



中国科学院大学
University of Chinese Academy of Sciences

Hadron spectroscopy and exotics at LHCb

傅金林
中国科学院大学

HFCPV
November 10-14, 2021

Outline

- ✓ Conventional hadrons

excited D_s^+ , B_s^0 , Ξ_b^0 , Ξ_{cc}^+ , Ω_{cc}^+

- ✓ Tetraquarks

$X(c\bar{c}s\bar{s})$, $Z_{cs}(c\bar{c}u\bar{s})^+$, $T_{cc}^+(cc\bar{u}\bar{d})$

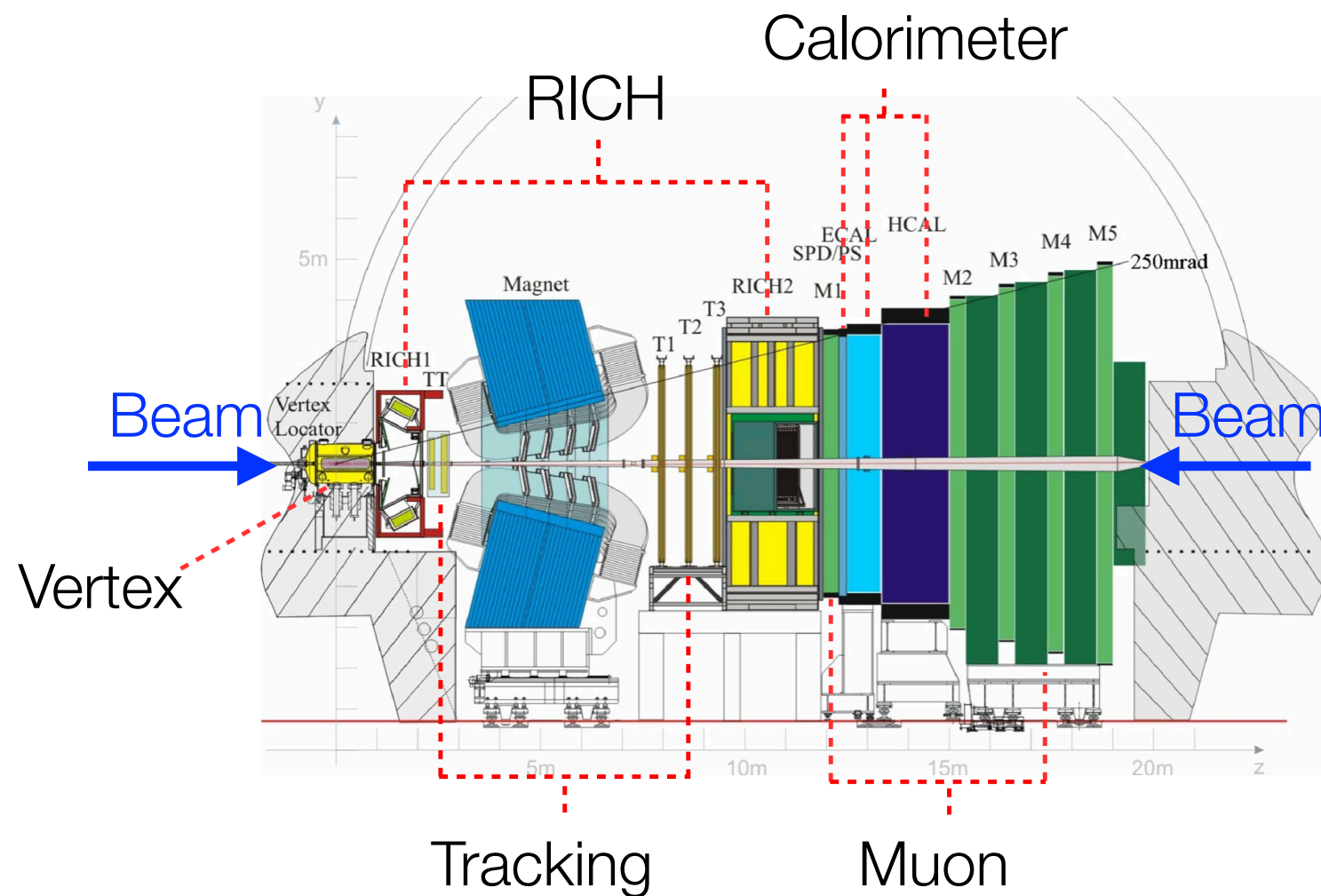
- ✓ Pentaquarks

$P_{cs}(c\bar{c}uds)^0$, $P_c(c\bar{c}uud)^+$

LHCb detector

Int. J. Mod. Phys. A 30 (2015) 1530022

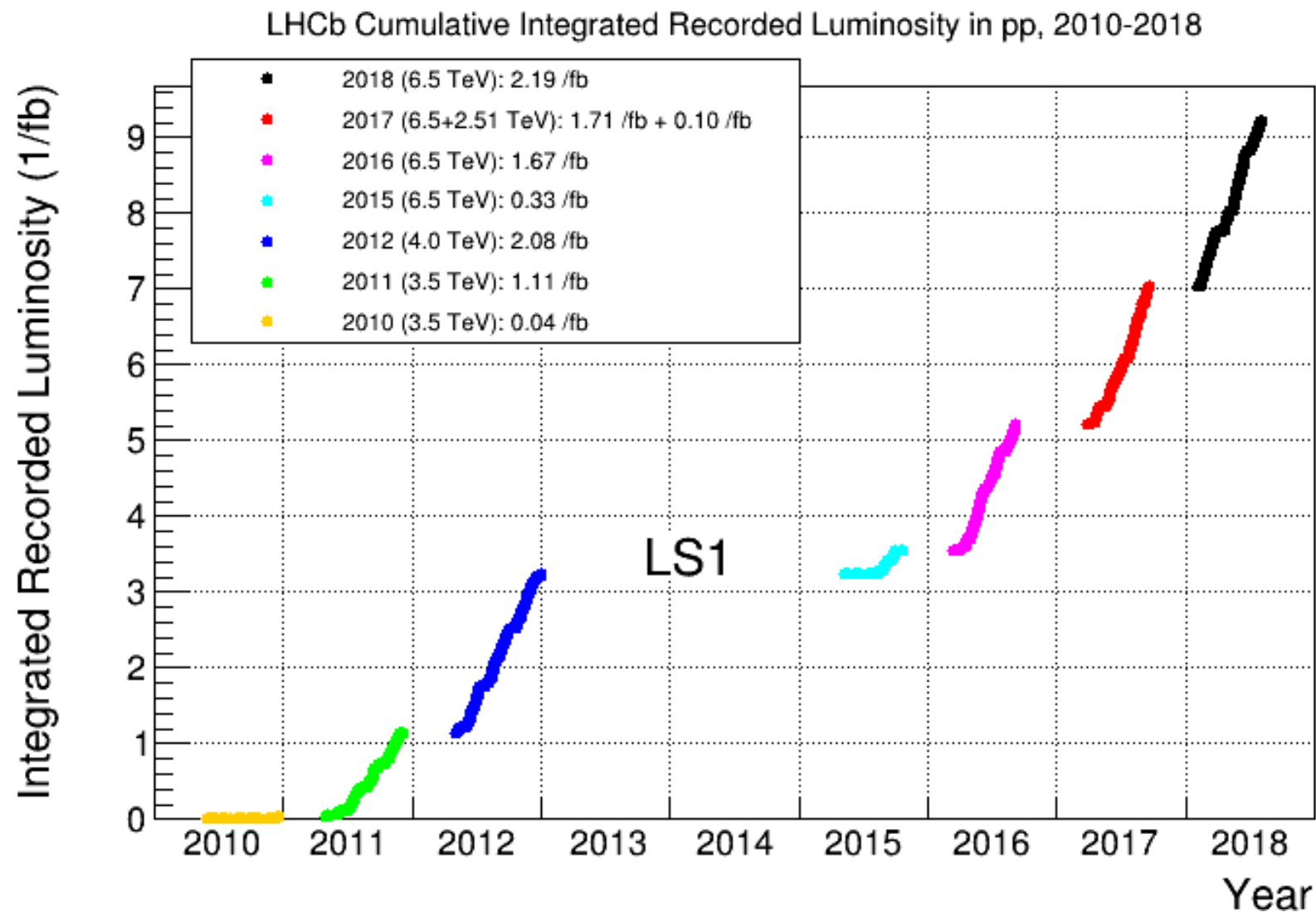
LHCb is a forward spectrometer



$2 < \eta < 5$, 40% of heavy quark production

Excellent time resolution, IP resolution, mass resolution, tracking, PID performance

Data set



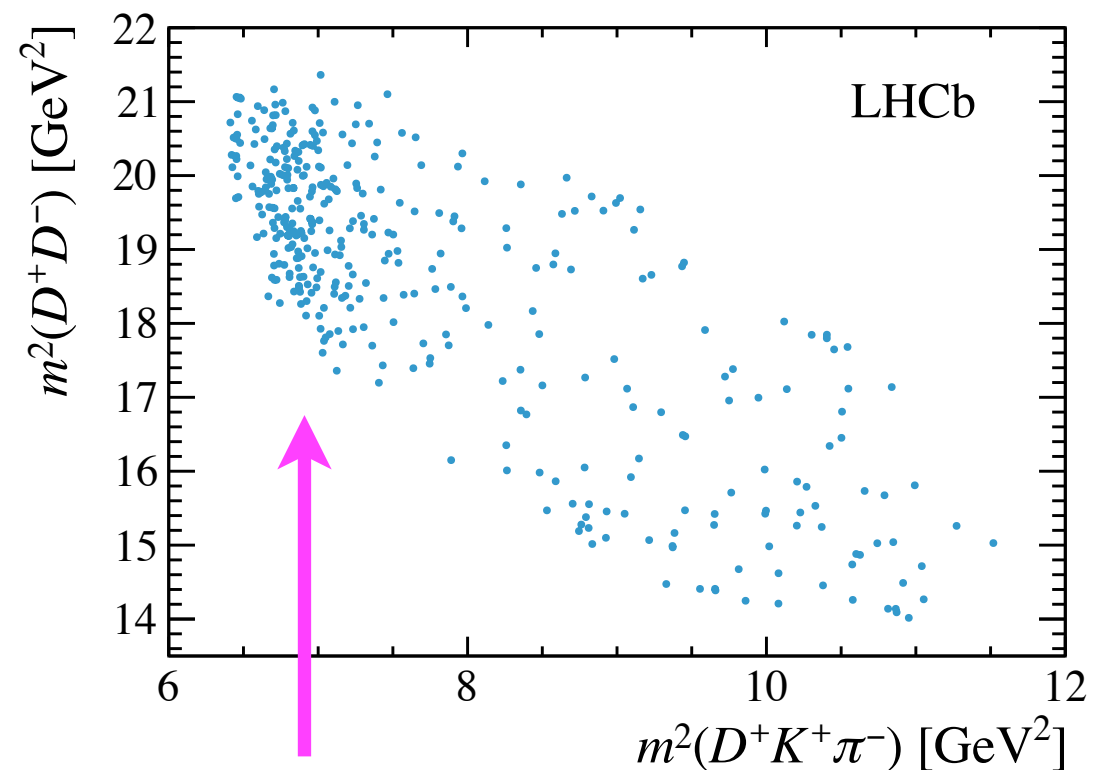
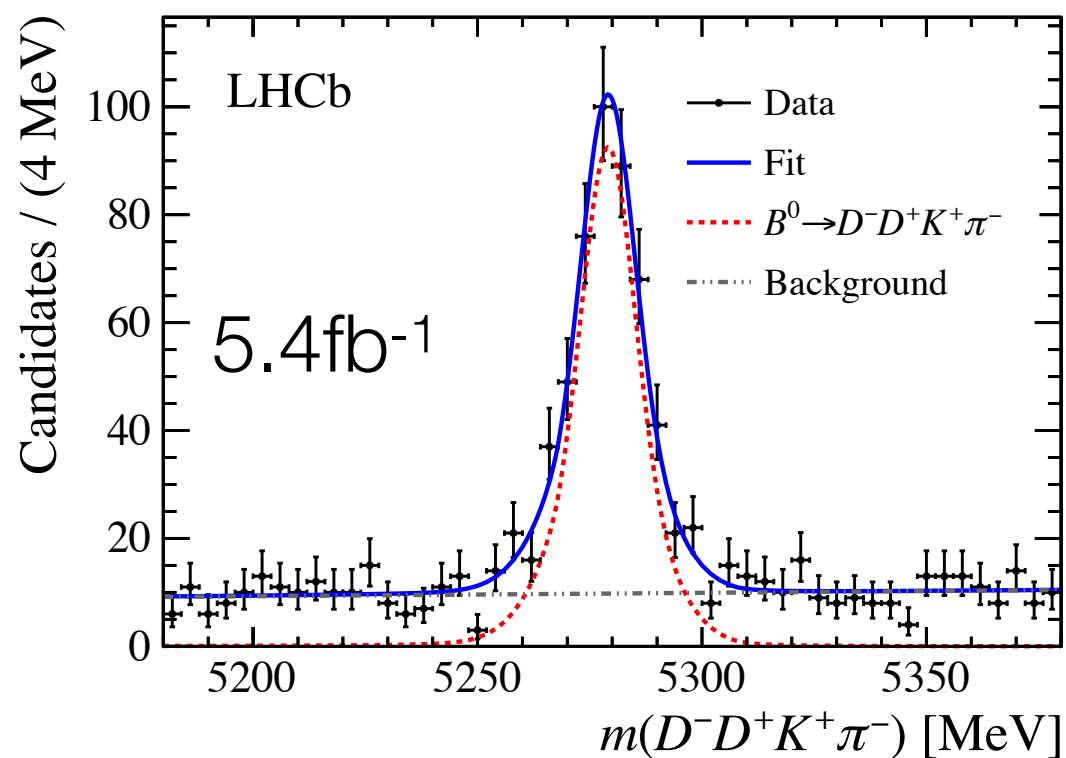
Run1: @7/8 TeV
2010-12, 3fb⁻¹

Run2: @13TeV
2015-18, 6fb⁻¹

- 9fb⁻¹ pp collision sample collected in run1+run2
- 10¹¹ b hadrons, 10¹² c hadrons produced
- Cover all heavy flavour hadrons

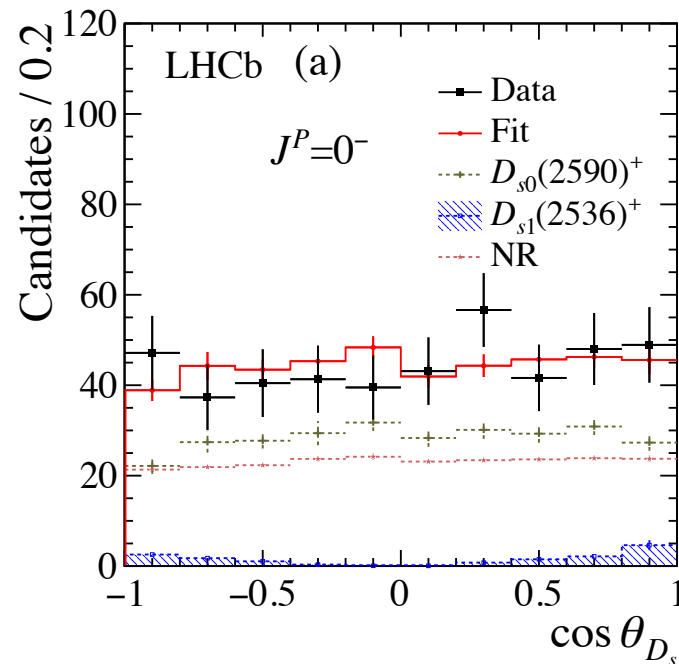
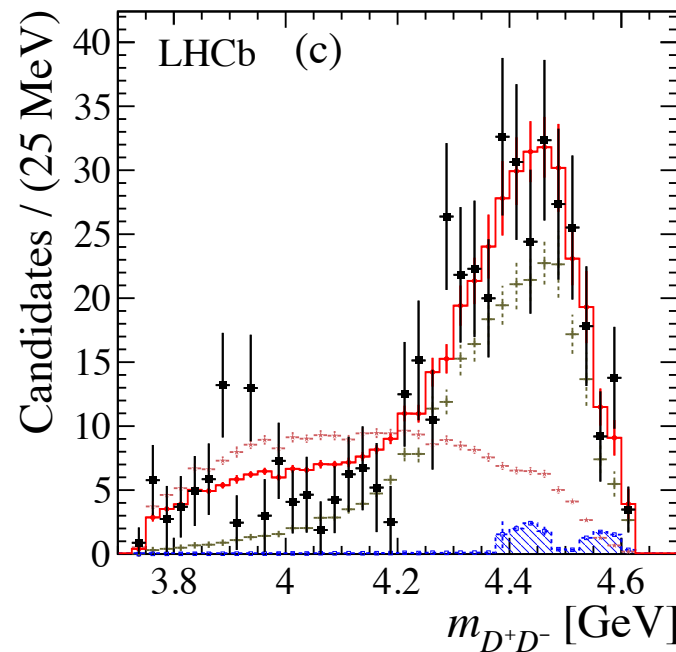
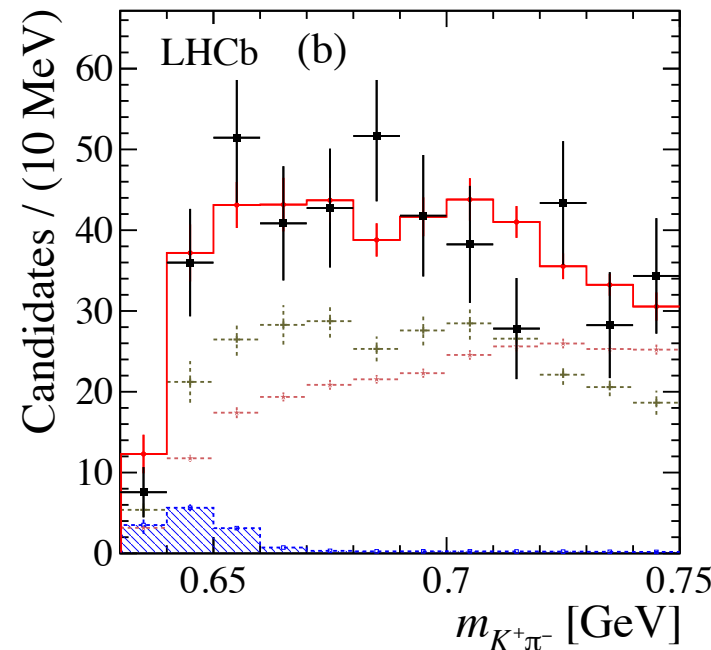
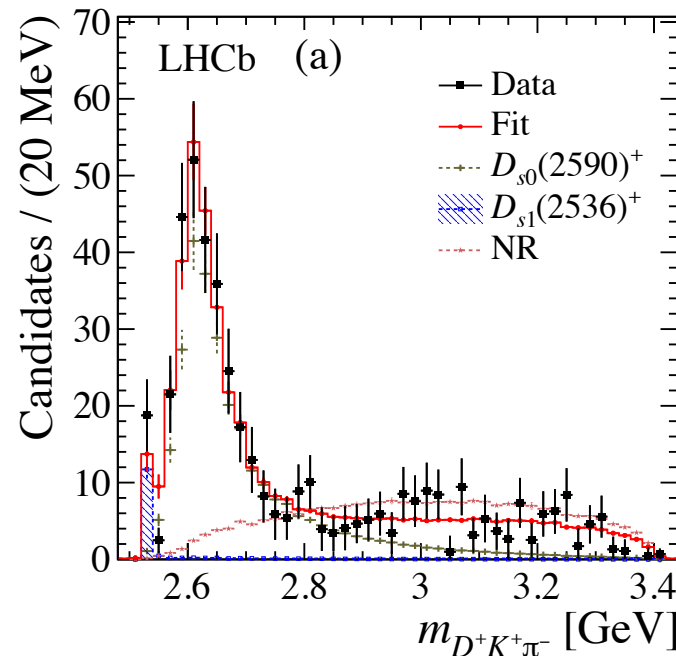
Excited D_s^+ search in $B^0 \rightarrow D^- D^+ K^+ \pi^-$ decays

- $B^0 \rightarrow D^- D^+ K^+ \pi^-$ reconstructed with $m(K^+ \pi^-) < 750 \text{ MeV}$ [PRL 126\(2021\)122002](#)
- Allows for $0^-, 1^+, 2^-$ in $D^+ + (K^+ \pi^-)(0^+)$ system



Observation of a new excited D_s^+ state

PRL 126(2021)122002



- Amplitude analysis performed
- New state observed $\sim 2590\text{MeV}$ with significance $>10\sigma$
- Spin-parity 0^- is favored

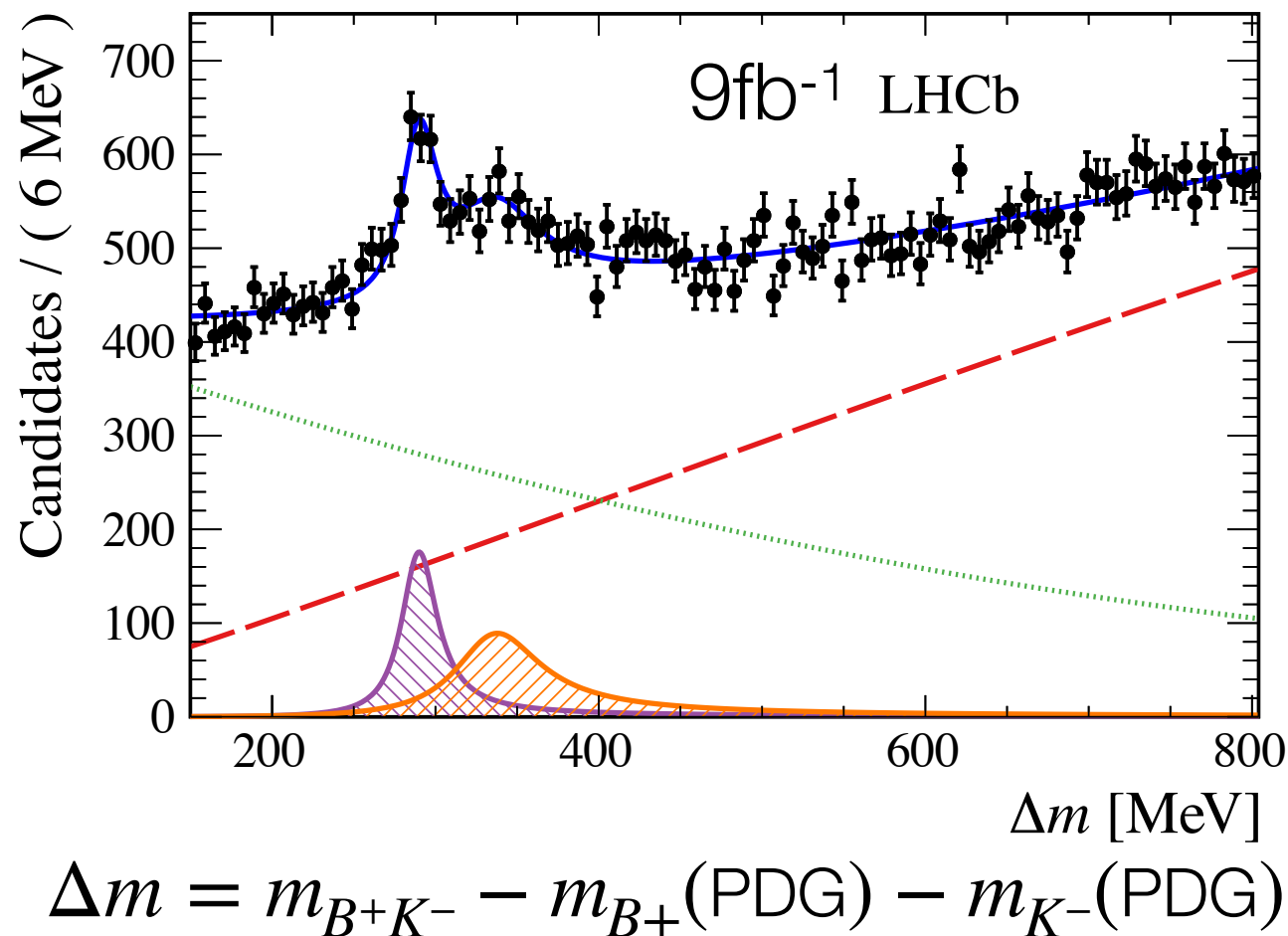
$$m_R = 2591 \pm 6 \pm 7 \text{ MeV}$$

$$\Gamma_R = 89 \pm 16 \pm 12 \text{ MeV}$$

- Denoted as $D_{s0}(2590)^+$, a strong candidate of $D_s(2^1S_0)^+$

Observation of new excited B_s^0 states

EPJC 81(2021)601



$$m_1 = 6063.5 \pm 1.2 \pm 0.8 \text{ MeV}$$

$$\Gamma_1 = 26 \pm 4 \pm 4 \text{ MeV}$$

$$m_2 = 6114 \pm 3 \pm 5 \text{ MeV}$$

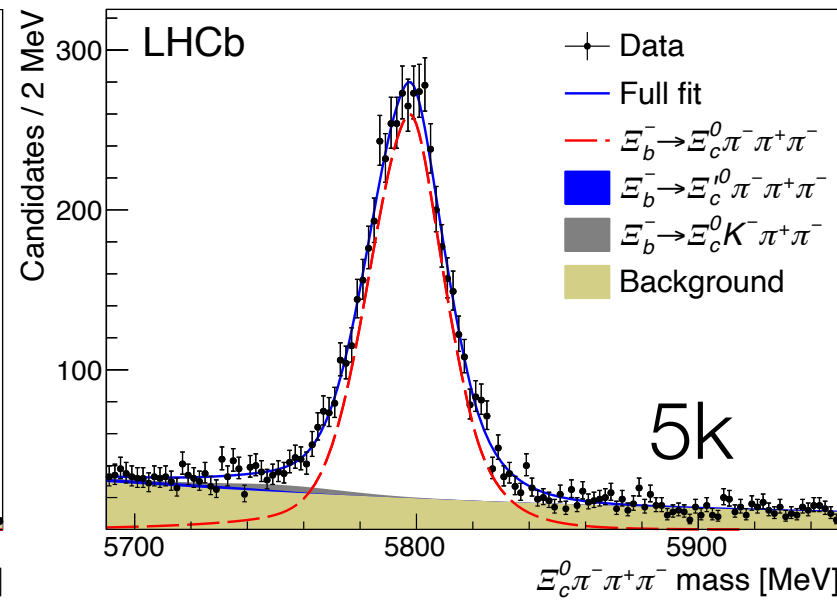
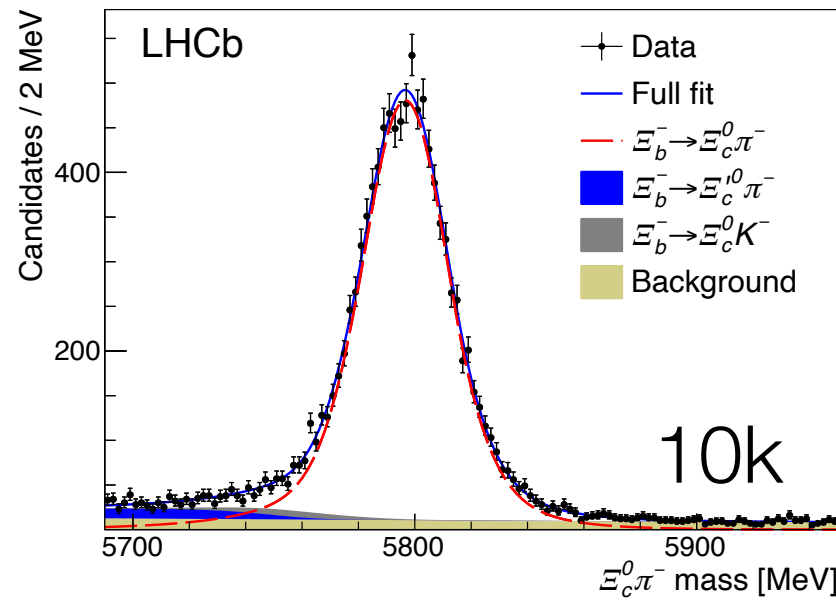
$$\Gamma_2 = 66 \pm 18 \pm 21 \text{ MeV}$$

- Search for excited B_s^0 in B^+K^- system
- Combine B^+ with a prompt K^- , B^+ reconstructed via $J/\psi K^+$, $\bar{D}^0 \pi^+$
- Structures observed $\sim 300\text{MeV}$
- Two-peak hypothesis prefer with significance $>7\sigma$ vs one peak

Observation of a new excited Ξ_b^0 state in $\Xi_b^- \pi^+$

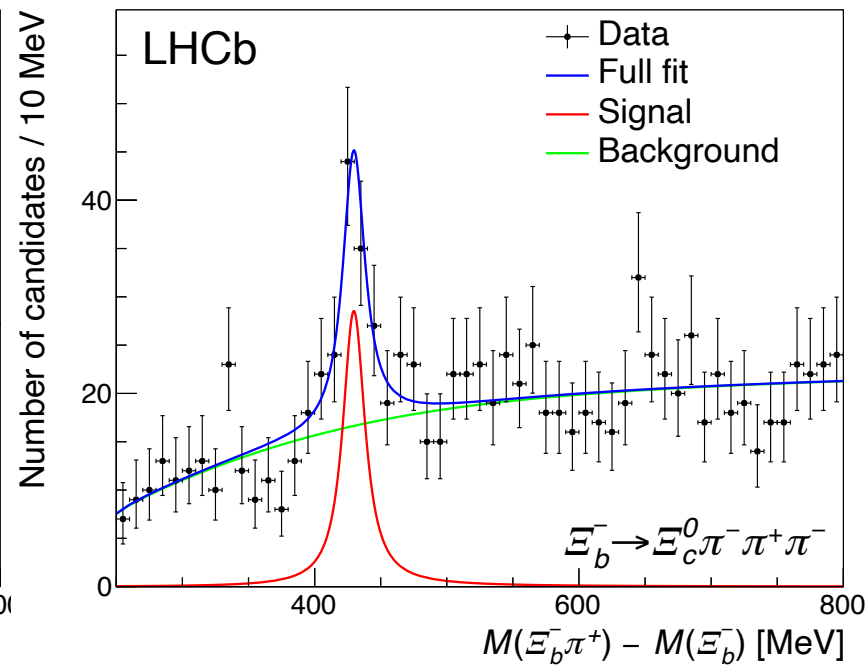
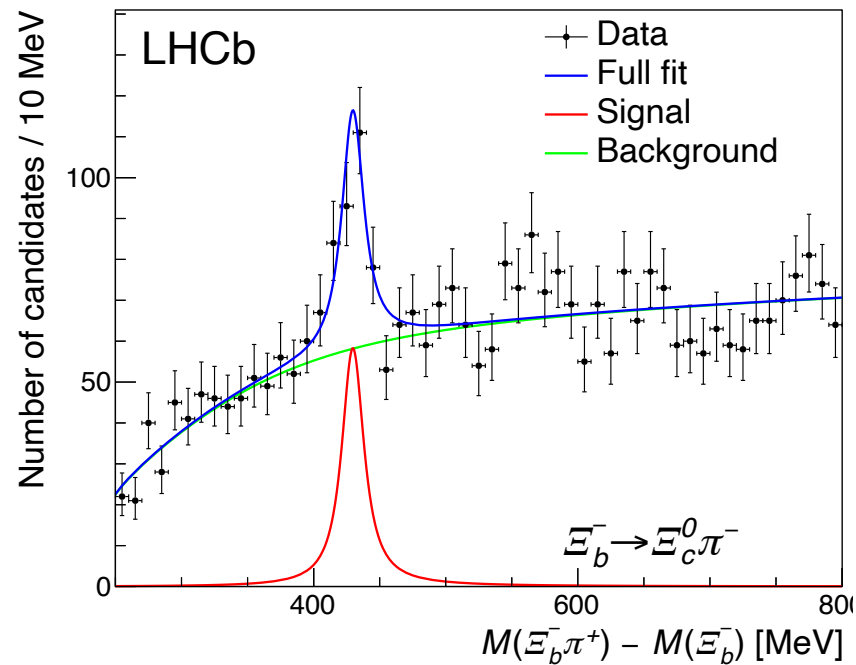
PRD 103(2021)012004

- Ξ_b^- reconstructed via $\Xi_c^0 \pi^-$ and $\Xi_c^0 \pi^- \pi^+ \pi^-$



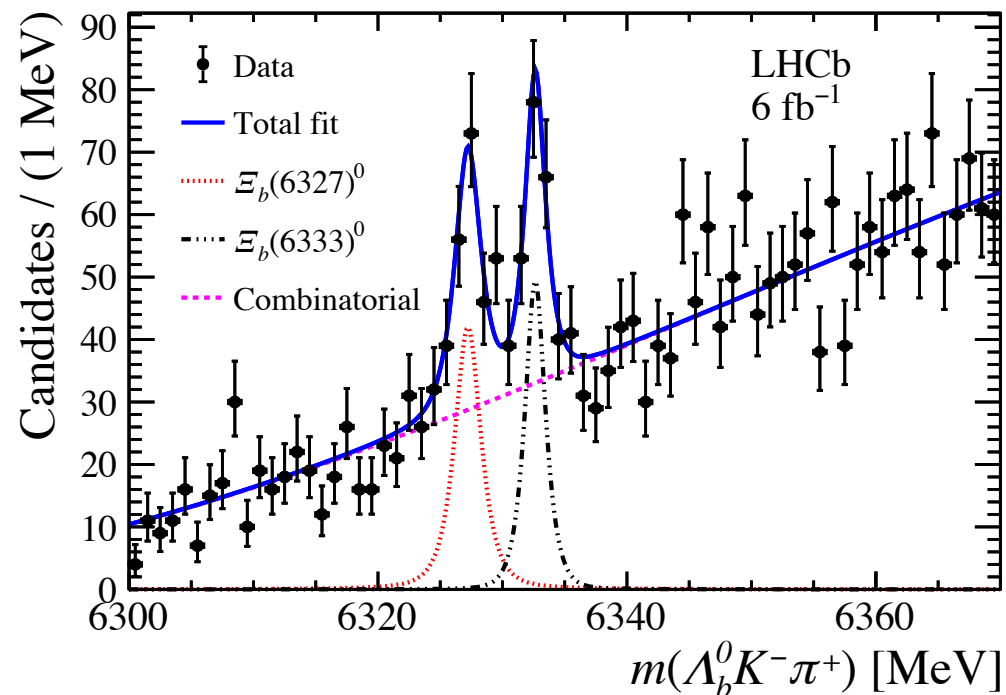
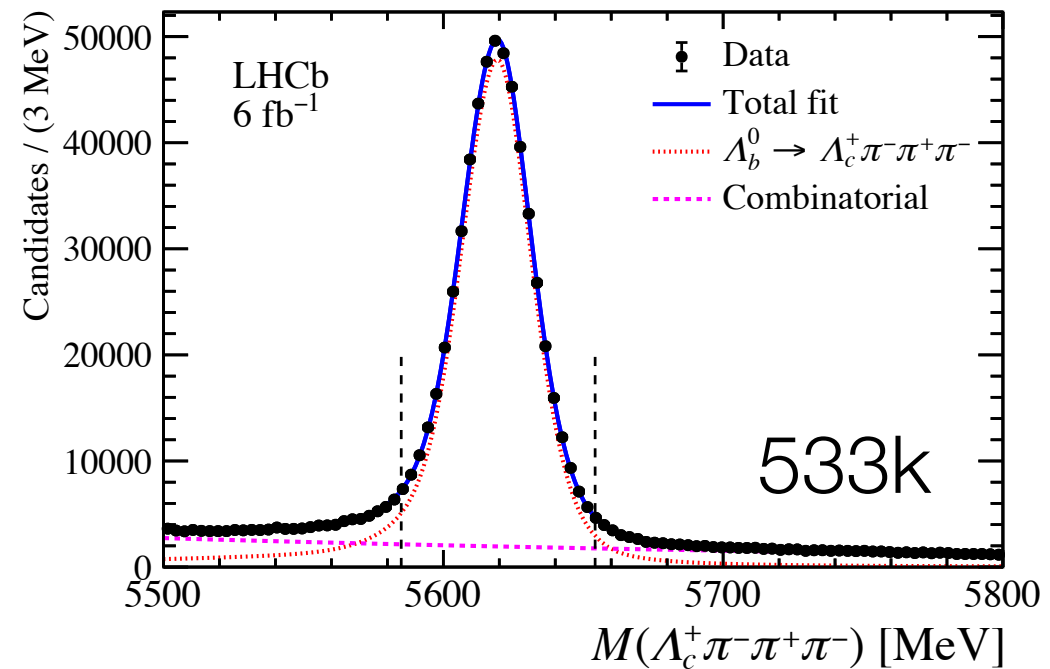
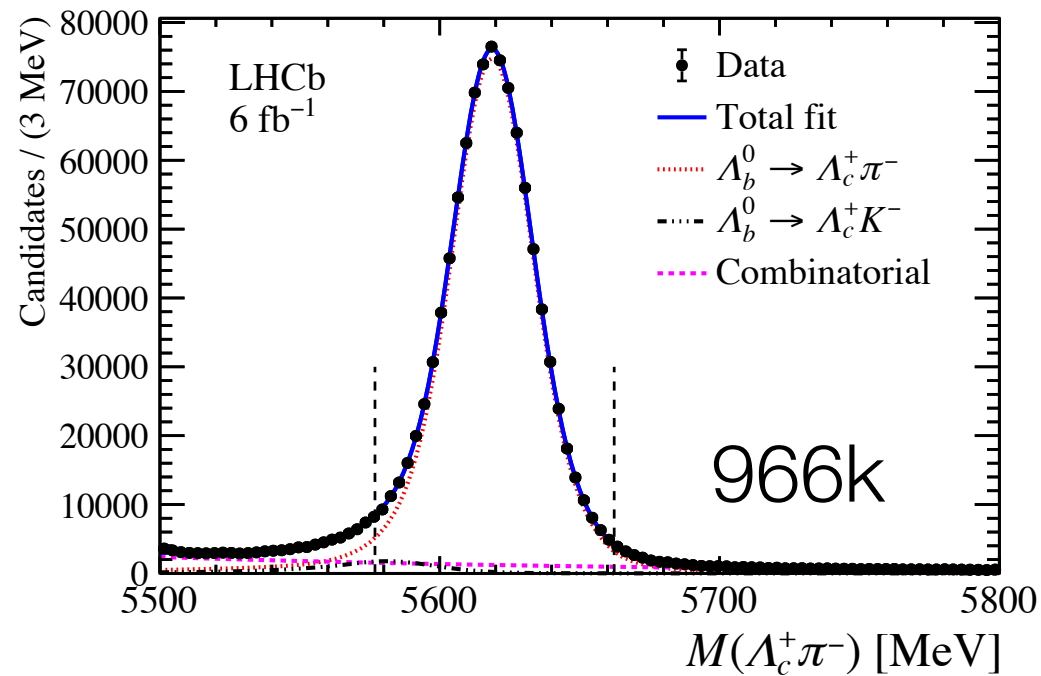
$$m = 6227.1_{-1.5}^{+1.4} \pm 0.5 \text{ MeV}$$

$$\Gamma = 18.6_{-4.1}^{+5.1} \pm 1.4 \text{ MeV}$$



Observation of excited Ξ_b^0 states in $\Lambda_b^0 K^- \pi^+$

- Λ_b^0 reconstructed via $\Lambda_c^+ \pi^-$ and $\Lambda_c^+ \pi^- \pi^+ \pi^-$ LHCb-PAPER-2021-025, arXiv:2110.04497



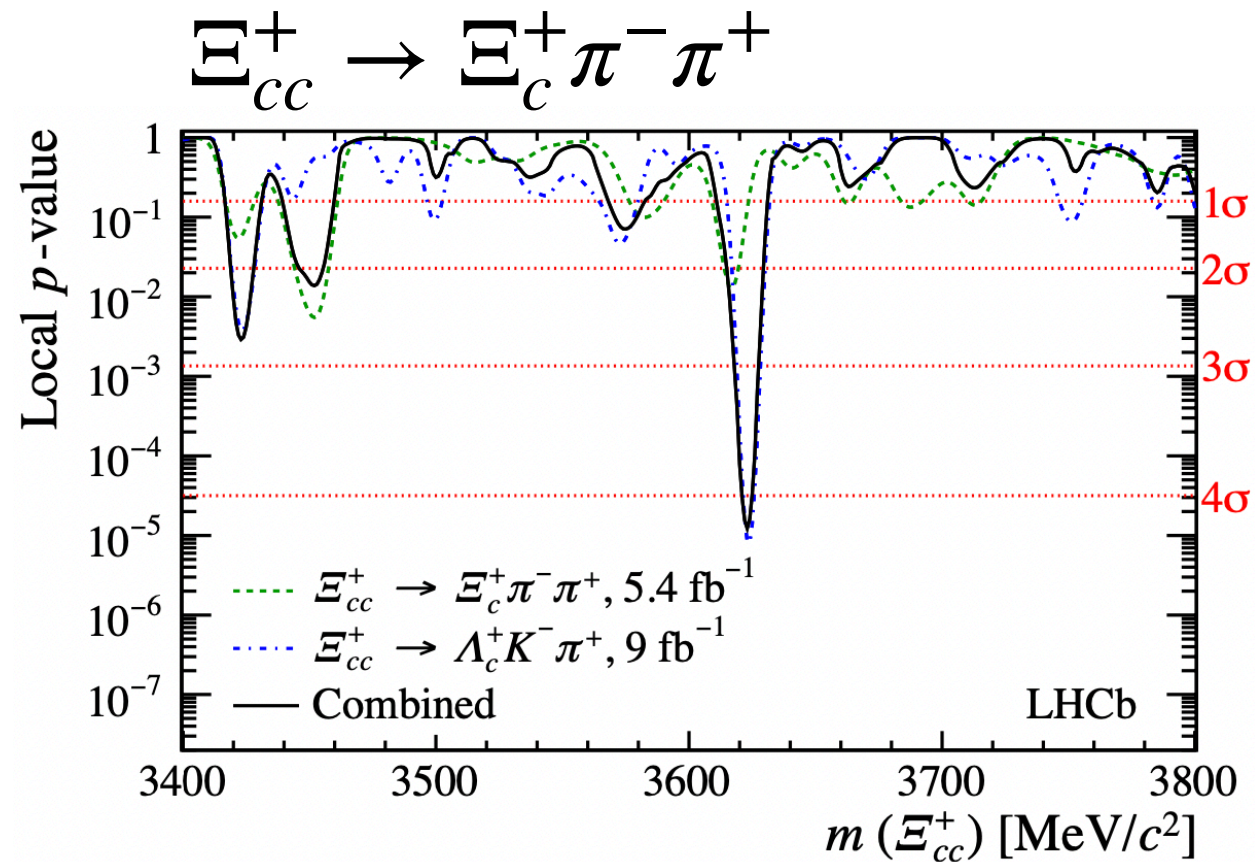
$$m(\Xi_b(6327)^0) = 6327.28_{-0.21}^{+0.23} \pm 0.08 \pm 0.24 \text{ MeV}$$

$$\Gamma(\Xi_b(6327)^0) < 2.20(2.56) \text{ MeV @ 90\%(95\%) CL.}$$

$$m(\Xi_b(6333)^0) = 6332.69_{-0.18}^{+0.17} \pm 0.03 \pm 0.22 \text{ MeV}$$

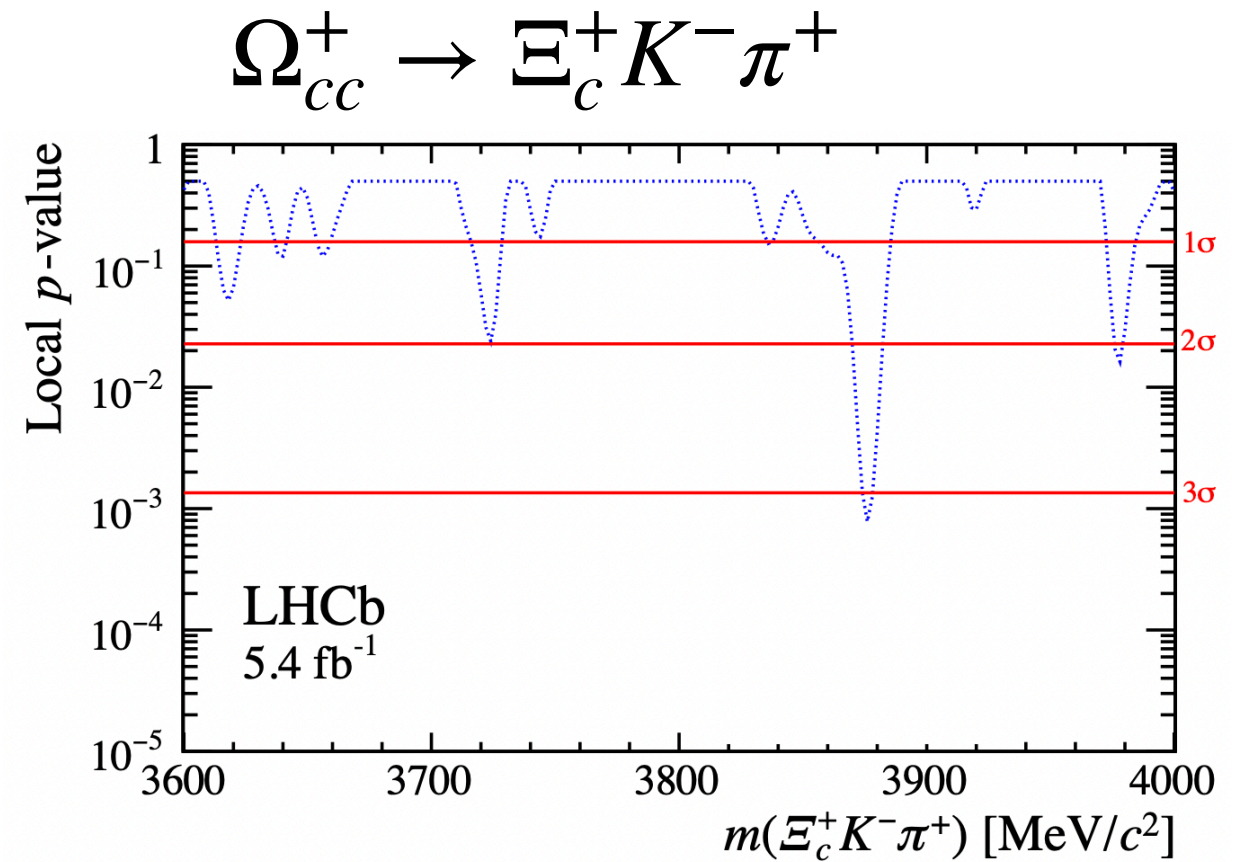
$$\Gamma(\Xi_b(6333)^0) < 1.55(1.85) \text{ MeV @ 90\%(95\%) CL.}$$

Search for Ξ_{cc}^+ and Ω_{cc}^+



local(global)significance
 $4.0\sigma(2.9\sigma)$, combined

[arXiv:2109.07292](https://arxiv.org/abs/2109.07292)



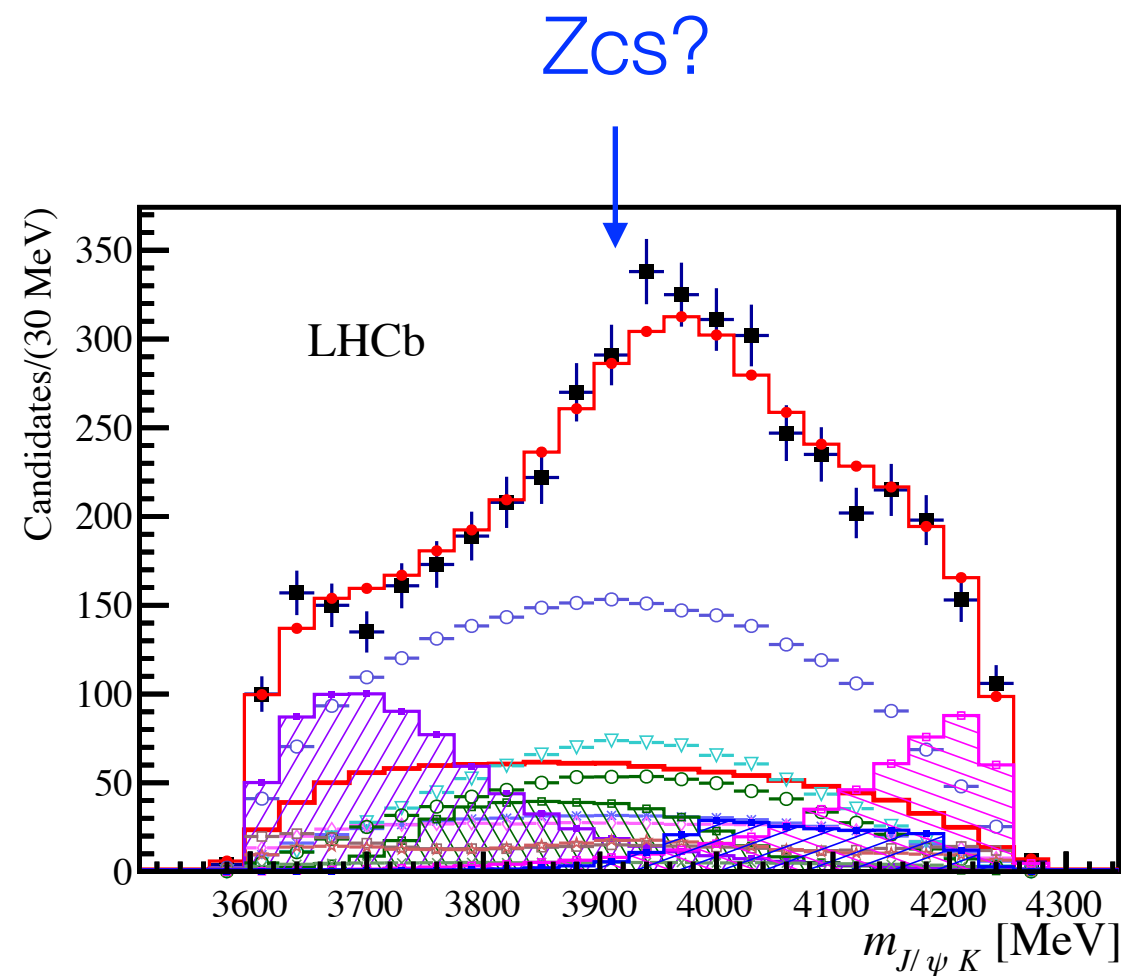
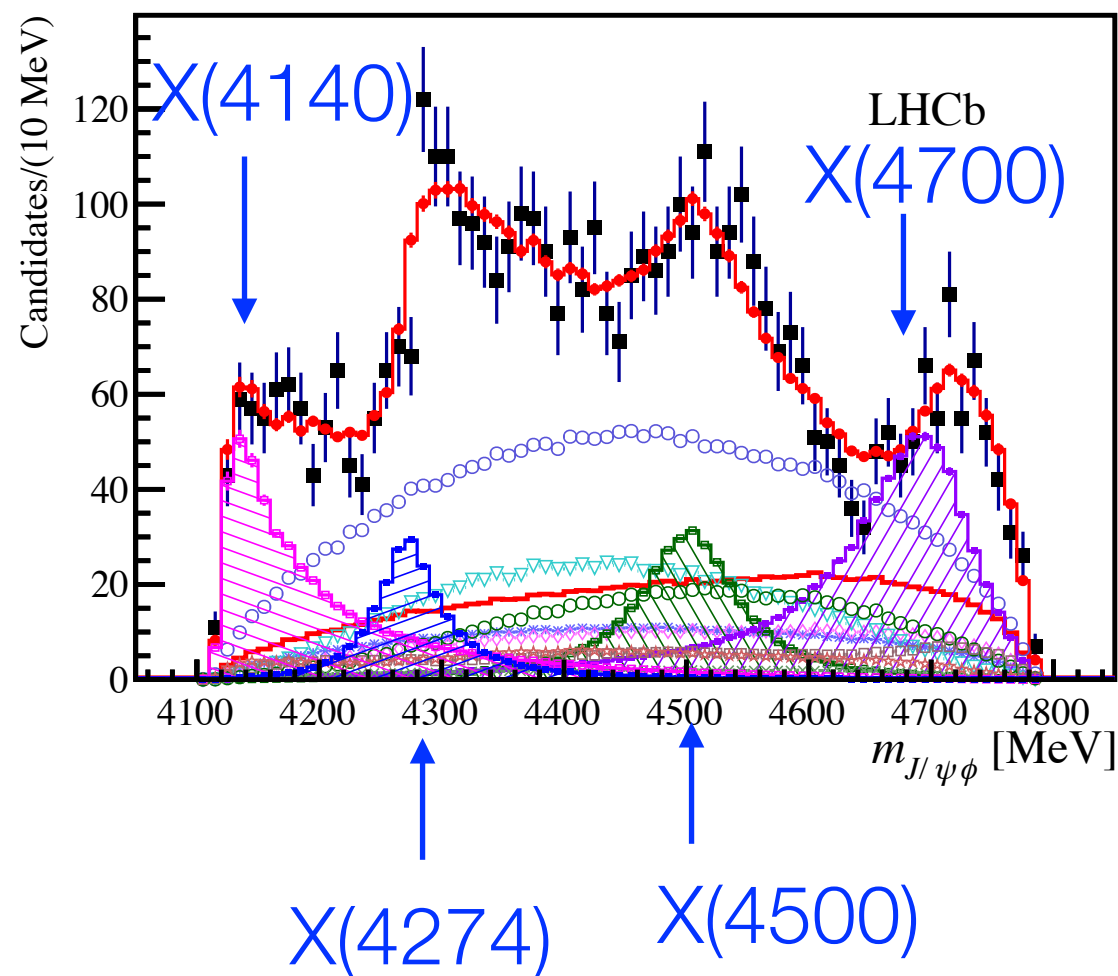
local(global) significance
 $3.2\sigma(1.8\sigma)$

[SCPMA64\(2021\)101062](https://arxiv.org/abs/2109.07292)

Tetraquark search in $B^+ \rightarrow J/\psi \phi K^+$ decays

PRL 118(2017)022003

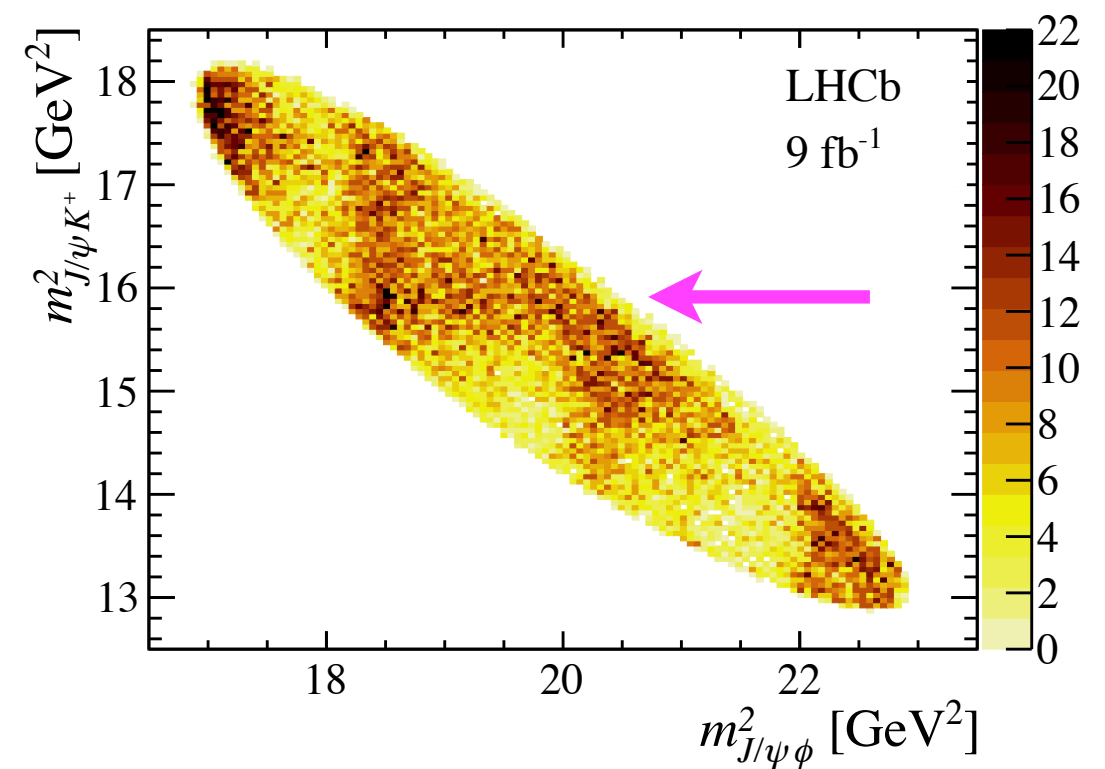
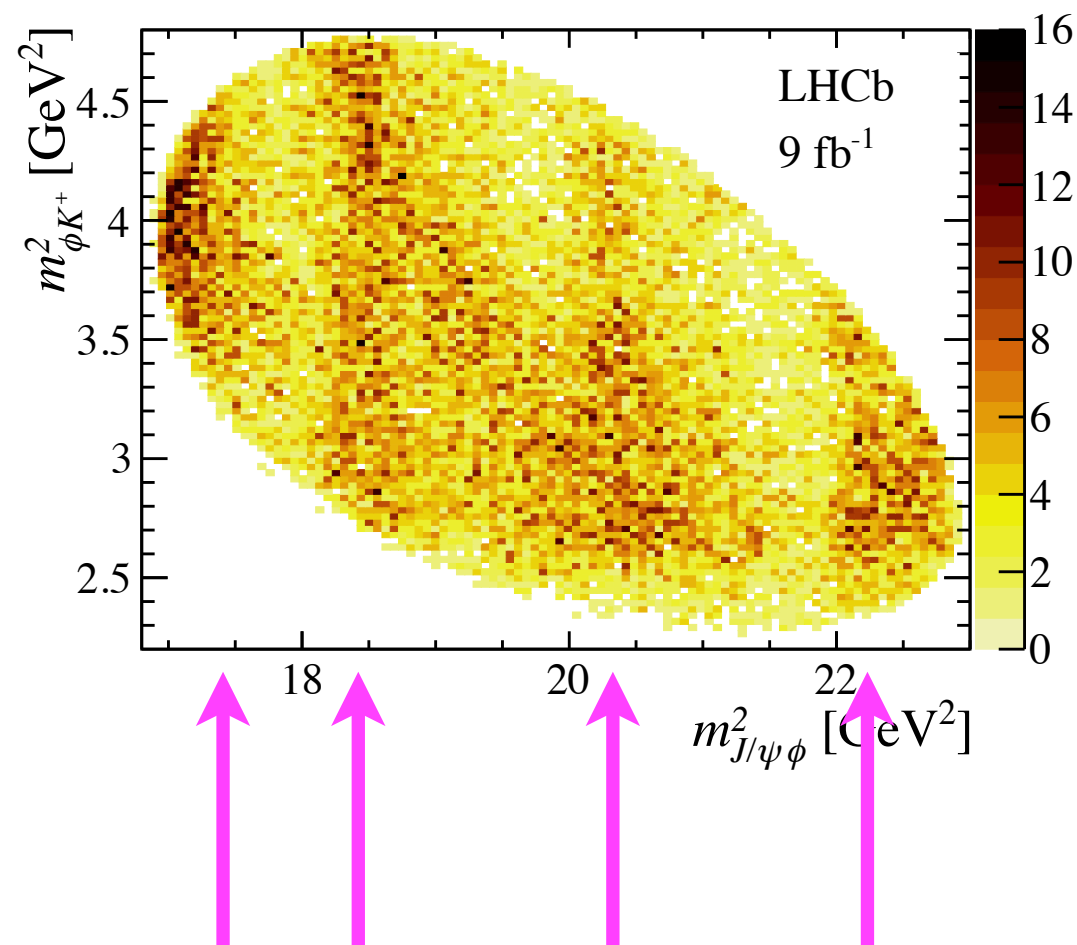
- First studied with run1 dataset, $\sim 4k$ signals for amplitude analysis
- Four $X(c\bar{c}s\bar{s}) \rightarrow J/\psi \phi$ structures observed and possible hint for $Z_{cs}(c\bar{c}u\bar{s}) \rightarrow J/\psi K^+$



$B^+ \rightarrow J/\psi \phi K^+$ decays with run1 and run2

PRL 127(2021)082001

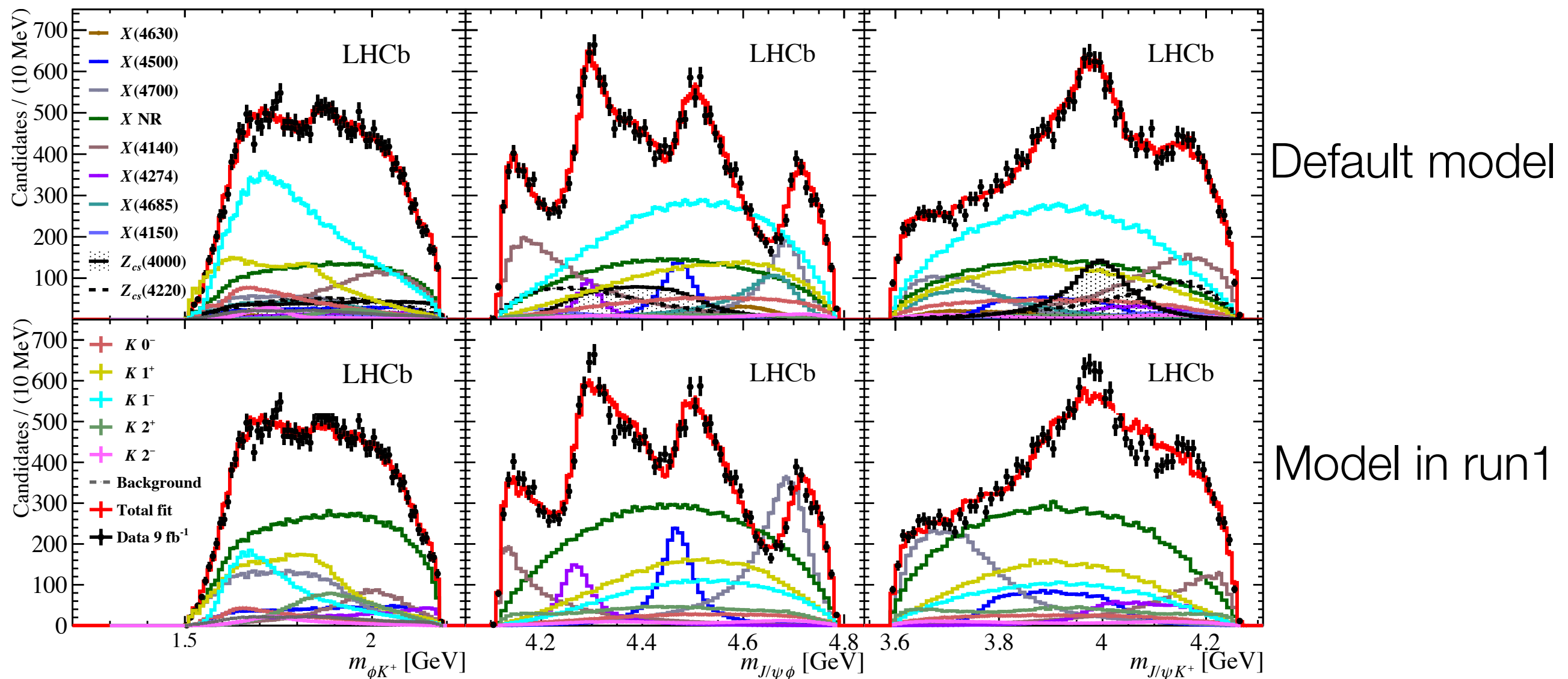
- Updated selection with run1+run2, ~24k signals with purity ~96%
- Clear bands in the $m_{J/\psi\phi}^2$ and $m_{J/\psi K^+}^2$ distributions



Models in amplitude analysis

PRL 127(2021)082001

- Model in run1 can not describe new data
- More X and Z_{cs} states needed



Results of amplitude fit

PRL 127(2021)082001

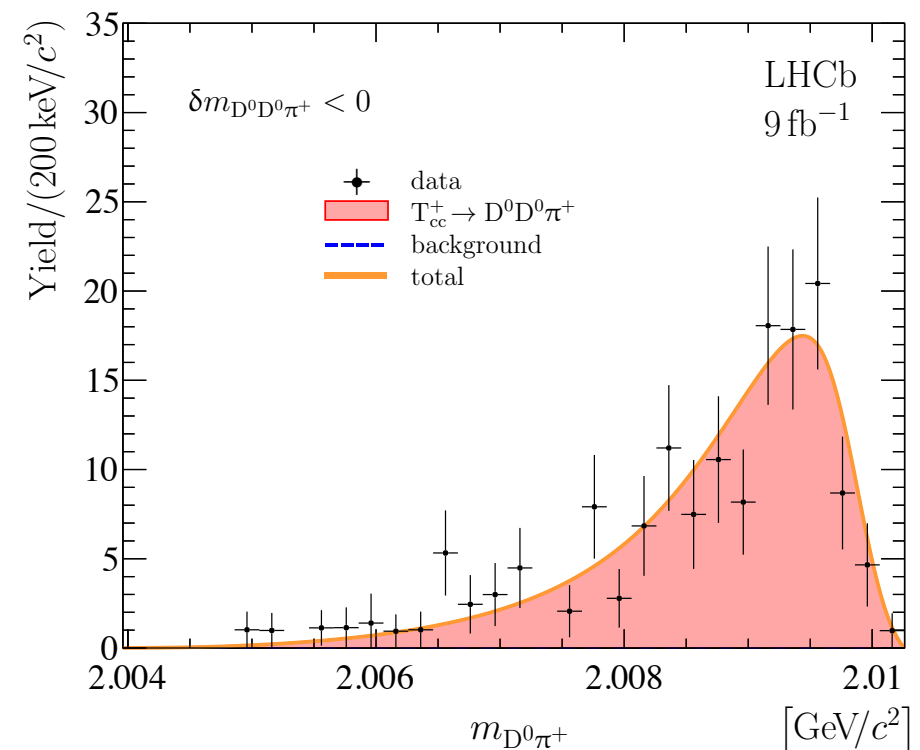
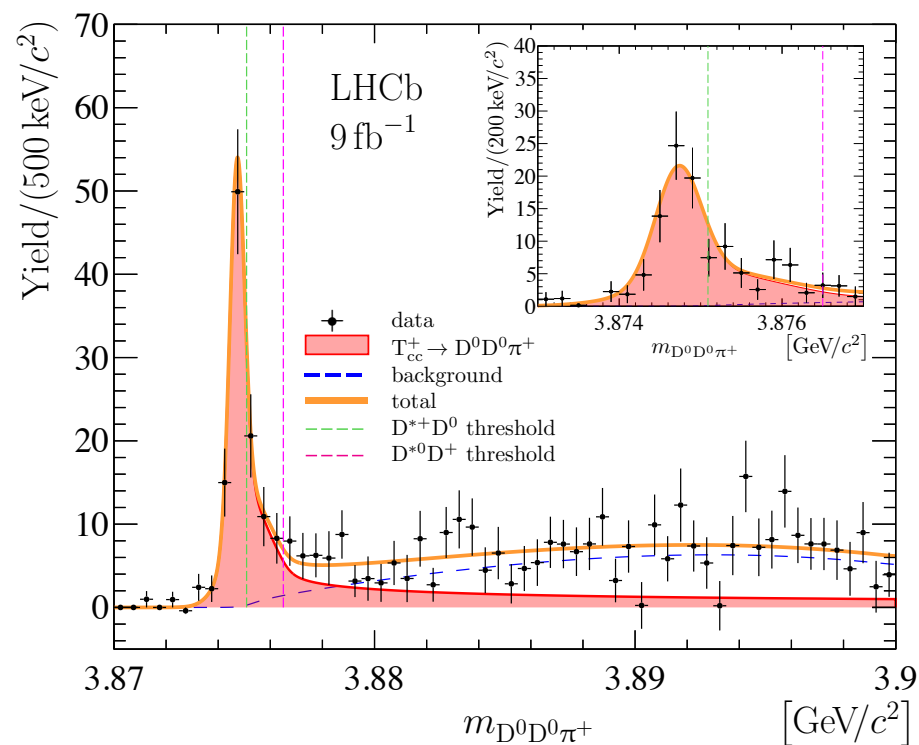
- Four X states observed in run1 confirmed
- New observation of $X(4685)(1^+)$, $X(4630)$, $Z_{cs}(4000)^+(1^+)$ and $Z_{cs}(4220)^+(1^+ \text{ or } 1^-)$

	significance(σ)	M [MeV]	Γ [MeV]
$X(0^+)$			
$X(4500)$	20	$4474 \pm 3 \pm 3$	$77 \pm 6_{-8}^{+10}$
$X(4700)$	17	$4694 \pm 4_{-3}^{+16}$	$87 \pm 8_{-6}^{+16}$
$X(1^+)$			
$X(4140)$	13	$4118 \pm 11_{-36}^{+19}$	$162 \pm 21_{-49}^{+24}$
$X(4274)$	18	$4294 \pm 4_{-6}^{+3}$	$53 \pm 5 \pm 5$
$X(4685)$	15	$4684 \pm 7_{-16}^{+13}$	$126 \pm 15_{-41}^{+37}$
$X(1^-)$			
$X(4630)$	5.5	$4626 \pm 16_{-110}^{+18}$	$174 \pm 27_{-73}^{+134}$
$X(2^-)$			
$X(4150)$	4.8	$4164 \pm 18 \pm 33$	$135 \pm 28_{-30}^{+59}$
$Z_{cs}(1^+)$			
$Z_{cs}(4000)$	15	$4003 \pm 6_{-14}^{+4}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9	$4216 \pm 24_{-30}^{+43}$	$233 \pm 52_{-73}^{+97}$

Observation of T_{cc}^+ ($cc\bar{u}d$)

arXiv:2109.01038, 2109.01056

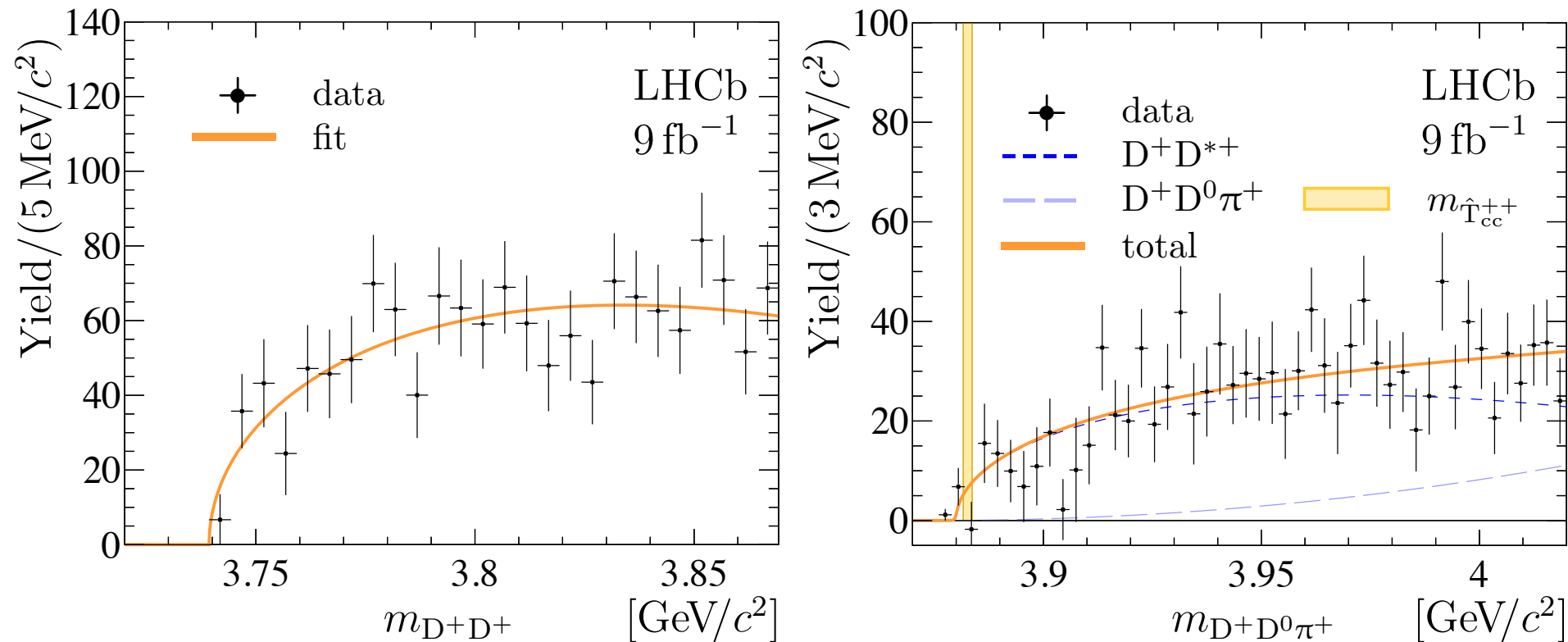
- Search in prompt $D^0 D^0 \pi^+$ system with $D^0 \rightarrow K^- \pi^+$
- Observed a very narrow peak T_{cc}^+ , consistent with decay via off-shell D^{*+}



Observation of T_{cc}^+ ($cc\bar{u}\bar{d}$)

arXiv:2109.01038, 2109.01056

- No signal T_{cc}^{++} seen in $m_{D^+D^+}$ and $m_{D^+D^0\pi^+}$ distributions, i.e. isovector disfavored



- Consistent with $J^P=1^+$ ground state isoscalar

Theoretical predictions:

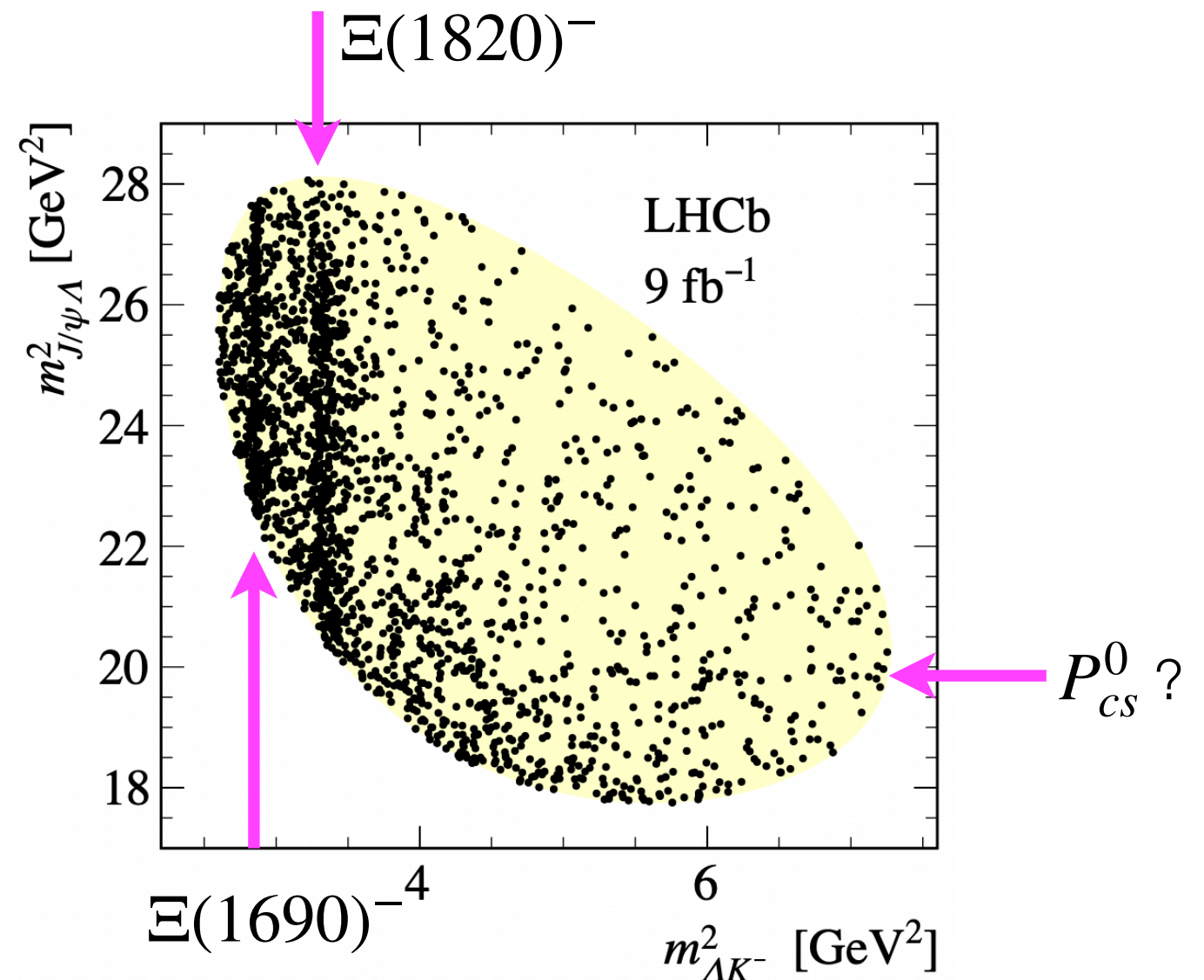
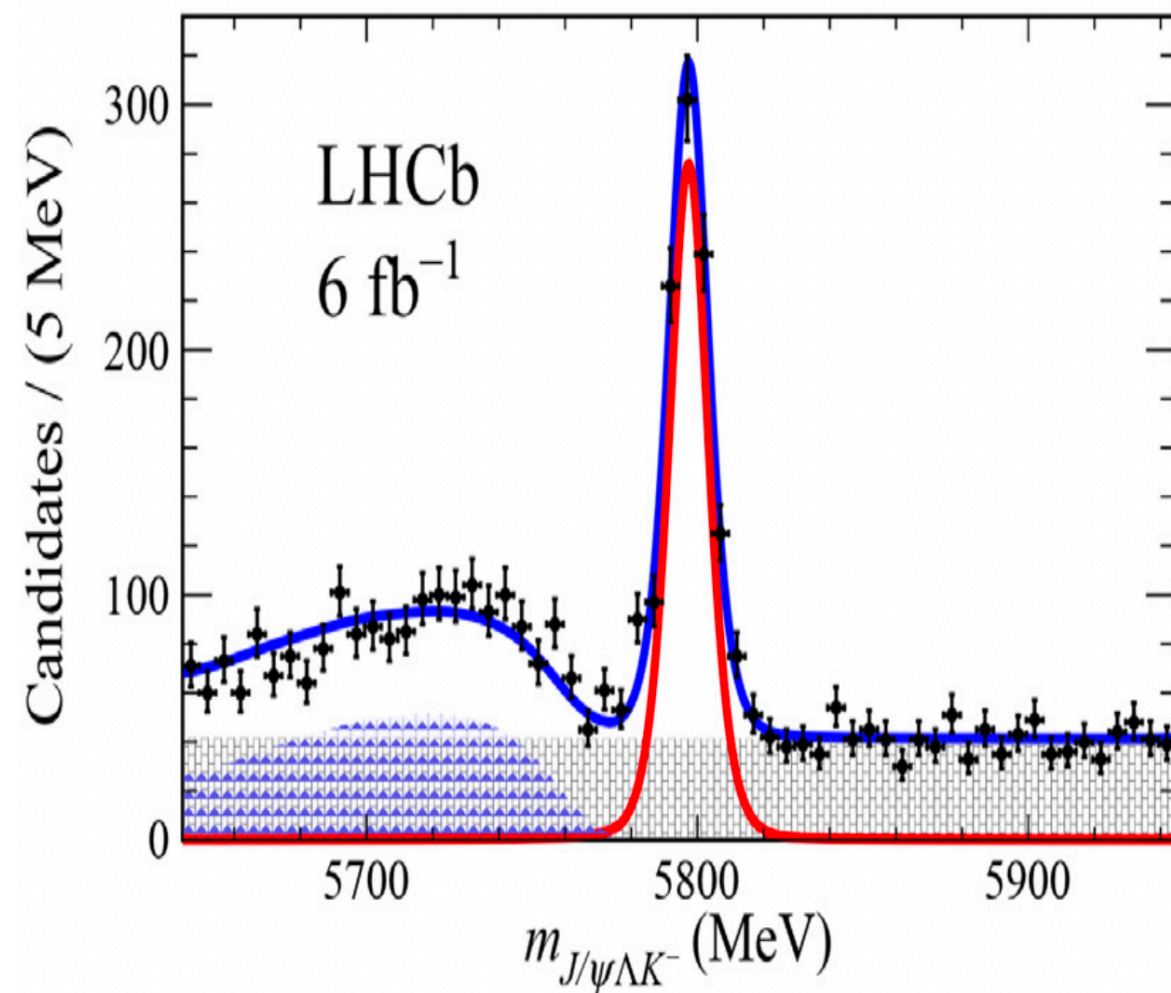
$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0}) \quad -300 < \delta m < 300 \text{ MeV}/c^2$$

$$\text{From fit } \delta m_U = -359 \pm 40^{+9}_{-6} \text{ keV}/c^2$$

P_{cs}^0 search in $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays

Sci.Bull.66(2021)1278-1287

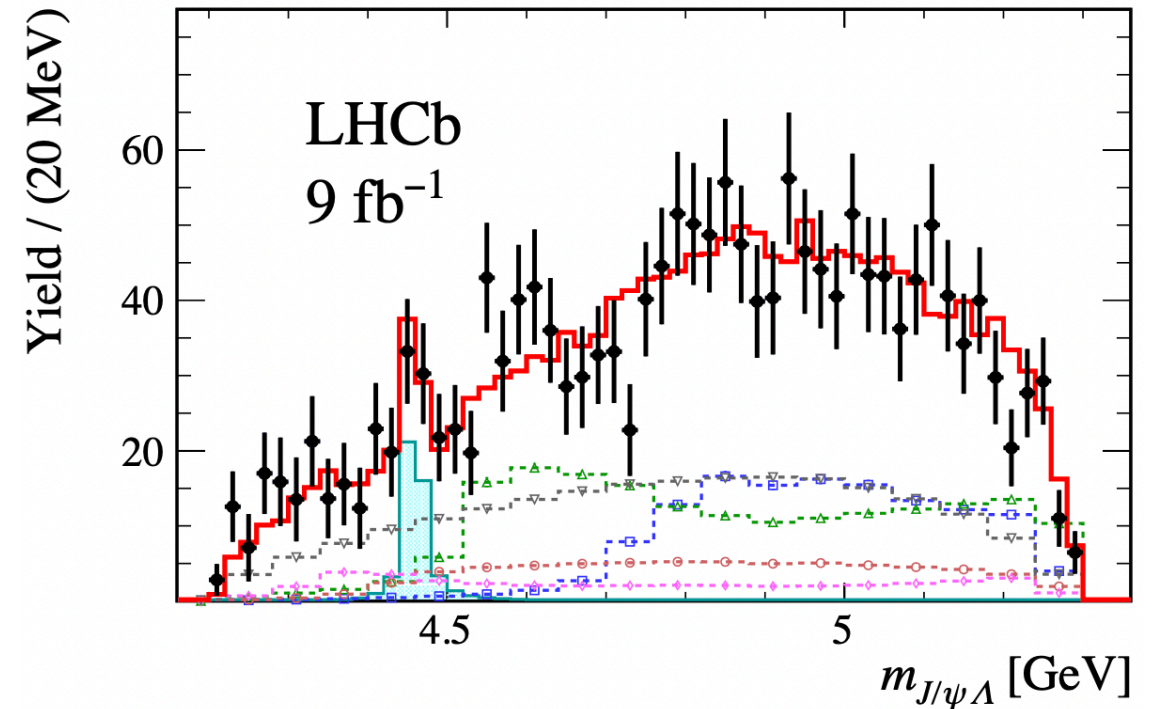
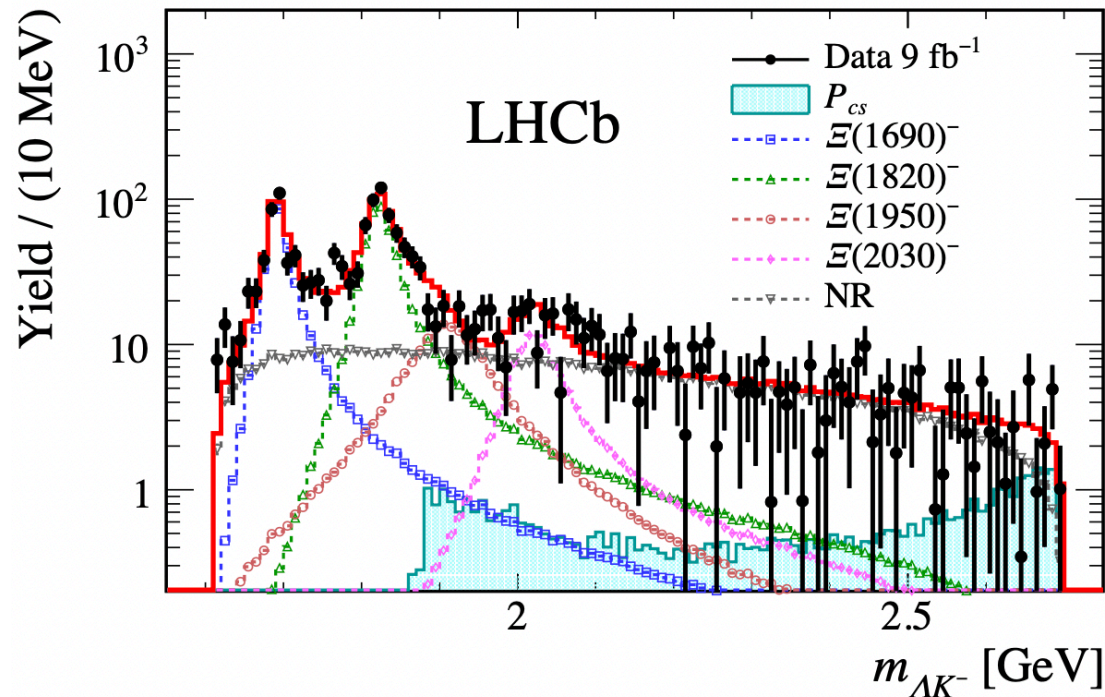
- ✓ 1750 signal candidates using 9fb^{-1} data, purity $\sim 80\%$
- ✓ Clear structures of Ξ^{*-} , hint for P_{cs}^0 ?



Amplitude analysis results

Sci.Bull.66(2021)1278-1287

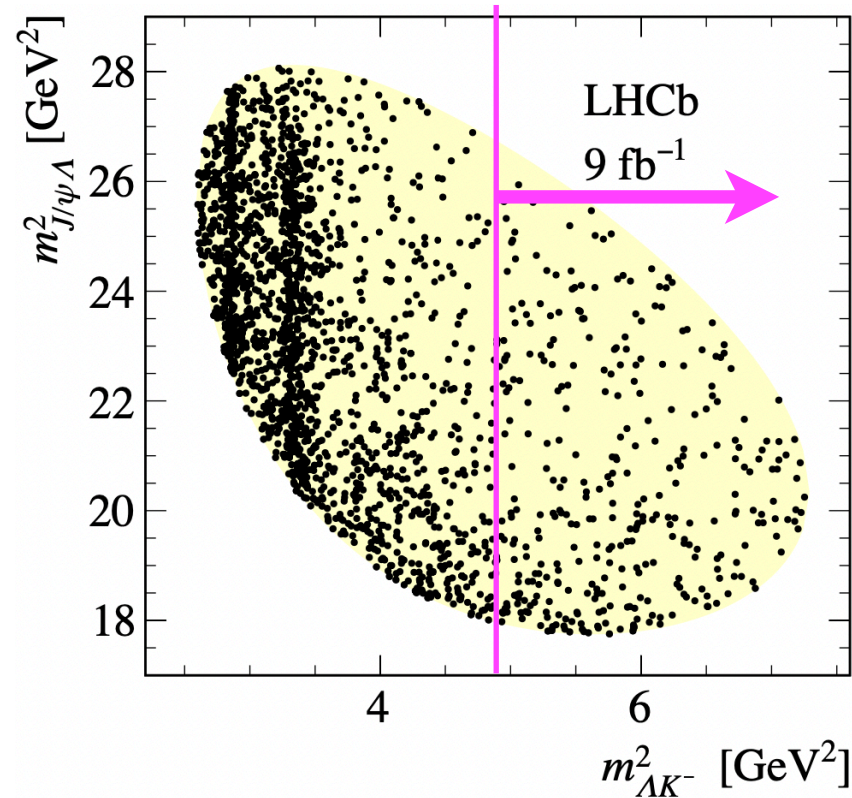
First evidence for hidden-charm pentaquark with strangeness $P_{cs}(4459)^0$, with significance of 3.1σ



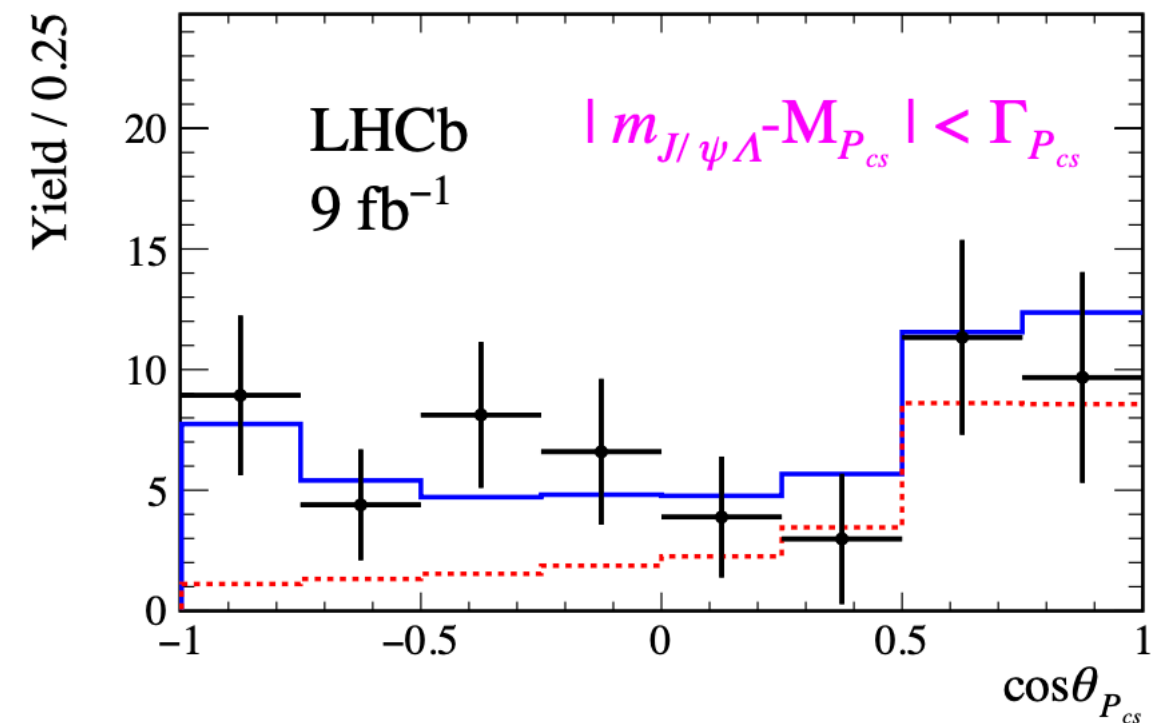
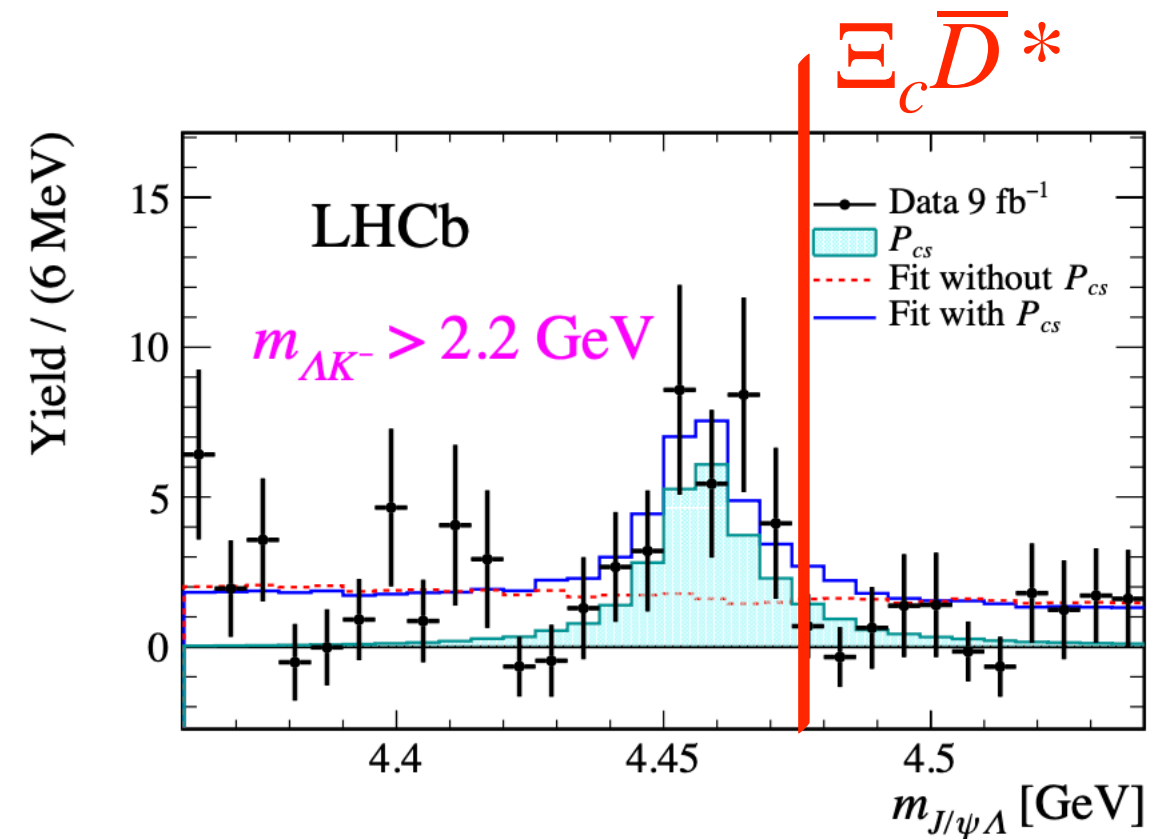
State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3^{+1.2}_{-0.4}$	$25.9 \pm 9.5^{+14.0}_{-13.5}$	$22.1^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5^{+1.0}_{-0.6}$	$36.0 \pm 4.4^{+7.8}_{-8.2}$	$32.9^{+3.2+6.9}_{-6.2-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5^{+5.8+49.9}_{-3.5-9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3^{+1.8+3.8}_{-1.8-4.1}$
NR	—	—	$35.8^{+4.6+10.3}_{-6.4-11.2}$

Highlight of $P_{cs}^0(4459)$ contribution

Sci.Bull.66(2021)1278-1287



$P_{cs}^0(4459)$ improves the description of mass and angular distribution

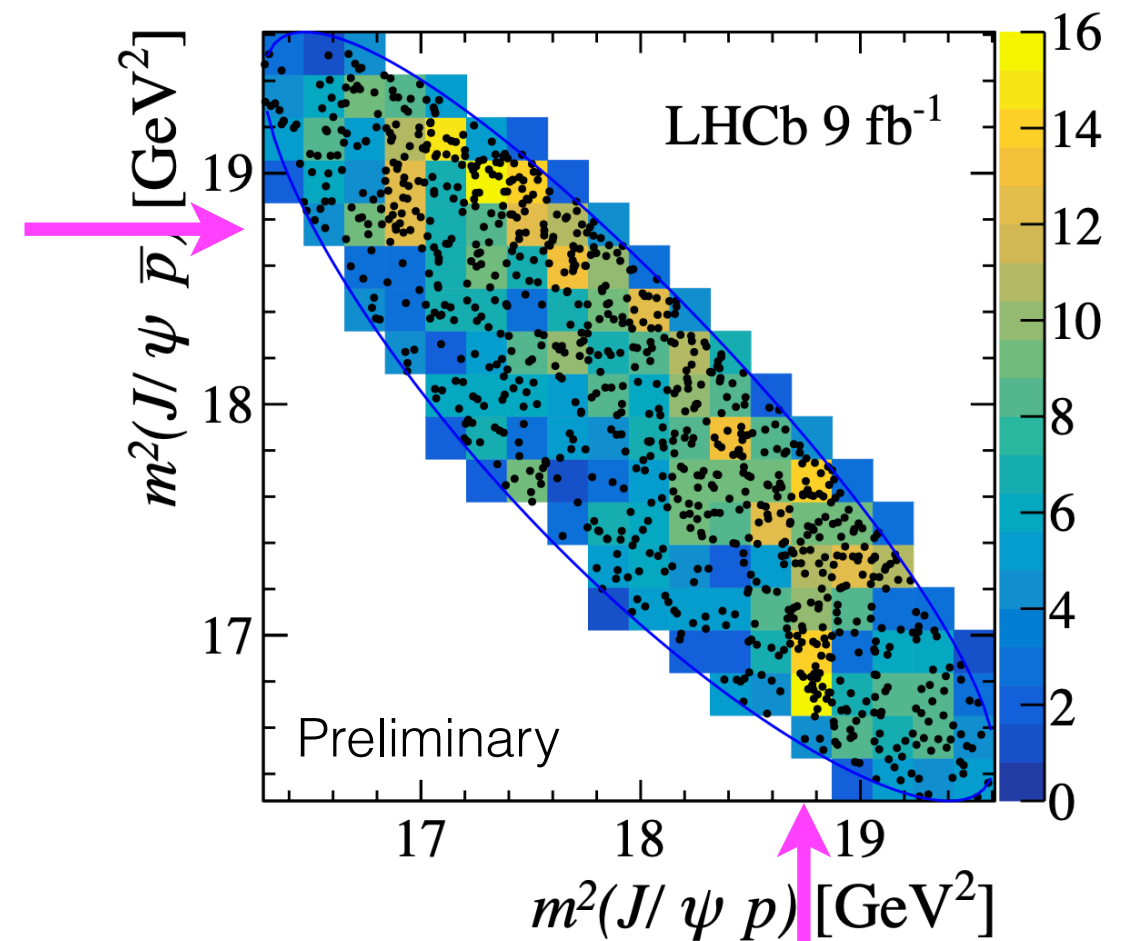
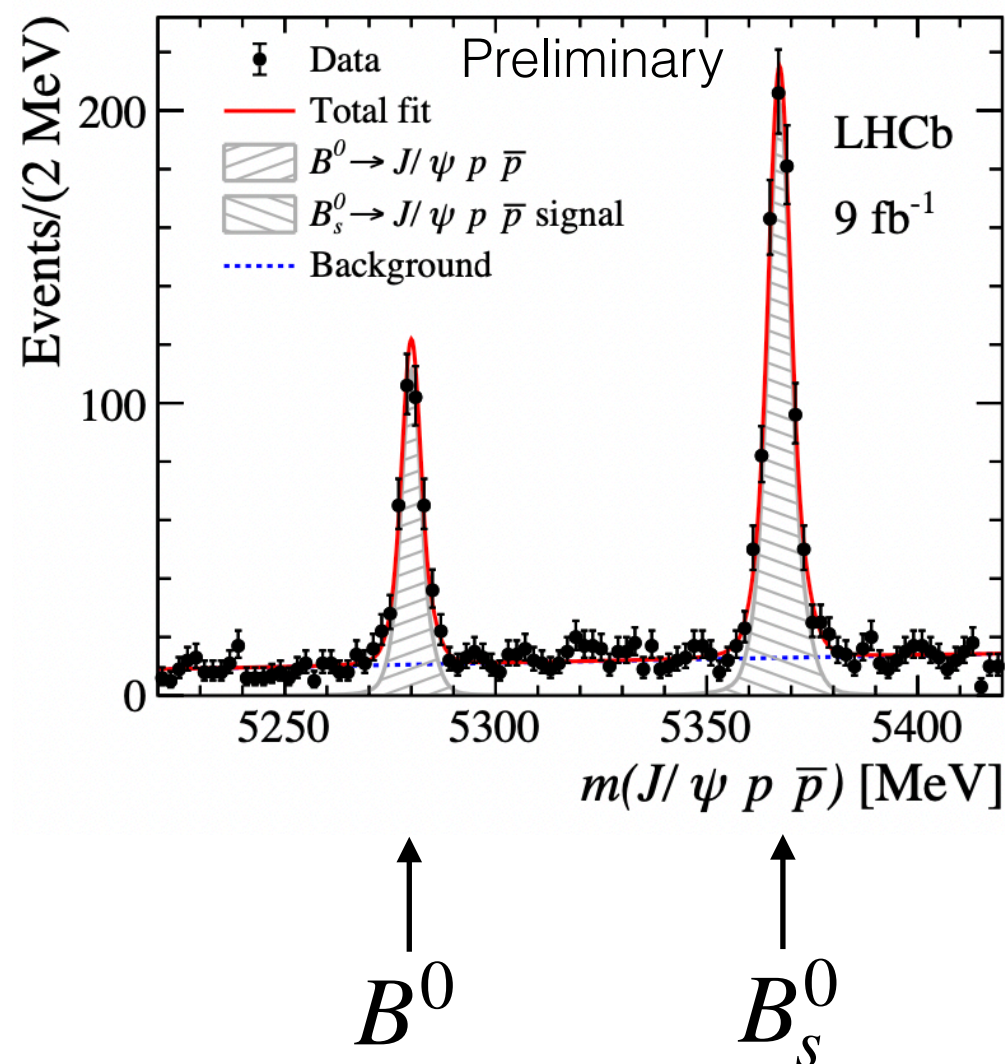


P_c^+ search in $B_s^0 \rightarrow J/\psi p \bar{p}$ decays

arXiv:2108.04720

- ✓ First observed by LHCb using 5.2 fb⁻¹ data PRL122(2019)191804
- ✓ Full amplitude analysis using 9 fb⁻¹ data

~800 B_s^0 in 3 σ window
with 85% purity



Default amplitude model

arXiv:2108.04720

- ✓ 4D amplitude using helicity formalism

- ✓ Untagged B decay

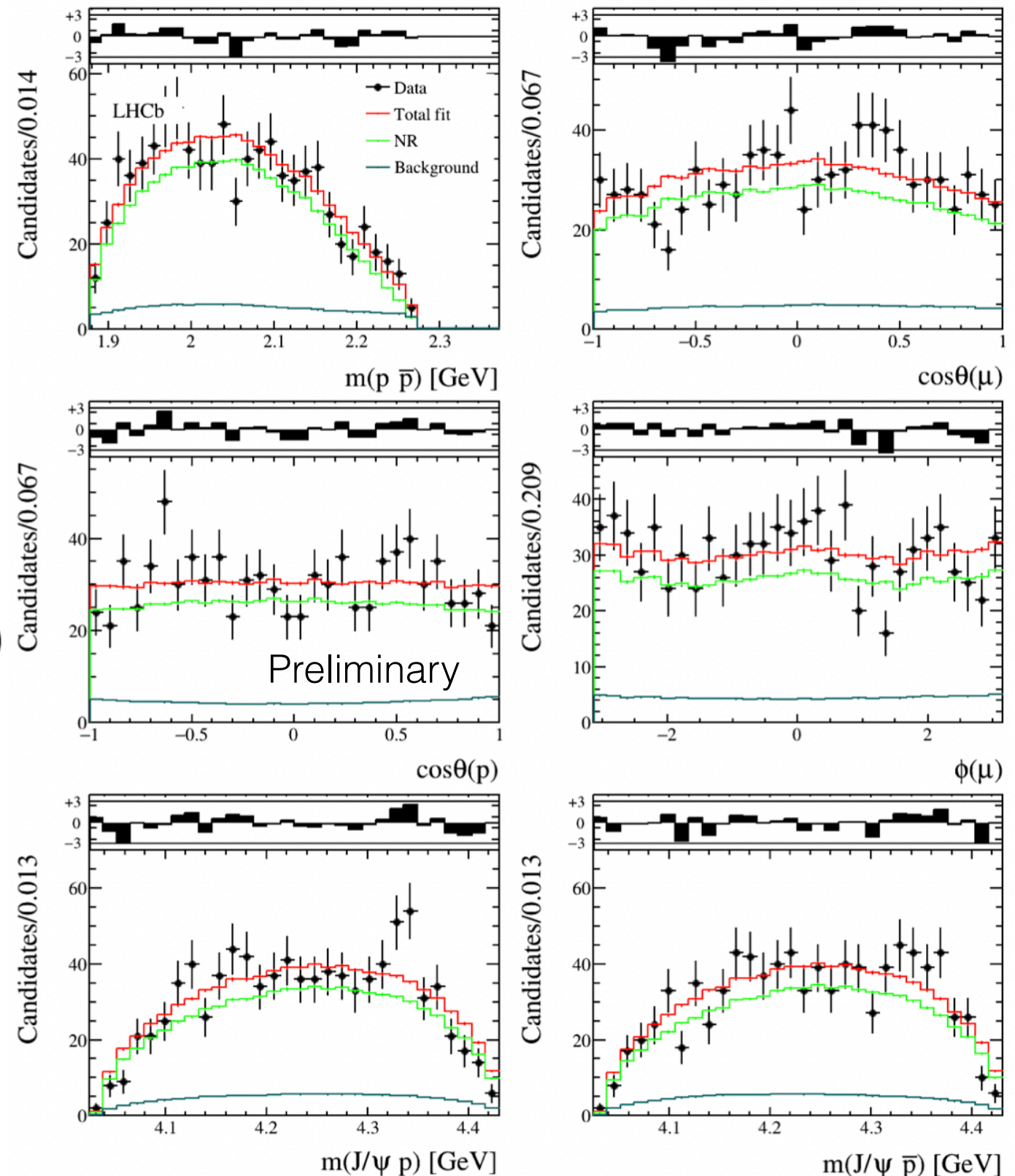
CP conservation:

$$\mathcal{M}(\bar{B}^0) = \mathcal{M}(B^0)$$

Total amplitude:

$$|\bar{\mathcal{M}}|^2 = \frac{1}{2} (|\mathcal{M}(B^0)|^2 + |\mathcal{M}(\bar{B}^0)|^2)$$

- ✓ Default model can not describe data well



Amplitude fit with P_c

arXiv:2108.04720

✓ Add $P_c^+ \rightarrow J/\psi p, P_c^- \rightarrow J/\psi \bar{p}$

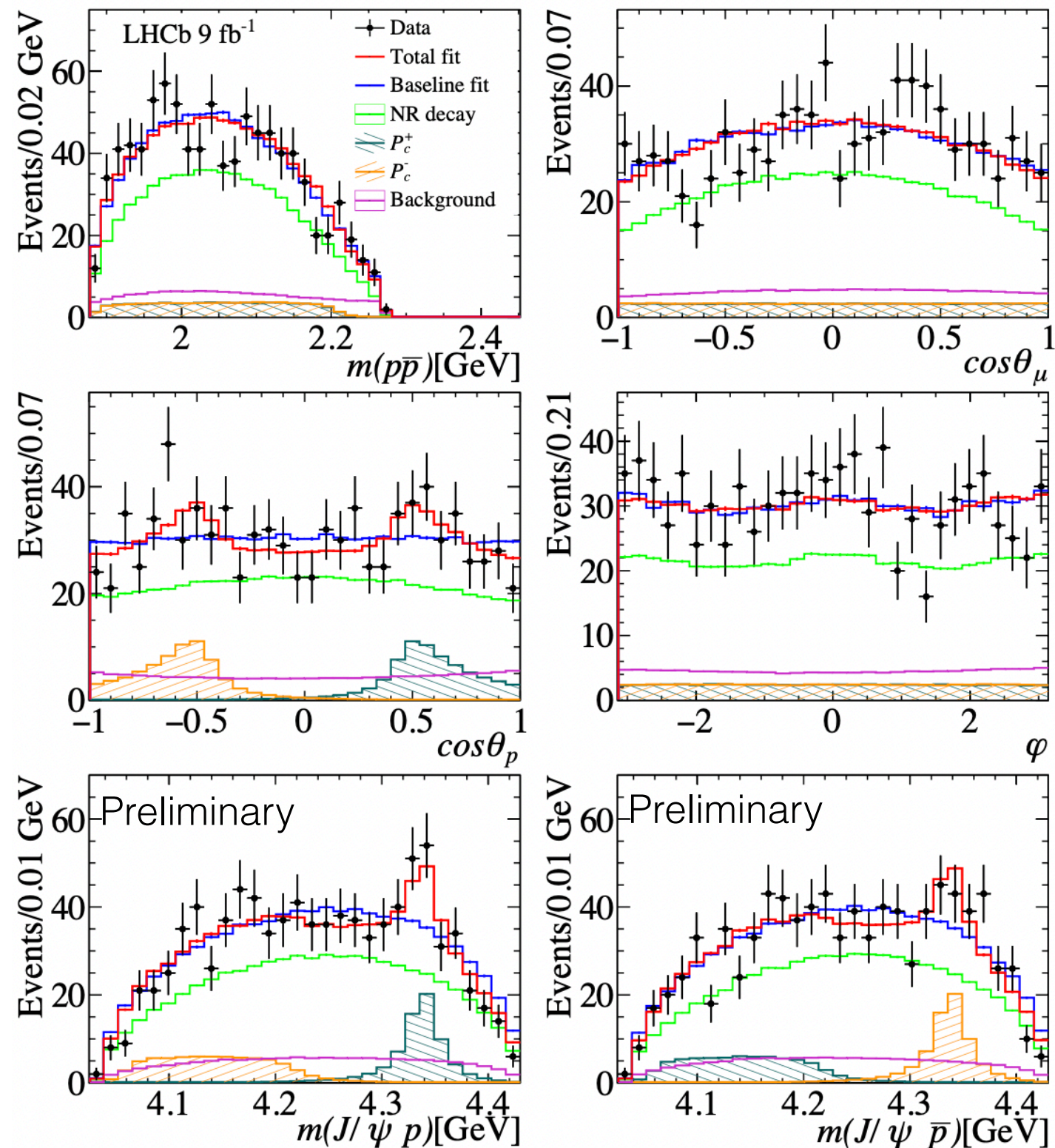
✓ The same mass, width and couplings for $P_c^\pm$

✓ Evidence for new $P_c(4337)^+$

$$M_{P_c} = 4337_{-4}^{+7}(\text{stat})_{-2}^{+2}(\text{syst}) \text{ MeV}$$

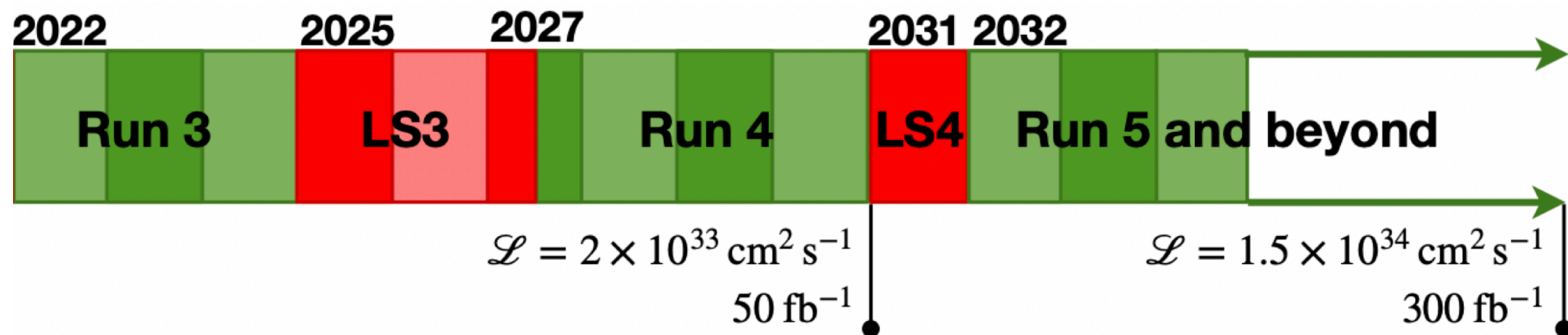
$$\Gamma_{P_c} = 29_{-12}^{+26}(\text{stat})_{-14}^{+14}(\text{syst}) \text{ MeV}$$

✓ No evidence for $P_c(4312)^+$,
and structures in $p\bar{p}$ system



Summary

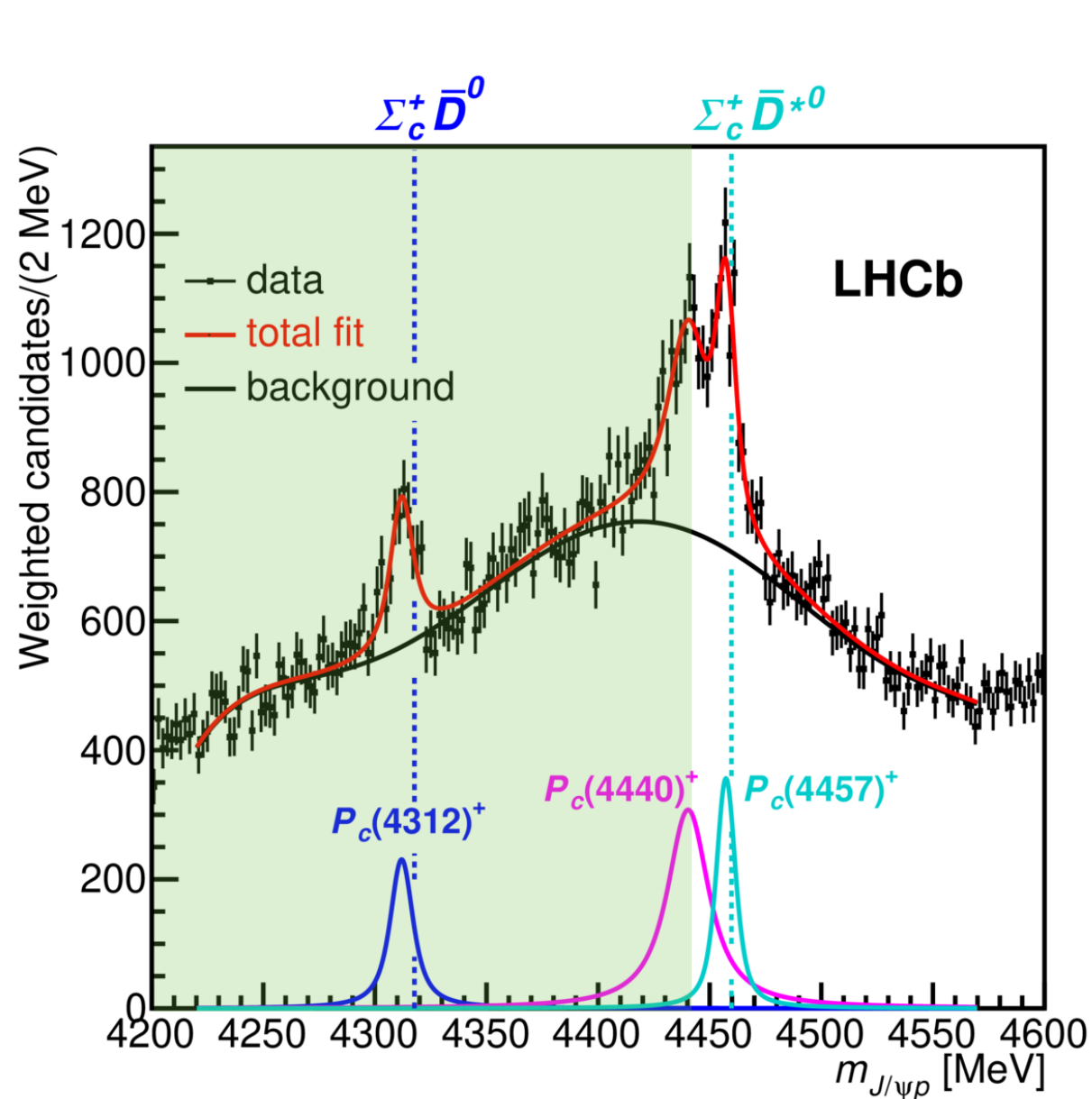
- Recent results on spectroscopy at LHCb are presented
Observed several excited D_s^+ , B_s^0 , and Ξ_b^0 , and tetraquarks
Evidence for pentaquarks
- LHCb Upgrade will restart soon, and lots of interesting results are expected



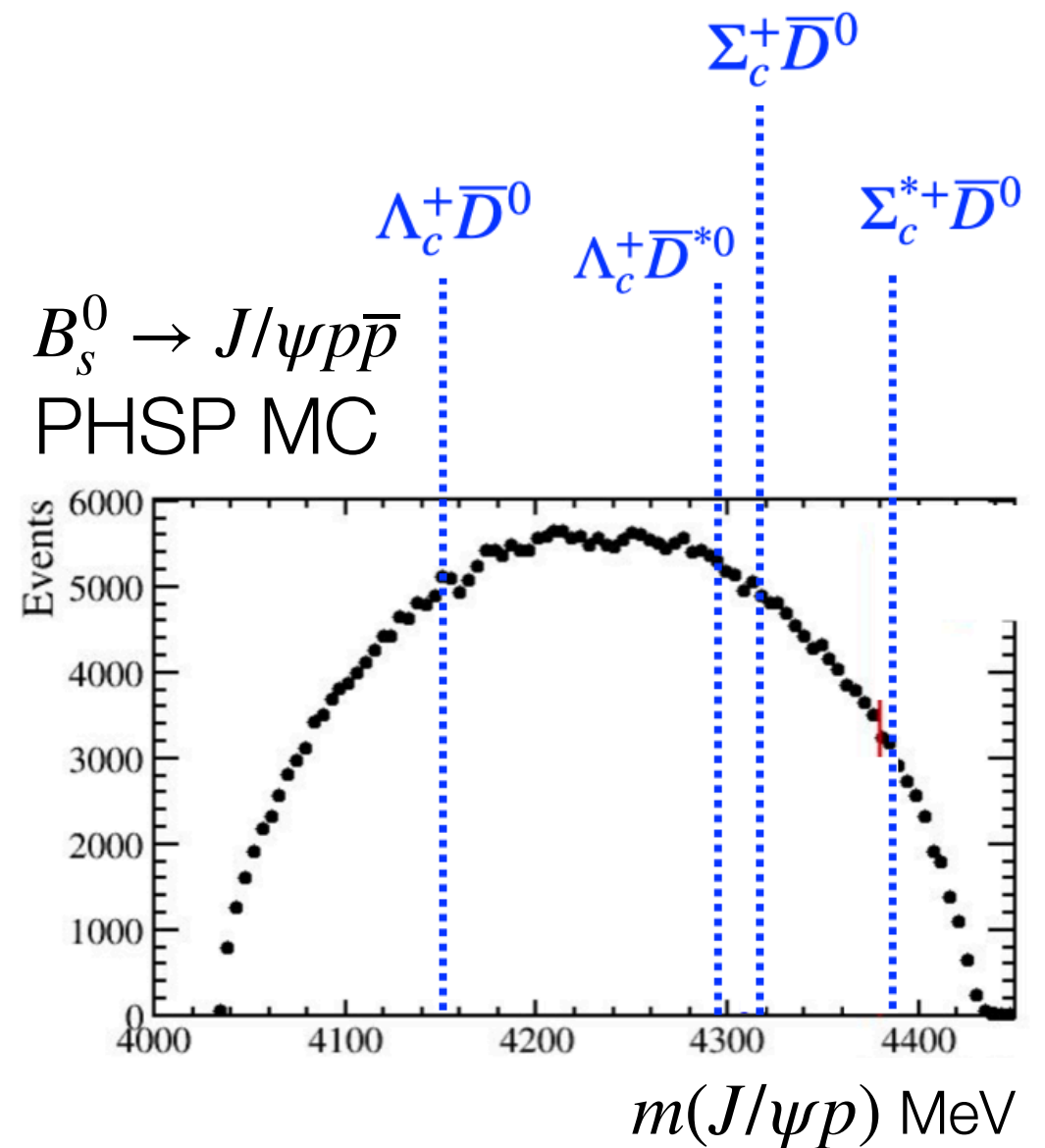
Thank you!

Invariant mass coverage

- ✓ Several thresholds covered in the $m(J/\psi p)$ distribution
- ✓ Check P_c^+ structures in 2019



PRL 122 (2019) 222001



Evidence of a new structure

LHCb-PAPER-2021-018 in preparation

- ✓ New pentaquark-like state with significance $3.1 \sim 3.7\sigma$ for $J^P(1/2^\pm, 3/2^\pm)$

$$M_{P_c} = 4337_{-4}^{+7}(\text{stat})_{-2}^{+2}(\text{syst}) \text{ MeV}$$

$$\Gamma_{P_c} = 29_{-12}^{+26}(\text{stat})_{-14}^{+14}(\text{syst}) \text{ MeV}$$

can not distinguish J^P due to limited sample size

- ✓ No evidence for $P_c^+(4312)$, glueball, and $p\bar{p}$ enhancement