Exotic hadrons at LHCb

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Outline

- ✓ Introduction
- ✓ X(3872) production
- ✓ Tetraquark $X(c\bar{c}s\bar{s})$, $Z_{cs}(c\bar{c}u\bar{s})^{+}$, $T_{cc}^{+}(cc\bar{u}\bar{d})$ searches
- ✓ Pentaquark $P_{cs}(c\bar{c}uds)^{0}$, $P_{c}(c\bar{c}uud)^{+}$ searches
- ✓ Summary

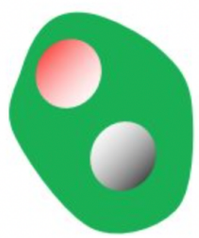
Introduction

Exotic hadrons study will help to understand dynamics and improve the knowledge of QCD

Conventional

Meson

$q\bar{q}$



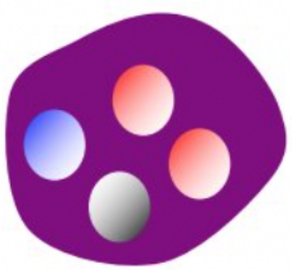
Baryon

qqq

Exotic

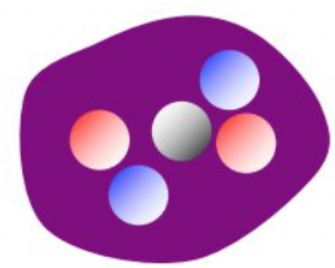
Tetraquark

$qq\bar{q}\bar{q}$



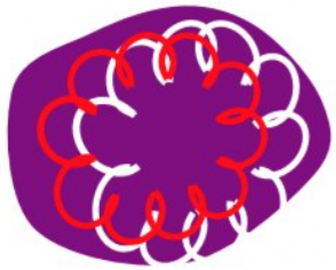
Pentaquark

$qqqq\bar{q}$



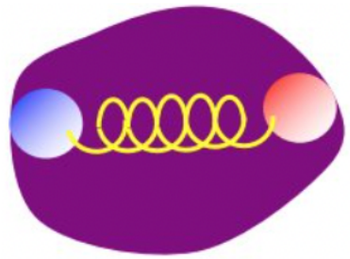
Glueballl

gg



Hybrid

$q\bar{q}g$



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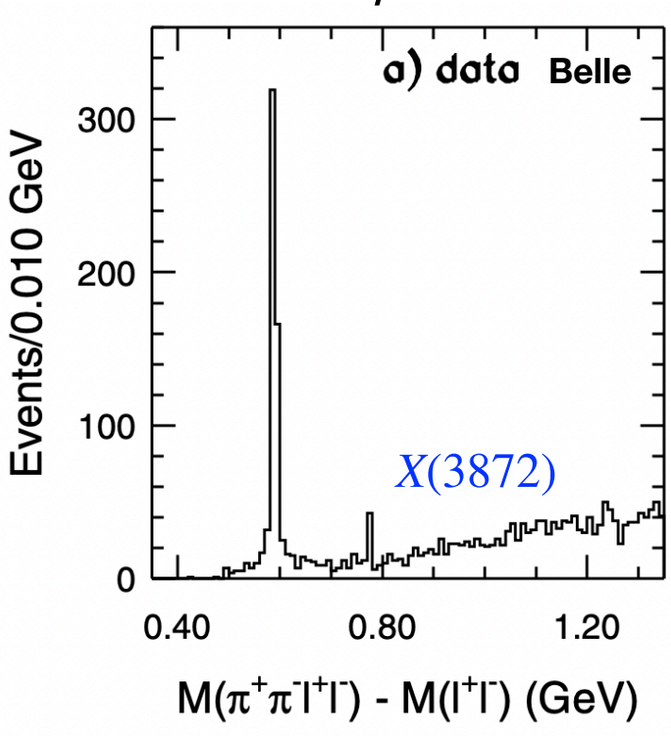
Introduction

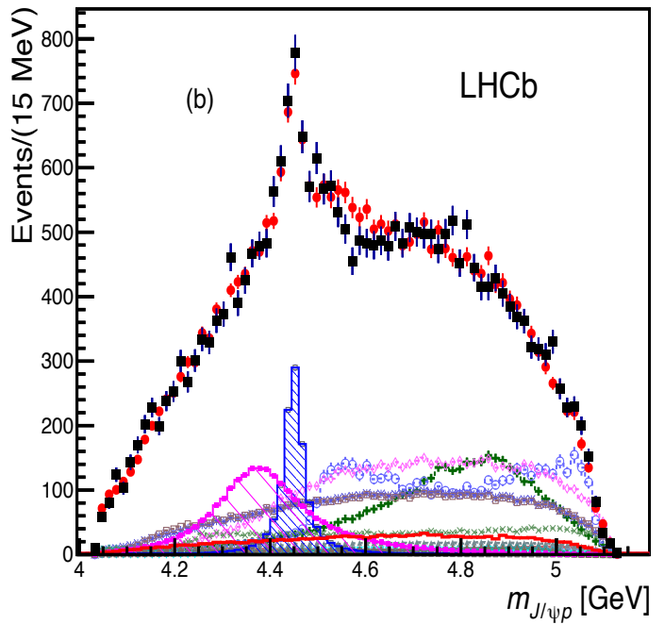
Exotic era kicked off by discovery of X(3872) at Belle in 2003, and dozens of structures observed until now

$B^+ \to J/\psi\pi^+\pi^-K^+$

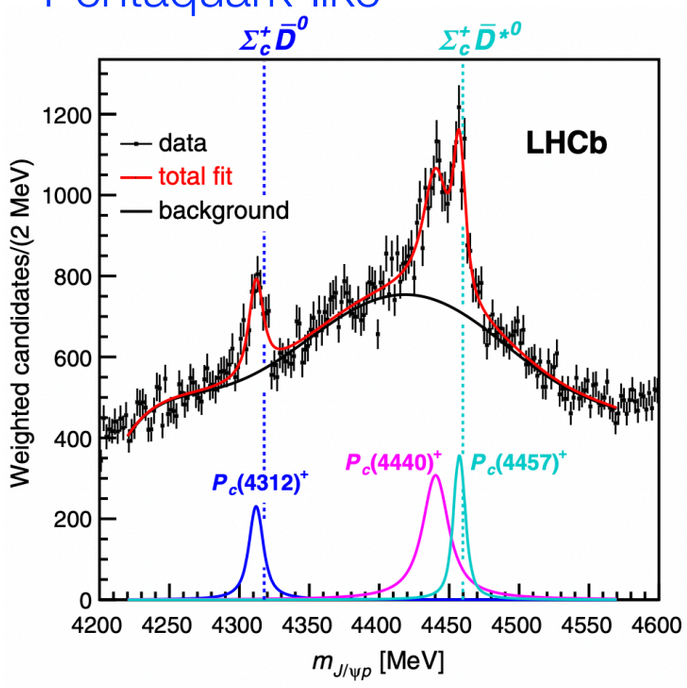


PRL91(2003)262001

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



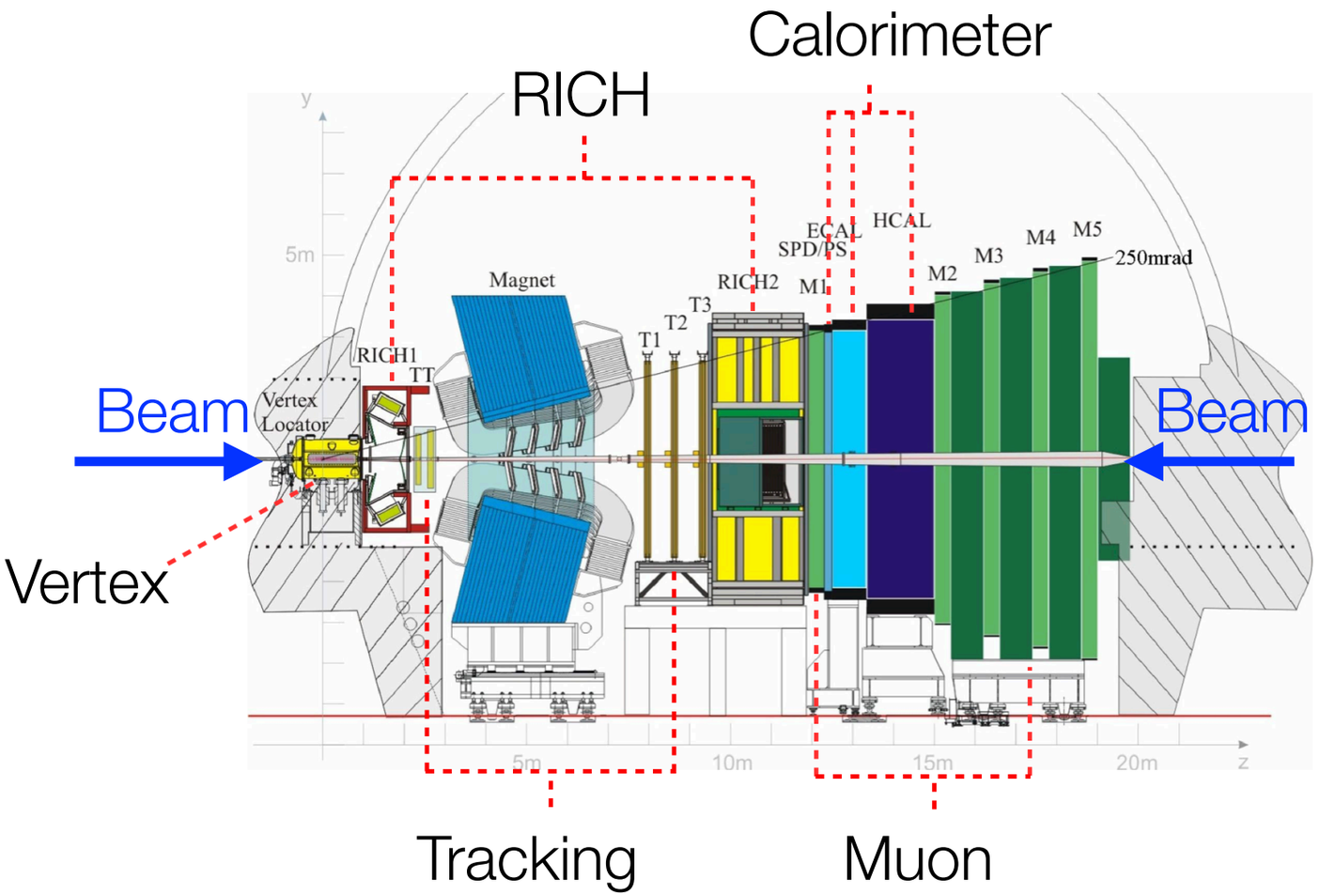
PRL115(2015)072001



PRL122(2019)222001

LHCb detector

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

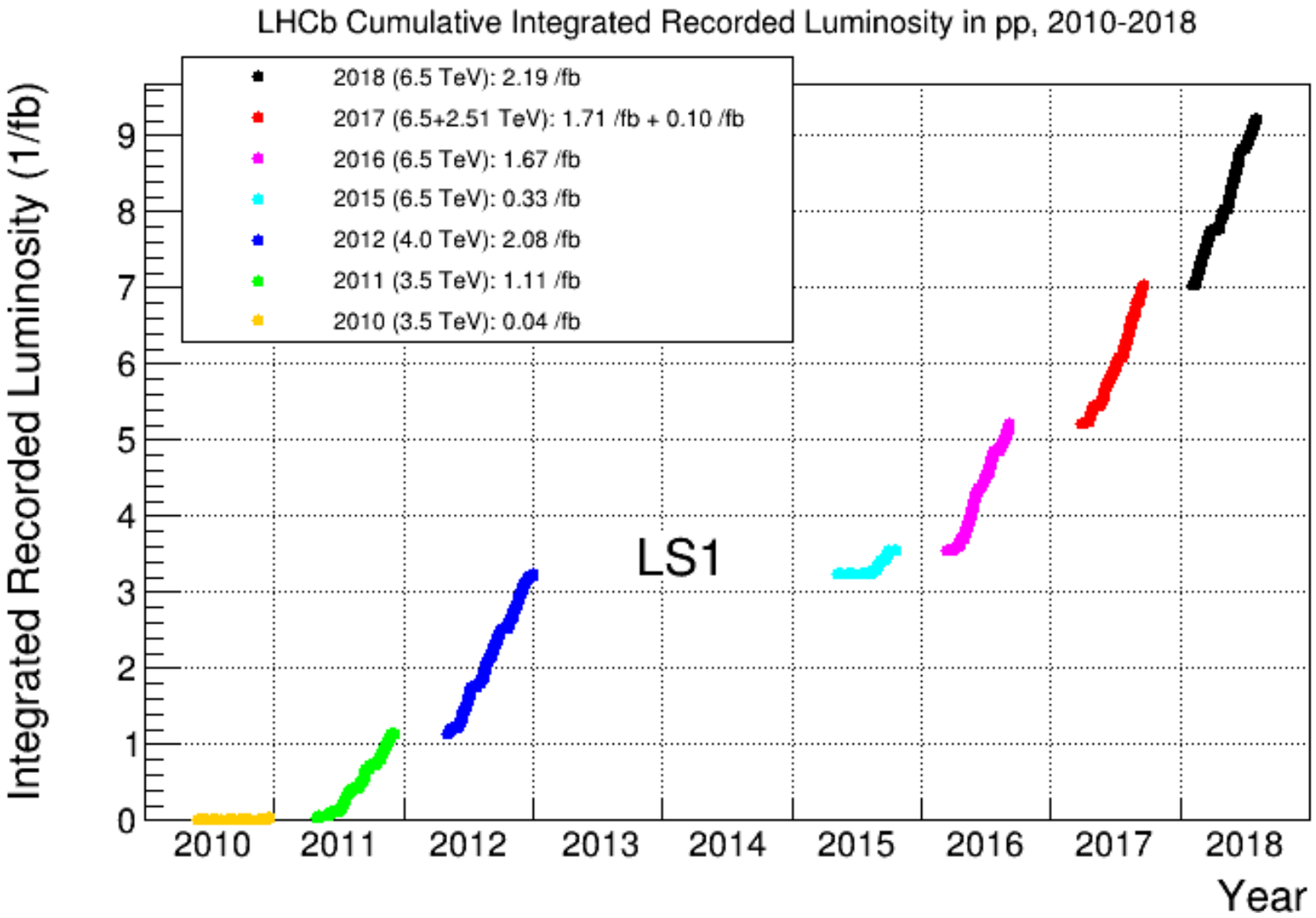


LHCb is a forward spectrometer

Acceptance $2 < \eta < 5$

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

Data set



- $9fb^{-1}$ pp collision sample collected in run1+run2
- 10^{11} b hadrons, 10^{12} c hadrons produced
- Cover all heavy flavour hadrons

Run1: @7/8 TeV

2010-12, $3fb^{-1}$

Run2: @13TeV

2015-18, $6fb^{-1}$

$X(3872)$ state

- The first exotic state, and confirmed by different experiments
- Its nature remains a mystery

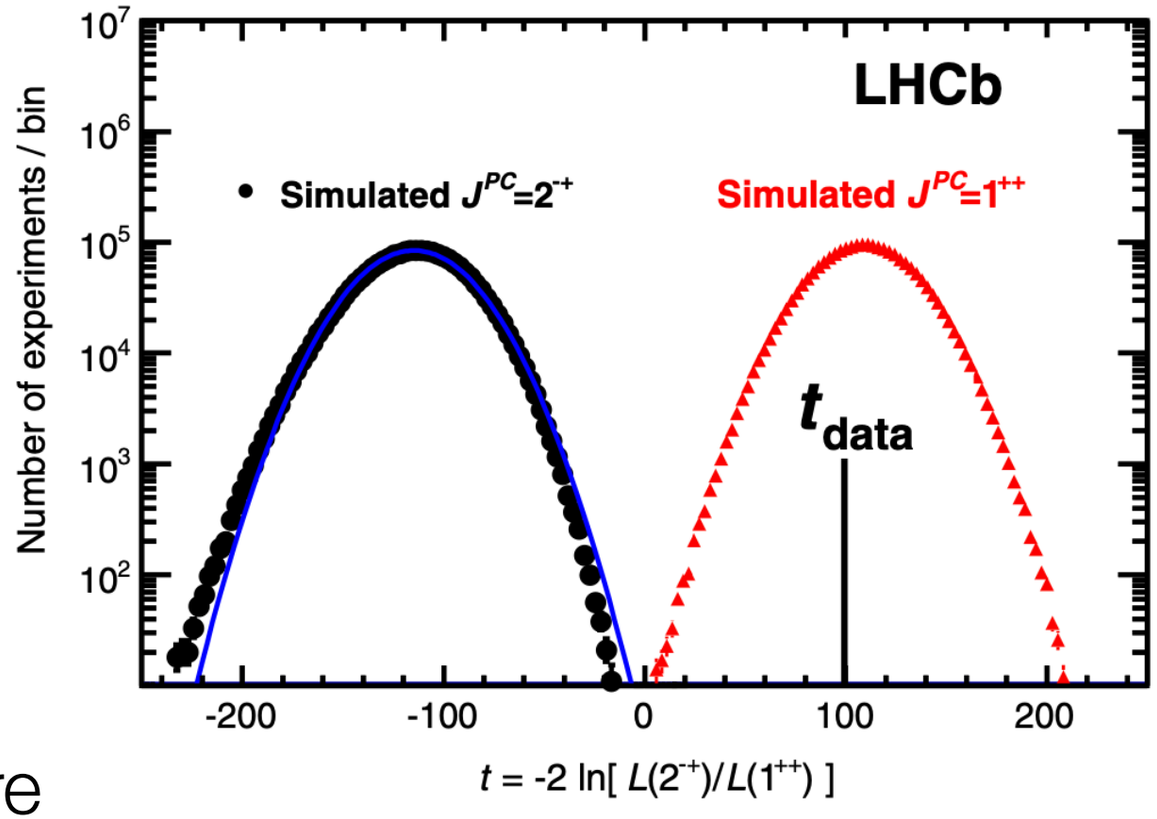
✓ 1^{++} determined by LHCb
rules out $\eta_{c2}(1^1D_2)$ state

✓ $X(3872) \to J/\psi\pi^+\pi^-,\pi^+\pi^-$
predominantly from ρ^0
indicates isospin violation

✓ Possible explanations:

molecule, tetraquark,
charmonium-molecule mixture

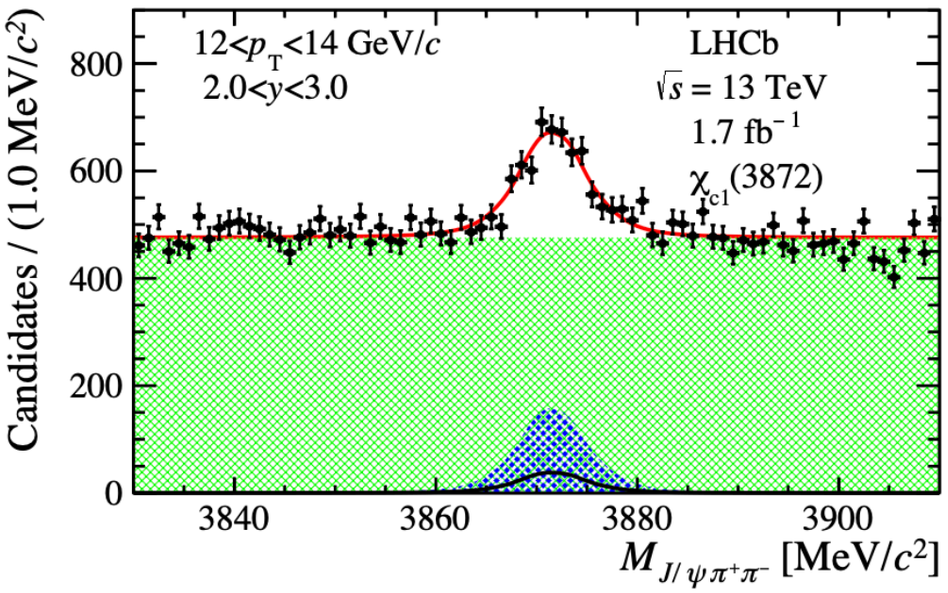
PRL 110(2013)222001

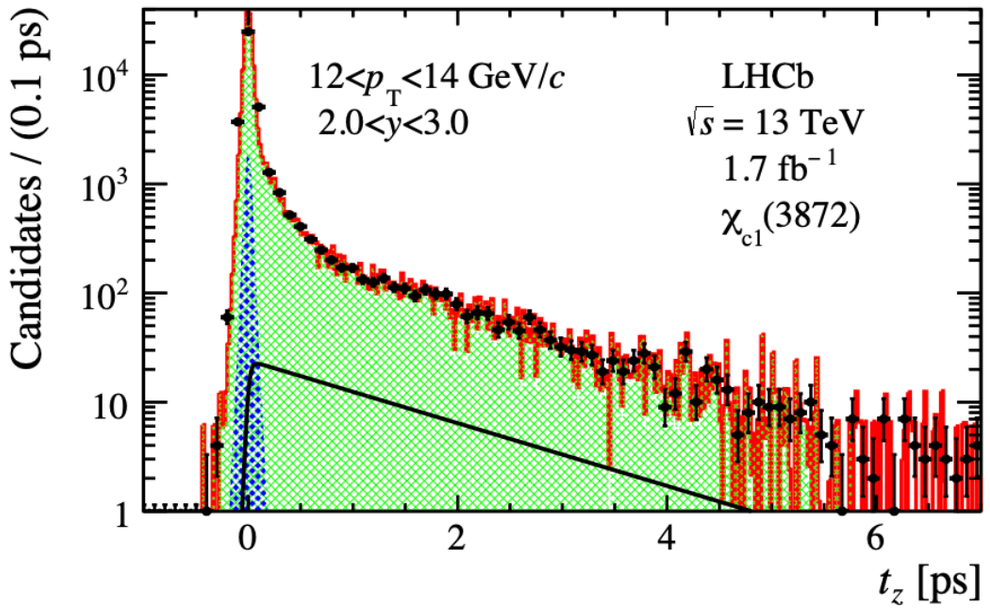


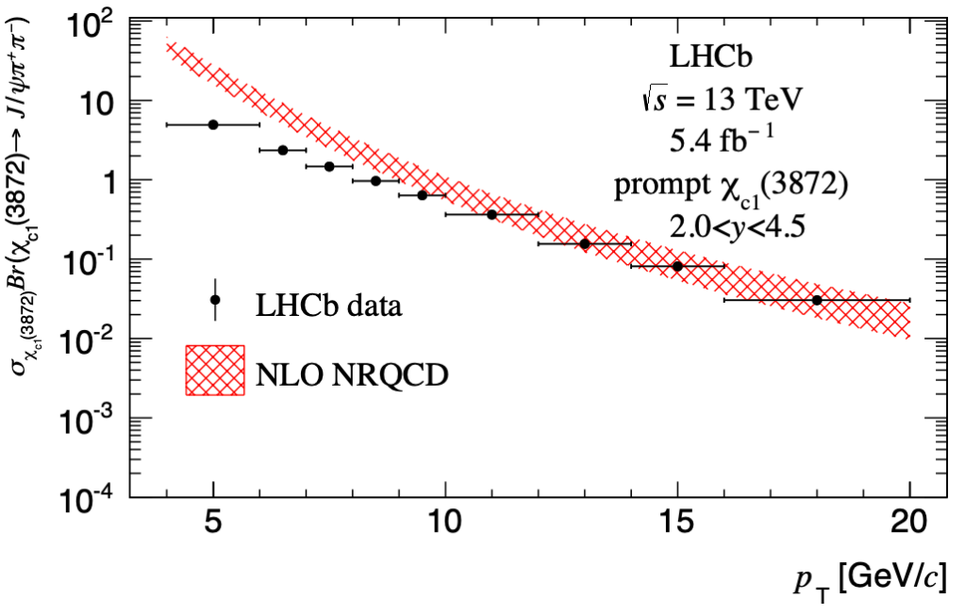
$X(3872)$ production

arXiv:2109.07360

Measured prompt and non-prompt production assuming X not polarized







NRQCD: assuming short-distance production dominantly through $\chi_{c1}(2P)$ in $\chi_{c1}(2P) - D^0\overline{D}^{*0}$ mixing model

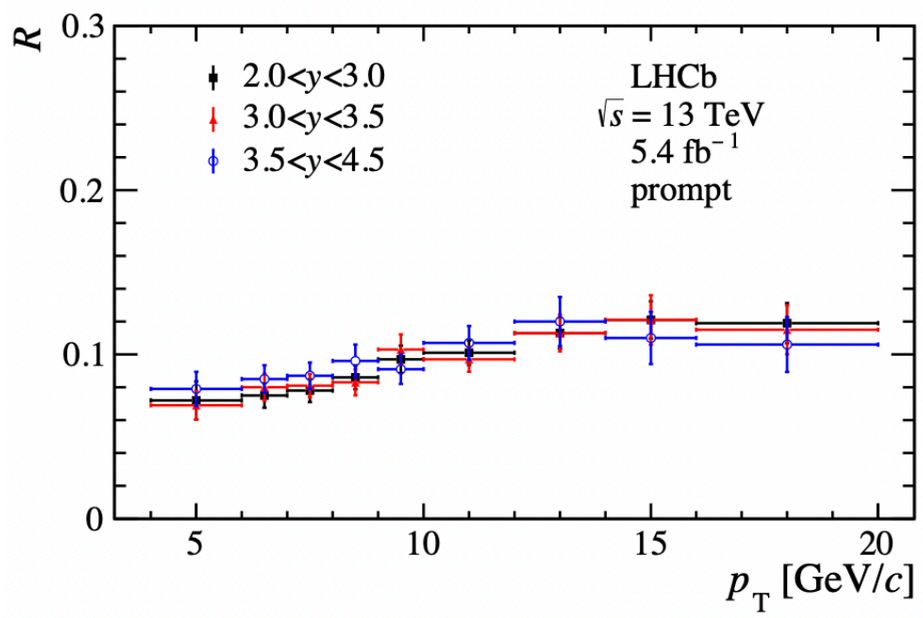
PRD96(2017)074014

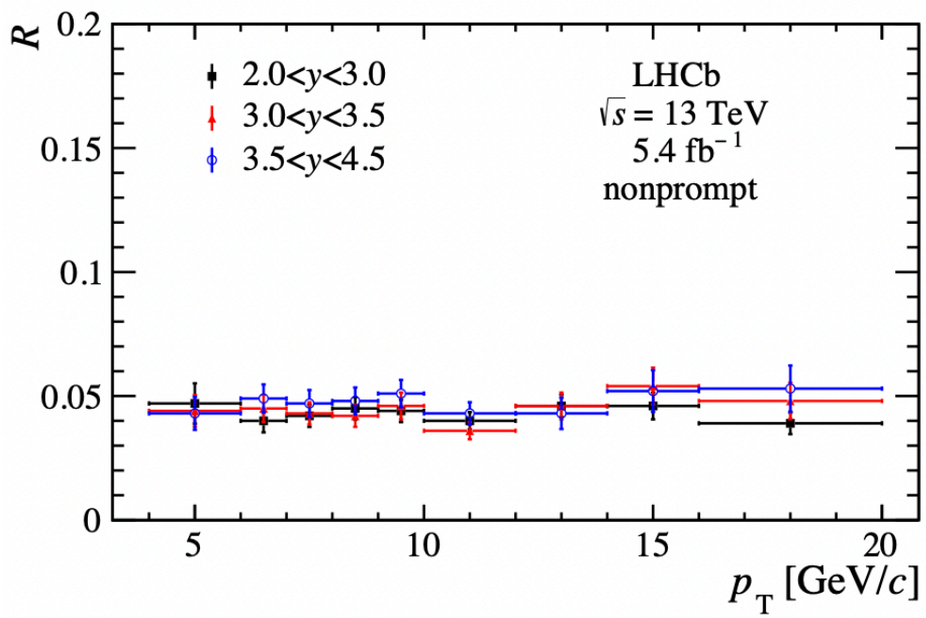
$X(3872)$ production

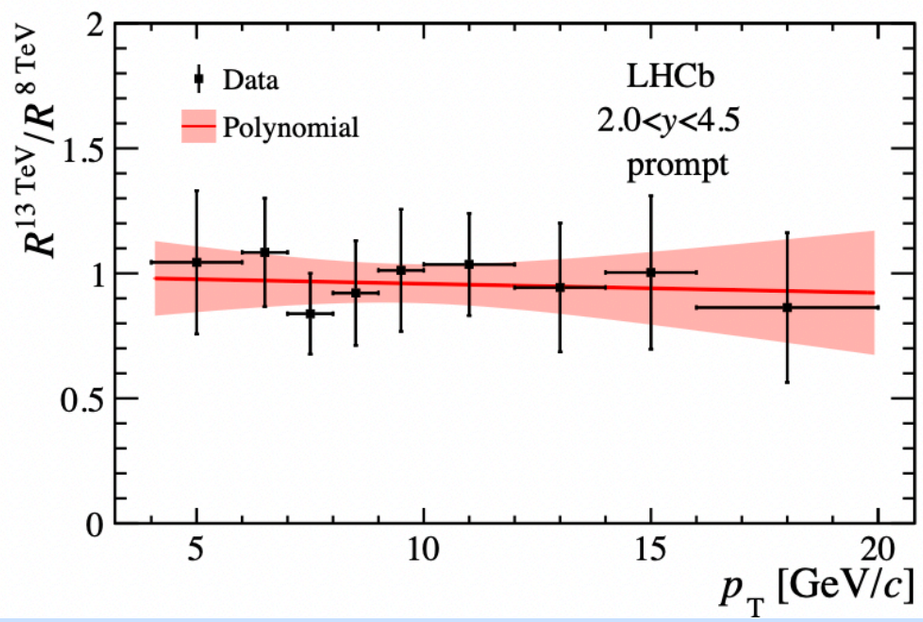
arXiv:2109.07360

- First measured ratios of differential cross-section times branching fraction

$$R \equiv \frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$





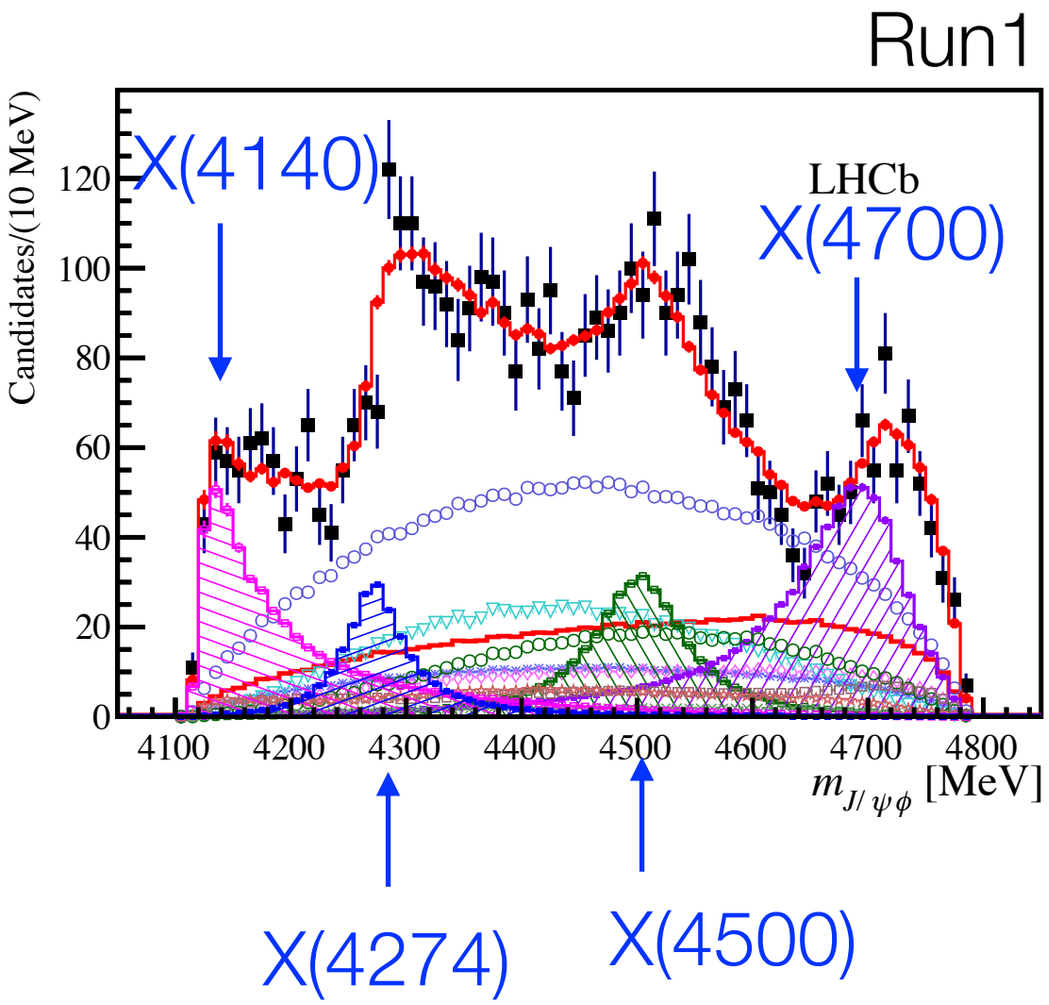


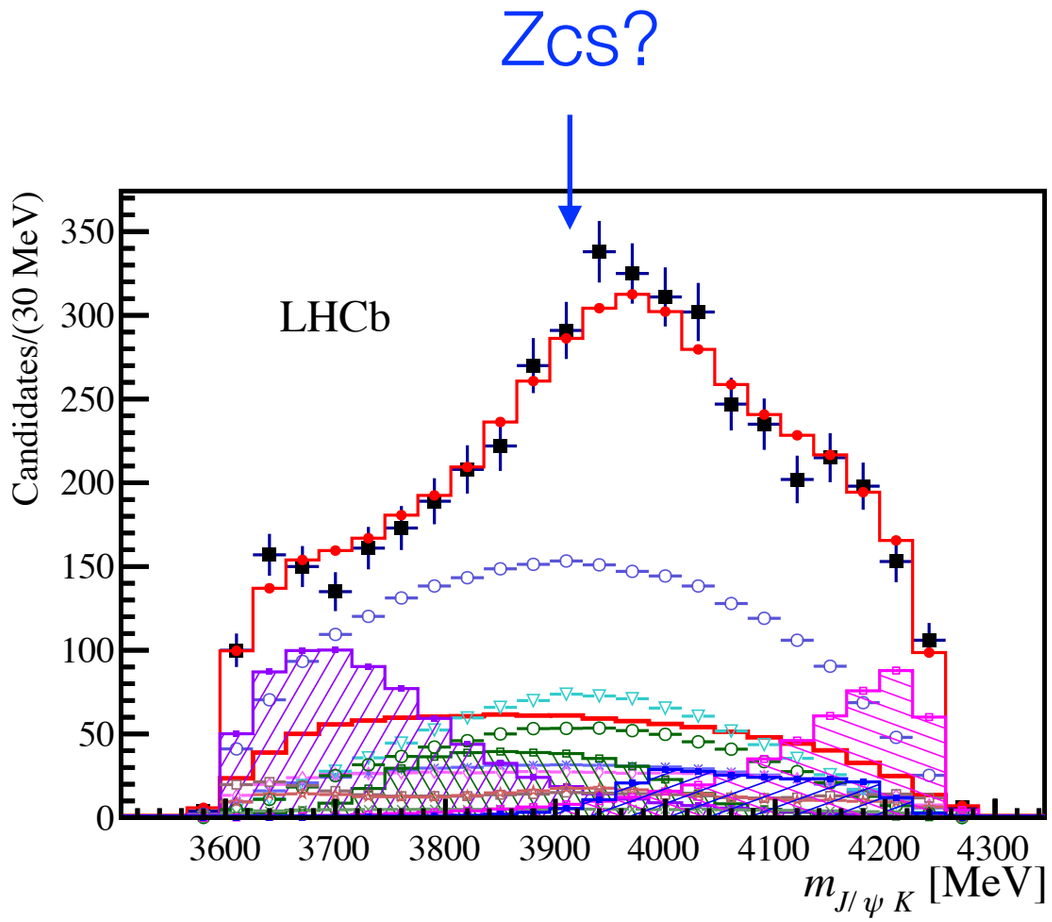
- Prompt results compatible between 8 and 13 TeV, no PT dependence

Tetraquarks in $B^+ \to J/\psi\phi K^+$ decays

PRL 118(2017)022003

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

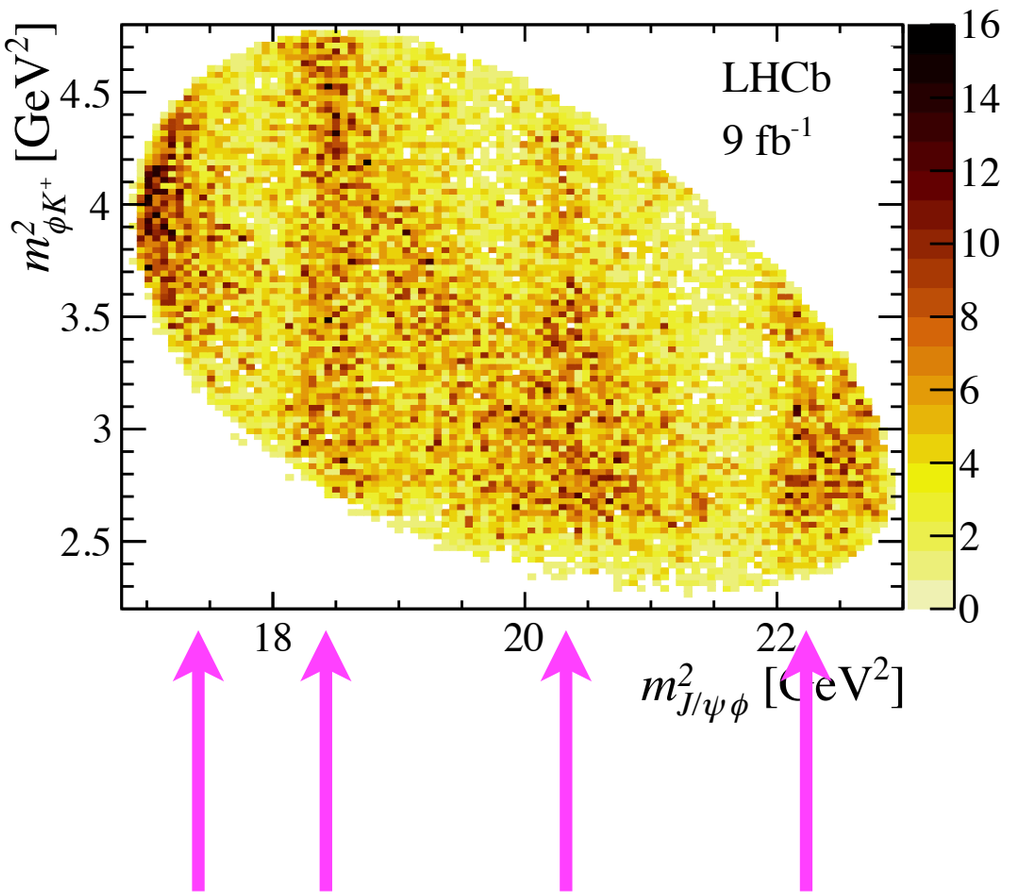


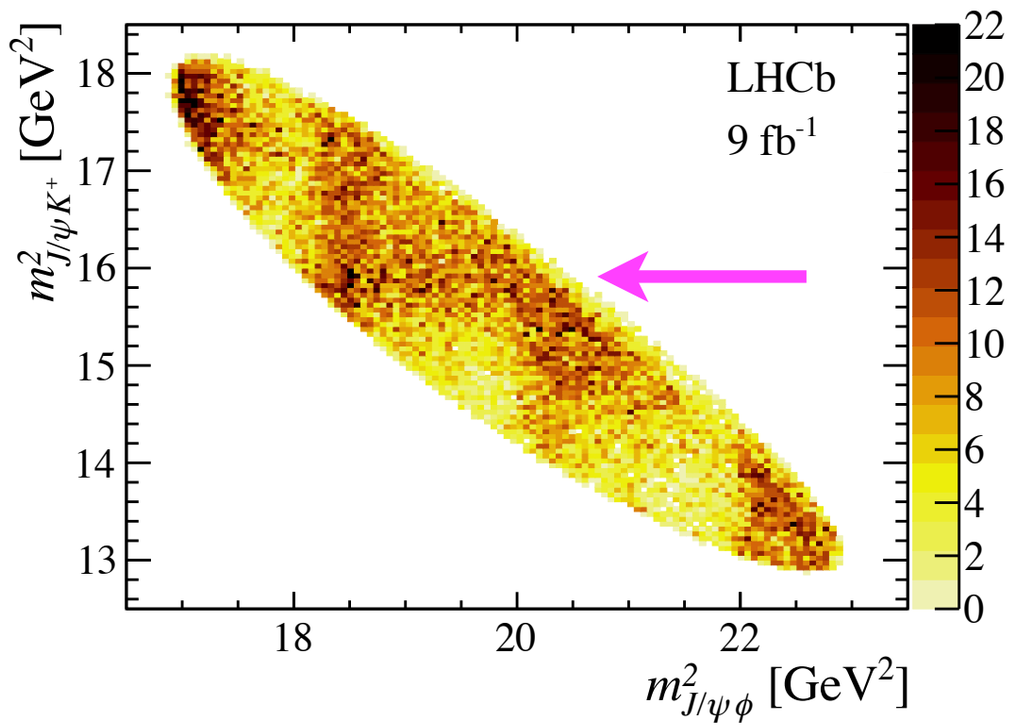


$B^+ \to J/\psi\phi K^+$ decays with run1 and run2

PRL 127(2021)082001

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

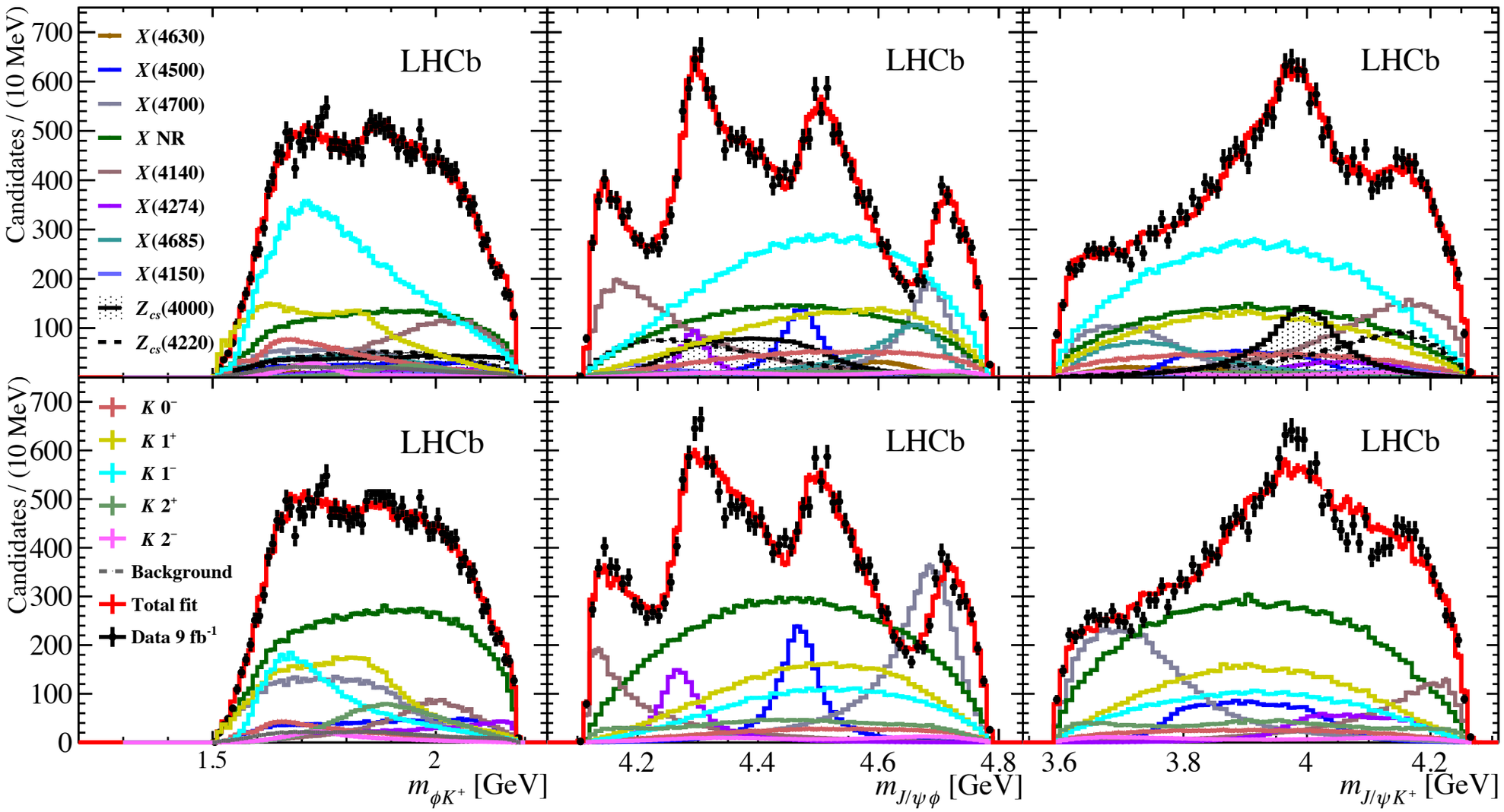




Models in amplitude analysis

PRL 127(2021)082001

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



Default model

Model in run1

Results of amplitude fit

PRL 127(2021)082001

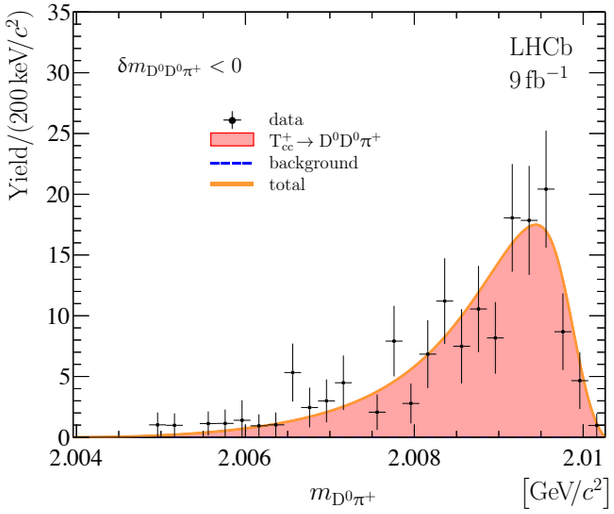
- Four X states observed in run1 confirmed
- New observation of X(4685)(1^+), X(4630), $Z_{cs}(4000)^+(1^+)$ and $Z_{cs}(4220)^+(1^+$ or $1^-)$

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

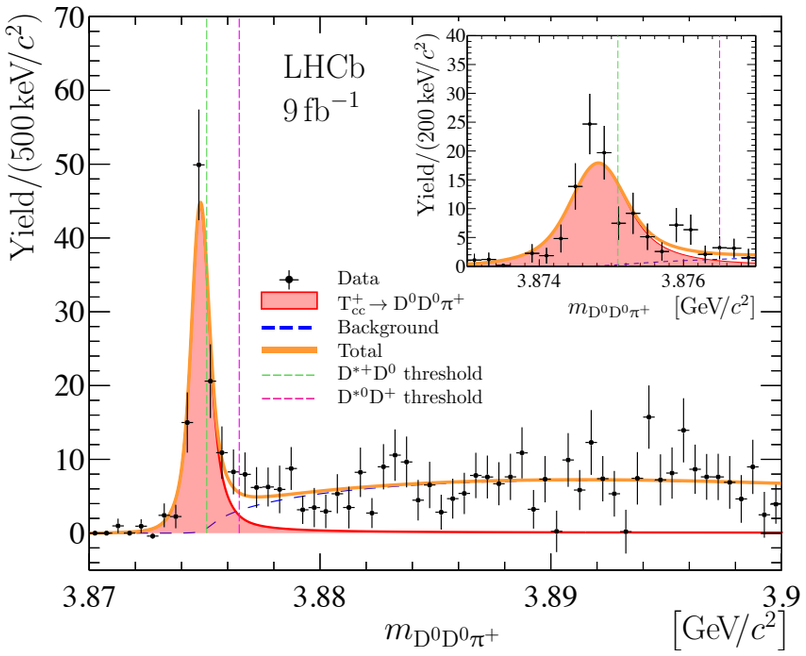
Observation of $T_{cc}^{+}\,(cc\bar{u}\bar{d})$

arXiv:2109.01038, 2109.01056

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

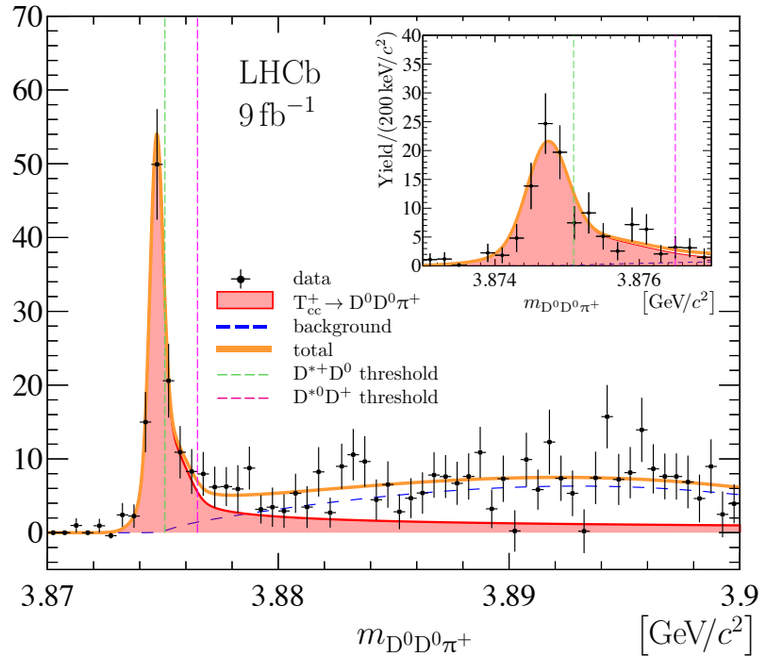


P-wave RBW



Parameter	Value
N	117 ± 16
$\delta m_{\rm BW}$	-273 ± 61 keV/c^2
$\Gamma_{\rm BW}$	410 ± 165 keV

Unitarized BW



Parameter	Value
N	186 ± 24
$\delta m_{\rm U}$	-359 ± 40 keV/c^2
$\lvert g\rvert$	3×10^4 GeV (fixed)

better access to tail above threshold

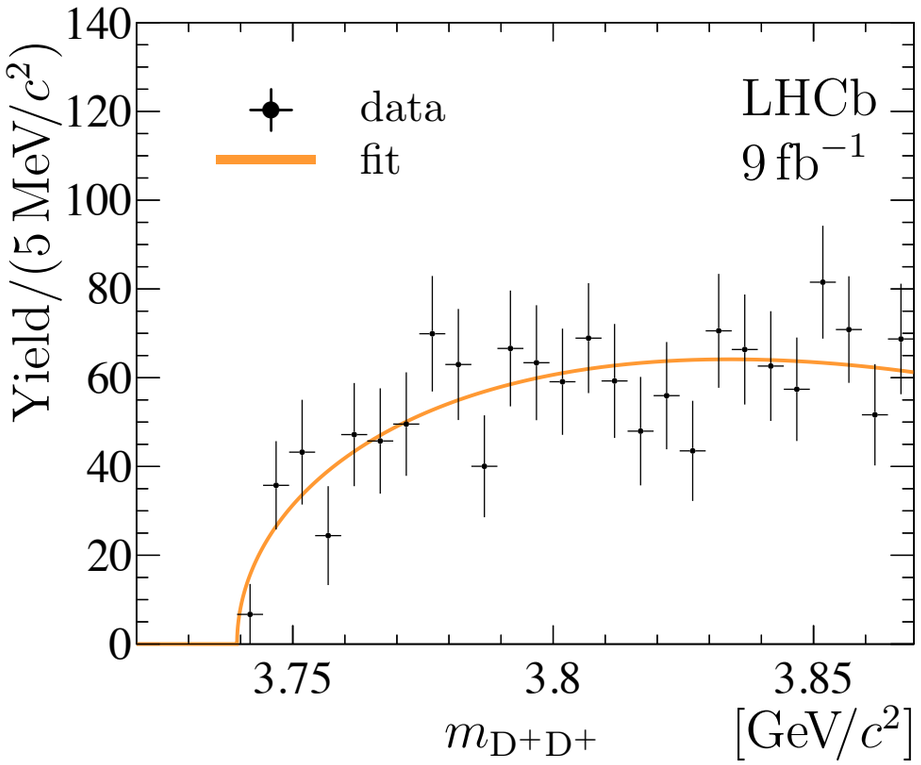
Peak below $D^{*+}D^0$ threshold with large significance

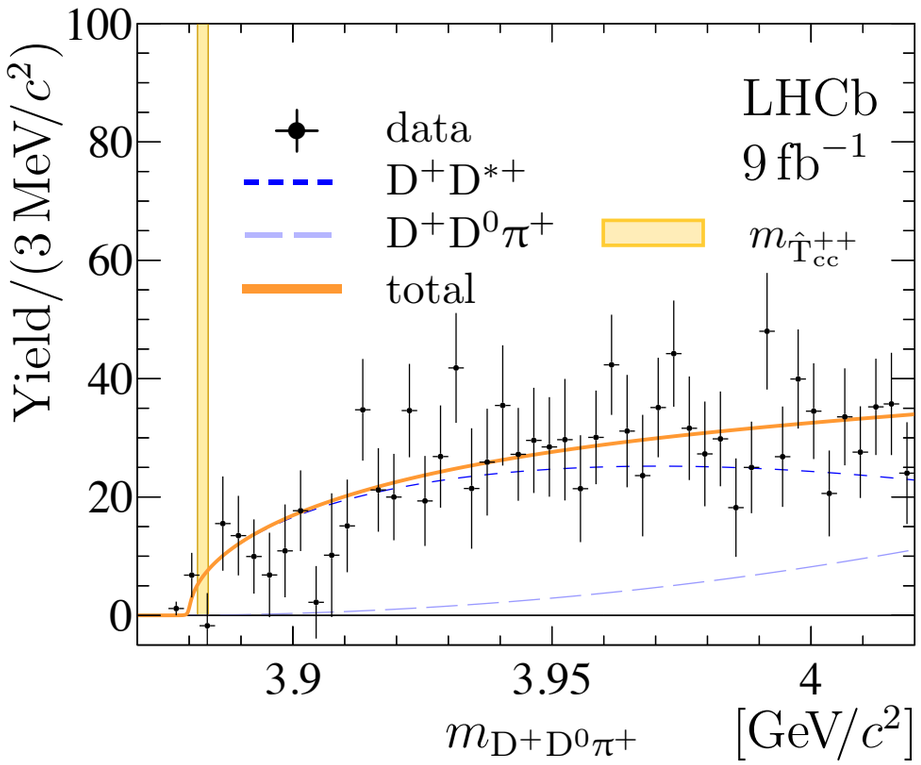
Observation of T_{cc}^{+} $(cc\bar{u}\bar{d})$

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

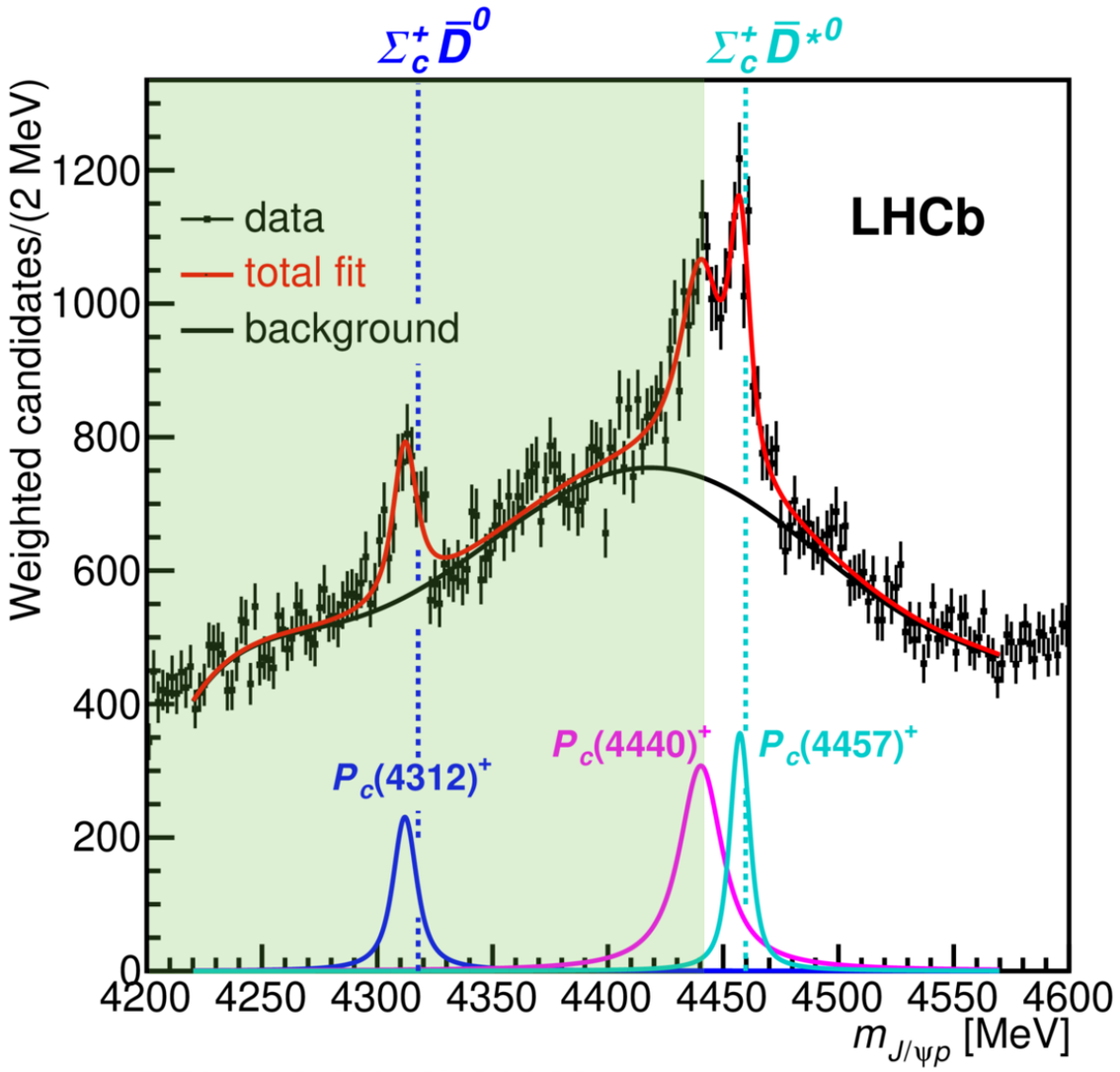
- Consistent with $J^P=1^+$ ground state isoscalar



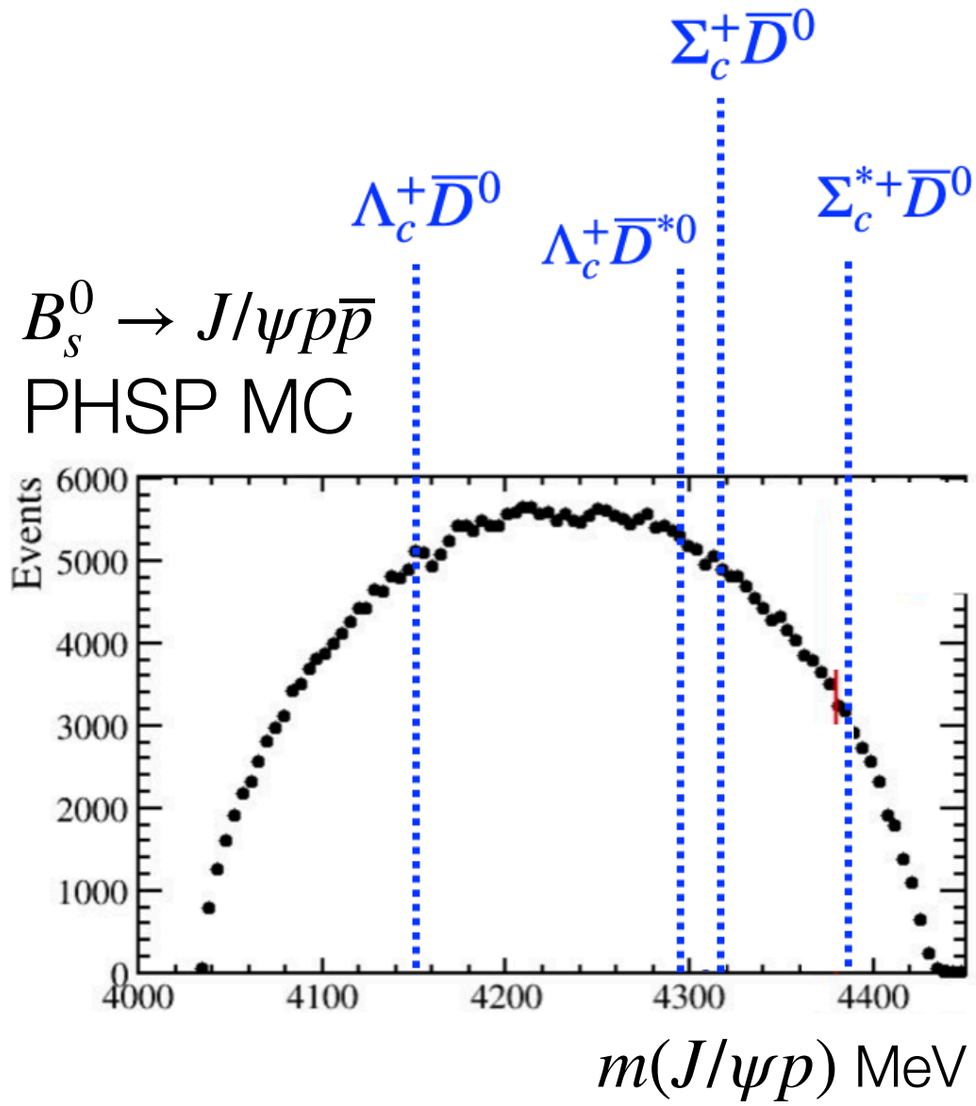


P_c^+ search in $B_s^0 \to J/\psi p\bar{p}$ decays

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



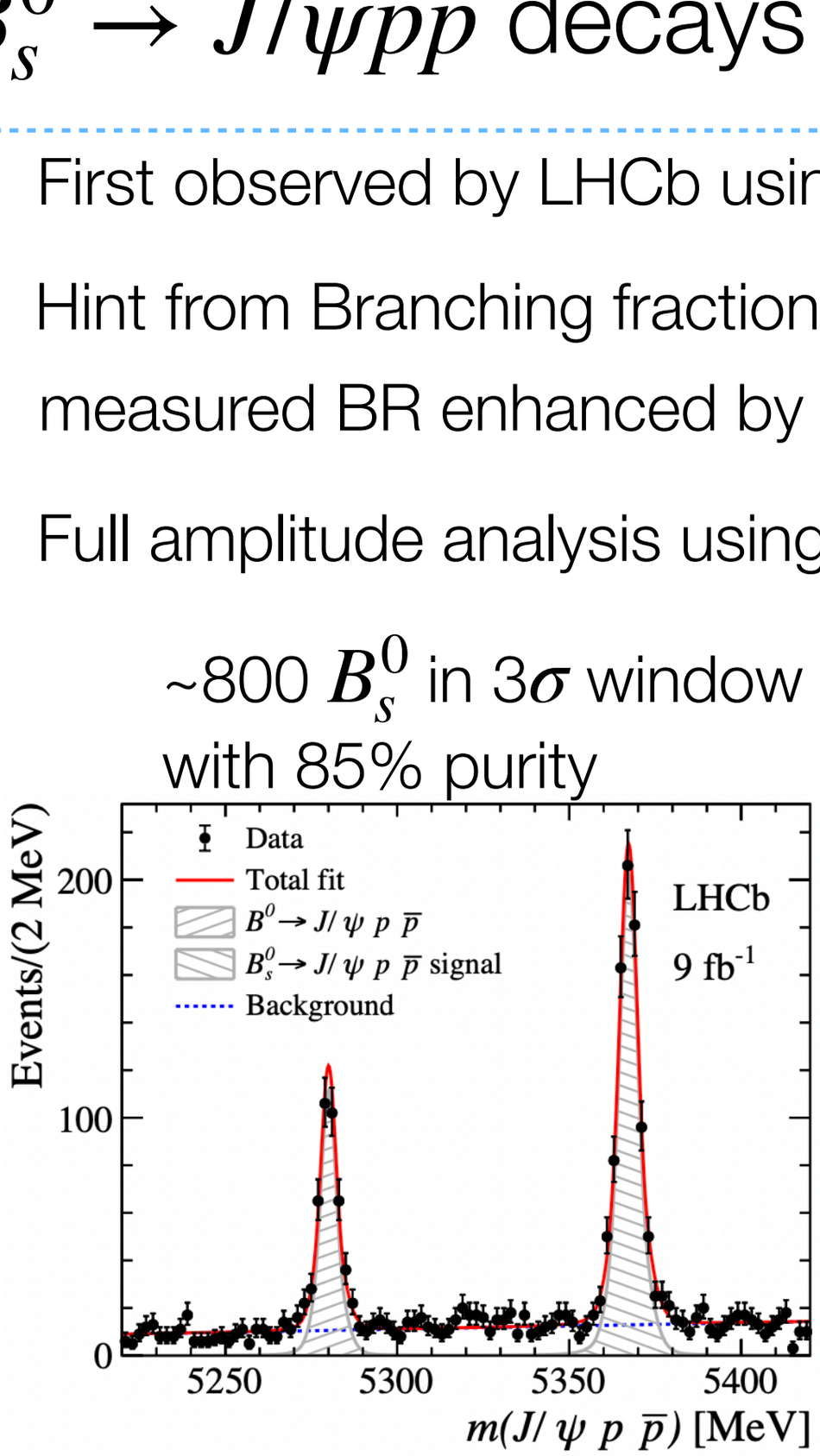
PRL 122 (2019) 222001

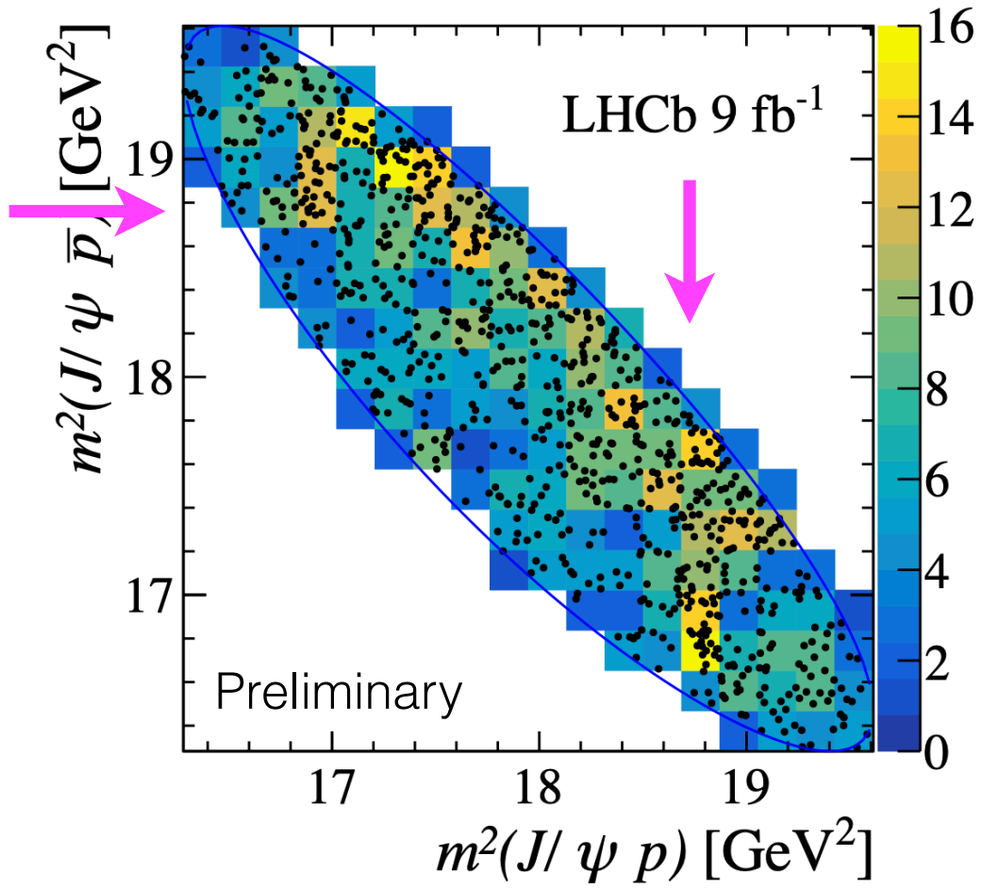


$B_s^0 \to J/\psi p\bar{p}$ decays

- First observed by LHCb using 5.2fb^{-1} data
- Hint from Branching fraction measurement PRL122(2019)191804
  measured BR enhanced by 2 orders w.r.t estimation w/o resonances
- Full amplitude analysis using 9fb^{-1} data

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





Baseline amplitude model

arXiv:2108.04720

- 4D amplitude using helicity formalism

- Untagged B decay

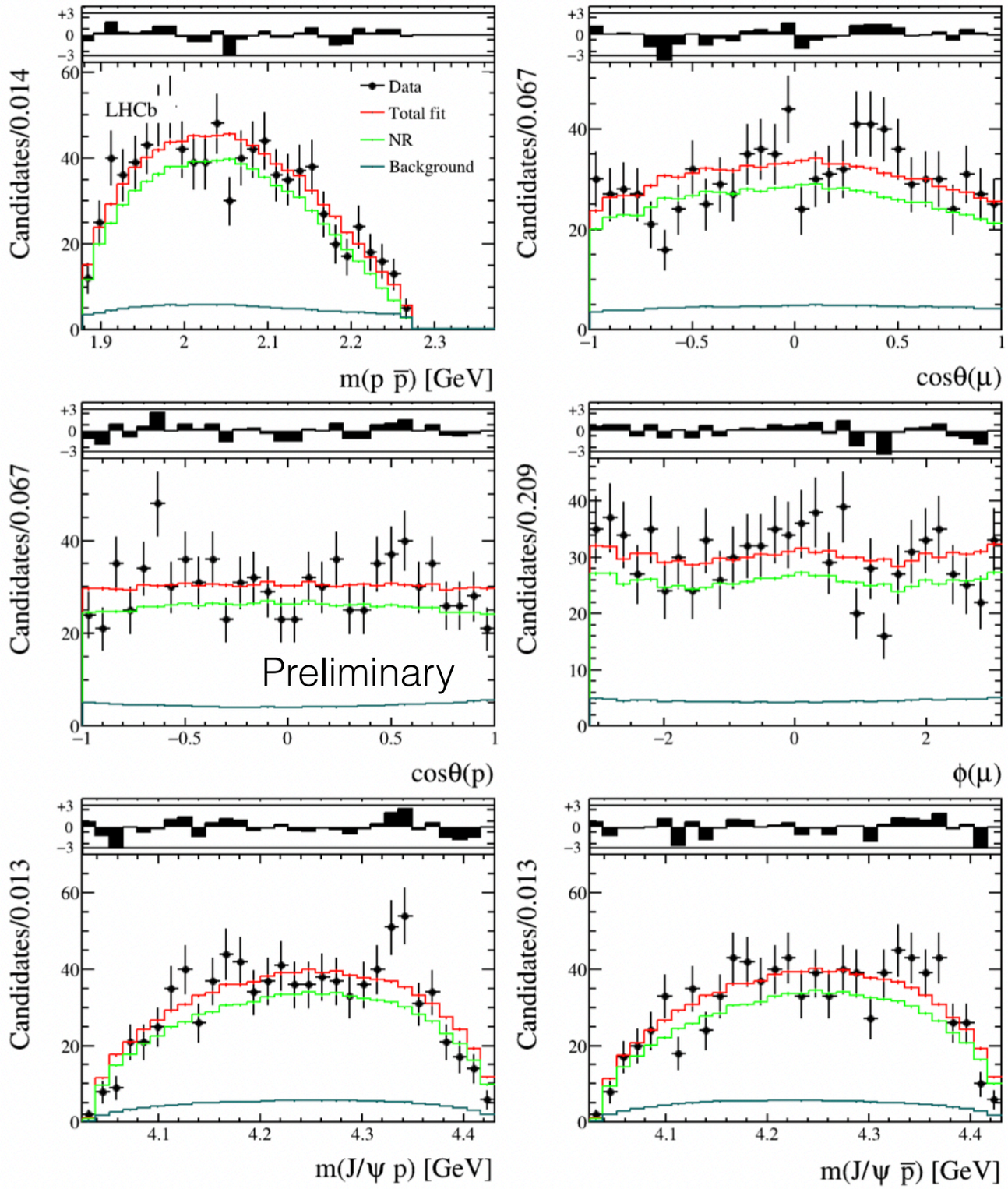
  CP conservation:

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

  Total amplitude:

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

- Baseline model can not describe data well



Amplitude fit with P_c

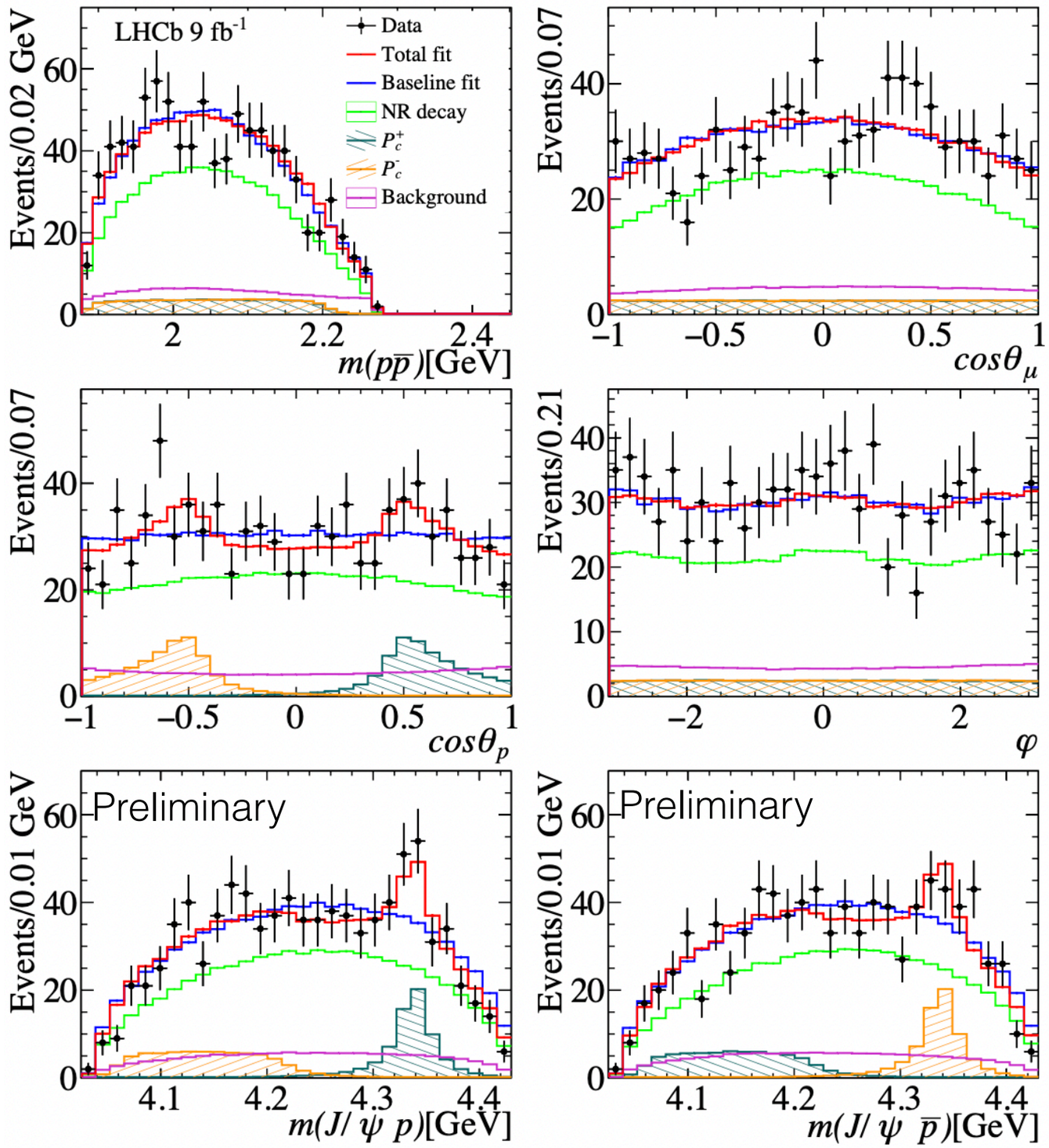
arXiv:2108.04720

- Add $P_c^+ \to J/\psi p, P_c^- \to J/\psi \bar{p}$
- The same mass, width and couplings for $P_c^{\pm}$
- Evidence for new $P_c(4337)^+$ significance 3.1~3.7σ for $J^P(1/2^{\pm},3/2^{\pm})$

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

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

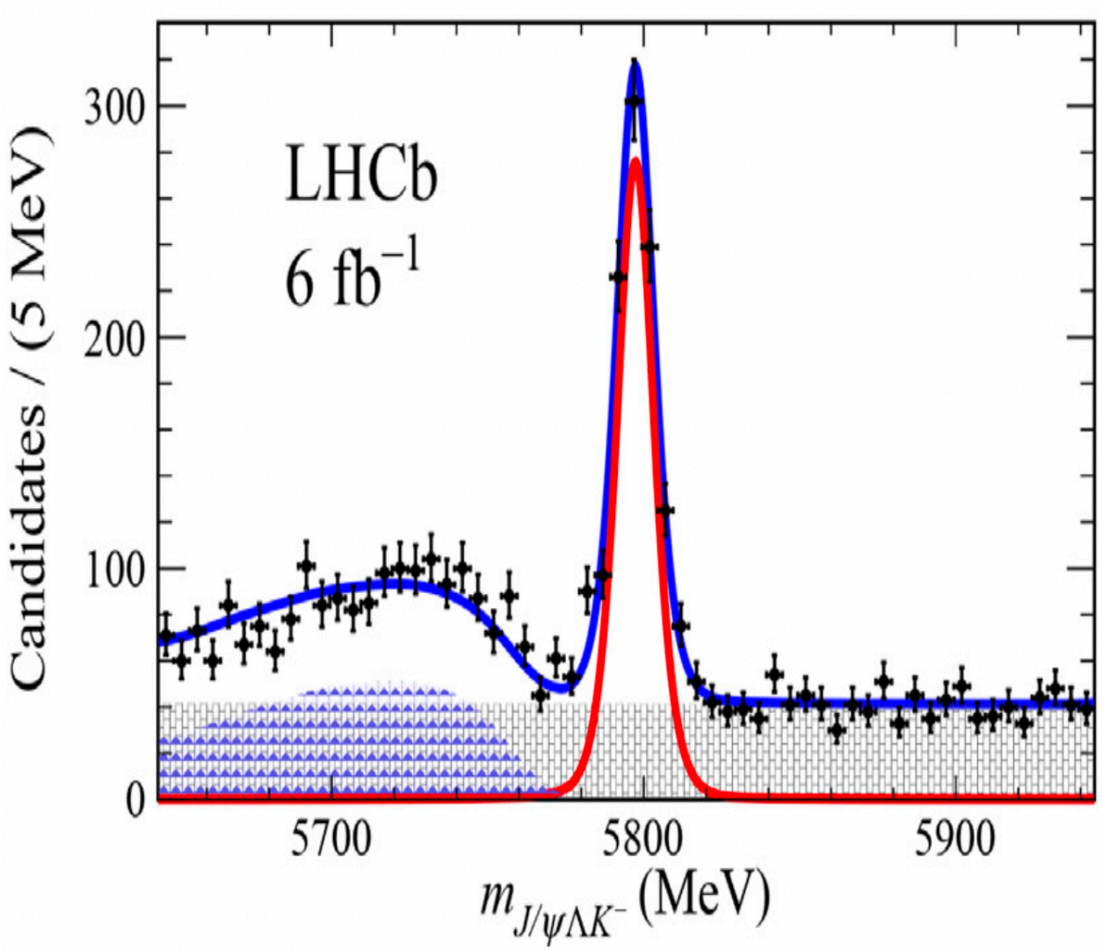
- No evidence for $P_c(4312)^+$, and structures in $p\bar{p}$ system

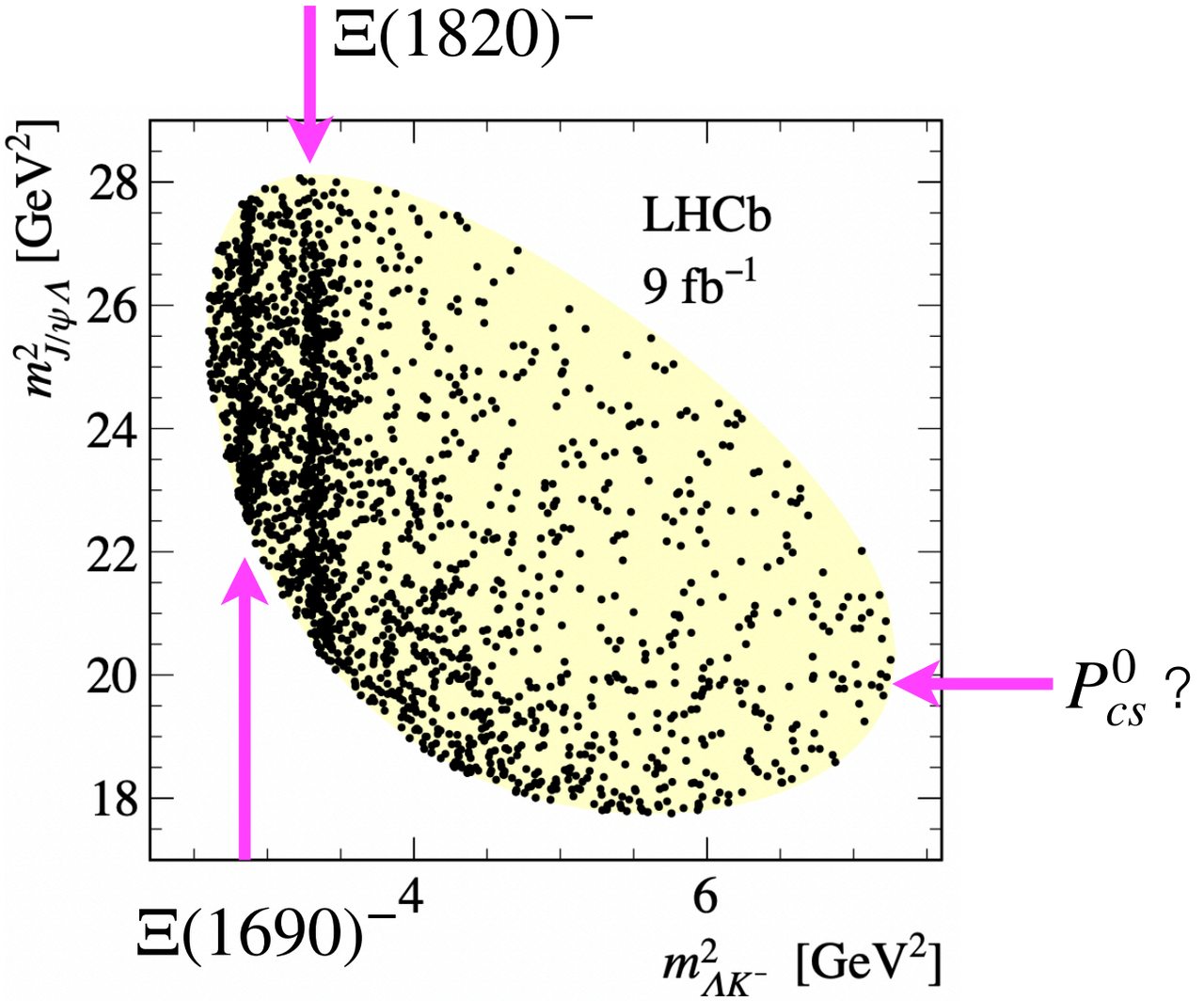


P_{cs}^0 search in $\Xi_b^- \to J/\psi\Lambda K^-$ decays

Sci.Bull.66(2021)1278-1287

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

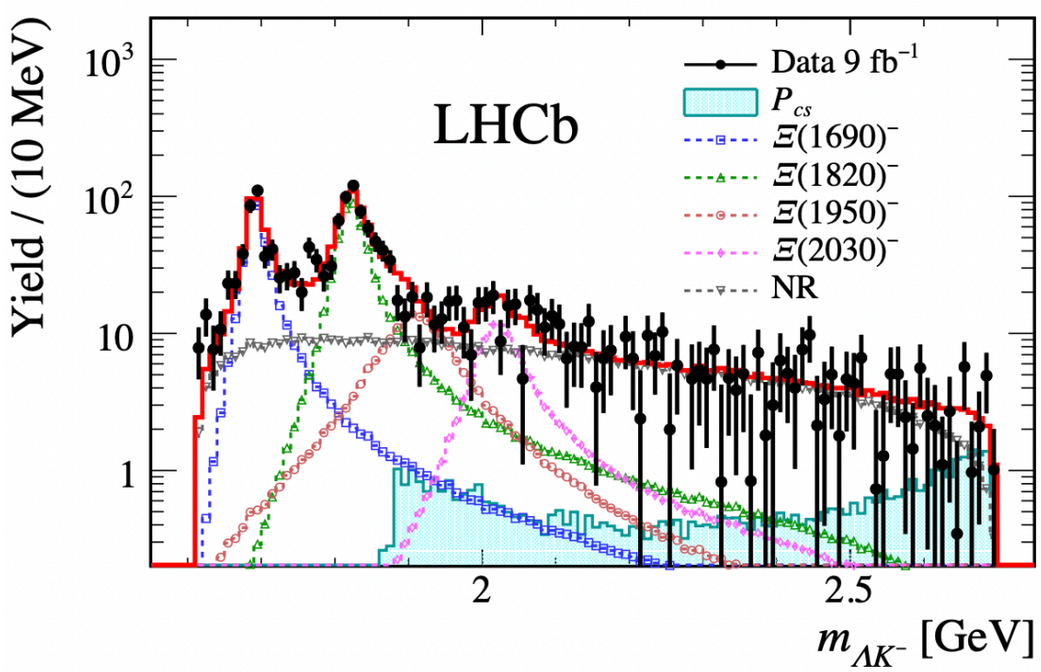


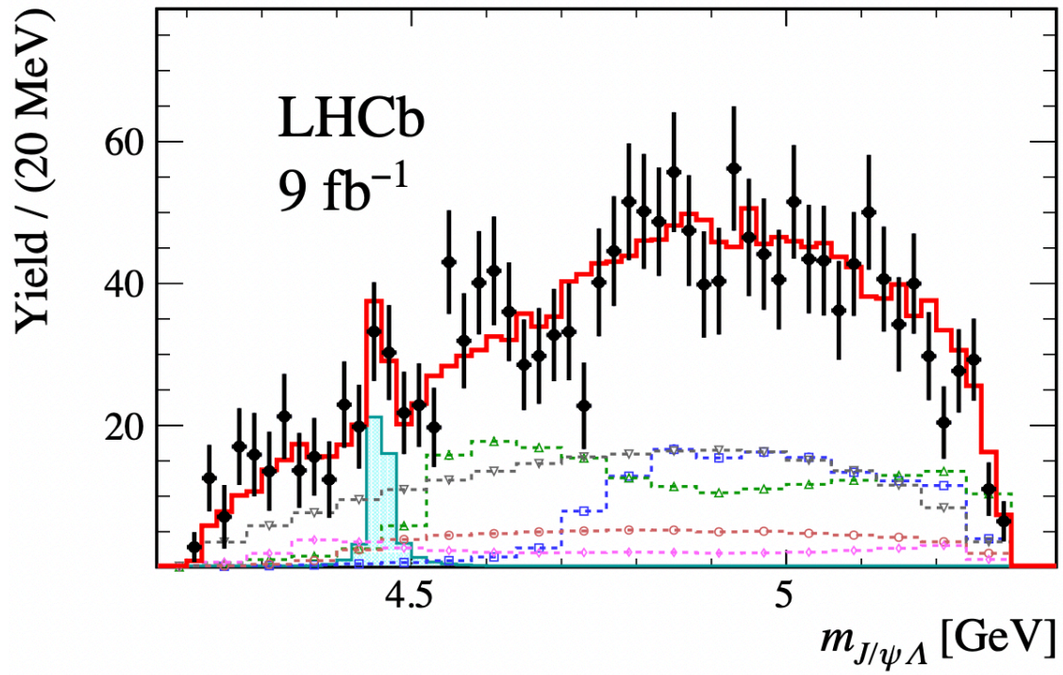


Amplitude analysis results

Sci.Bull.66(2021)1278-1287

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

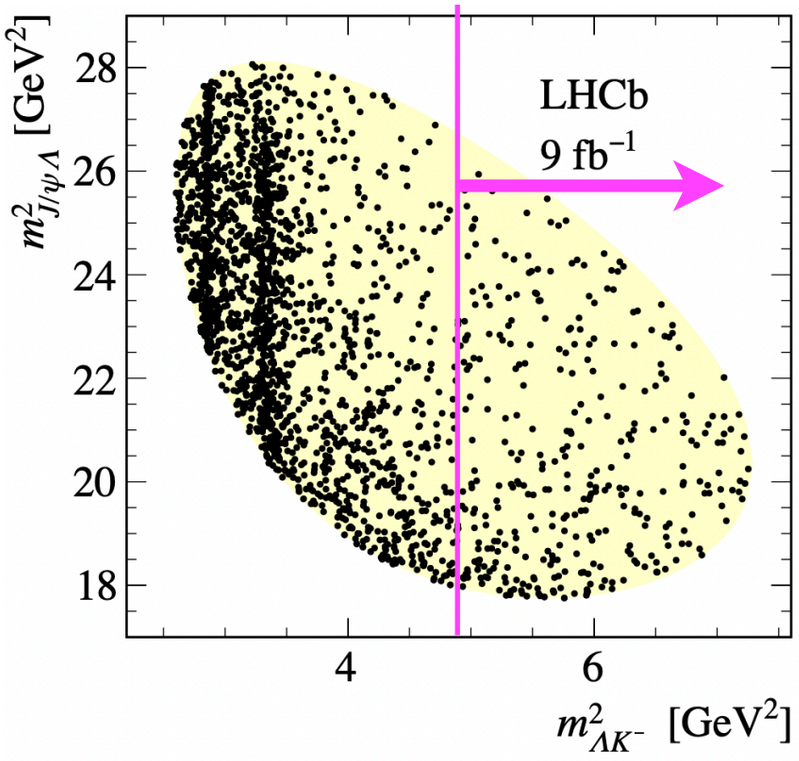




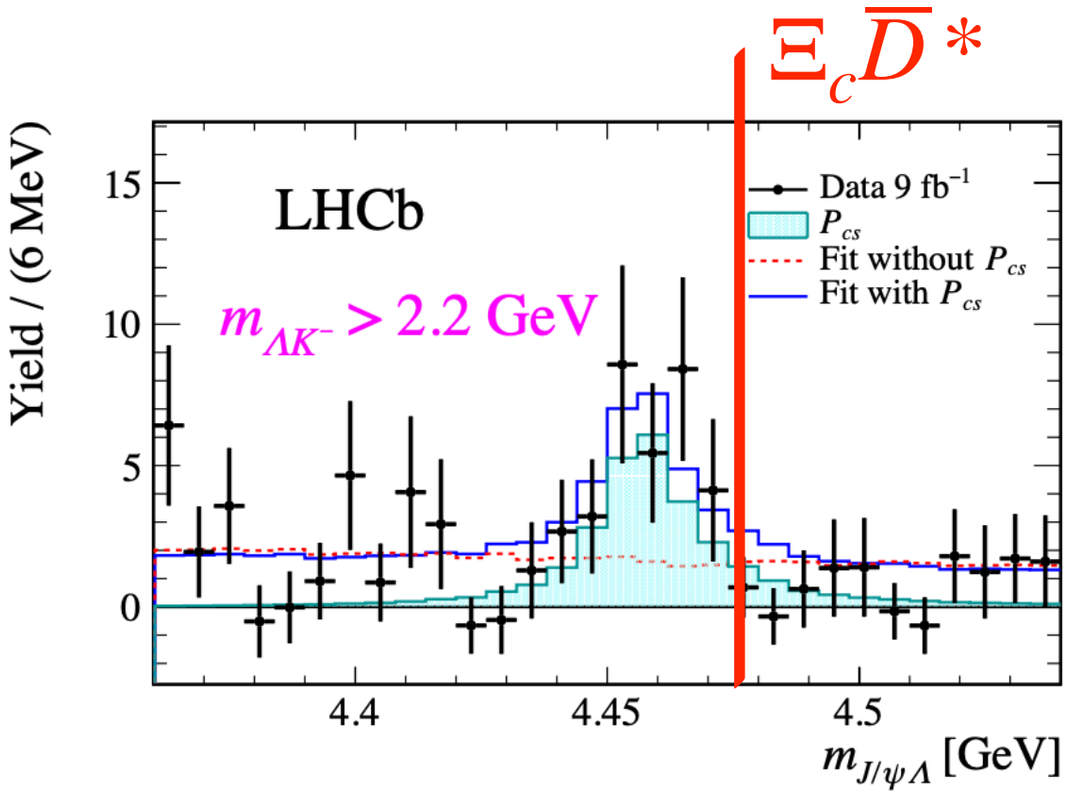
State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2+6.9}_{-6.2-4.1}$
$\Xi(1950)^-$	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	–	–	$35.8\,^{+4.6+10.3}_{-6.4-11.2}$

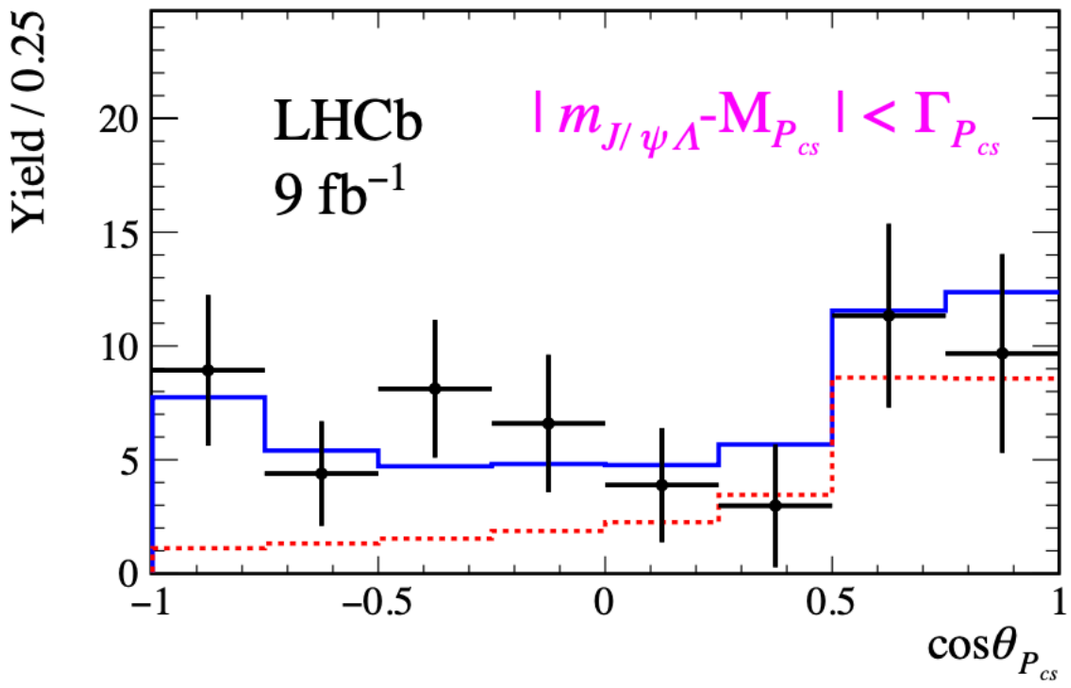
Highlight of $P_{cs}^{0}(4459)$ contribution

Sci.Bull.66(2021)1278-1287



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

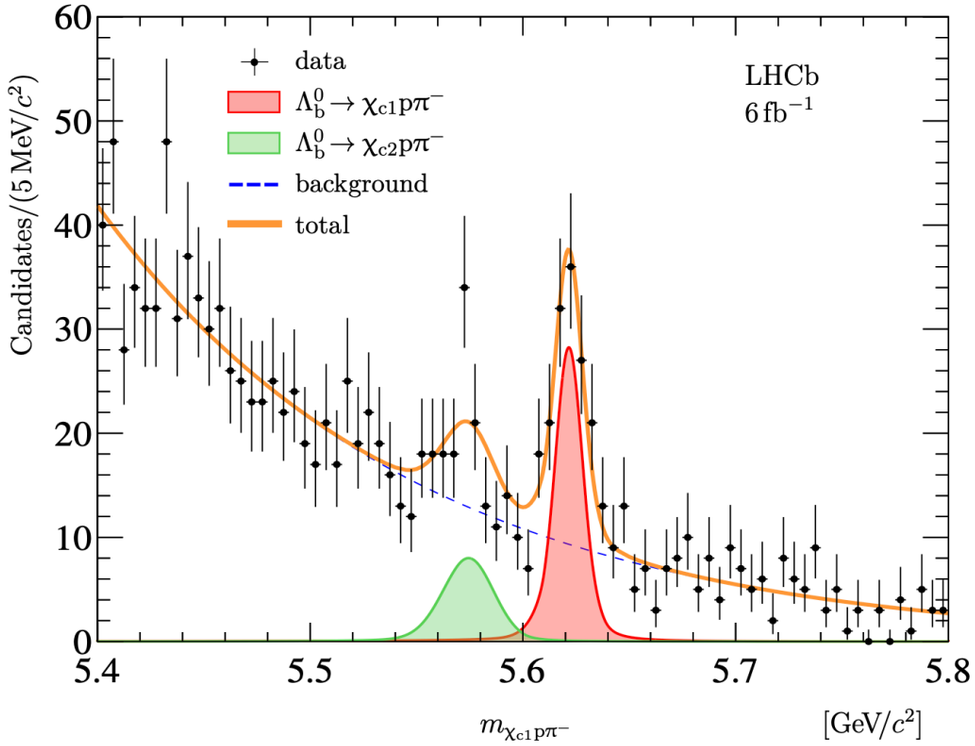


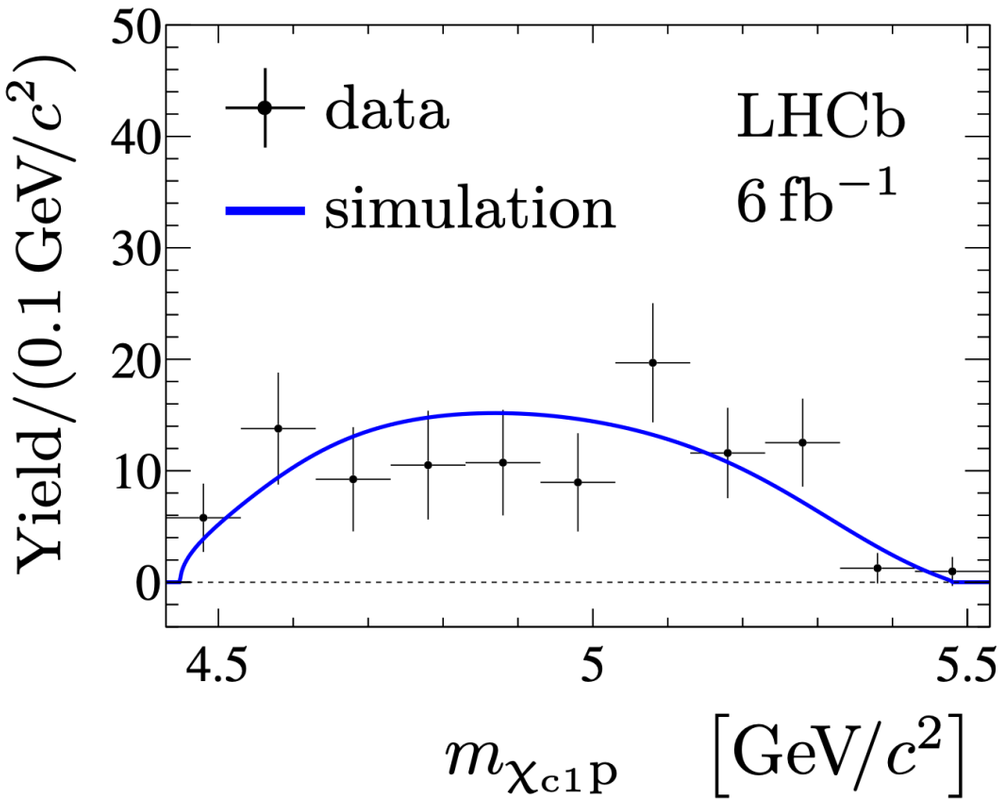


Pentaquark searches in $\Lambda_b^0 \to \chi_{c1} p \pi^-$ decays

JHEP 05(2021)95

- Extend pentaquark searches to $\chi_{c1}p$ system
- First observation of decay using run2 data
- No evidence for structures in $m_{\chi_{c1}p}$ distribution





Pentaquark searches in $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decays

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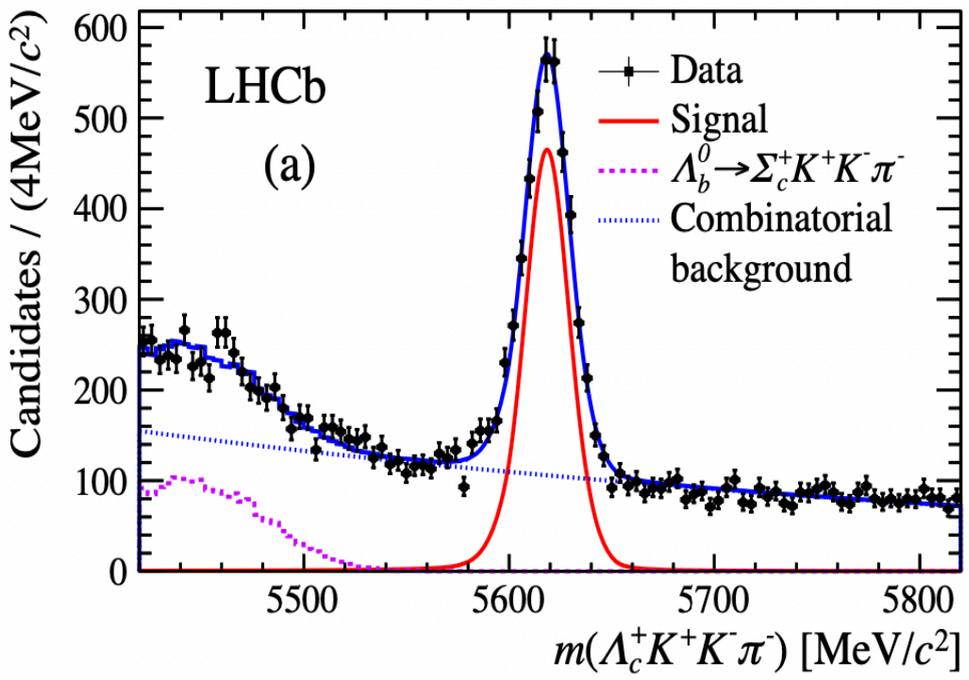
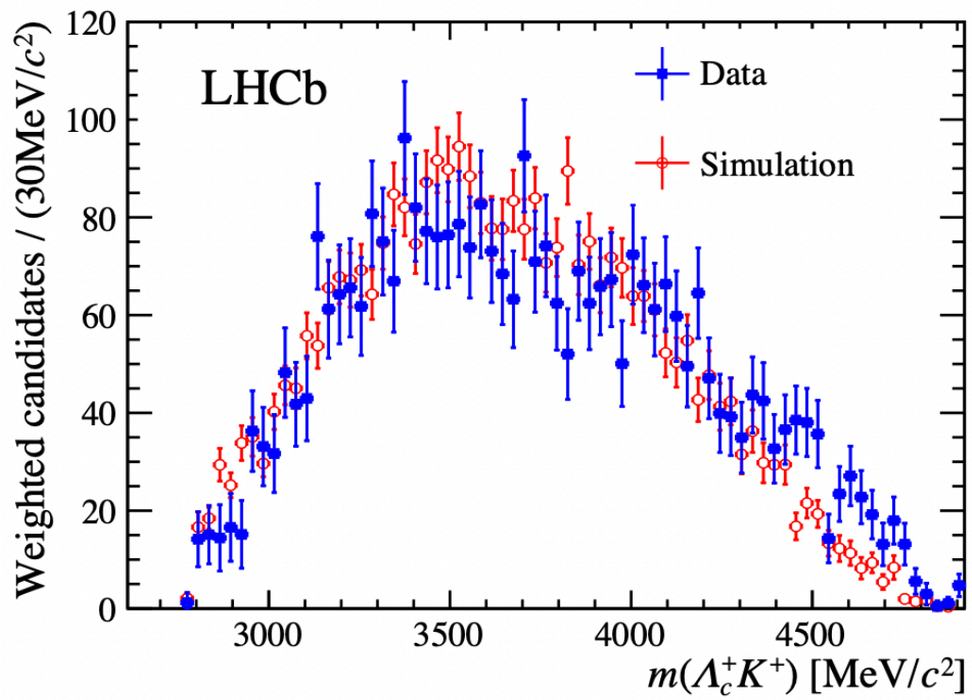
- Search for open-charm pentaquark $c\bar{s}uud \to \Lambda_c^+ K^+$
- No evidence seen using run1 data





Summary

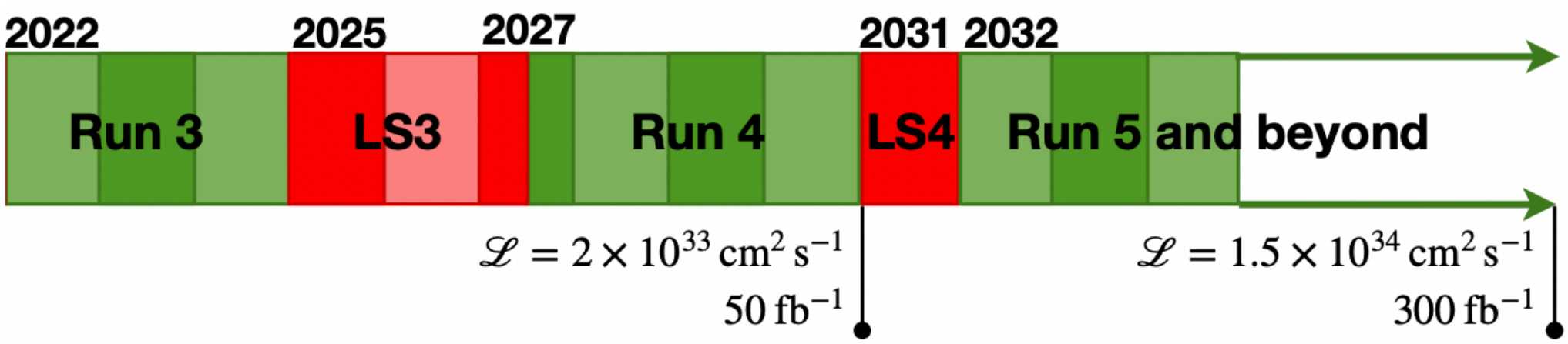
- Recent results on exotic hadrons at LHCb are presented

  X(3872) production

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

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

- LHCb Upgrade will restart soon, and lots of interesting results are expected



Thank you!