Search for pentaquarks in B-meson decays at LHCb

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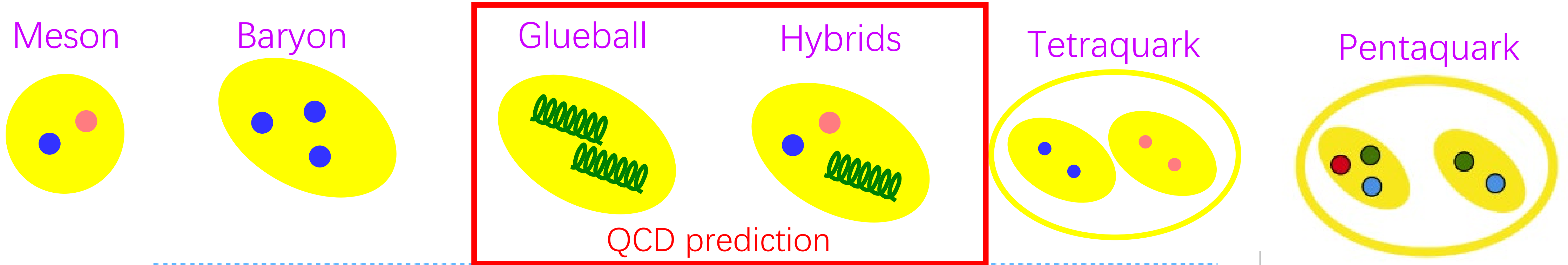
Outline

- A brief introduction of pentaquark
- Searching pentaquark states at LHCb
- $B^- \to J/\psi\Lambda\bar{p}$
- $B_s^0 \to J/\psi p\bar{p}$
- Summary

A brief introduction of pentaquark

A brief introduction of pentaquark

- The existence of multi-quark states is predicted by the quark model
- Minimal content $qqqq\bar{q}$



A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING II *)

G. Zweig **)

CERN---Geneva

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Brief history of multi-quark

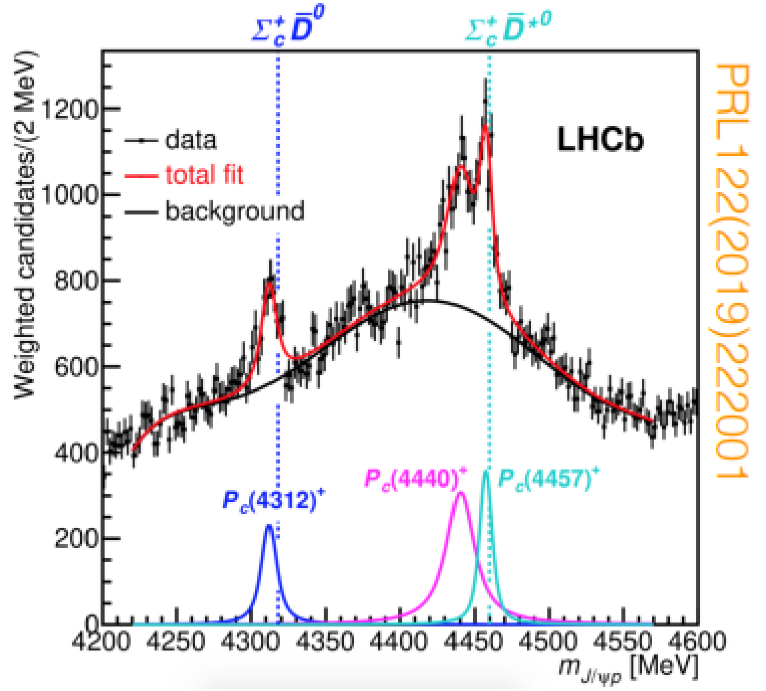
2003: The first tetraquark candidate $X(3872)$ was discovered by Belle.

2015+2019: Three hidden-charm pentaquark states $P_\psi^N(4312)^+, P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$ were observed by LHCb.

Phys. Rev. Lett. 115, 072001 (2015)
Phys. Rev. Lett. 122, 222001 (2019)

Observation in $\Lambda_b^0 \to pK^- J/\psi$

$P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$



Exotic hadron naming convention

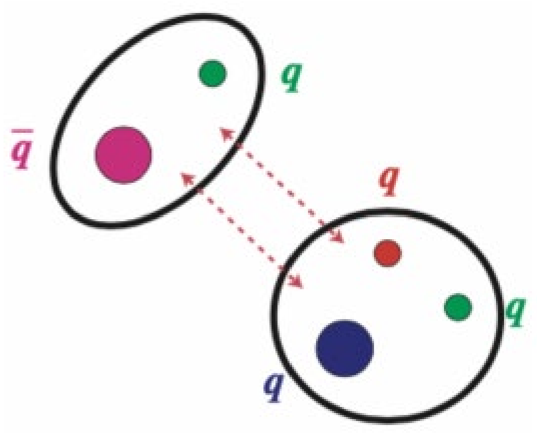
Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G=1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

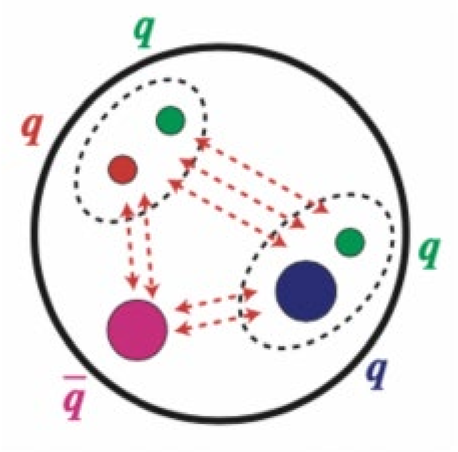
LHCb-PUB-2022-013
arXiv:2206.15233

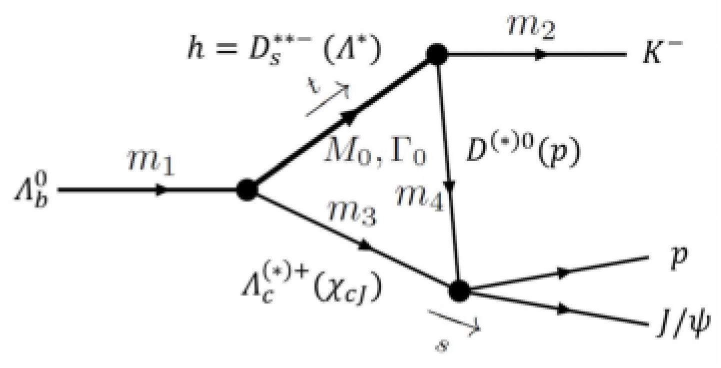
- T for tetraquarks, P for pentaquarks
- P states: i.e. $P_\psi^N(4312)^+$, $P_{\psi s}^\Lambda(4459)^0$
  - Superscript: denotes isospin, $\Lambda, N, \Sigma, \Delta$ for $I=0, \frac{1}{2}, 1, \frac{3}{2}$
  - Subscript: Υ, ψ, ϕ for hidden beauty, charm, strangeness; b, c, s for open flavor quantum numbers

What is pentaquark?

Hadronic Molecules	Compact pentaquark	Rescattering effects







Rev. Mod. Phys. 90(2018)015004

PRD103(2021)112006

Eur.Phys.J.C 82 (2022) 7, 581

Phys. Rept. 668(2017)1

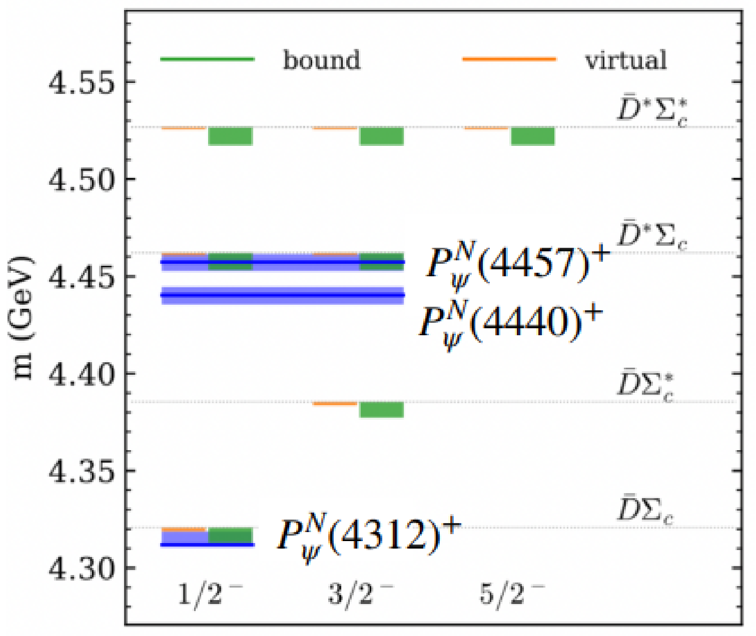
Few Body Syst. 57 (2016)1185

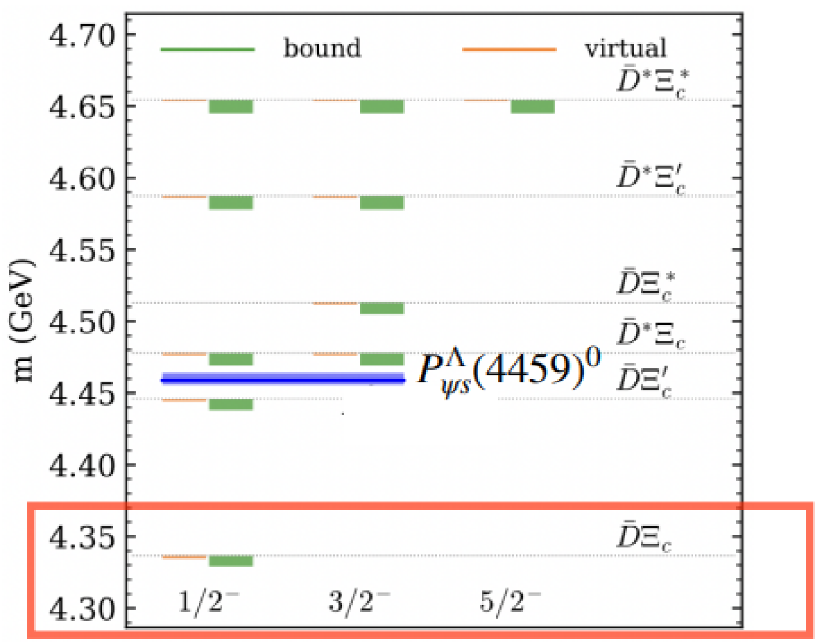
Prog. Part. Nucl. Phys. 112 (2020)103757

More pentaquarks states?

contact terms which are resummed to generate poles. It turns out that if a system is attractive near threshold by the light meson exchange, there is a pole close to threshold corresponding to a bound state or a virtual state, depending on the strength of interaction and the cutoff. In total, 229 molecular states are predicted. The observed near-threshold structures with hidden-charm, like the

Progr.Phys.41(2021)65-93



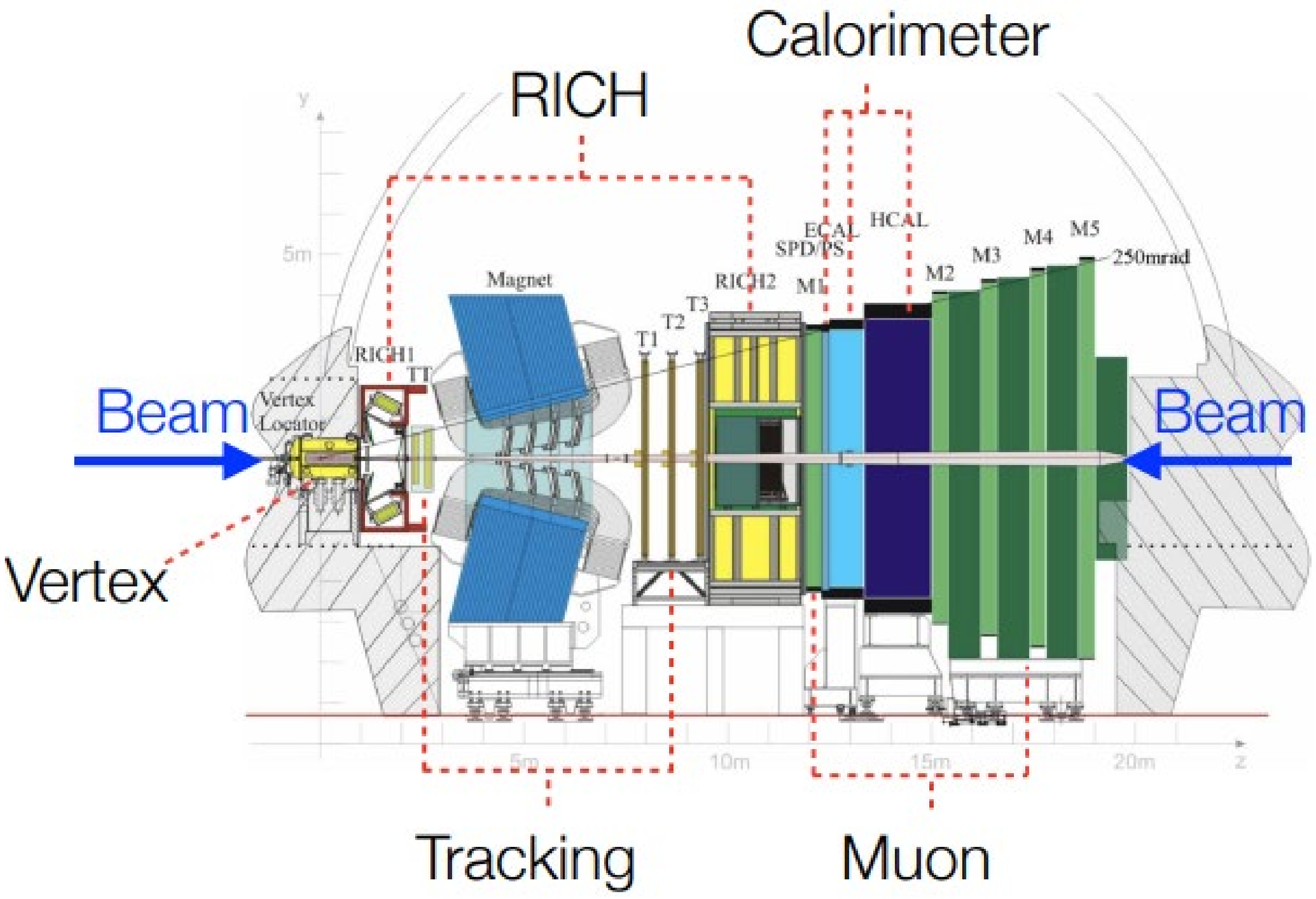


Searching pentaquark states at LHCb

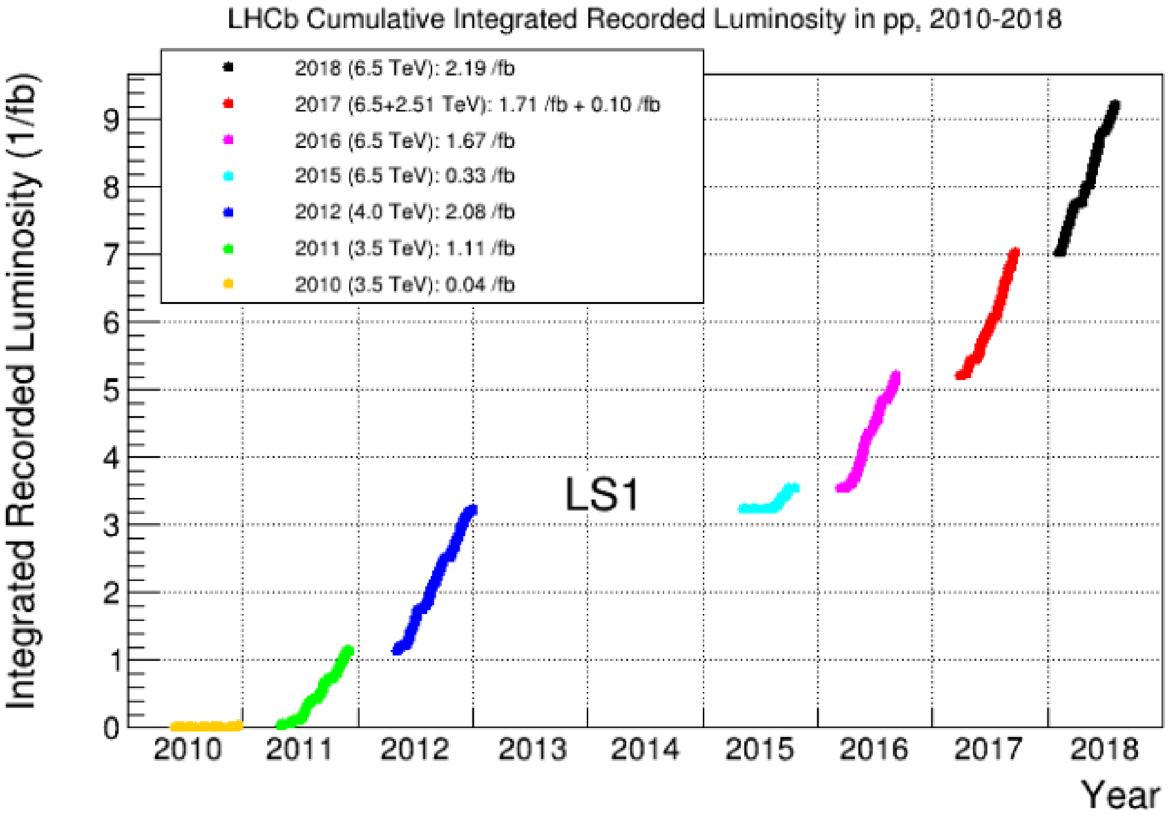
LHCb detector and performance

$2 < \eta < 5$, about 25% of $b\bar{b}$ pairs inside LHCb acceptance

Excellent time, IP, mass resolution, and excellent tracking, PID performance.



LHCb collected luminosity



Run1: @7/8 TeV

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

Run2: @13TeV

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

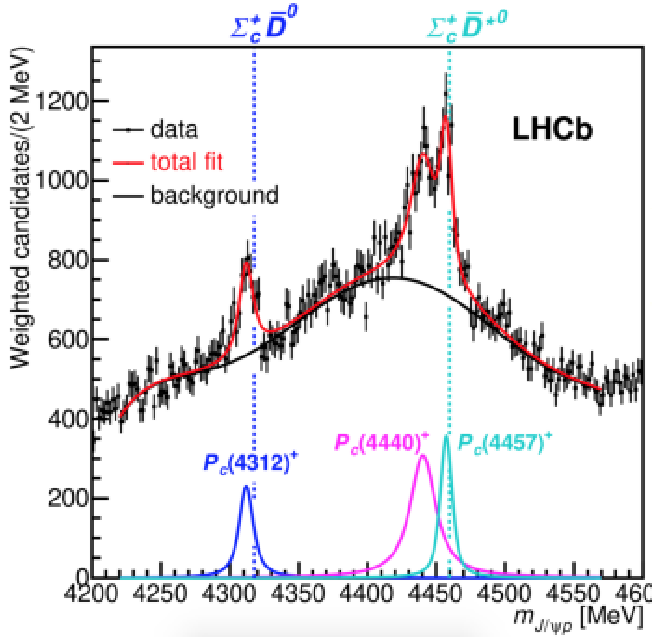
- $9\ \mathrm{fb}^{-1}$ pp collision sample collected in run1+run2
- Large b hadrons produced

$$\begin{array}{ccccccc} B^+ & : & B^0 & : & B^0_s & : & \Lambda^0_b \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \end{array}$$

Pentaquark candidates in B-baryon decays

Observation in $\Lambda_b^0 \to pK^- J/\psi$

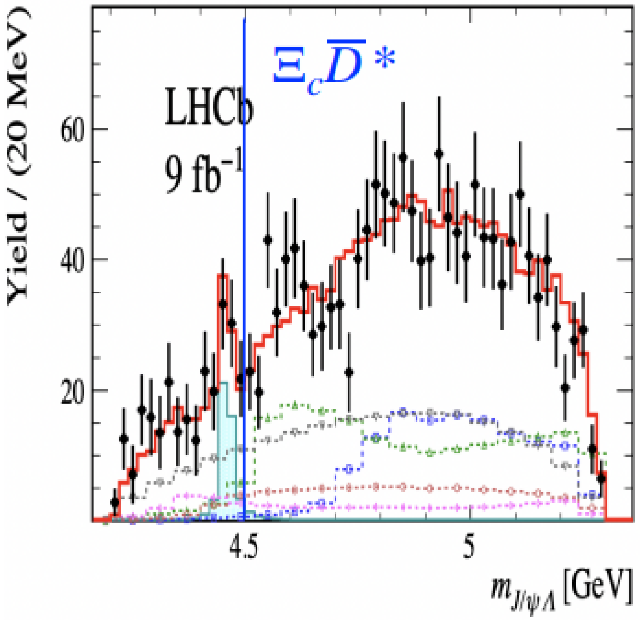
$P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$



PRL122(2019)222001

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

$P_{\psi s}^\Lambda(4459)^0$



Sci.Bull.66(2021)1278

- Excellent mass resolution is needed for narrow structures
- The interesting structures related to thresholds
- Spin and parity not determined

Why in *B*-meson decays?

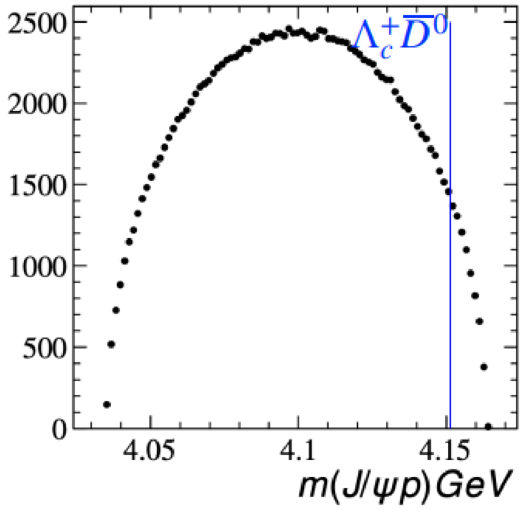
- Small Q-value, providing excellent mass resolution, allows to search for narrow structures
- Search for pentaquark and anti-pentaquark states at the same time
- Sensitive to structures in baryon and anti-baryon system

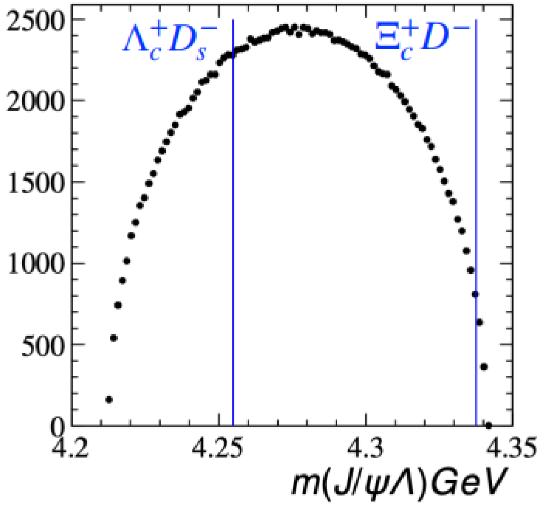
Amplitude analysis of $B^- \to J/\psi\Lambda\bar{p}$ decays

LHCb-PAPER-2022-031 in preparation

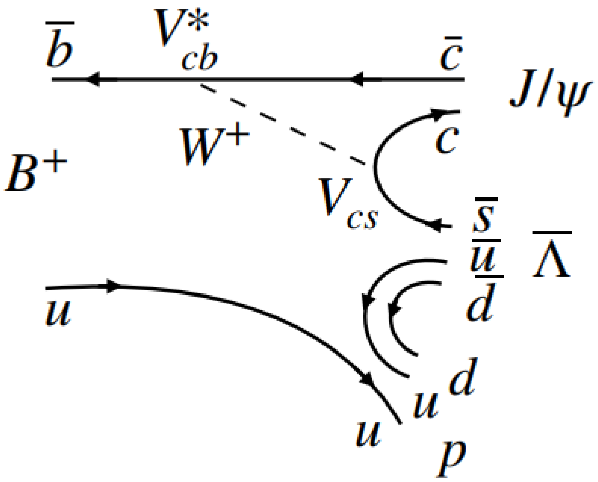
$B^- \to J/\psi\Lambda\bar{p}$ decays

- Q value: 128 MeV
- Thresholds:
  - $J/\psi\bar{p}$ $(c\bar{c}, \bar{u}\bar{u}\bar{d})$: $\Lambda_c^- D^0$ $(\bar{u}\bar{d}\bar{c}, c\bar{u}$
  - $J/\psi\Lambda$ $(c\bar{c}, uds)$: $\Lambda_c^+ D_s^-$ $(udc, \bar{c}s)$ and $\Xi_c^+ D^-(usc, \bar{c}d)$



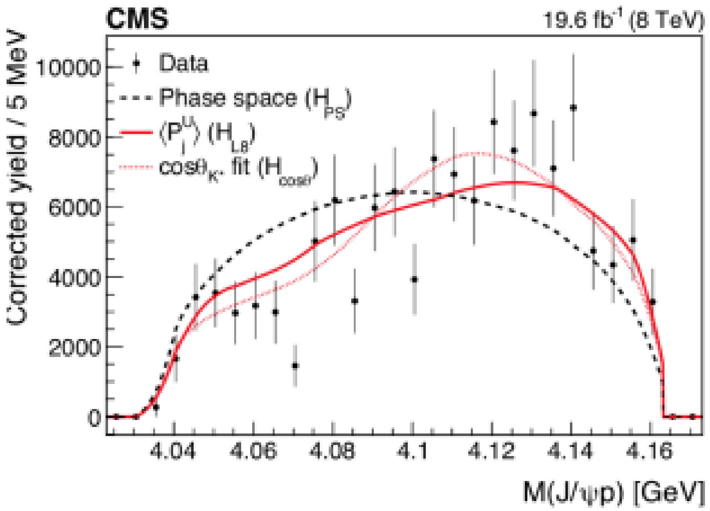


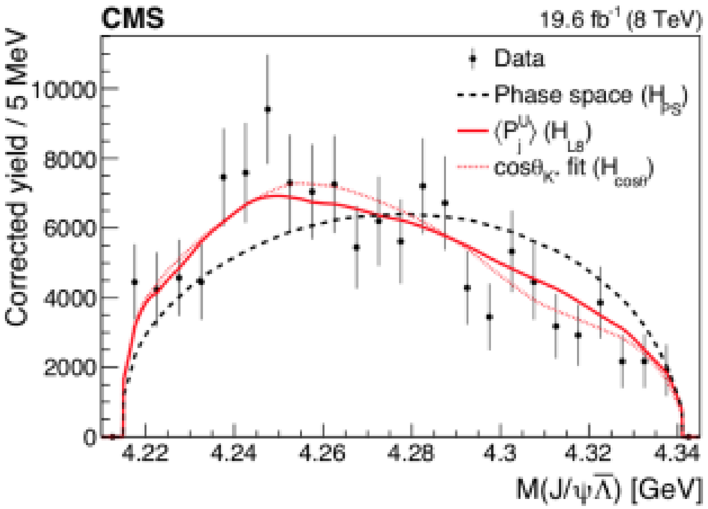
Leading Feynman diagram

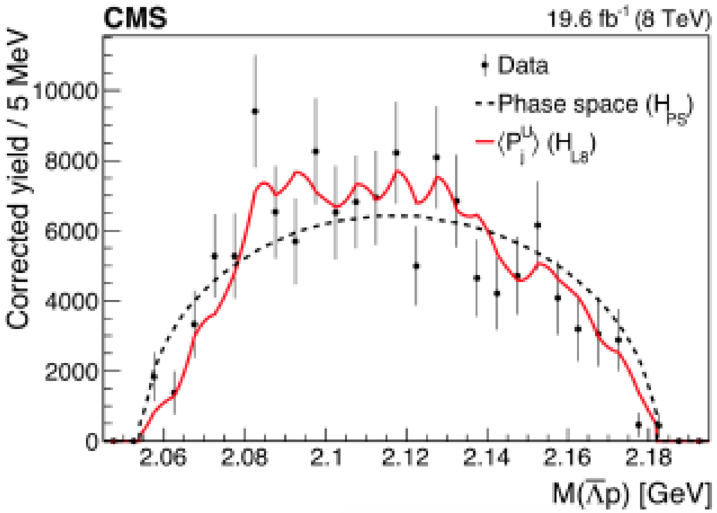


$B^- \to J/\psi\Lambda\bar{p}$ at CMS

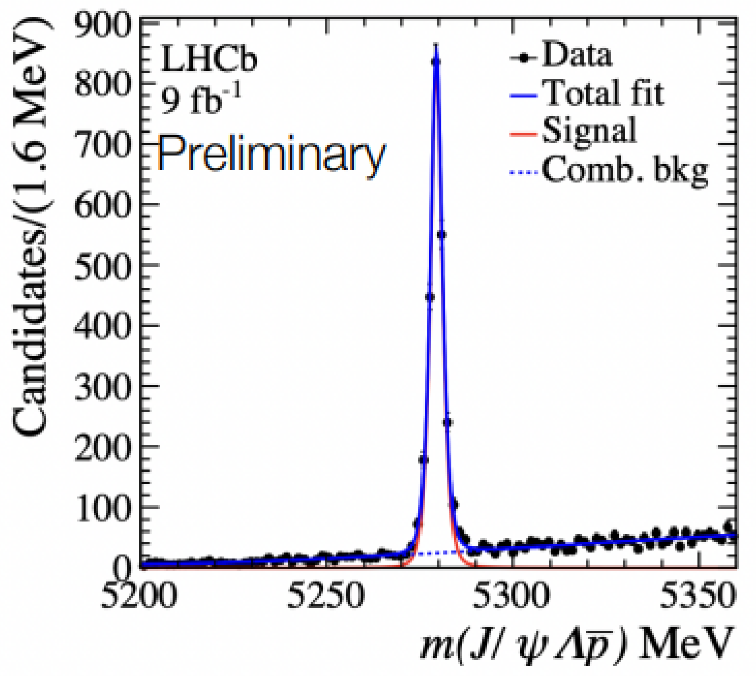
- Limited statistics ~450 signals @8TeV
- Pure phase space hypothesis can not describe data
- $K^{*+}_{2,3,4}$ contributions decrease the incompatibility with data







$B^- \to J/\psi\Lambda\bar{p}$ data sample

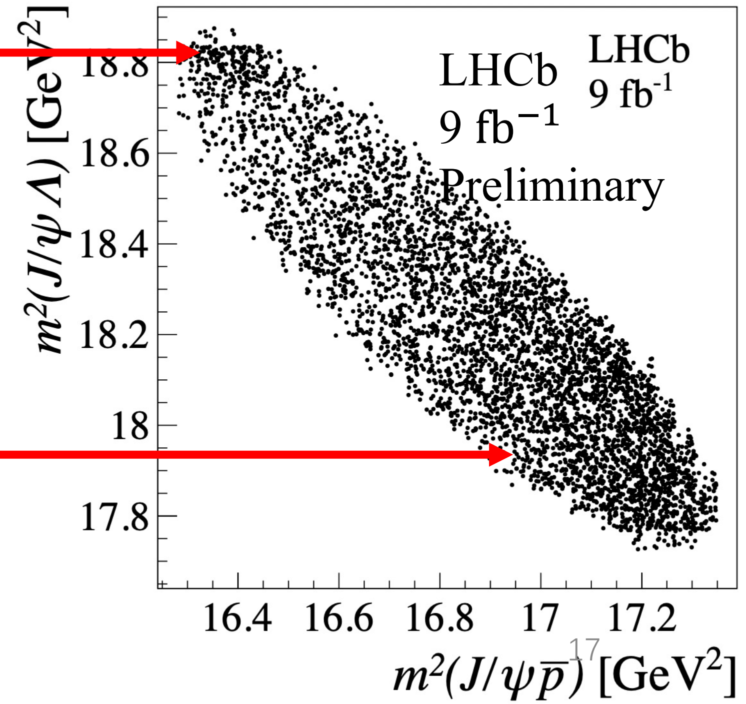


LHCb run1+run2, 9 fb^{-1} dataset:

- Signal window $\pm 2.5\ \sigma$
- Total 4600 signal candidates
- Purity 93%
- B mass resolution 2 MeV

Narrow structure in $m(J/\psi\Lambda)$

Activity in the $m(J/\psi\Lambda)$ system



$B^- \to J/\psi\Lambda\bar{p}$ amplitude analysis

- Helicity formalism amplitude and assuming no CPV
- Three decay chains: $J/\psi K^{*-}(\to \Lambda\bar{p})$, $\Lambda P_{\psi}^{N-}(\to J/\psi\bar{p})$ and $\bar{p}P_{\psi s}^{\Lambda}(\to J/\psi\Lambda)$
- Resonant lineshape: Relativistic Breit-Wigner (RBW)
- Λ decay parameter fixed to PDG value
- Non-resonant (NR) lineshape: constant or 2^{nd} order polynomial
- Un-binned maximum likelihood fit:

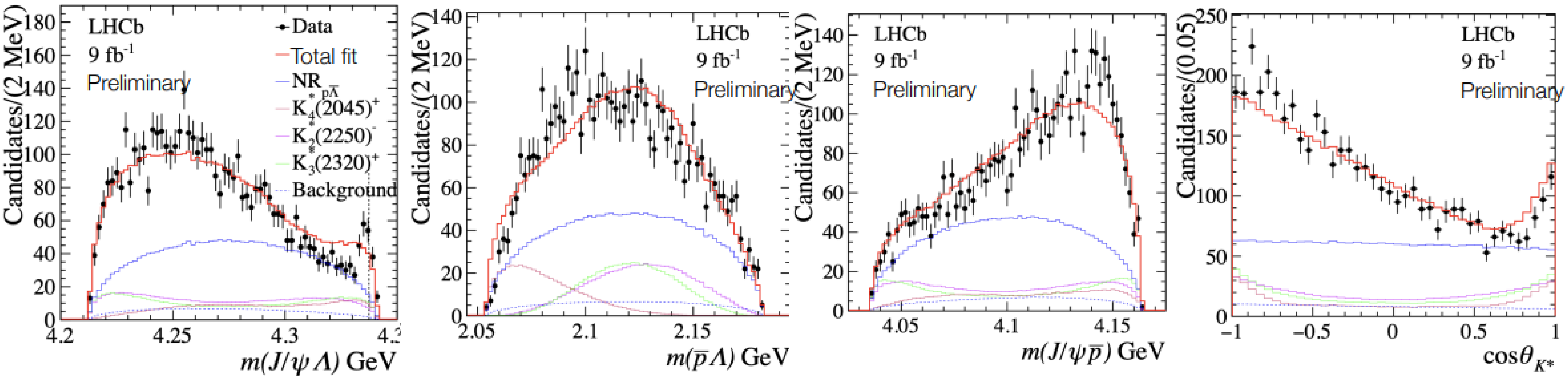
$$-2\log\mathcal{L}(\vec{\omega}) = -2\sum_i \log\left[(1-\beta)\mathcal{P}_{\text{sig}}(m_{\bar{p}\Lambda,i},\vec{\Omega}_i|\vec{\omega}) + \beta\mathcal{P}_{\text{bkg}}(m_{\bar{p}\Lambda,i},\vec{\Omega}_i)\right]$$

Model with only K^{*+}

$K^{*+}_{2,3,4}$ + NR($p\overline{\Lambda}$) can not describe data well, especially for the $m(J/\psi\Lambda)$ distribution.

Resonance	Mass (MeV)	Natural width (MeV)	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

$\chi^2_{max}/ndof$=123/33



Amplitude models

Baseline model	NR($\bar{p}\Lambda$)	constant	Nominal model
	NR($\bar{p}J/\psi$)	2nd order poly.	
	$P_{\psi s}^{\Lambda}(J/\psi\Lambda)$	RBW	

Nominal model fitting results

- First strangeness pentaquark candidate $P_{\psi s}^{\Lambda}(4338)^0$ near threshold of $\Xi_c^+ D^-$ was discovered.

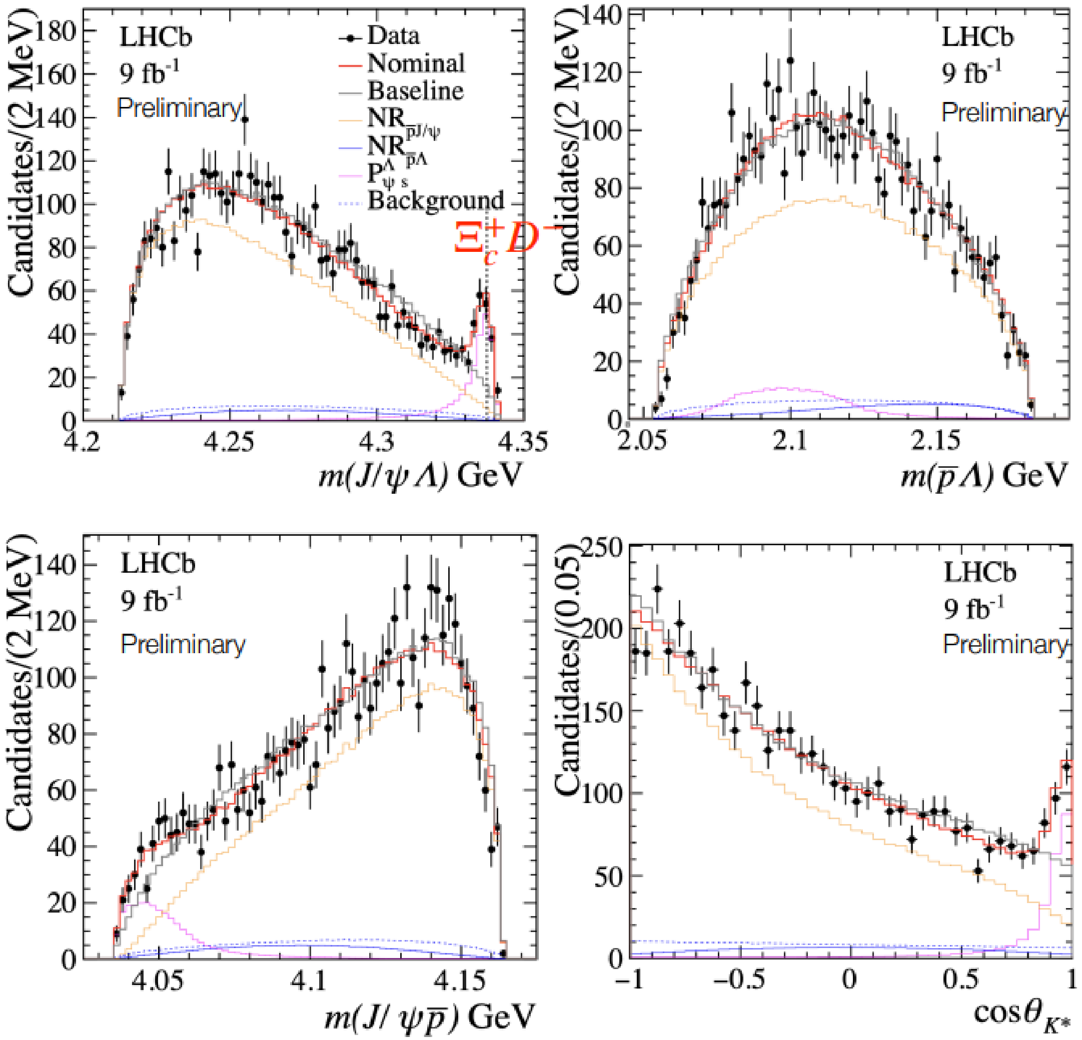
$m\left(P_{\psi s}^{\Lambda}\right) = 4338.3 \pm 0.7 \pm 0.4$ MeV

$\Gamma\left(P_{\psi s}^{\Lambda}\right) = 7.0 \pm 1.2 \pm 1.3$ MeV

Spin ½ assigned

½- preferred

½+ excluded at 90% C.L.



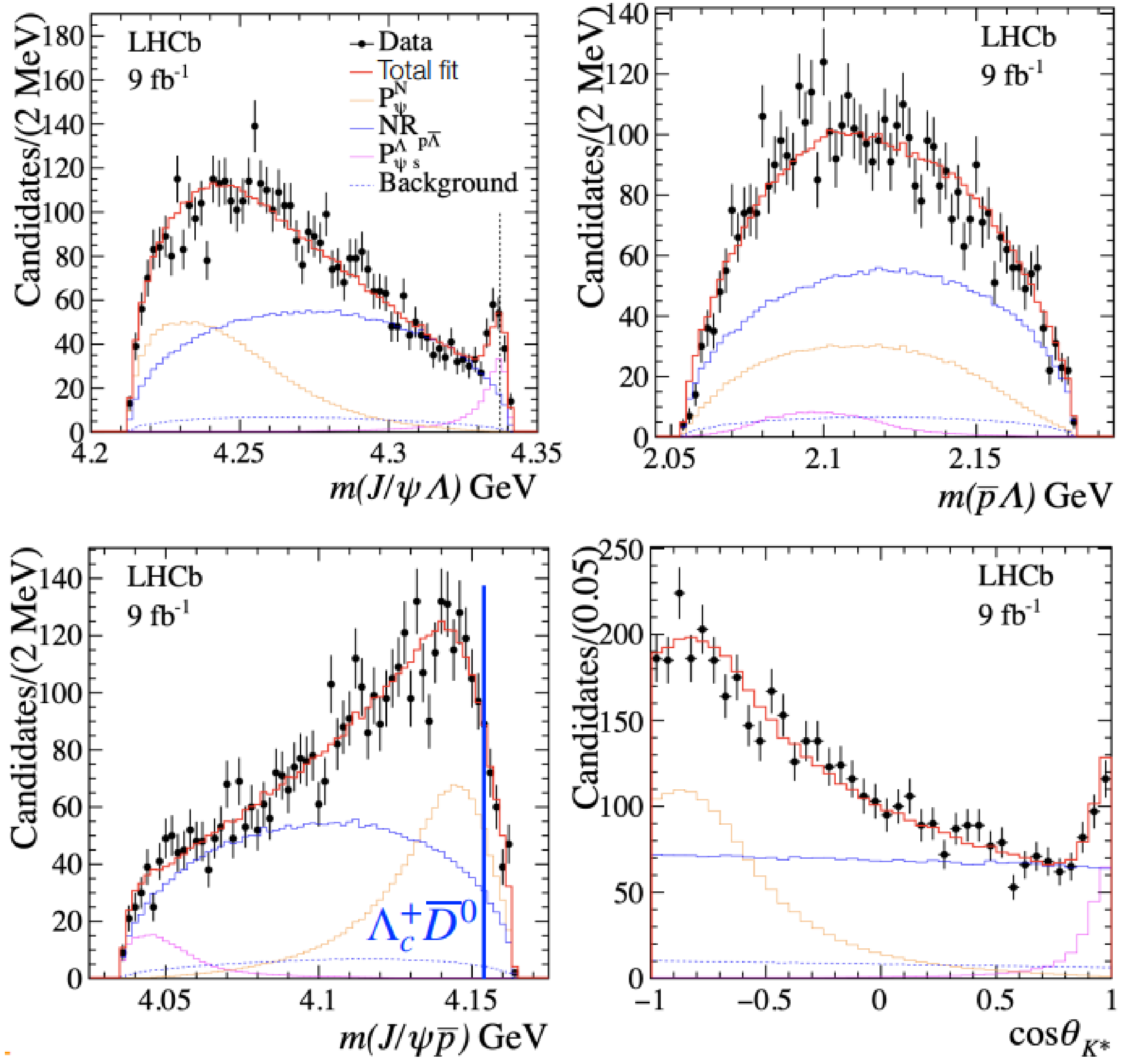
Amplitude mode with $P_{\psi s}^{\Lambda}$ and P_{ψ}^{N}

- Amplitude mode with additional RBW(P_{ψ}^{N}) for possible resonance around $\Lambda_c^+\overline{D}^0$

$$m\left(P_{\psi s}^{\Lambda}\right) = 4338.8 \pm 1.1 \text{ MeV}$$
$$\Gamma\left(P_{\psi s}^{\Lambda}\right) = 8.4 \pm 1.6 \text{ MeV}$$

$$m\left(P_{\psi}^{N}\right) = 4152.3 \pm 2.0 \text{ MeV}$$
$$\Gamma\left(P_{\psi}^{N}\right) = 41.8 \pm 6.0 \text{ MeV}$$

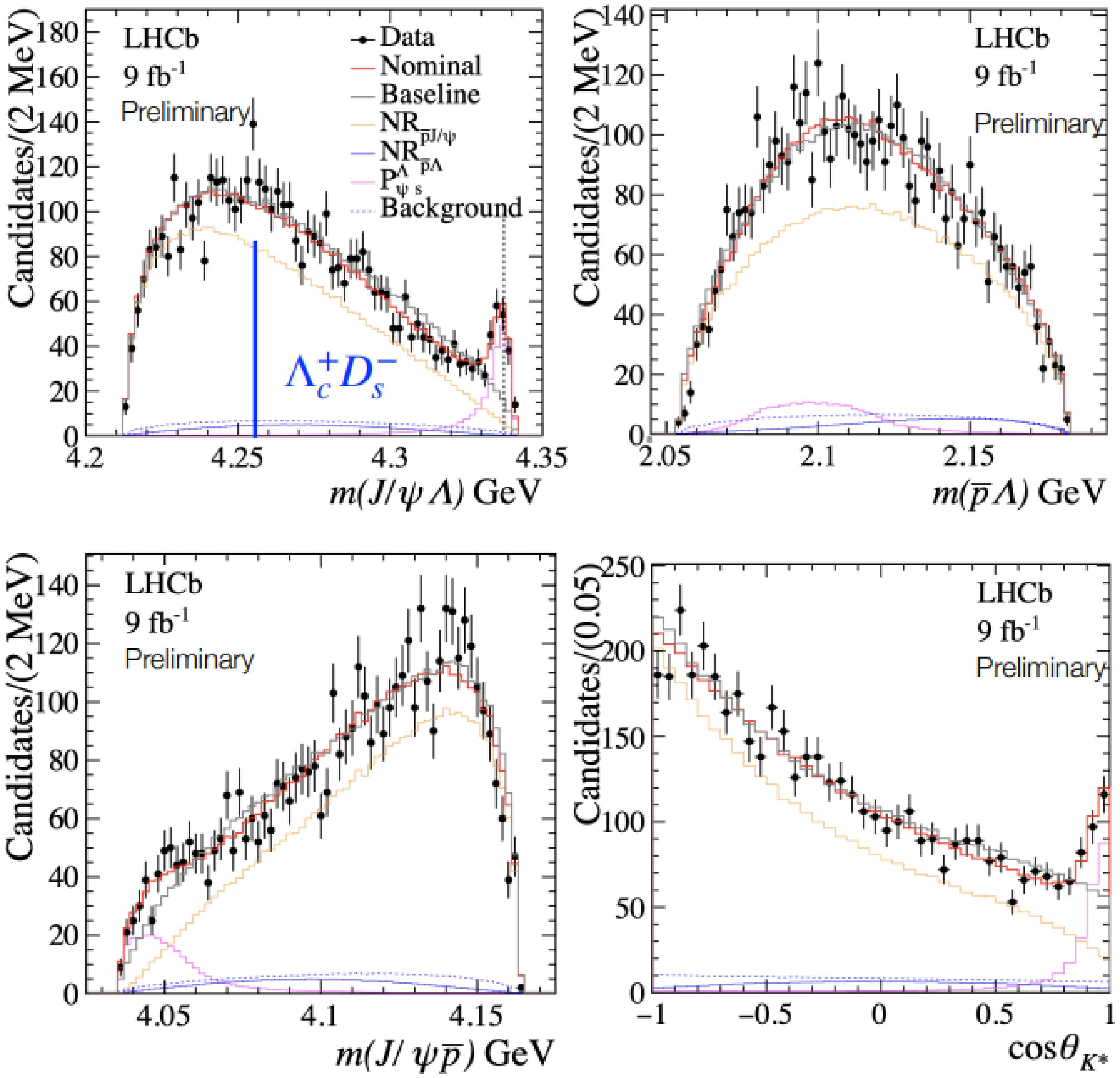
However, $-2\Delta logL \sim 80$, worse than nominal fit ⇒ no evidence of $P_{\psi}^{N}(4152)^+$



Amplitude mode with second $P_{\psi s}^{\Lambda}$

- There is one bin exceed around the threshold of $\Lambda_c^+ D_s^-$
- A second RBW($P_{\psi s}^{\Lambda}$) is added to the nominal model
- $p-$value ≈ 0.2, which determined from toys MC

  $\Rightarrow$ no evidence of $P_{\psi s}^{\Lambda}(4255)^0$

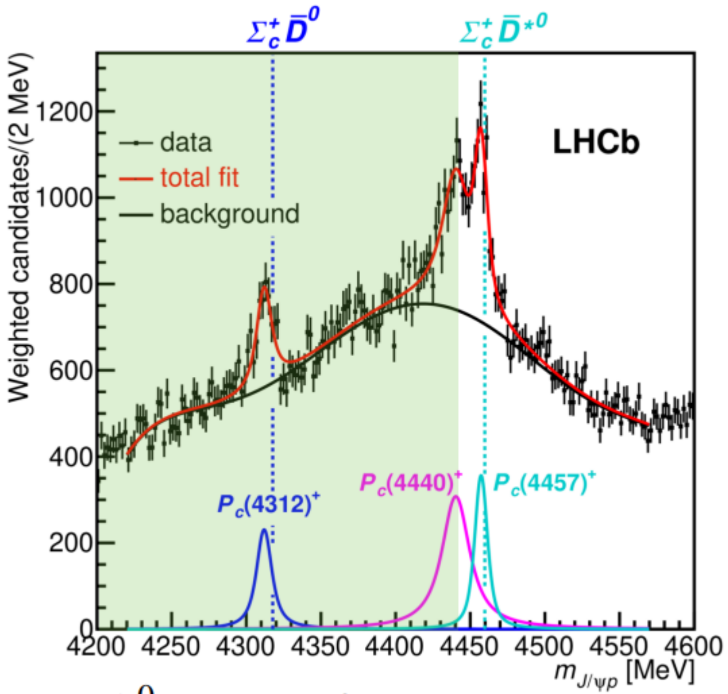


Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$ decays

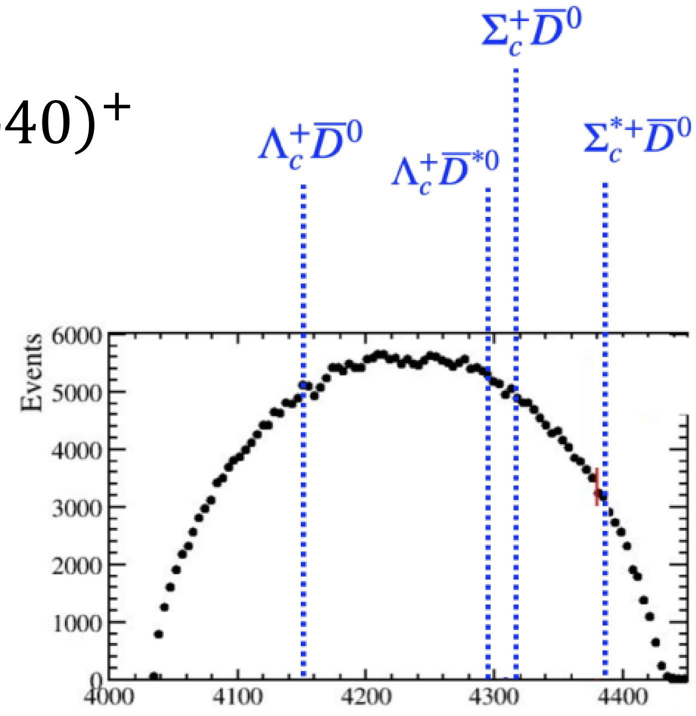
PRL128(2022)062001

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

- Q value: 393 MeV
- $m(J/\psi p)$ cover 4 thresholds
- Check $P_\psi^N(4312)^+$ and $P_\psi^N(4440)^+$

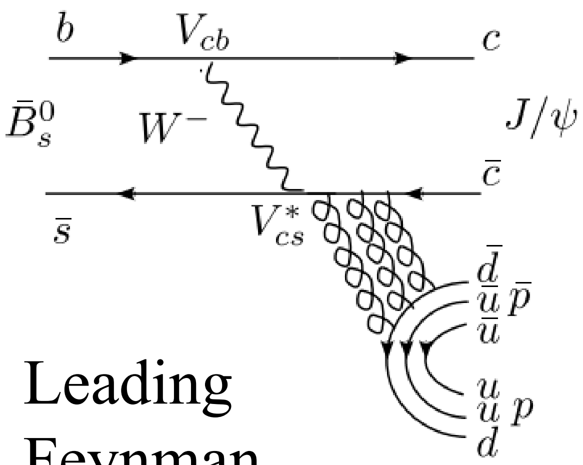


$\Lambda_b^0 \to pK^-J/\psi$



$m(J/\psi p)$ MeV

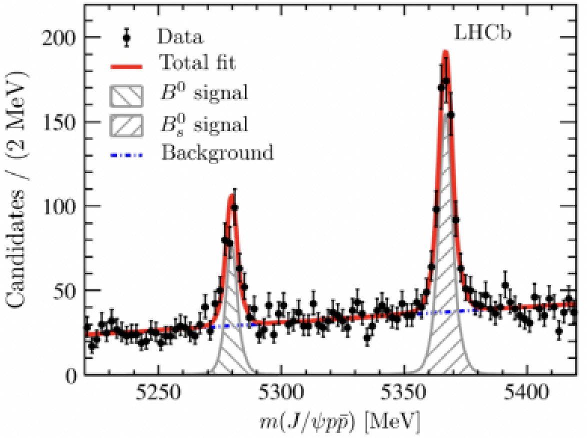
$B_s^0 \to J/\psi p\bar{p}$



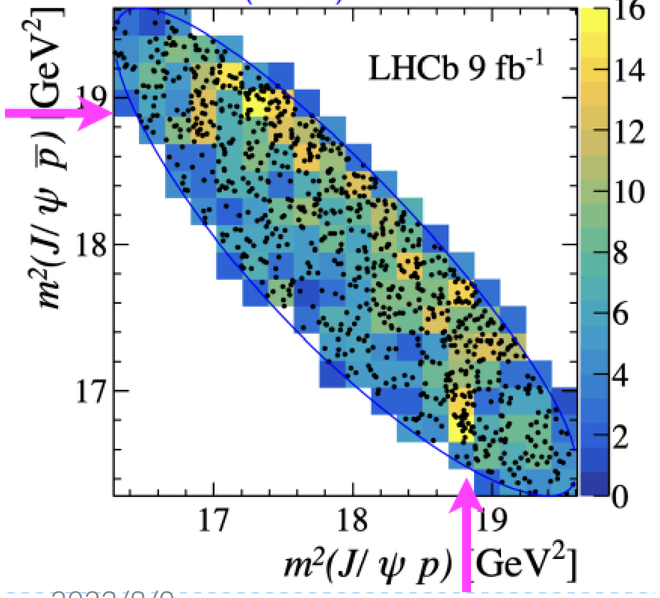
Leading Feynman diagram

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

PRL 122(2019)191804



PRL128(2022)062001



- $B_s^0 \to J/\psi p\bar{p}$ was observed at LHCb in 2019 firstly

$$\mathcal{B}(B_s^0 \to J/\psi p\bar{p}) = [3.58 \pm 0.19(\text{stat}) \pm 0.39(\text{syst})] \times 10^{-6}$$

enhanced by 2 orders w.r.t. estimation w/o resonant contributions

LHCb run1+run2, 9 fb^{-1} dataset:
Total 780 signal candidates
Purity 85%
B mass resolution 3 MeV

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

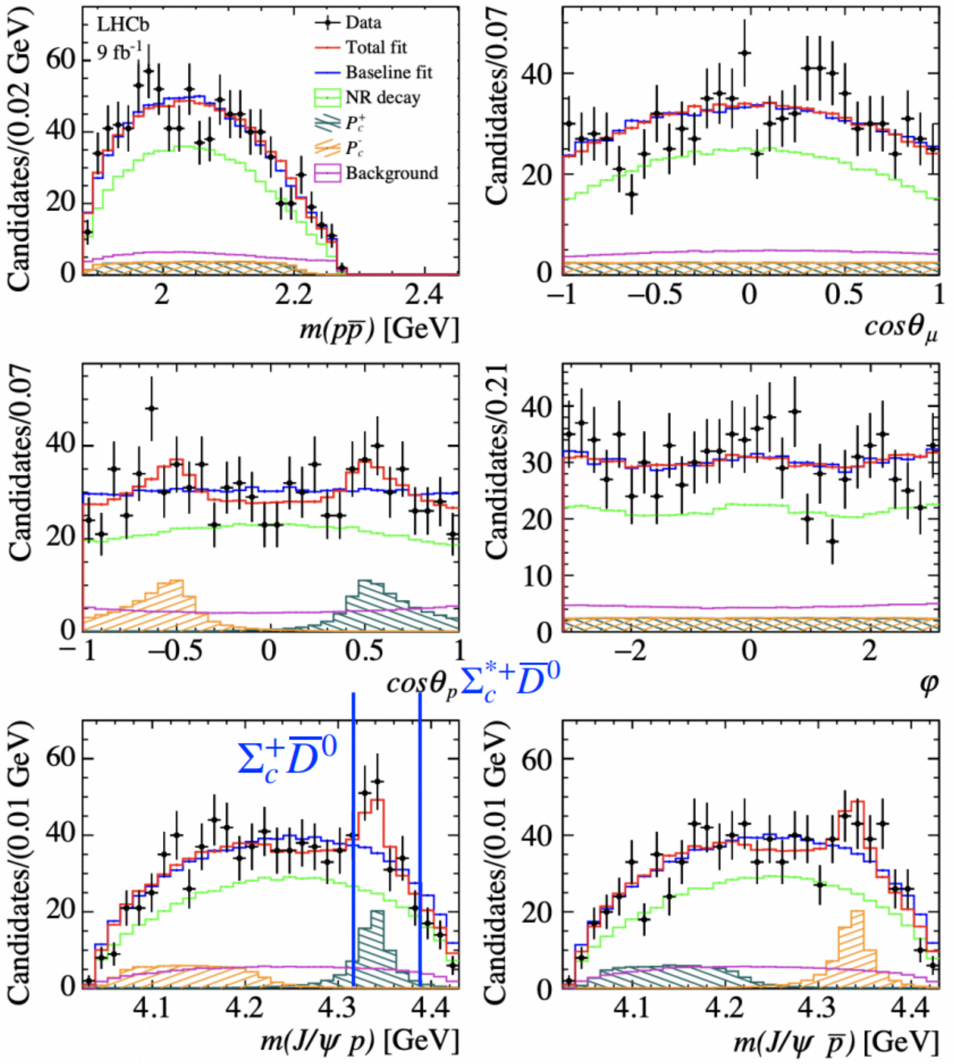
- Helicity formalism amplitude and assuming no CPV
- Three decay chains: $J/\psi X(\to p\bar{p})$, $\bar{p}P_\psi^{N+}(\to J/\psi p)$ and $pP_\psi^{N-}(\to J/\psi\bar{p})$
- Resonant lineshape: Relativistic Breit-Wigner (RBW)
- The flavor of B_s^0 is untagged, so the total amplitude

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

- Same fit strategy as $B^+ \to J/\psi\bar{\Lambda}p$ analysis

Nominal model fitting results

- Two amplitude models
  - Baseline: NR($p\bar{p}$)
  - Nominal: NR($p\bar{p}$) + RBW($P_\psi^{N\pm}$)
- The mass, width and couplings for $P_\psi^{N\pm}$ are same
- Evidence for a charged pentaquark candidate $P_\psi^{N\pm}(4337)$
- Significance: 3.1~3.7 σ for $J^P(1/2^\pm, 3/2^\pm)$

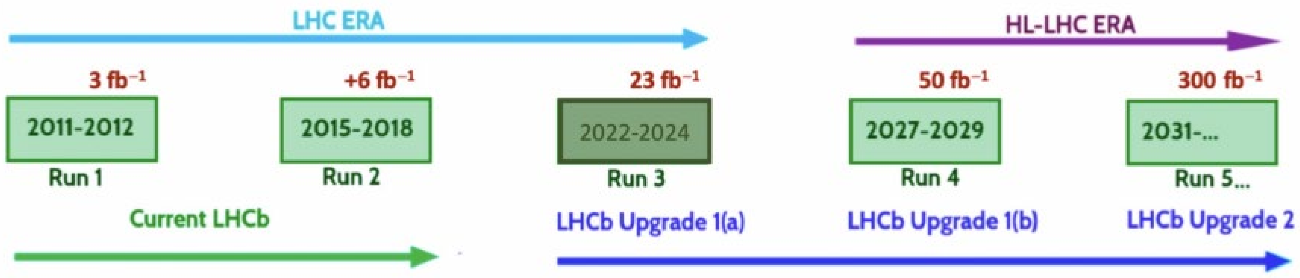


$M(P_\psi^{N\pm}) = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})$ MeV
$\Gamma(P_\psi^{N\pm}) = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})$ MeV

No evidence for $P_\psi^{N\pm}(4312)$ and $P_\psi^{N\pm}(4440)$

Summary

- Observation of first neutral pentaquark candidate $P^{\Lambda}_{\psi s}(4338)^0$ with strangeness in $B^- \to J/\psi \Lambda \bar{p}$ decays
    - Narrow state close to $\Xi_c^+ D^-$ threshold
    - Spin ½ assigned, negative parity preferred
- Evidence for a charged pentaquark candidate $P^{N}_{\psi}(4337)^+$ in $B_s^0 \to J/\psi p \bar{p}$ decays
- No evidence for structures around thresholds of $\Lambda_c^+ \overline{D}^0$ and $\Lambda_c^+ D_s^-$
- Run3 is coming, expect to have more structures in following years



Thank you!