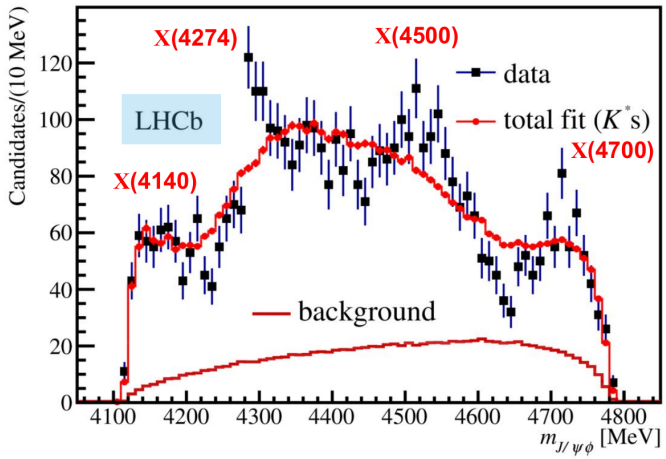
Chin. Phys. C 42 (2018) 023106

- $P_c(4312)^+$ with fixed mass and width added to model - No evidence for narrow $P_c(4312)^+$. Fit fraction $< 2.86\%$ at 90% CL
- Additional $f_J(2220)$ (glueball candidate) added with mass/width fixed - no evidence of such a state
- No evidence of near-threshold enhancement in $m_{p\bar{p}}$

Exotic states in $B^+ \to J/\psi\,\phi K^+$

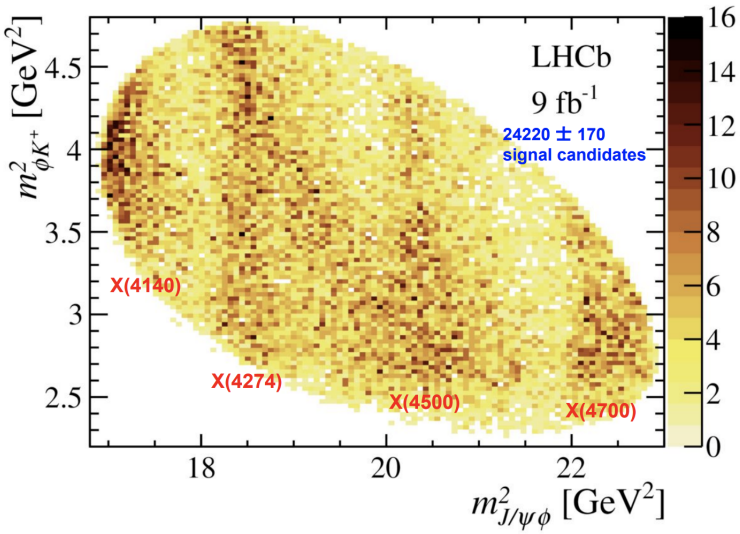
Run 1 amplitude analysis

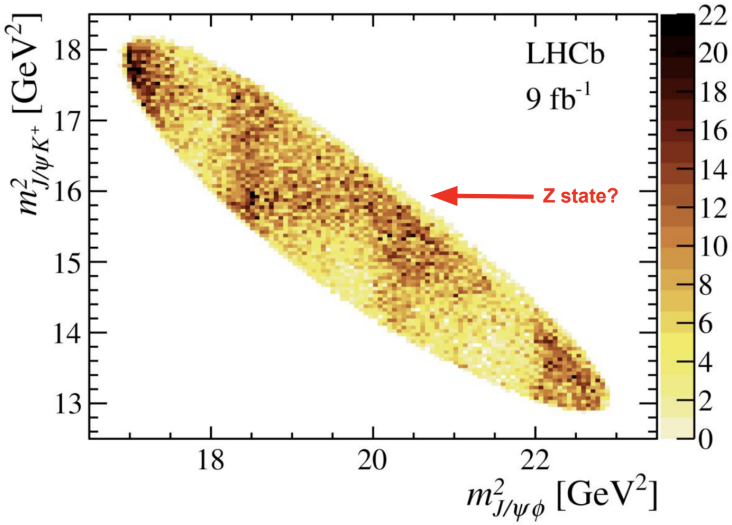
- Data not described by conventional K^{*+} states
  - four $X \to J/\psi\phi$ states seen at $> 5\sigma$
- 3σ signal for $Z_{cs}^+ \to J/\psi K^+$



Phys. Rev. Lett. 118, 022003

Full run 1+2 analysis has 6x signal yield and 6x less combinatorial background

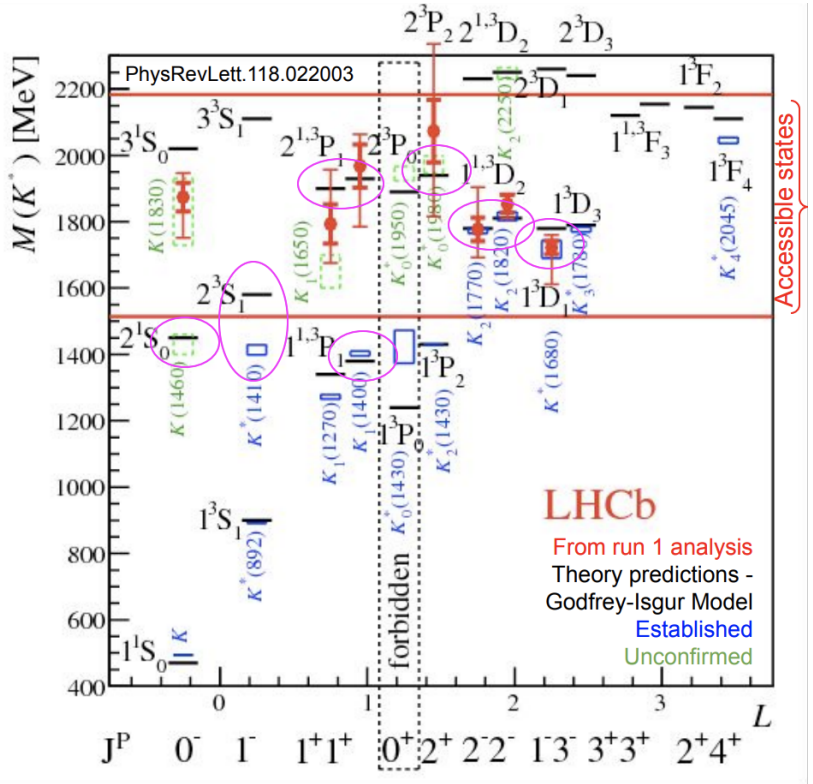




Phys. Rev. Lett. 127 (2021) 082001

Conventional $K^{*+} \to \phi K^+$ decay chain

- Include tails of $K^*(1410)$, $K(1460)$ and $K_1(1400)$ which peak below $m_{\phi K^+}$ threshold (additions to run 1 model)
- Nine K^{*+} states included in default model - unconfirmed states have floating mass/widths
- Seven more predicted by Godfrey-Isgur model [PRD 32 (1985) 189)] considered in systematic studies



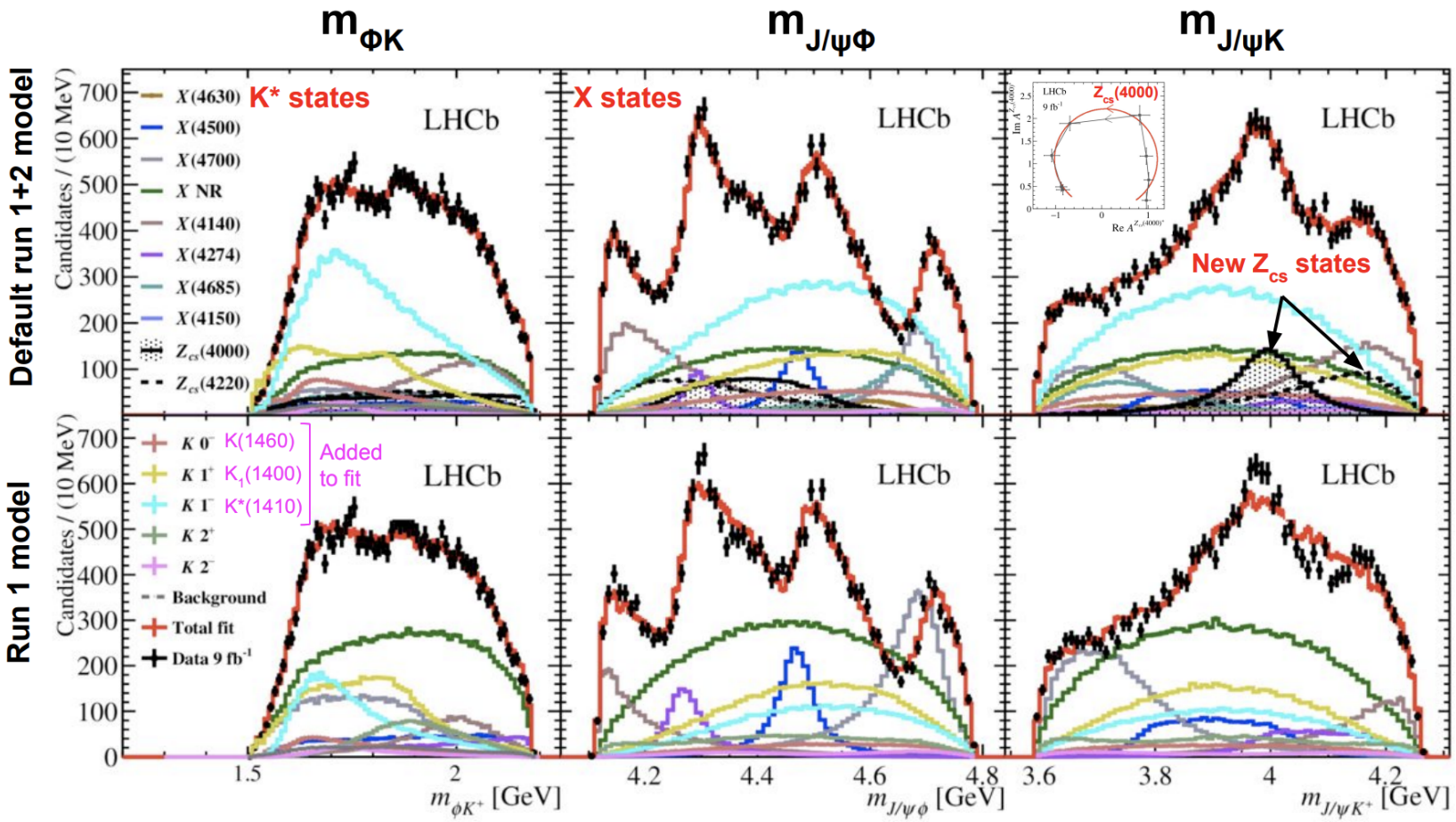
Phys. Rev. Lett. 118, 022003

- Exotic X and Z_{cs}^+ states added to amplitude model
- In total seven X states, two Z_{cs}^+ states and NR $J/\psi\phi$ added each at $> 5\sigma$

Exotic Z_{cs}^{+} and X states in $B^{+} \to J/\psi\,\phi K^{+}$

New Z_{cs}^{+} states!

- 1^{+} $Z_{cs}^{+}(4000)$ observed at high significance (15σ) and resonant nature seen via quasi-model-independent method
- Broader $1^{+}/1^{-}$ $Z_{cs}^{+}(4220)$ state seen at 5.9σ

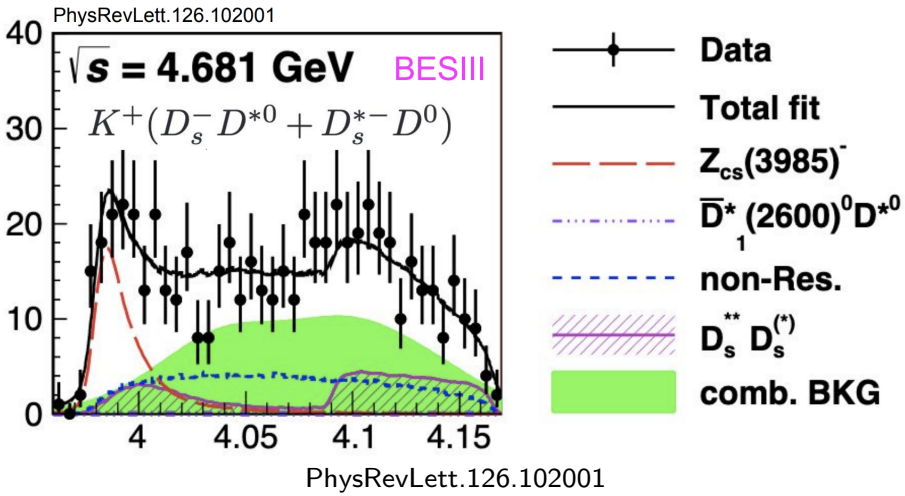


Phys. Rev. Lett. 127 (2021) 082001

Exotic Z_{cs}^{+} and X states in $B^{+} \to J/\psi\,\phi K^{+}$

First observation of exotic states with $c\bar{c}u\bar{s}$ decaying to $J/\psi\,K^{+}$

- No evidence new narrow $Z_{cs}^{+}(4000)$ is the $Z_{cs}^{+}(3985)$ state reported by BESIII in $D_s^{-} D^{*0} + D_s^{*-} D^{0}$
- $Z_{cs}^{+}(3985)$ has $\Gamma \approx 13$MeV - All reported states here are relatively wide



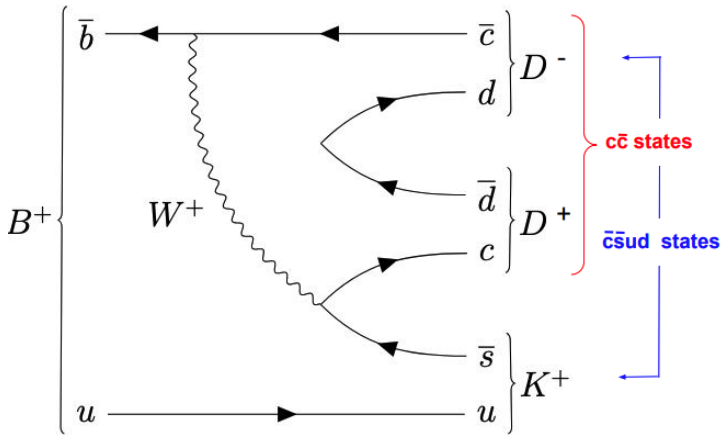
PhysRevLett.126.102001

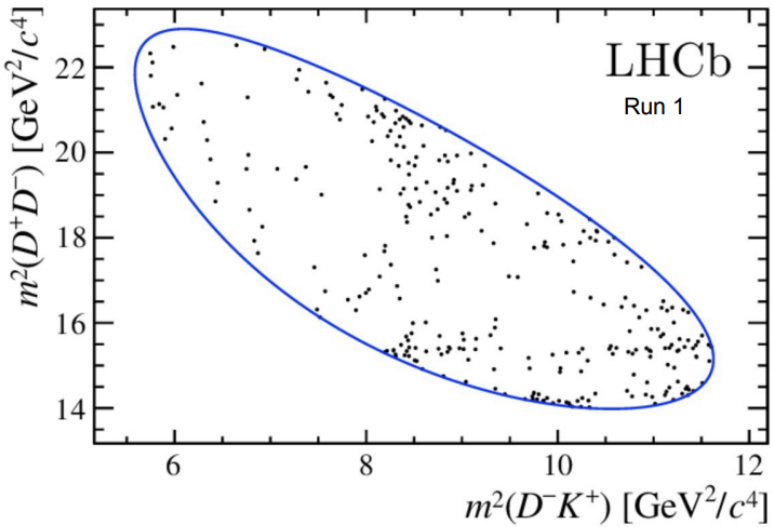
Four previous X states confirmed and additional X(4685) and X(4630) states seen at $> 5\sigma$

State	Mass (MeV)	Width (MeV)	spin
$Z_{cs}^{+}(4000)$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	1^{+}
$Z_{cs}^{+}(4220)$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$1^{+}/1^{-}$
$X(4685)$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^{+}
$X(4630)$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$1^{-}(2^{-})$

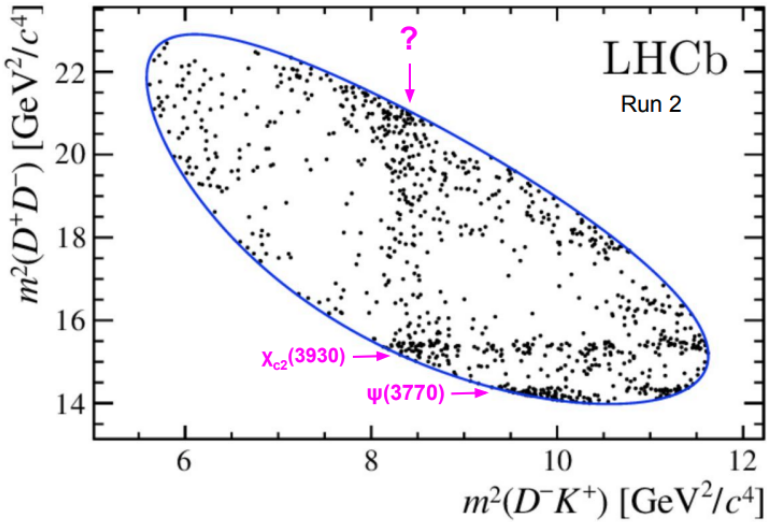
Exotic states in $B^+ \to D^+ D^- K^+$

- Conventional charmonia contributions expected in $D^+ D^-$ system
- Any other contributions would be exotic with neutral $\bar{c}\bar{s}ud$ or doubly charged $c\bar{d}u\bar{s}$





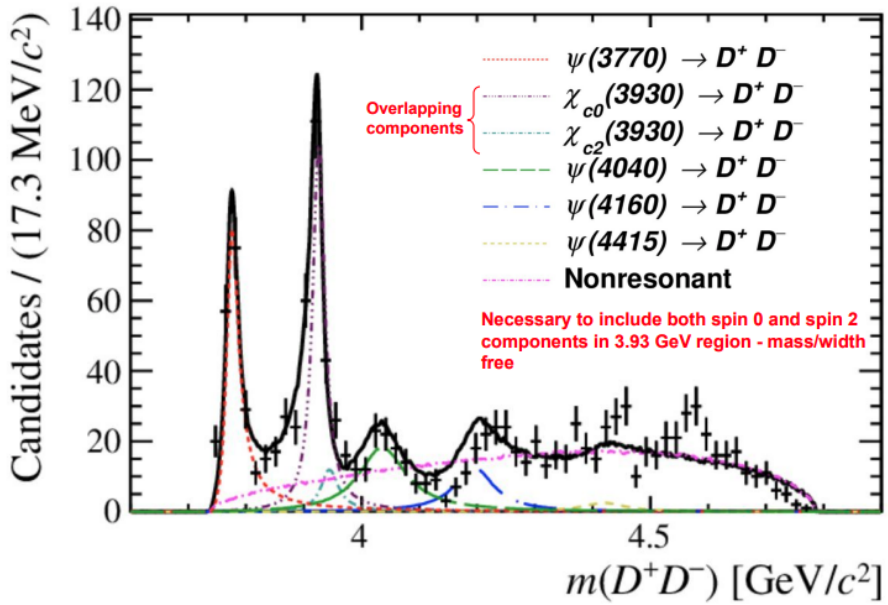
Phys. Rev. D102 (2020) 112003

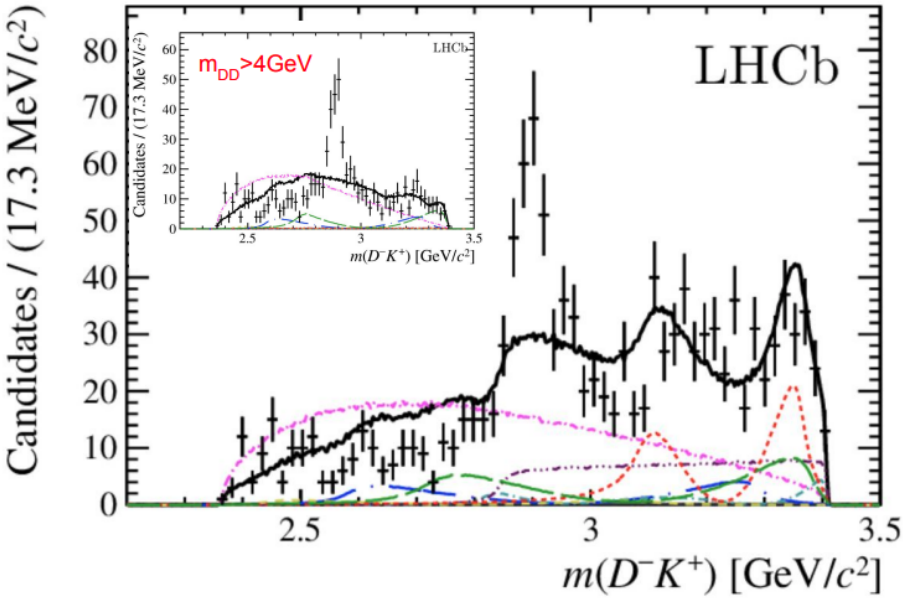


Conventional $[c\bar{c}] \to D^+D^-$ decay chain

Charmonia resonances considered

Partial wave (J^{PC})	Resonance	Mass (MeV/c^2)	Width (MeV)
S wave (0^{++})	$\chi_{c0}(3860)$	3862 ± 43	201 ± 145
	$X(3915)$	3918.4 ± 1.9	20 ± 5
P wave (1^{--})	$\psi(3770)$	3778.1 ± 0.9	27.2 ± 1.0
	$\psi(4040)$	4039 ± 1	80 ± 10
	$\psi(4160)$	4191 ± 5	70 ± 10
	$\psi(4260)$	4230 ± 8	55 ± 19
	$\psi(4415)$	4421 ± 4	62 ± 20
D wave (2^{++})	$\chi_{c2}(3930)$	3921.9 ± 0.6	36.6 ± 2.1
F wave (3^{--})	$X(3842)$	3842.71 ± 0.20	2.79 ± 0.62

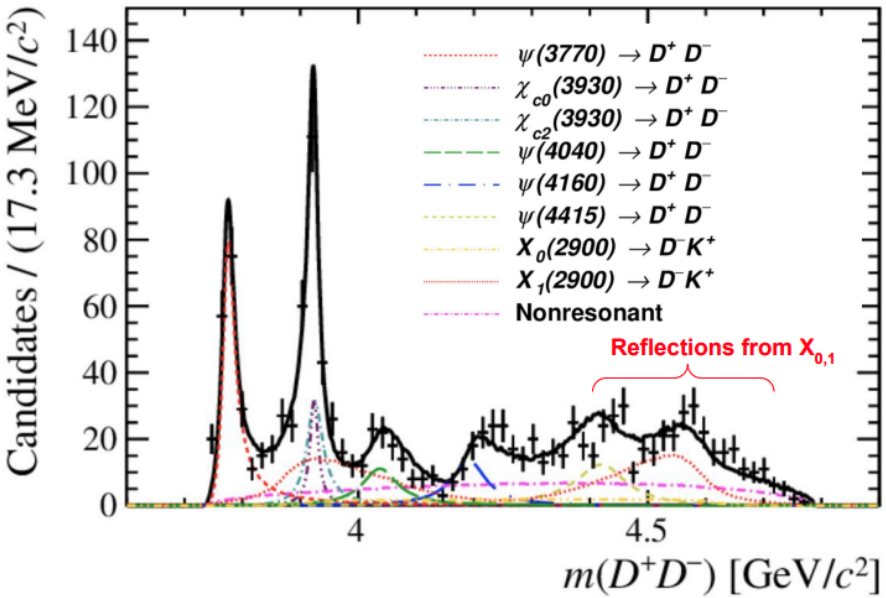


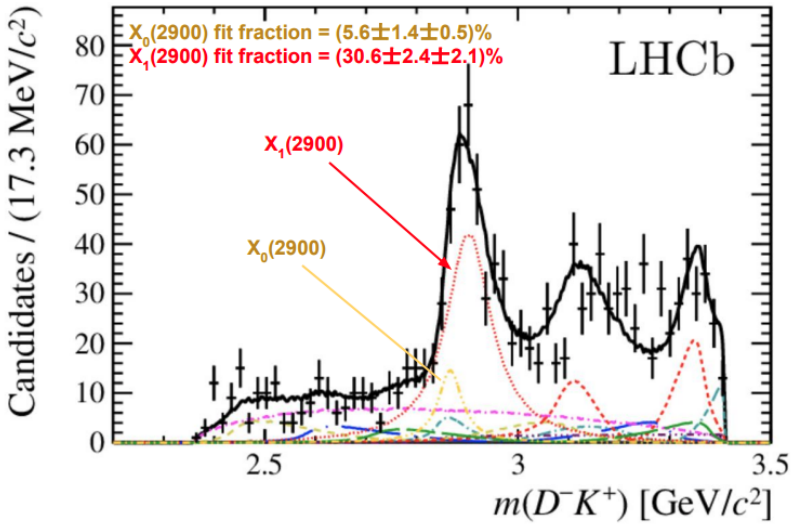


- Data supports additional spin 0 $\chi_{c0}(3930)$ that overlaps with $\chi_{c2}(3930)$
- Data cannot be described through conventional D^+D^- contributions alone
- Supported by model-independent moments analysis [Phys. Rev. Lett. 125 (2020) 242001]

Exotic $[\bar{c}\bar{s}ud] \to D^- K^+$ decay chain

Add two $[\bar{c}\bar{s}ud] \to D^- K^+$ contributions to amplitude model

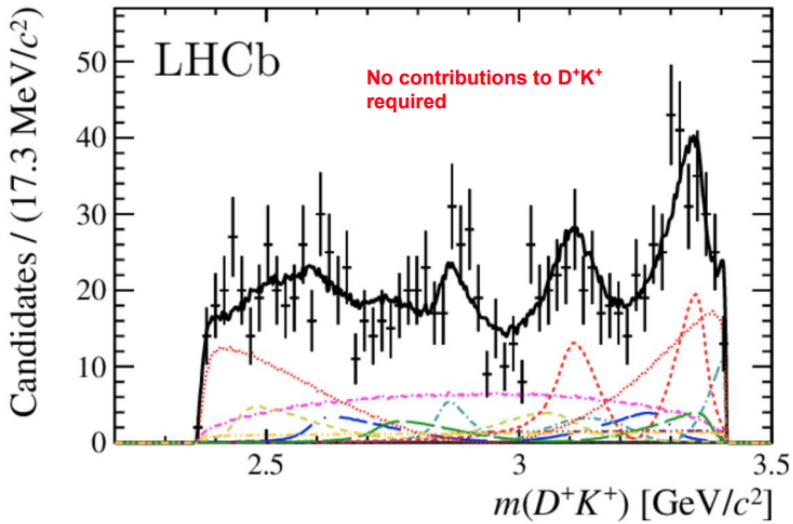




- Significant contributions from $[\bar{c}\bar{s}ud]$ states - 30% contribution from $X_1(2900)$

State	Mass (GeV)	Width (GeV)
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

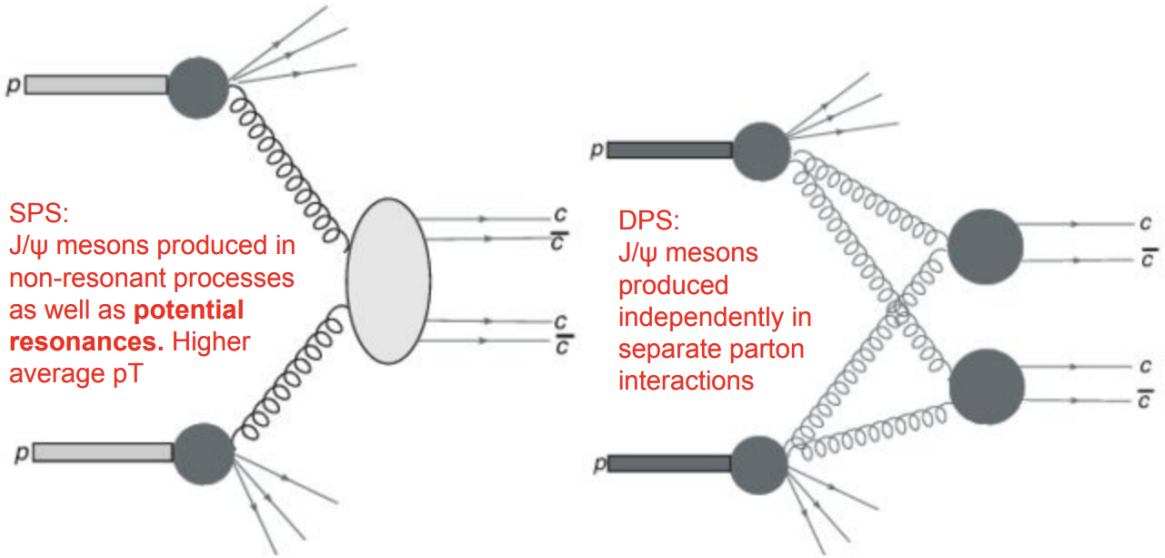
- If interpreted as resonances first observation of exotics with open flavour
- No $[c\bar{d}u\bar{s}] \to D^+ K^+$ contributions required



Phys. Rev. D102 (2020) 112003

Exotic $T_{cc\bar{c}\bar{c}}$ in prompt-J/ψ pairs

- All hadrons observed so far contain at most 2 heavy quarks
- Theoretical predictions for tetraquarks consisting of only heavy quarks $T_{Q_1 Q_2 \bar{Q}_3 \bar{Q}_4}$ where $Q_i = b/c$ in range 5.8 - 7.4 GeV
- LHCb has reported no evidence for $T_{bb\bar{b}\bar{b}}$ [JHEP 10 (2018) 086]
- Search for a $T_{cc\bar{c}\bar{c}}$ tetraquark in prompt J/ψ-pair invariant mass spectrum using full Run 1+2 dataset
- Prompt J/ψ-pairs at LHCb produced through SPS or DPS

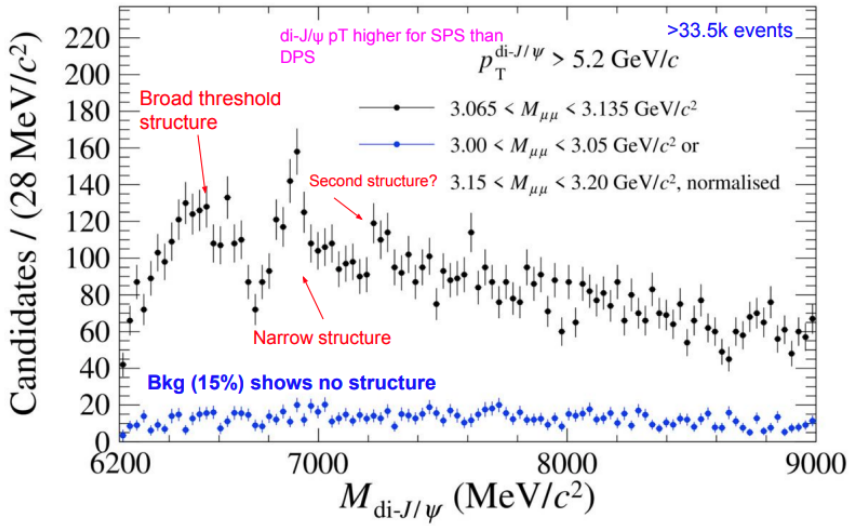


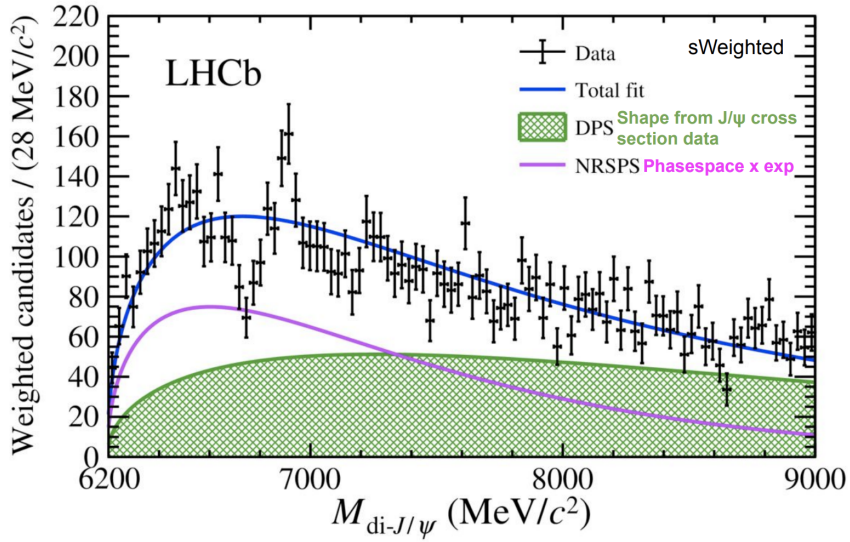
Exotic $T_{cc\bar{c}\bar{c}}$ in prompt-J/ψ pairs

Structures in di-J/ψ spectrum

- "Threshold enhancement" - broad structure just above di-J/ψ mass ranging from 6.2-6.8 GeV
- $X(6900)$ - narrow structure at 6.9 GeV
- Hint of structure at 7.2 GeV
- Note background shows no structure and efficiency variation is marginal

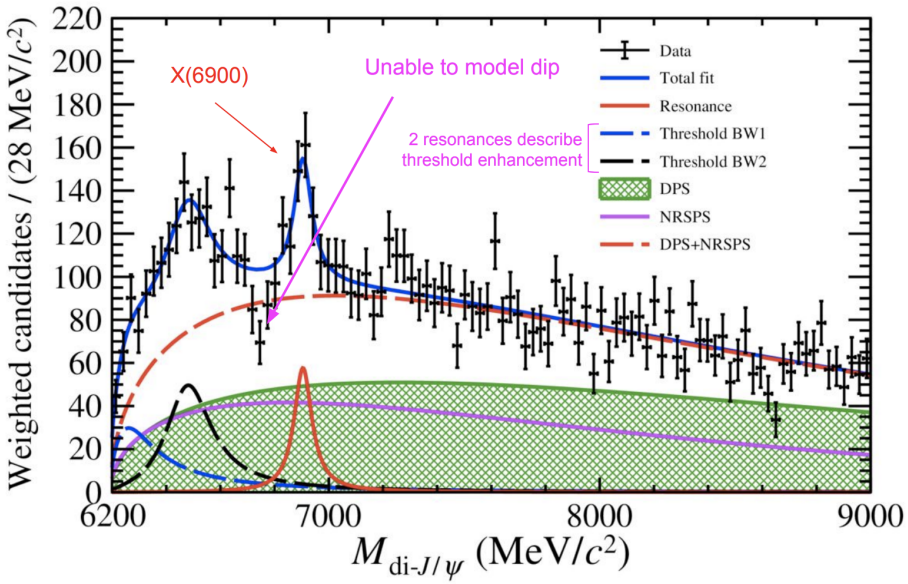
- SPS dominates at high di-J/ψ pT, DPS dominates at high $m_{di-J/\psi}$
- J/ψ-pair invariant mass spectrum inconsistent with non-resonant SPS and DPS continuum distribution

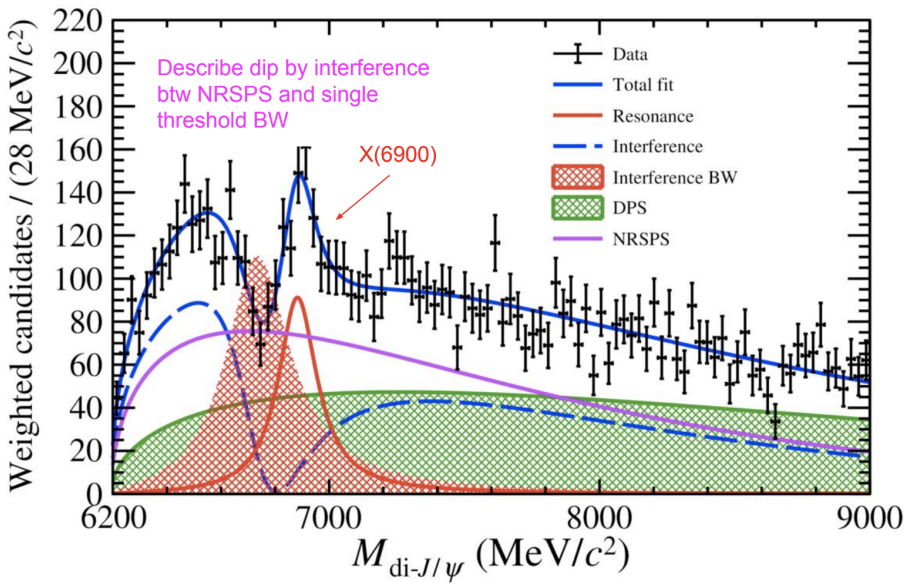




Sci. Bull. 65 (2020) 1983

Exotic $T_{cc\bar{c}\bar{c}}$ in prompt-J/ψ pairs





Sci. Bull. 65 (2020) 1983

Model 1:
- 2 BW model threshold enhancement
- Single BW models $X(6900)$
- Second structure of low significance

$$m(X(6900)) = 6905 \pm 11 \pm 7 \text{ MeV}$$
$$\Gamma(6900) = 80 \pm 19 \pm 33 \text{ MeV}$$

Model 2:
- Allow wide BW at threshold to interfere with NRSPS
- Simplistic - whole NRSPS interferes with a single threshold contribution with same J^P
- Improved fit quality

$$m(X(6900)) = 6886 \pm 11 \pm 11 \text{ MeV}$$
$$\Gamma(6900) = 168 \pm 33 \pm 69 \text{ MeV}$$

Narrow structure at 6.9 GeV consistent with BW lineshape and broad structure at di-J/ψ mass threshold with $> 5\sigma$ significance

Exotic state near $D^{*+}D^0$ mass threshold: T_{cc}^+

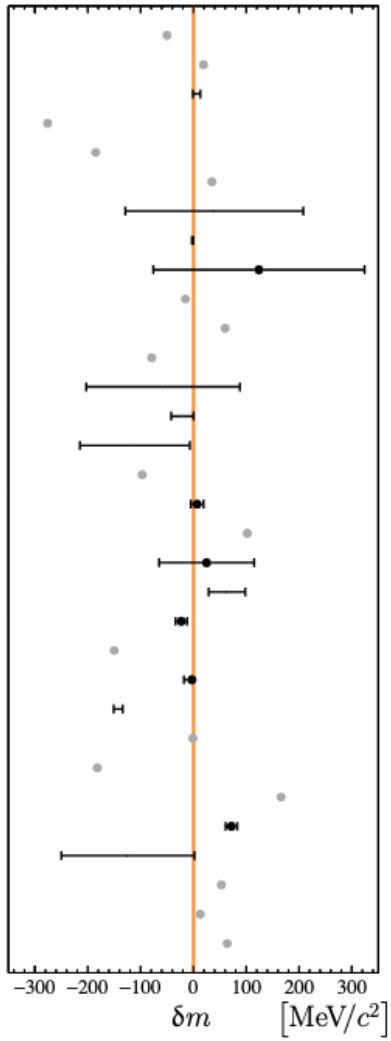
Many, many models predict a hadron with two heavy quarks and two light anti-quarks $T_{Q_1 Q_2 \bar{q}_3 \bar{q}_4}$ where $Q_i = b/c$

Predictions for an isoscalar $cc\bar{u}\bar{d}$ state with

- Spin-parity assignment $J^P = 1^+$
- Mass relative to the $D^{*+}D^0$ mass threshold $-300 < \delta m < 300$ MeV

$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

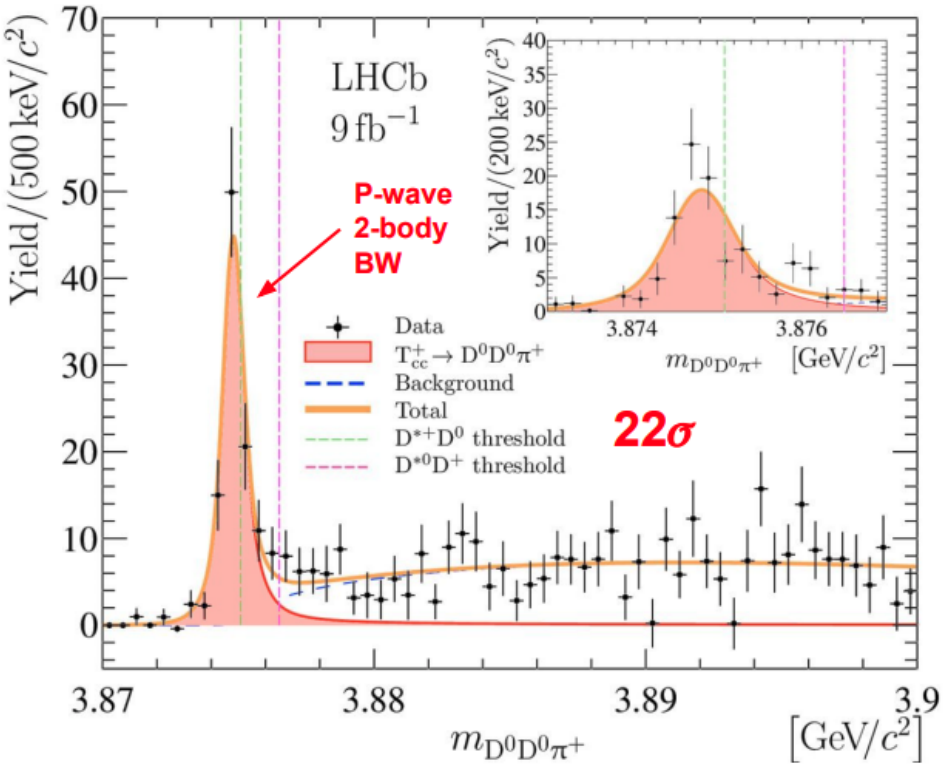
Using mass measurement of $\Xi_{cc}^{++}[ccu]$ [JHEP 02 (2020) 049] infer that mass of $cc\bar{u}\bar{d}$ is close to $D^{*+}D^0$ threshold



arXiv:2109.01056

Exotic state near $D^{*+}D^0$ mass threshold: T_{cc}^+

Can search for T_{cc}^+ using prompt $D^0D^0\pi^+$ final state



arXiv:2109.01038

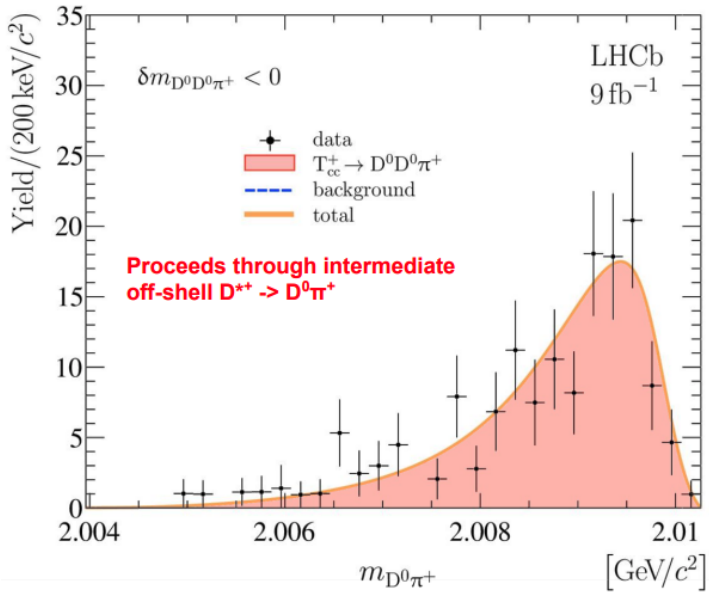
- Very narrow peak near $D^{*+}D^0$ mass threshold
- Describe using P-wave BW motivated by J^P predictions
- Hypothesis that $\delta_m < 0$ is 4.3σ (hadronic molecule?)
- Mass/width consistent with expected isoscalar 1^+ tetraquark ground state

δm_{pole} (keV)	Γ_{pole} (keV)
$-360 \pm 40^{+4}_{-0}$	$48 \pm 2^{+0}_{-14}$

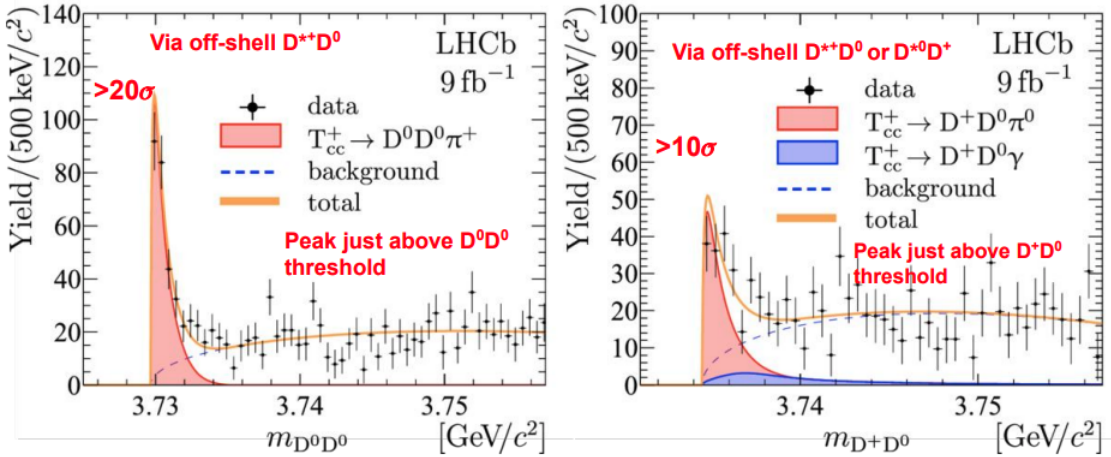
- Measured width smallest of any exotic to date - long lived with respect to strong decays
- Near threshold mass, narrow width and role in prompt hadroproduction shows genuine resonant nature

Exotic state near $D^{*+}D^0$ mass threshold: T_{cc}^+

- $D^0\pi^+$ spectrum consistent with hypothesis that $T_{cc}^+ \to D^0 D^0 \pi^+$ decays via intermediate off-shell D^{*+}
- Favours the T_{cc}^+ 1^+ assignment (would be S-wave decay)



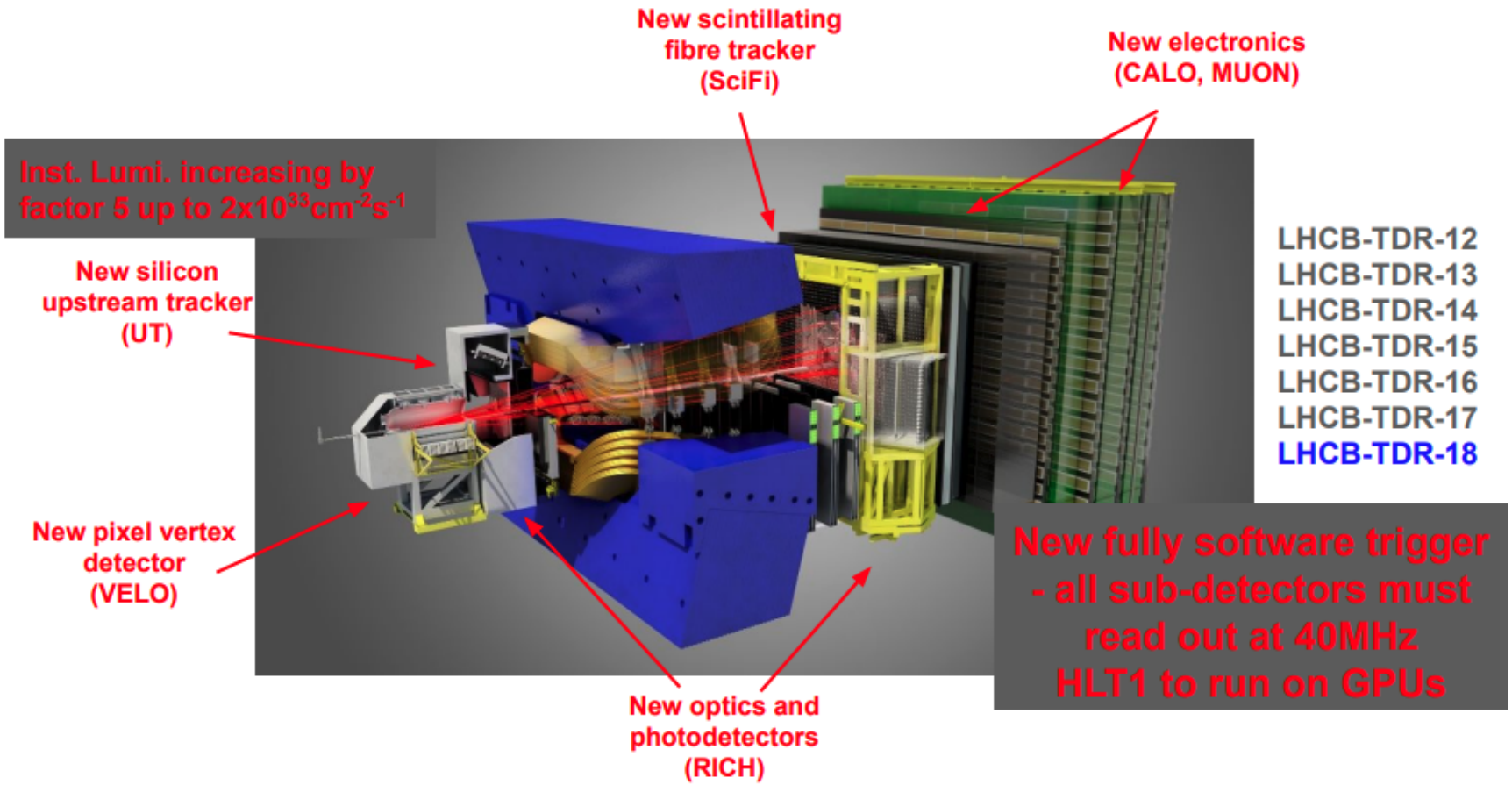
- Due to small δm and small energy release in $D^{*+} \to D^0\pi^+$ gives narrow peak just above D^0D^0 threshold
- This is replicated in $T_{cc}^+ \to D^+D^0\pi^0/\gamma$ decays via $D^{*+/0}$



arXiv:2109.01056

Absence of signal in $D^0D^+\pi^+$ indicates isoscalar nature

Looking forward to Run 3...



Removal of L0-trigger will provide increased efficiency and reduced systematic uncertainties to hadronic modes in particular!

Backup