FPCP2022

Exotic Hadrons at LHCb

Chuangxin Lin

(On behalf of the LHCb Collaboration)

University of Chinese Academy Sciences

FPCP 2022, 24^{th} May, Mississippi (USA), virtual participation

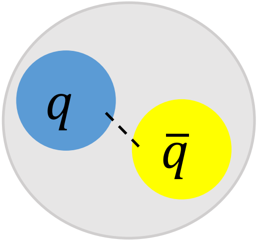
Introduction

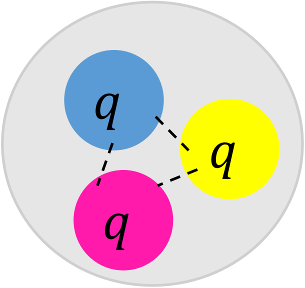
Phys. Lett., 8:214-215 (1964)

Hadron spectroscopy is very important to probe low-energy non-perturbative QCD dynamics

Conventional hadrons:
Quarks are confined in mesons and baryons

mesons





baryons

Multi-quarks states are first predicted in 1964 in quark model original paper, by M. Gell-Mann and G. Zweig

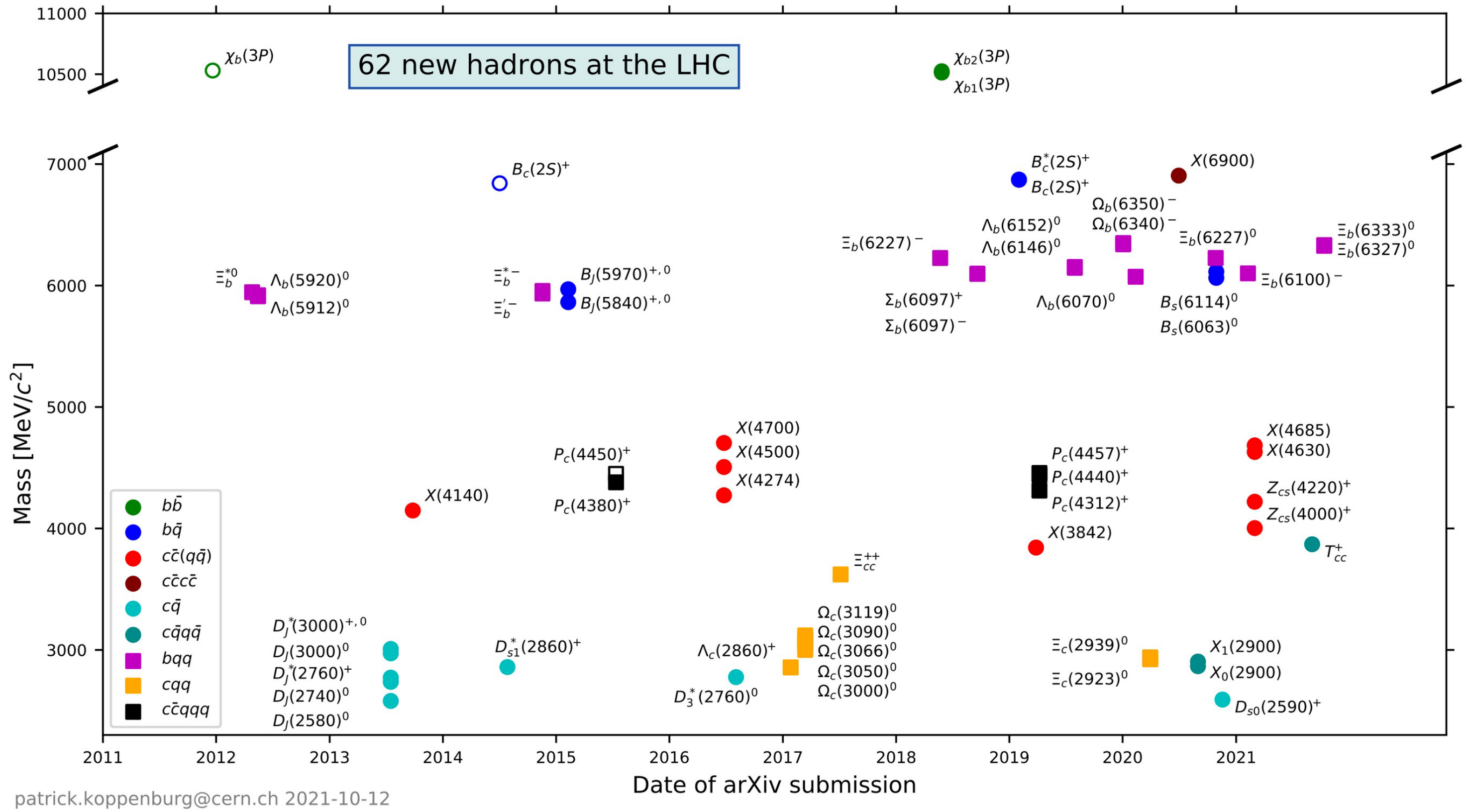
Exotic hadrons:
different multi-quarks compounds are allowed

tetraquarks

pentaquarks

Spectroscopy at LHCb

62 new hadrons discovered at LHC and 18 of them are ‘exotic’

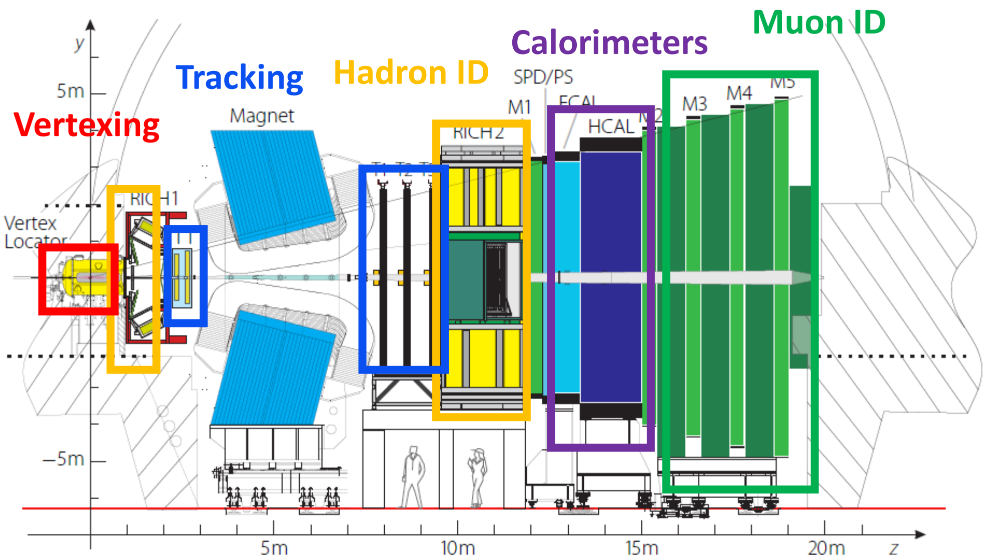


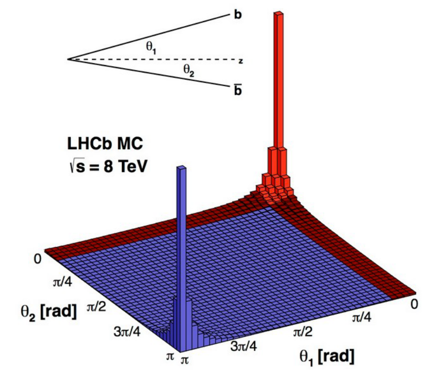
A real new hadrons discovery machine, major contribution to the hadron taxonomy

How multi-quark states bind is still largely mysterious!

The LHCb experiment

JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022



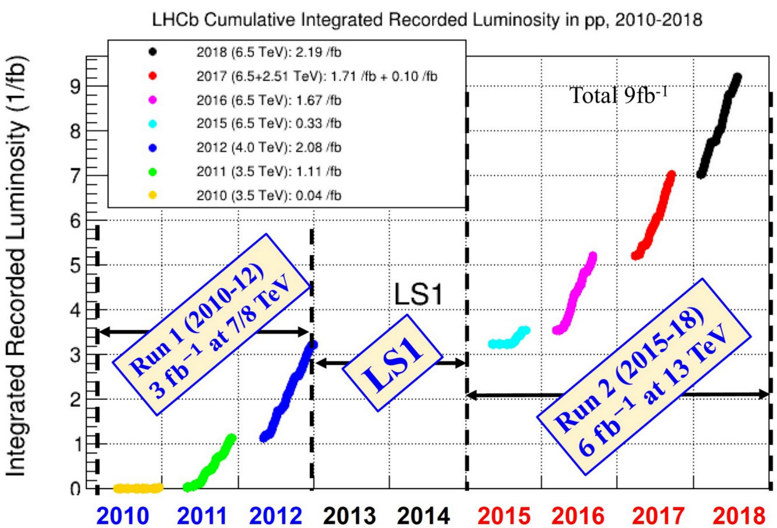


Single arm spectrometer, 25% of $b\bar{b}$ pairs produced in the acceptance

Designed to study heavy hadron decays

Unique kinematic region: high rapidity ($2 < \eta < 5$) and low p_{T}

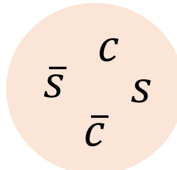
Excellent tracking, momentum resolution and particle identification

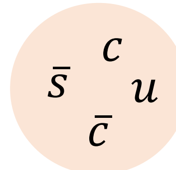


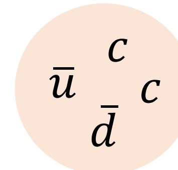
Overview of selected results

PRL 118, 022003 (2017), PRL 127, 082001 (2021)
arXiv:2109.01056v2, arXiv:2109.01038

Tetraquarks:





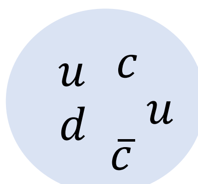


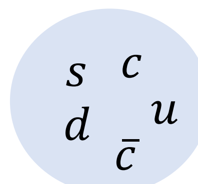
Observation of new $X \to J/\psi\,\phi$ and $Z_{cs} \to J/\psi\,K^+$ states in $B^+ \to J/\psi\,\phi K^+$

Study of the Doubly-charmed tetraquark T_{cc}^+ in prompt $D^0D^0\pi^+$

Sci.Bull. 66, 13, 1278-1287 (2021)
PRL 128 (2022) 062001

Pentaquarks:





Evidence of $J/\psi\,\Lambda$ structure in $\Xi_b^- \to J/\psi\,\Lambda K^+$

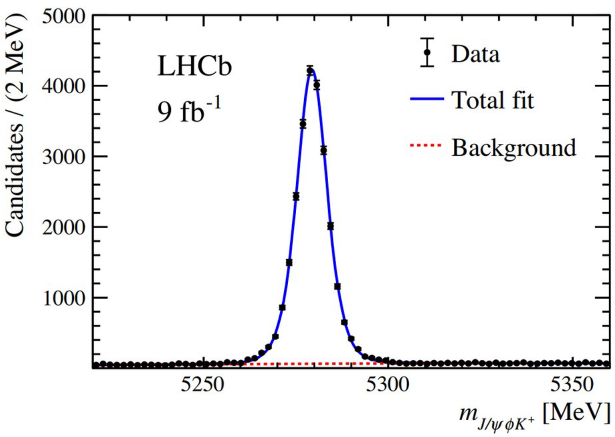
Searching for pentaquarks in $B_s^0 \to J/\psi\,p\bar{p}$

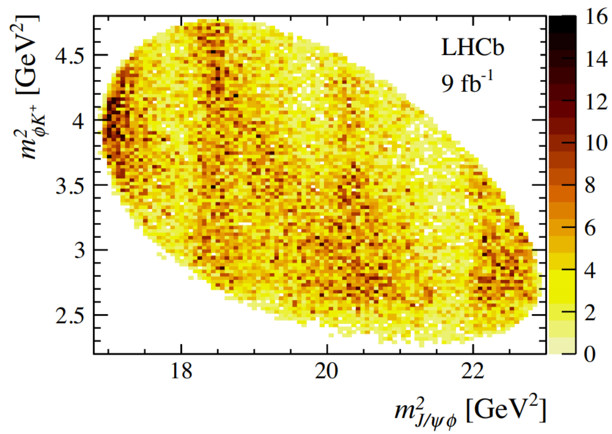
Study of $B^+ \to J/\psi\,\phi K^+$

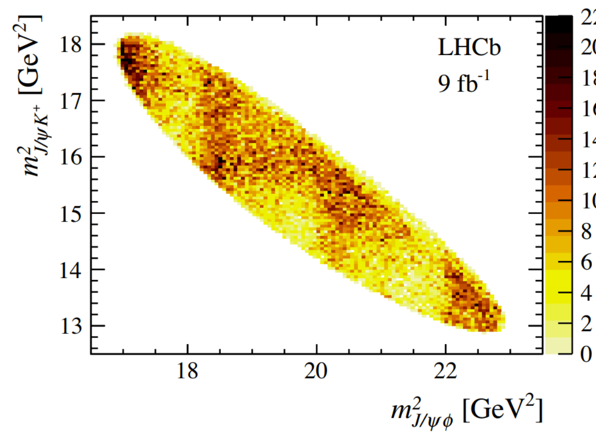
PRL 118, 022003 (2017), PRL 127, 082001 (2021)

Analysis with full dataset and improved selection ~**24K signal candidates** (Run1 ×6)

Efficiency improved by 15% and the background reduced by factor 6 than Run1



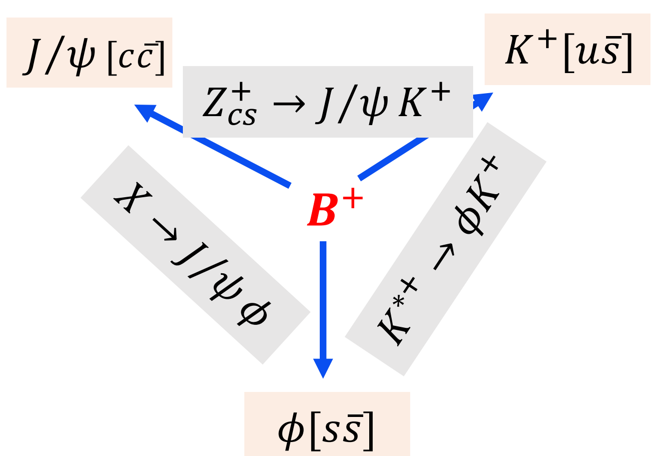




Clear structures in 2D Dalitz plots, both in the $J/\psi\,K^+$ and $J/\psi\,\phi$ masses

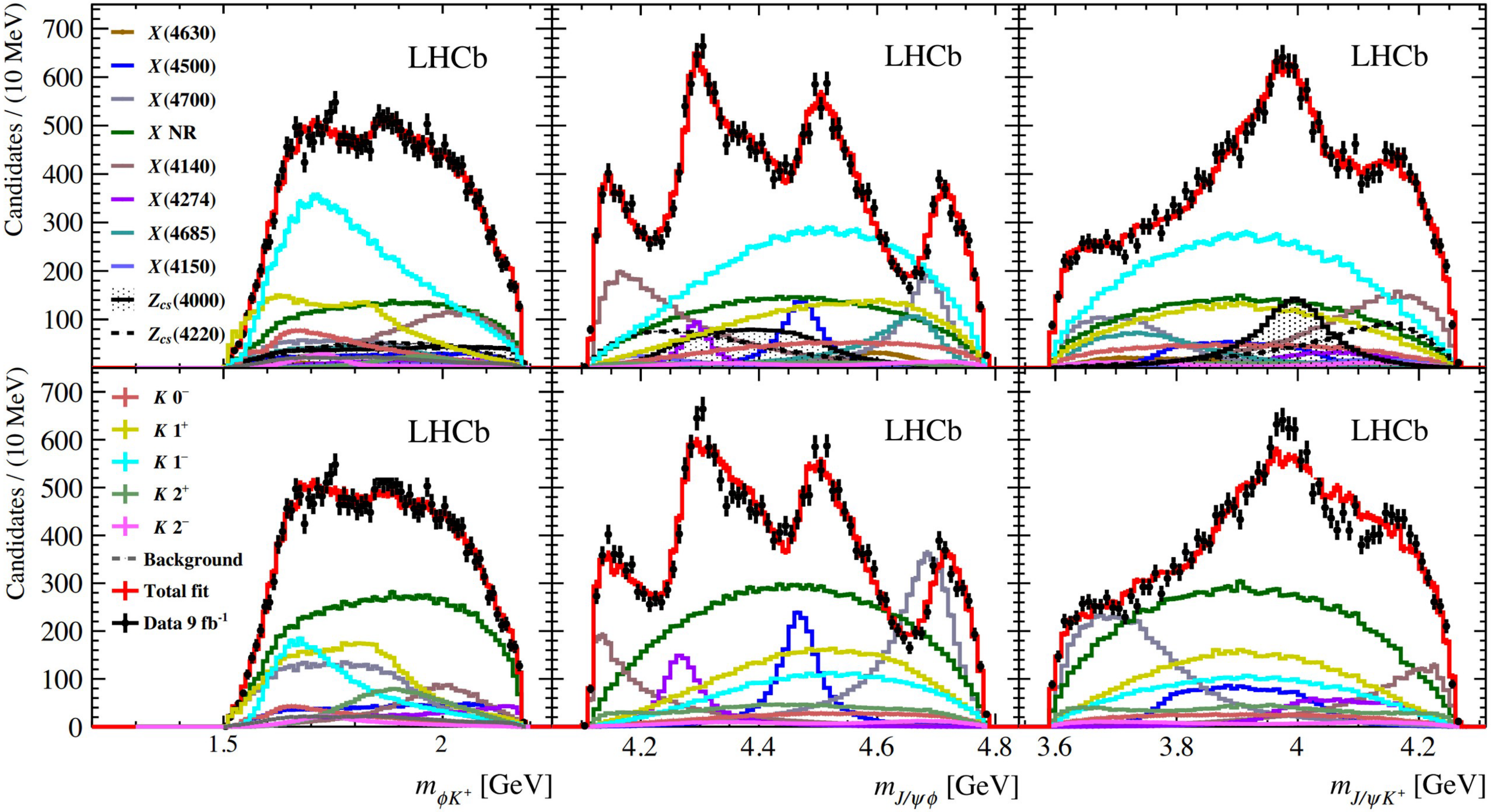
6D amplitude analysis to decouple all contribute resonance (Z_{cs}, X, K^*)

For each decay chain (Z_{cs}, X, K^*) six variables in the fit (mass and five angles)



Amplitude fit

PRL 127, 082001 (2021)



Updated model

Run1 model

Model used in the Run1 analysis not completely satisfactory to full dataset

Need to add other exotic states (Z_{cs}, X)

$B^+ \to J/\psi\, \phi K^+$ results

PRL 127, 082001 (2021)

J^P		Contribution	Significance (σ)	M_0 (MeV)	Γ_0 (MeV)	FF (%)
1^+	2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
	2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
	1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
2^-	1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
	1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}_{-8}$
	2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5^{+11}_{-17}$
2^-	2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	$318 \pm 82^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2^{+1.0}_{-3.8}$
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
0^+		$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
		$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
		$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
1^+		$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
		$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
		$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
1^+		$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
		$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

Resonances observed in the Run1 analysis confirmed

Two other $X \to J/\psi\,\phi$ states were observed, two $Z_{cs} \to J/\psi\, K^+$ states were observed, all with $> 5\sigma$

The J^P of $X(4685)$ and $Z_{cs}(4000)$ are firmly determined to be 1^+

Search for doubly-charmed T_{cc}^{+}

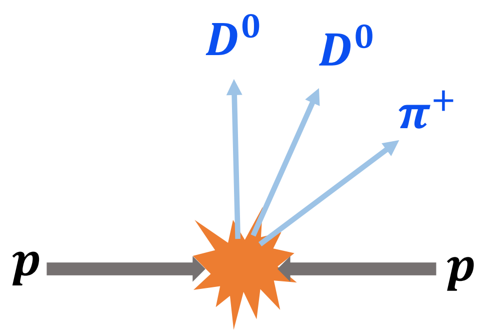
arXiv:2109.01056v2, arXiv:2109.01038

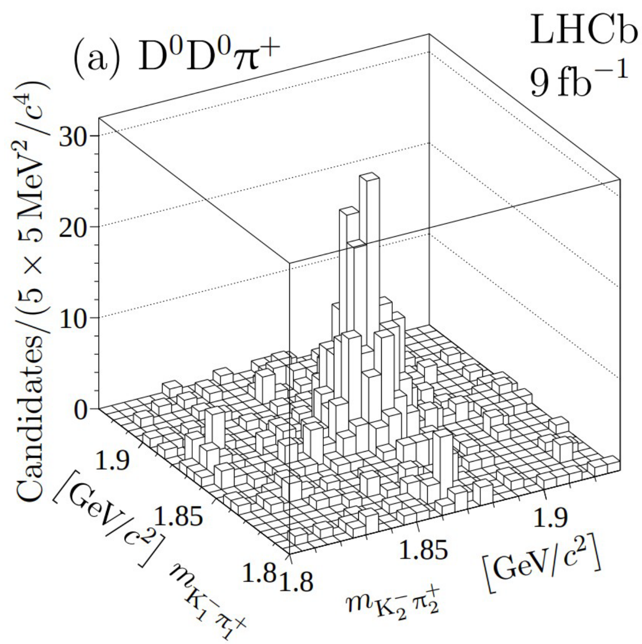
All the three particles are required to come from the same p-p interaction

D^0 reconstructed via the $D^0 \to K^+\pi^-$ decay

2D distribution of the mass of one D^0 versus the mass of another D^0 from selected $D^0D^0\pi^+$ combination shows the relatively small combinatorial background

To subtract background not originating from two D^0 candidates, an extended fit to the 2D distribution of the masses of the two D^0 candidates is performed





Observation of $T_{cc}^{+} \to D^0 D^0 \pi^+$

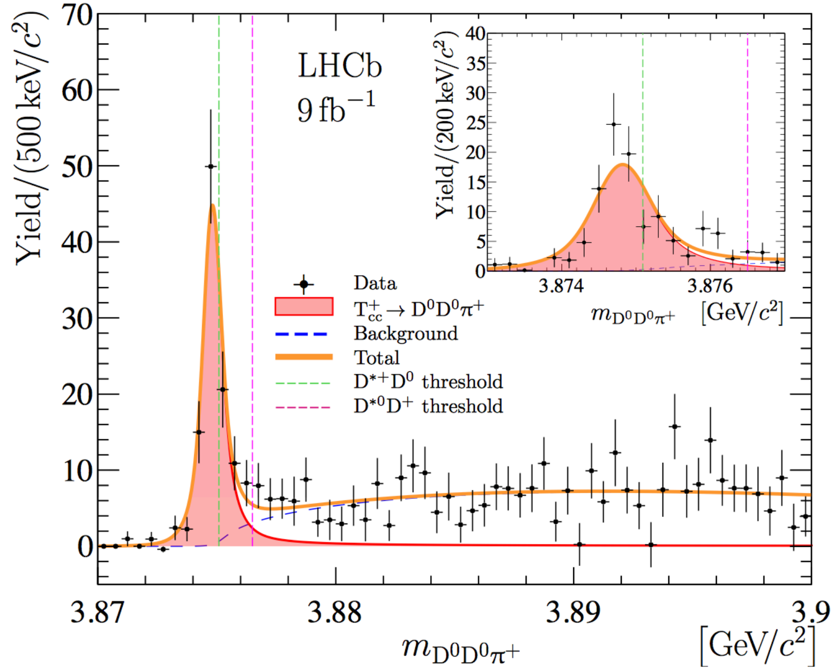
arXiv:2109.01056v2, arXiv:2109.01038

Very narrow state observed in $D^0 D^0 \pi^+$ mass spectrum at ≈ 3875 MeV

- Fit with 2-body relativistic Breit-Wigner
- Peak significance of 21.7σ with full LHCb dataset

First doubly-charmed tetraquark T_{cc}^{+} observed

- minimal quark content $cc\bar{u}\bar{d}$
- Close to $D^{*+}D^0$ threshold
- $m_{T_{cc}^+} - m_{D^{*+}} - m_{D^0} = -273 \pm 61 \pm 5^{+11}_{-14}$ keV
- $\Gamma_{T_{cc}^+} = 410 \pm 65 \pm 43^{+18}_{-38}$ keV
- Ground isoscalar state $J^P = 1^+$



The existence of T_{cc}^{+} suggests that the $T_{bb}^{-}(bb\bar{u}\bar{d})$ should be stable for strong and electromagnetic interaction

Properties of T_{cc}^{+}

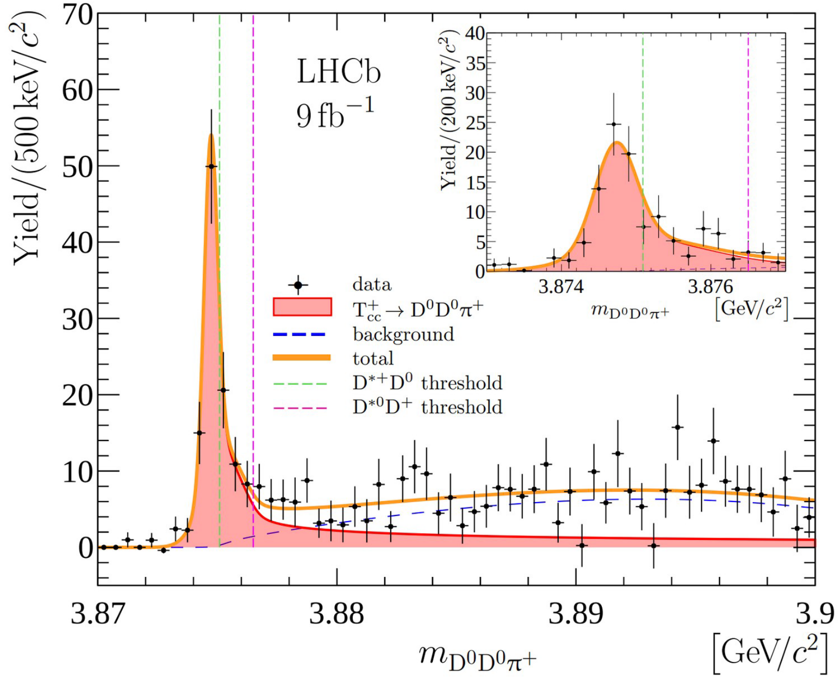
arXiv:2109.01056v2, arXiv:2109.01038

Properties of T_{cc}^{+} studied using an unitarised 3-body BW model

- Larger tail above $D^{*+}D^{0}$ threshold w.r.t. 2-body RBW
- Significance for below threshold peak at 9σ

Measured pole parameters, scattering length α and coupling constant $|g|$

- $\delta m_{pole} = -360 \pm 40^{+4}_{-0}$ keV
- $\Gamma_{pole} = 48 \pm 2^{+0}_{-14}$ keV
- $\alpha = [-(7.16 \pm 0.51) + i(1.85 \pm 0.28)]$ fm
- $|g| > 5.1(4.3)$ GeV at 90(95)% CL



Observed T_{cc}^{+} consistent with singlet state, no hint of T_{cc}^{0} and T_{cc}^{++} isospin partners

Study of $\Xi_b^- \to J/\psi\, \Lambda K^-$

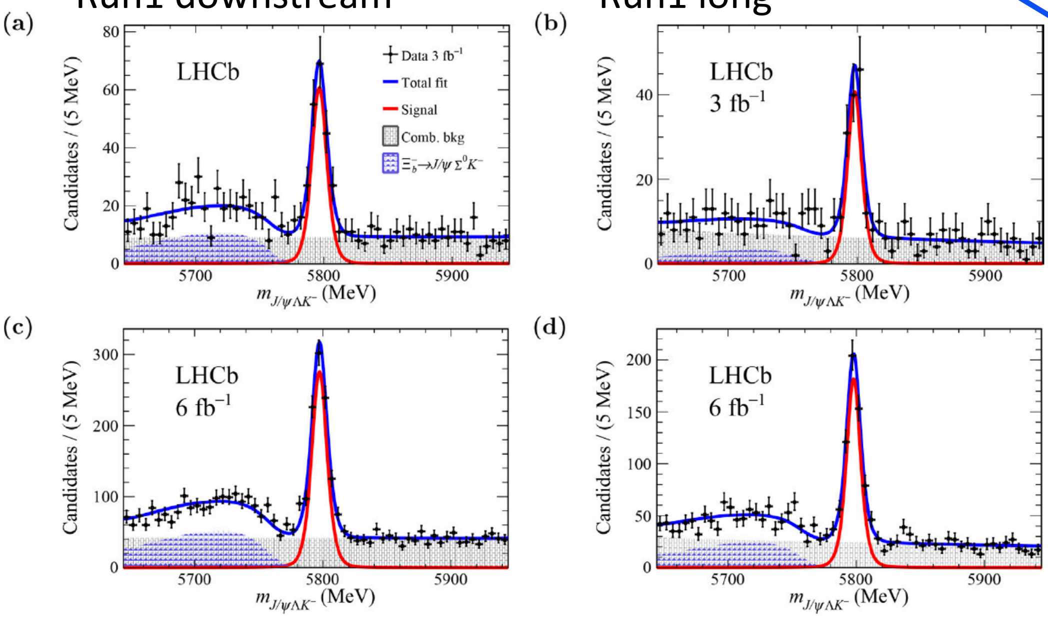
Sci.Bull. 66, 13, 1278-1287 (2021)

Selected 1750 ± 50 $\Xi_b^- \to J/\psi\, \Lambda K^-$ candidates using unbinned extended maximum-likelihood fit

$\boldsymbol{\Lambda K^+}$ spectrum dominated by $\boldsymbol{\Xi(1690)^-}$ and $\boldsymbol{\Xi(1820)^-}$ excited states

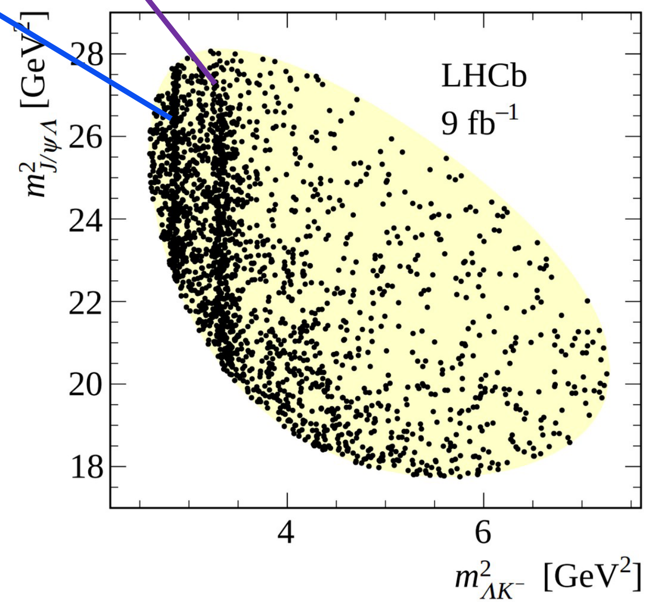
Run1 downstream

Run1 long



Run2 downstream

Run2 long



Long: Λ with a short flight distance that p and π have the decay vertex in the VELO (vertex detector)

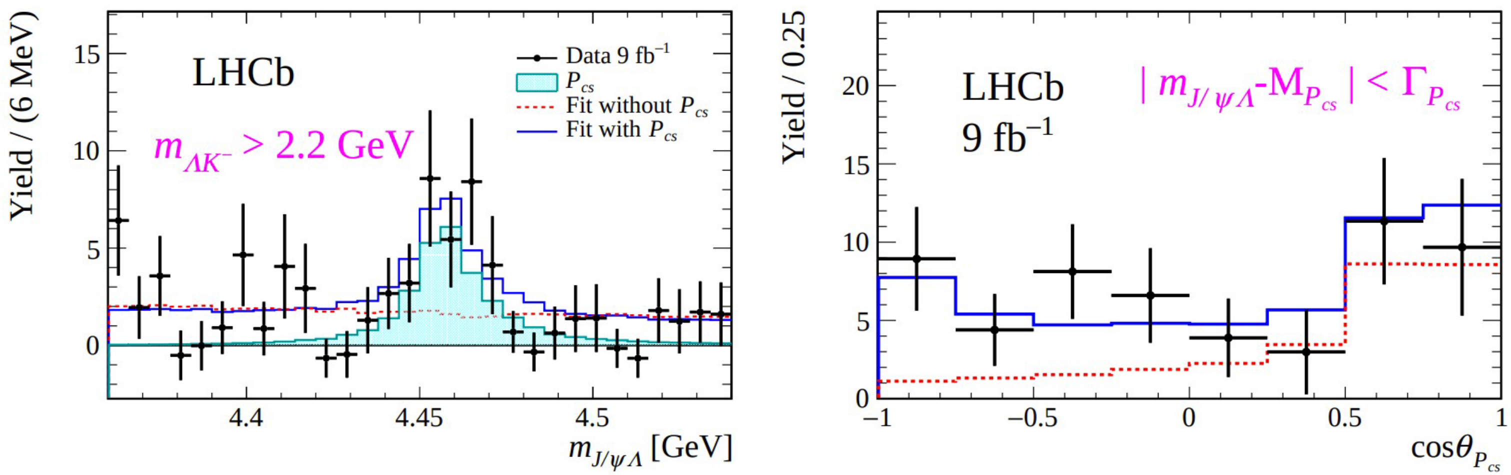
Downstream: p and π can't be formed in the VELO and are only reconstructed in the tracking stations

Evidence of $P_{cs}(4459)^0$

Sci.Bull. 66, 13, 1278-1287 (2021)

Amplitude analysis performed: statistics quite limited and only few components needed in the fit

Clear structure seen in the $J/\psi\,\Lambda$ mass spectrum , particularly in the non-resonant ΛK^- region, with a significance of 3.1σ



Mass close to the $\Xi_c D^*$ mass threshold:

$m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

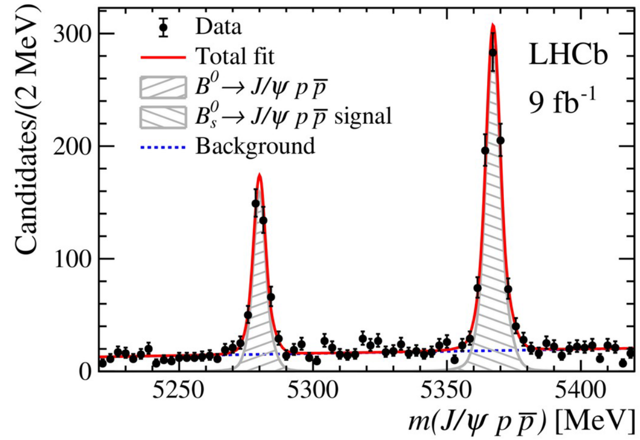
Study of $B^0_{(s)} \to J/\psi\, p\bar{p}$

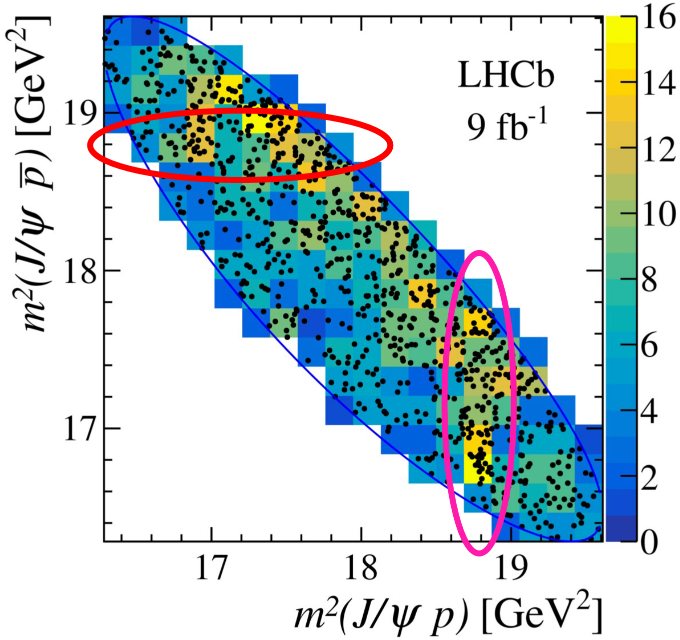
PRL 128 (2022) 062001

Decay very clean, good for searching pentaquarks ($J/\psi\, p$ and $J/\psi\, \bar{p}$) and glueball ($p\bar{p}$)

About **800** $\boldsymbol{B_s^0 \to J/\psi\, p\bar{p}}$ candidates selected in 3σ region with 85% purity

Dalitz plot shows hints of structures in $J/\psi\, p$ and $J/\psi\, \bar{p}$ invariant masses





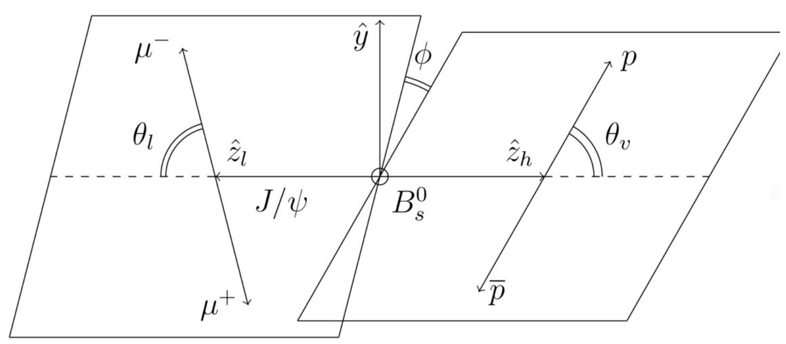
Amplitude analysis of the B_s^0 candidates performed and three interfering decay chains are considered in the amplitude model

$B_s^0 \to J/\psi\, X(\to p\bar{p})$

$B_s^0 \to P_c^+(\to J/\psi\, p)\bar{p}$

$B_s^0 \to P_c^-(\to J/\psi\, \bar{p})p$

4D phase space:
$\{m_{p\bar{p}}, cos\theta_l, cos\theta_v, \phi\}$



Evidence of P_c^+ and P_c^-

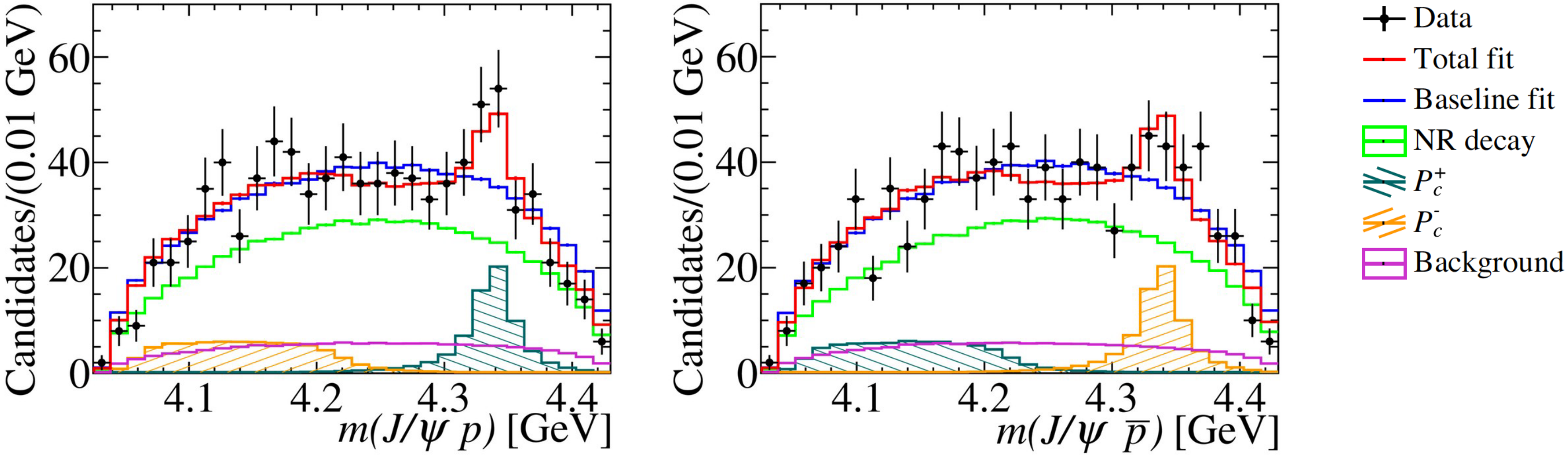
PRL 128 (2022) 062001

First fit model: a non-resonant decay + background (baseline)

Second model: two resonant contributions from P_c^+ and P_c^- are added, with identical masses, widths and couplings (baseline + Resonant contribution) $\chi^2/\text{ndof} = 0.998 \pm 0.008$

New pentaquark-like states P_c^+ and P_c^- with significance between $3.1\sim3.7\sigma$

$m = 4337^{+7}_{-4}(\text{stat}) \pm 2(\text{sys})\text{MeV}$, $\Gamma = 29^{+26}_{-12}(\text{stat}) \pm 14(\text{sys})\ \text{MeV}$



Conclusions

Presented a selection of the latest LHCb results on exotic spectroscopy

- ✓ Tetraquarks observation in $B^+ \to J/\psi\, \phi K^+$ decay
- ✓ Observation of doubly-charmed tetraquark $T_{cc}^+ \to D^0 D^0 \pi^+$
- ✓ Evidence of $J/\psi\, \Lambda$ structure in $\Xi_b^- \to J/\psi\, \Lambda K^+$
- ✓ Evidence of $J/\psi\, p(\bar{p})$ structure in $B_s^0 \to J/\psi\, p\bar{p}$

Provides a wealth of information for theory community

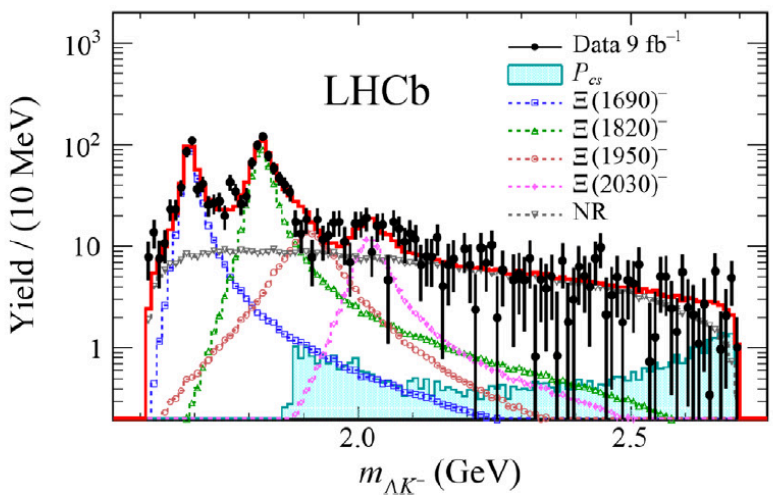
More data is need to confirm and better investigate these results

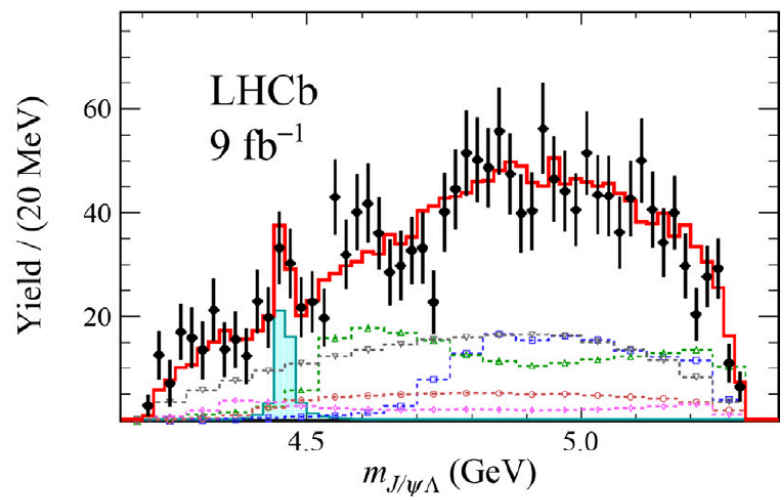
Thank you for your attention!

Backup slides

Results of $\Xi_b^- \to J/\psi\, \Lambda K^-$

Sci.Bull. 66, 13, 1278-1287 (2021)

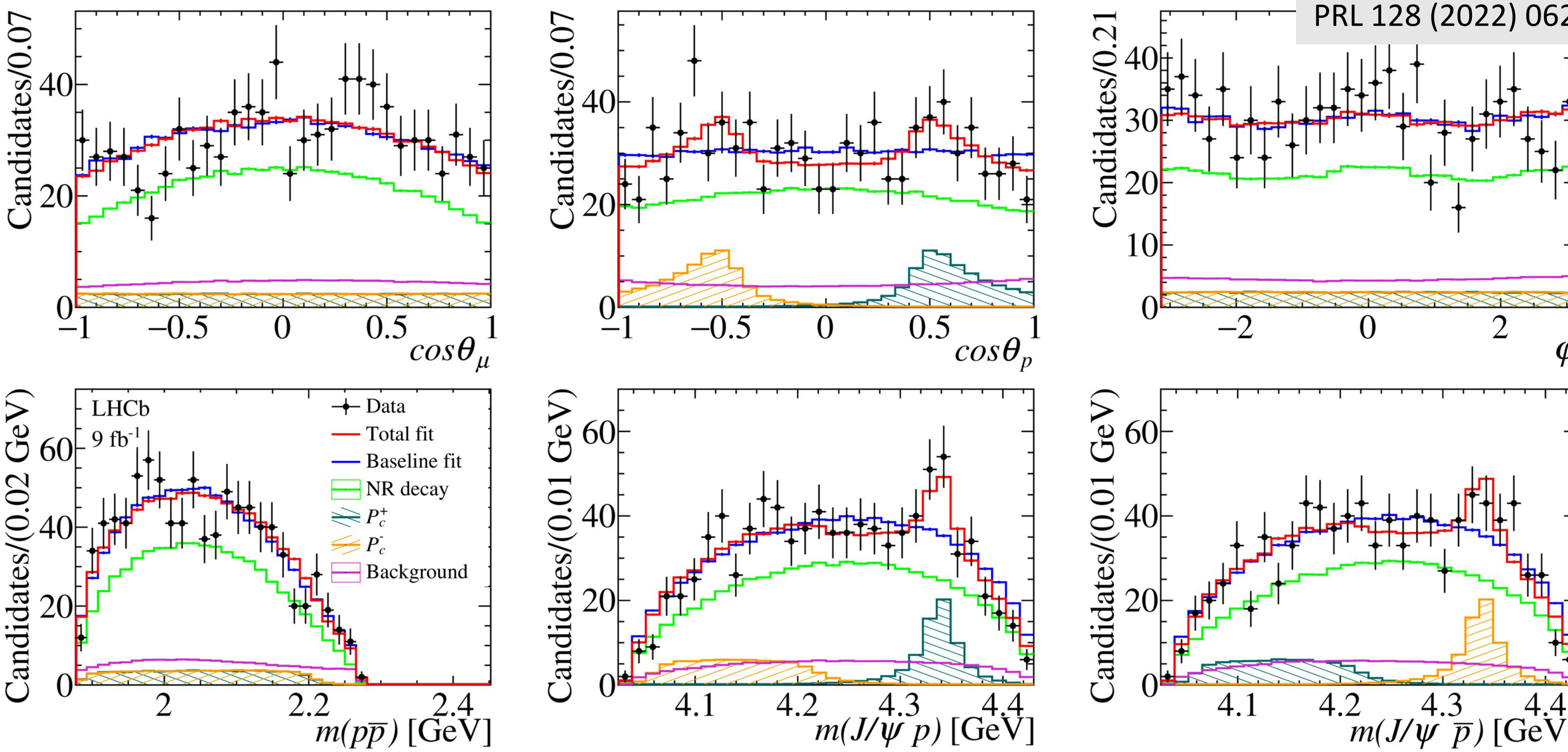




Source	$P_{cs}(4459)^0$			$\Xi(1690)^-$			$\Xi(1820)^-$	
	M_0	Γ_0	FF	M_0	Γ_0	FF	M_0	Γ_0
J^P	$^{+4.7}_{-0.3}$	$^{+0.0}_{-5.7}$	$^{+0.1}_{-1.3}$	$^{+1.2}_{-0.1}$	$^{+14.0}_{-0.9}$	$^{+6.7}_{-0.3}$	$^{+0.8}_{-0.2}$	$^{+1.4}_{-0.5}$
Model	$^{+0.7}_{-1.1}$	$^{+8.0}_{-2.0}$	$^{+0.7}_{-0.5}$	$^{+0.5}_{-0.4}$	$^{+1.8}_{-13.5}$	$^{+1.9}_{-8.9}$	$^{+1.0}_{-0.6}$	$^{+7.8}_{-8.2}$
Λ decay	$^{+0.0}_{-0.7}$	$^{+0.0}_{-4.7}$	$^{+0.0}_{-0.3}$	$^{+0.0}_{-0.4}$	$^{+0.2}_{-0.0}$	$^{+0.0}_{-0.8}$	$^{+0.0}_{-0.5}$	$^{+0.0}_{-7.2}$
sWeights	$^{+0.0}_{-0.2}$	$^{+0.3}_{-0.0}$	$^{+0.1}_{-0.0}$	$^{+0.1}_{-0.1}$	$^{+3.1}_{-0.2}$	$^{+1.4}_{-0.0}$	$^{+0.2}_{-0.2}$	$^{+2.2}_{-1.5}$
Efficiency	$^{+0.1}_{-0.1}$	$^{+0.0}_{-0.5}$	$^{+0.0}_{-0.1}$	$^{+0.1}_{-0.2}$	$^{+2.1}_{-1.5}$	$^{+0.8}_{-1.3}$	$^{+0.1}_{-0.2}$	$^{+1.1}_{-0.3}$
Final	$^{+4.7}_{-1.1}$	$^{+8.0}_{-5.7}$	$^{+0.7}_{-1.3}$	$^{+1.2}_{-0.4}$	$^{+14.0}_{-13.5}$	$^{+6.7}_{-8.9}$	$^{+1.0}_{-0.6}$	$^{+7.8}_{-8.2}$

Amplitude fit of $B_s^0 \to J/\psi\, p\bar{p}$

PRL 128 (2022) 062001



Source	M_{P_c}	Γ_{P_c}	$A(P_c)$	$f(P_c)$	p (%)	σ
NR(X) model	0.1	1.4	0.013	6.4	0.003	4.2
$J^P(P_c)$ assignment	2	12	0.100	5.5	0.2	3.1
Efficiency	0.2	4	0.012	0.4	0.001	4.4
Background	0.1	2	0.001	0.7	0.001	4.3
Hadron radius	0.7	4	0.034	1.7	0.02	3.7
Fit bias	$^{+0.2}_{-0.1}$	$^{+5}_{-2}$	$^{+0.040}_{-0.040}$	...	...	...
Total	2	14	0.11	8.6	...	3.1