Pentaquark states at LHCb

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Workshop on Near-Threshold Production of Heavy Quarkonium

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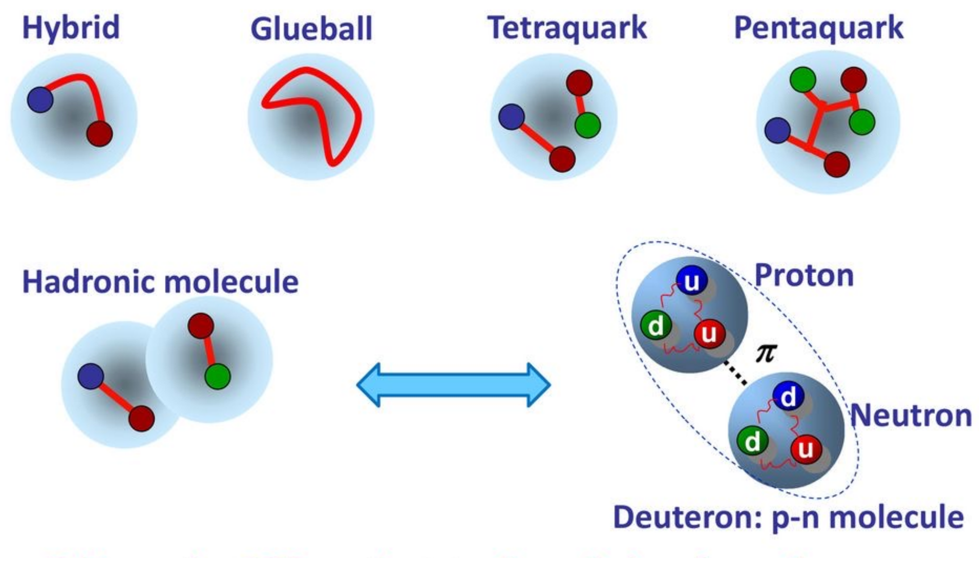
Exotic hadrons

- Exotic hadrons were proposed since the dawn of the quark model

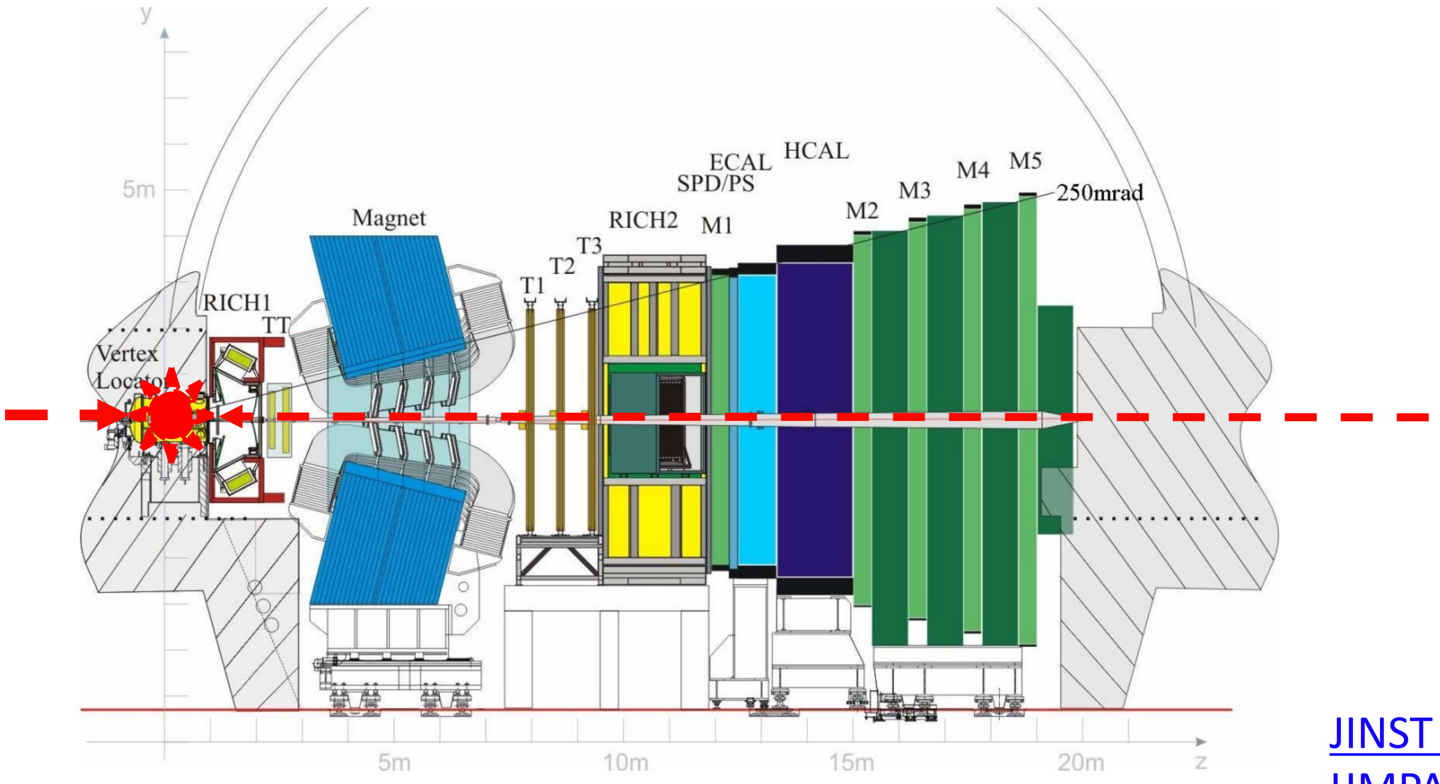
- Different compositions and binding schemes: $q\bar{q}g$ hybrid, glueball, compact multiquark state, molecular state …



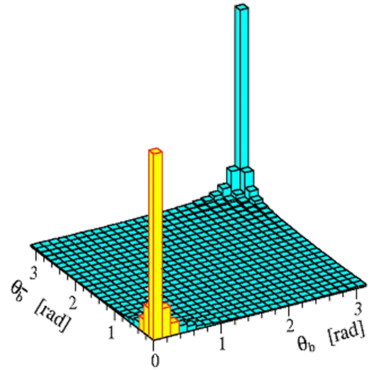
- Study of exotic hadrons can
  - provide new insights into internal structure and dynamics of hadrons
  - act as a unique probe to non-perturbative behavior of QCD

The LHCb detector

- A single-arm forward spectrometer covering $2 < \eta < 5$
- Designed for heavy flavour physics



$\bar{b}$ and b production angles

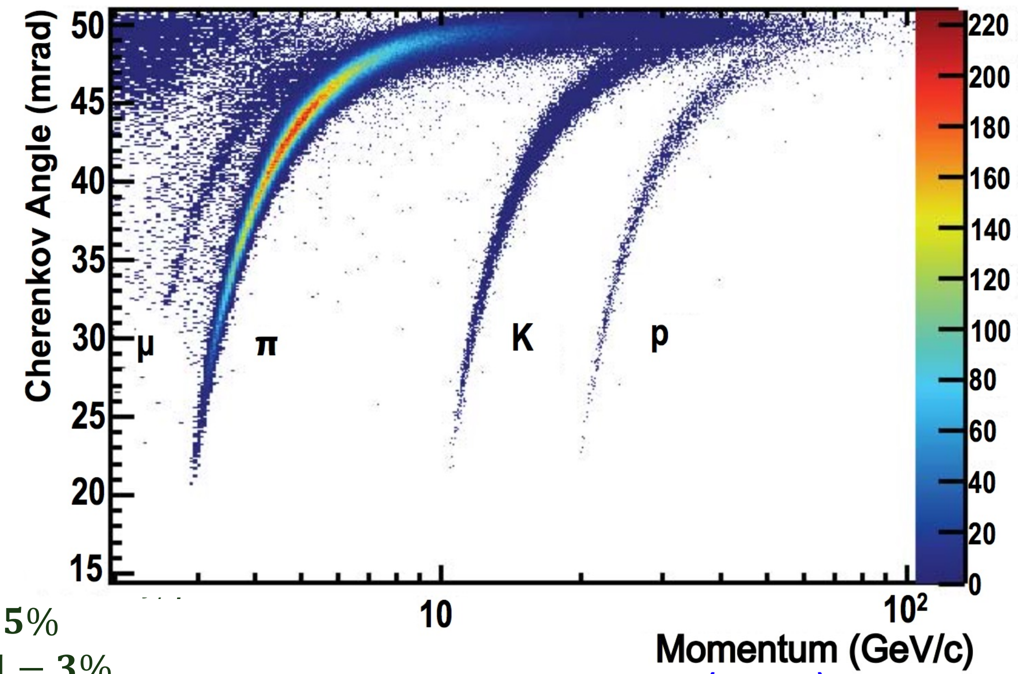


JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Why LHCb suitable for spectroscopy?

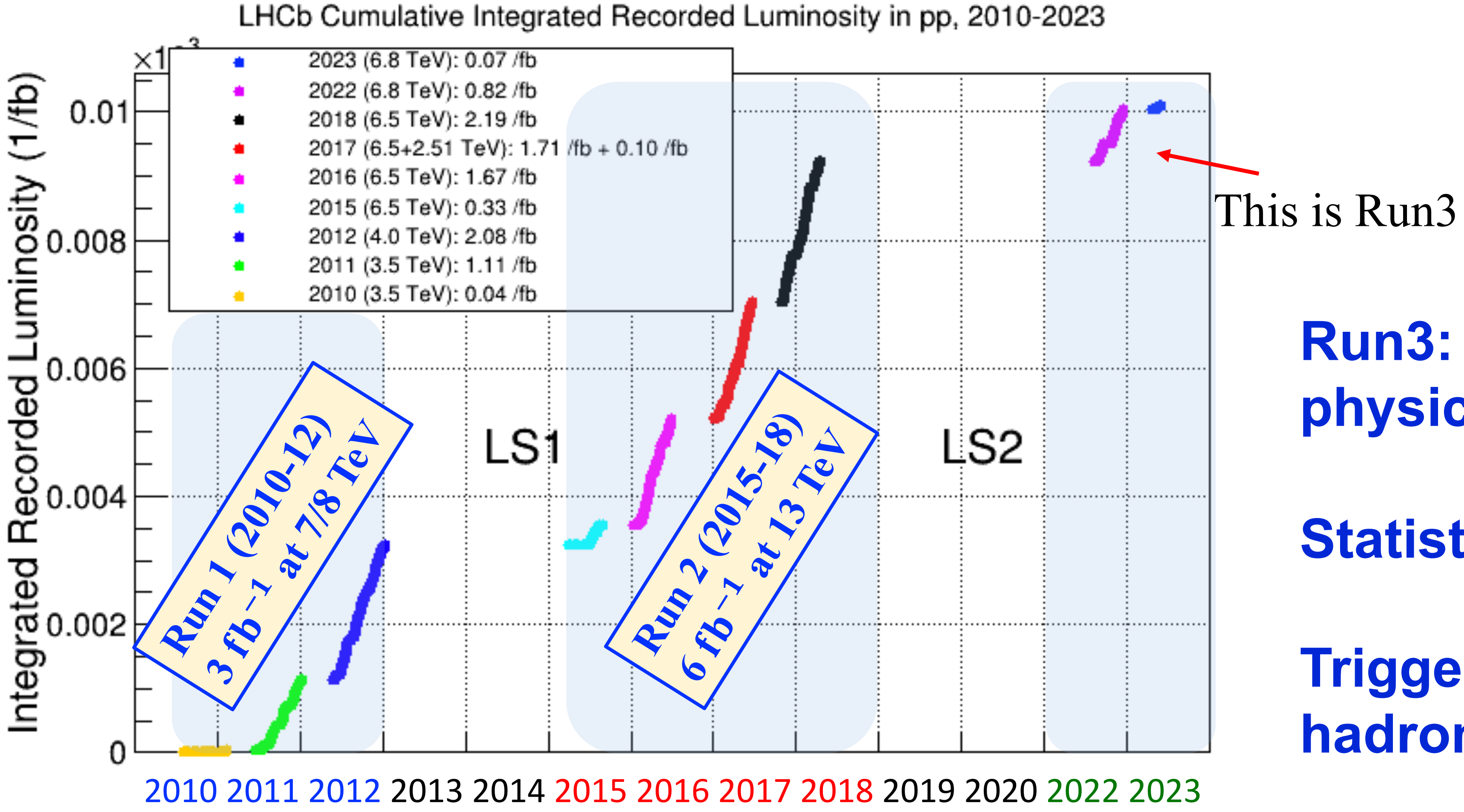
- Large statistics in LHCb acceptance
  - $\sim 6\times10^4\ b\bar{b}$ per second @ 13 TeV
  - $\sim 20\times$ yield for $c\bar{c}$ compared to $b\bar{b}$
- All kinds of hadrons can be produced
  - $\Xi_b, \Sigma_b, \Omega_b, \Lambda_b\ \ldots$
- Dedicated design of detector
  - Powerful particle identification
    - RICH $K-\pi$ separation: $\epsilon(K\to K)\sim 95\%$ mis-ID $\epsilon(\pi\to K)\sim 5\%$
      Muon ID: $\epsilon(\mu\to\mu)\sim 97\%$ mis-ID $\epsilon(\pi\to\mu)\sim 1-3\%$
  - Good momentum, mass resolution
    - Momentum: $\Delta p/p = 0.4\sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
      Mass : $\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B\to J/\psi X$ (constrainted $\mathrm{m}_{J/\psi}$)
  - Very precise vertex resolution
    - $\sigma_{\mathrm{IP}} = 20\mu\mathrm{m}$ to detect long-lived D and B decays

PID from Cherenkov



IJMPA 30 (2015) 1530022

LHCb collected luminosity



Run3: Hope to collect ~15 fb^{-1} physics data in 2024&2025

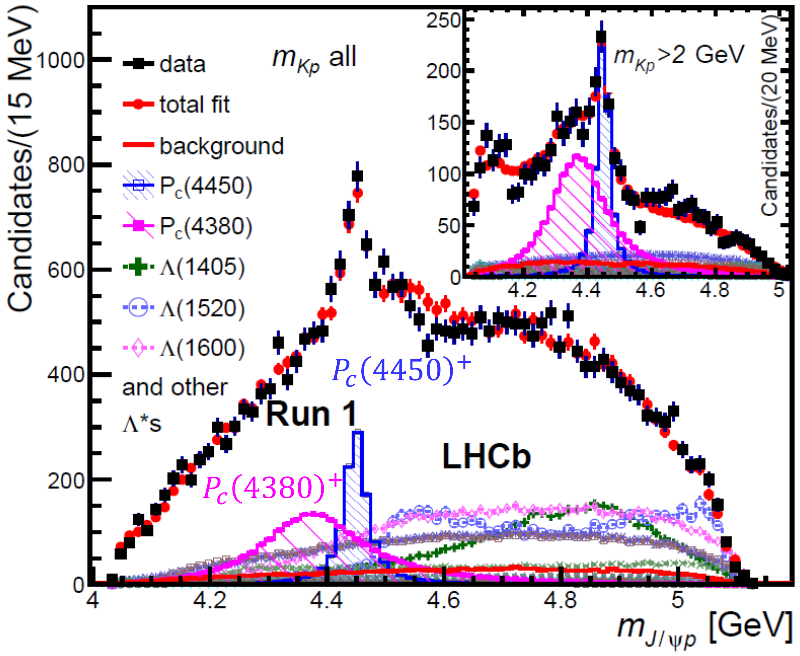
Statistics ~ 2× run1+2

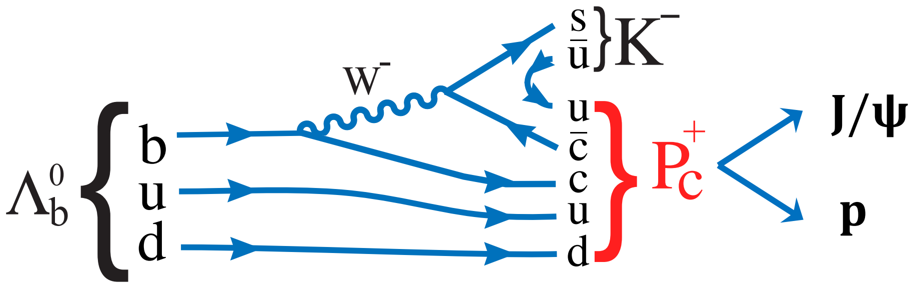
Trigger efficiency 2× for hadronic final state

LHCb observation in 2015

- **Two $J/\psi p$ resonant structures** are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ ← the prominent peak
  - $P_c(4380)^+$ ← required to obtain a good fit to the data
  - Consistent with **pentaquarks** with minimal quark content of $\boldsymbol{uudc\bar{c}}$

26k Λ_b signals **PRL 115 (2015) 072001 (most cited paper at LHCb so far)**





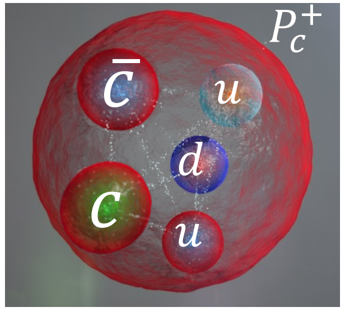
	$P_c(4380)^\pm$	$P_c(4450)^\pm$
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit Fraction (%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1

Lots of open questions

- Observation of LHCb opens a gate to study pentaquarks
- To interpret the nature of P_c, more studies are needed
  - Inner structures?
  - More states, SU(3) partners?
  - J^P, mode decay modes, production mechanism …?

Tightly-bound pentaquark?

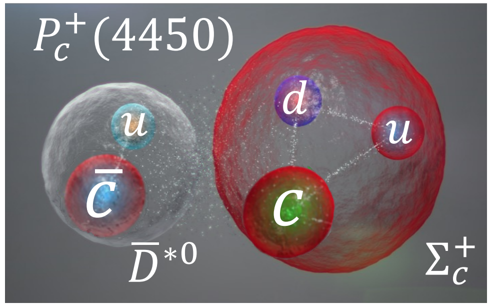
$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$



Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

Loosely-bound pentaquark?

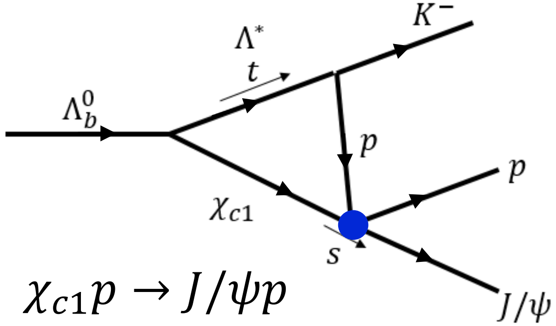
$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$



Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

Kinematical effect: triangle diagram?

$P_c(4450)^+ = \chi_{c1}p$ threshold?



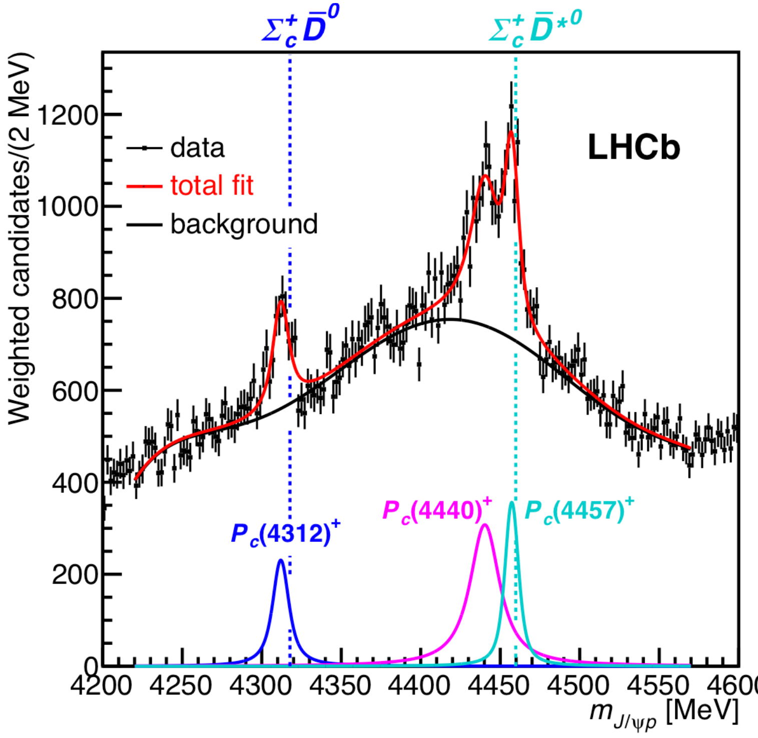
Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

Fine structures from update

- Run1+Run2, x10 $\Lambda_b^0 \to J/\psi p K^-$ yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)
- $P_c(4312)^+$ is observed
- $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$
- Their near-threshold masses **favour** the predicted "molecular" pentaquarks with meson-baryon substructure, but **other hypotheses are not ruled out**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010)
  - Wang,Huang,Zhang,Zou, PR C84, 015203 (2011)
  - Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012)
  - Wu,Lee,Zou, PR C85 044002 (2012)
  - Xiao,Nieves,Oset, PR D88 056012 (2013)
  - Karliner,Rosner, PRL 115, 122001 (2015)

246k Λ_b signals

PRL 122 (2019) 222001



1D $m_{J/\psi p}$ is fitted, ongoing amplitude analysis is in advanced stage

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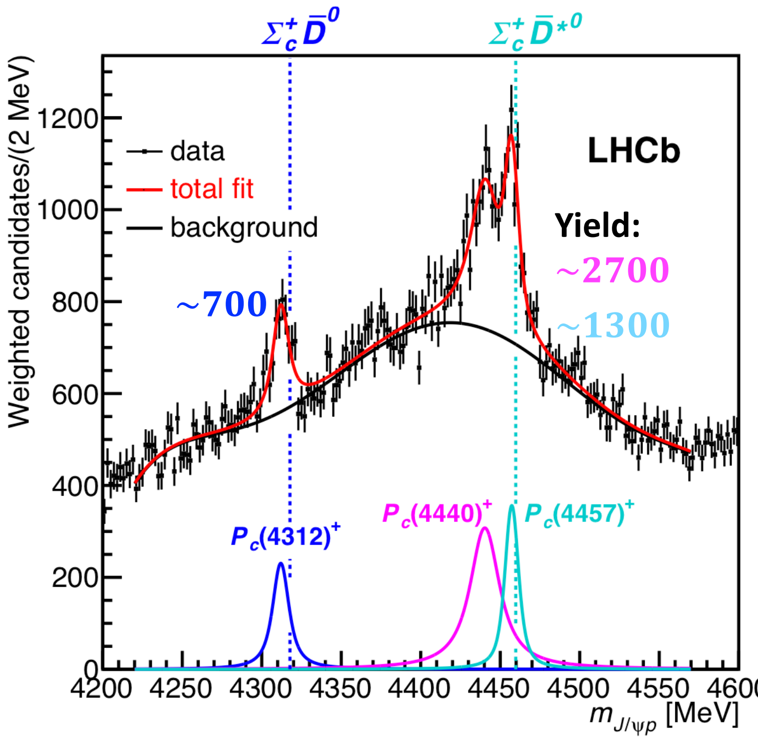


State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

1D $m_{J/\psi p}$ is fitted, ongoing amplitude analysis is in advanced stage

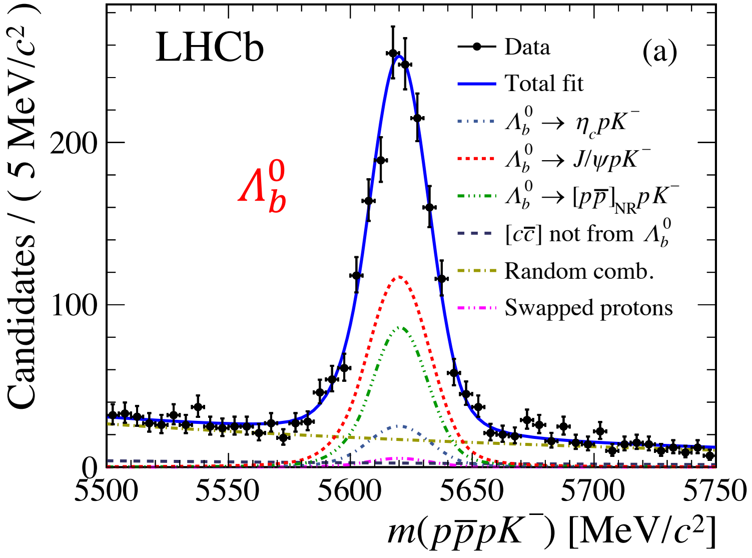
1st observation of $\Lambda_b^0 \to \eta_c p K^-$

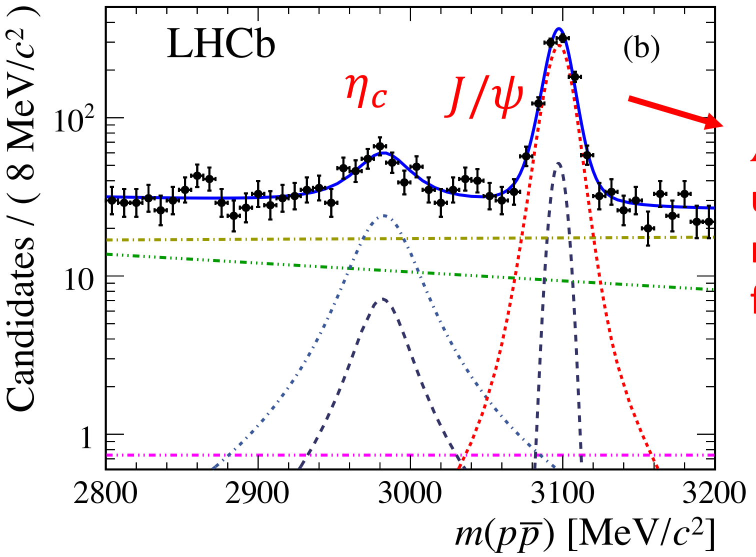
- **$\eta_c p$ final state is very sensitive to $1/2^-$ P_c, where $\eta_c p$ is in S-wave**
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$

  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- LHCb run2 data (5.5 fb^{-1}) using $\eta_c \to p\bar{p}$
- Fit 2D mass spectrum to confirm the existence
- Obtain $$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.333 \pm 0.050\ (\text{stat.}) \pm 0.019\ (\text{syst.}) \pm 0.032\ (\mathcal{B})$$

$P_c(4312)^+$ production fraction in $\Lambda_b^0 \to \eta_c p K^-$ is ~ 3% (predicted)

$\sim 170\ \Lambda_b^0 \to \eta_c p K^-$ signals





$\Lambda_b^0 \to J/\psi p K^-$ used as reference mode for branching fraction measurement

Search for P_c^+ in $\eta_c p$ system

[PRD 102 (2020) 112012]

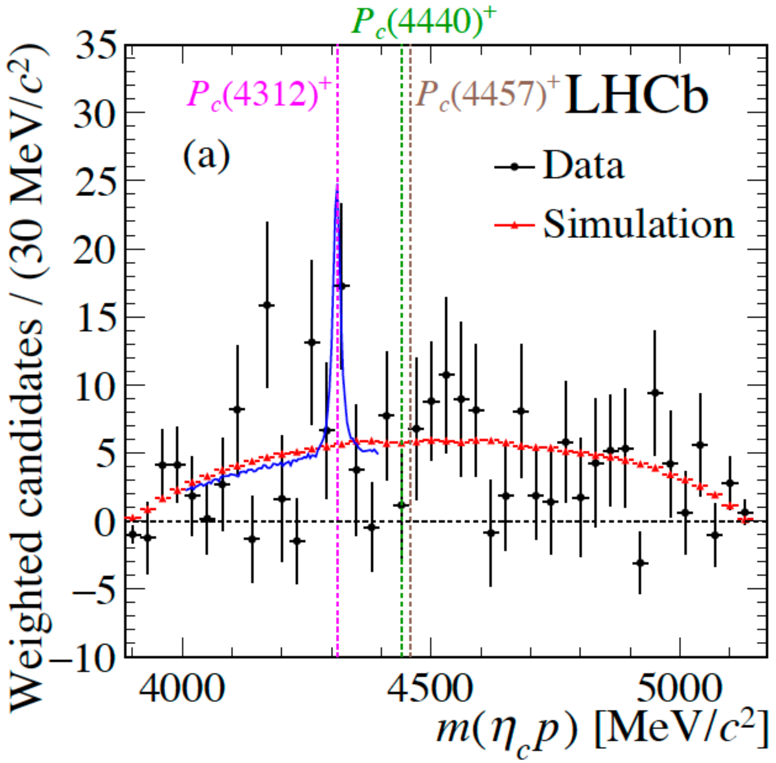
- Check background-subtracted $\eta_c p$ mass spectrum
  - sPlot technique. 2D mass as discriminating variable.

No significant $P_c(4312)^+$ contribution (~2σ)

P_c^+ production fraction obtained

$$R(P_c(4312)^+) < 24\% \text{ @ } 95\% \text{ C. L.}$$

much larger than the predicted value 3%
(no conclusion yet)

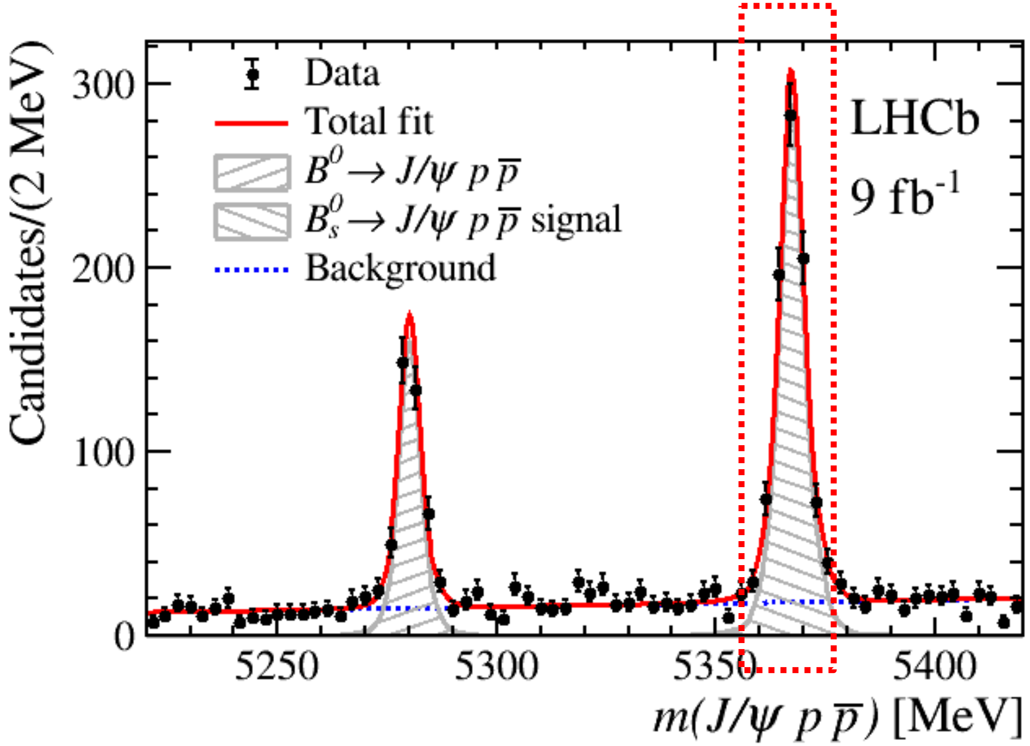


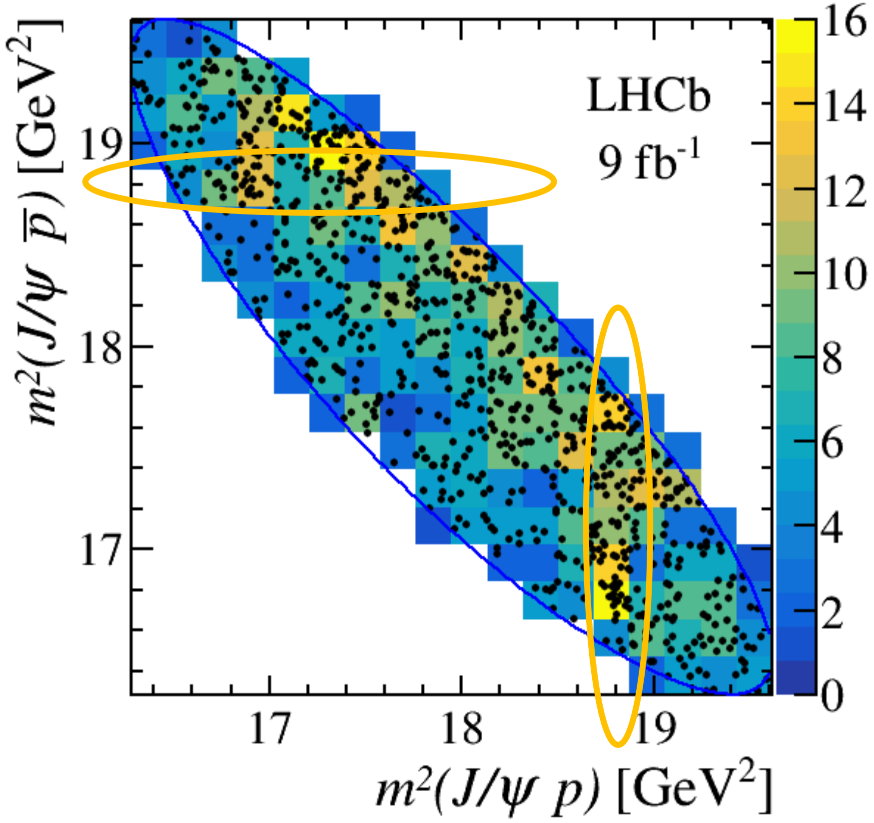
- **Need run3+4 data, amplitude fit can be performed**

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

[PRL 128 (2022) 062001]

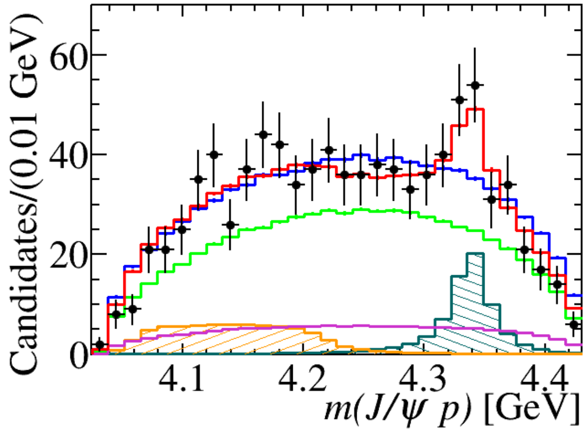
- 9 fb^{-1} Run 1+2 data: ~800 signals, purity ~85%
- Hints for new $J/\psi p$ ($J/\psi \bar{p}$) structure ?





Evidence of a new $J/\psi p$ structure

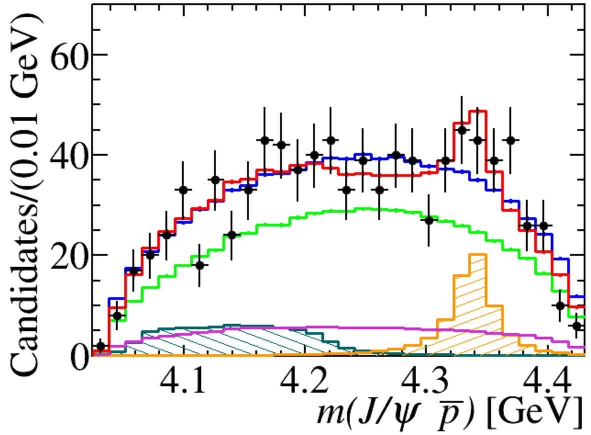
[PRL 128 (2022) 062001]



The measured mass and width:

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\,\text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\,\text{MeV},$$

Can't distinguish J^P due to limited sample size



Other contributions are tested, no evidence is seen:

- $P_c(4312)^+$ seen in $\Lambda_b^0 \to J/\psi p K^-$[PRL 122 (2019) 222001]
- Predicted glueball state $f_J(2220)(\to p\bar{p})$[EPJC 75, 101 (2015)]

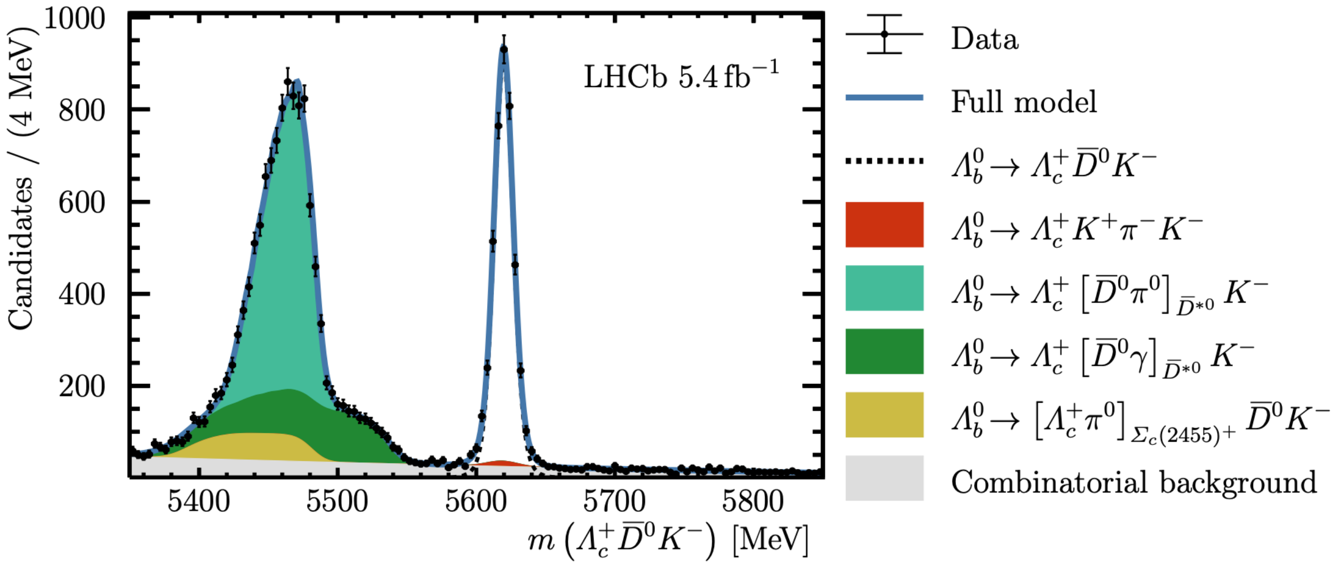
More data needed to confirm this structure

Observations of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ decays

- These decays can pave the way for future P_c^+ search in $\Lambda_c^+ \overline{D}^{(*)0}$ systems
  - which are open-charm equivalent of $J/\psi p$
  - $\overline{D}^{*0}$ is partially reconstructed with missing π^0/γ

$$N^{\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-} = 4010 \pm 70,$$

$$N^{\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-} = 10\,560^{+310}_{-290}$$



[arXiv:2311.14088]

- Branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (19.08^{+0.36+0.16}_{-0.34-0.18} \pm 0.38)\%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (58.9^{+1.8+1.7}_{-1.7-1.8} \pm 1.2)\%$$

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

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = (15.2^{+3.2}_{-2.8})\%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)} = (4.9^{+1.1}_{-0.9})\%$$

BFs of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ will come out soon

Sensitivity of $P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0}$ search in Λ_b^0 decays

- P_c^+ search in $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-$ is onging
- My estimation of the sensitivity
- From the previous slide, I obtain

  $$\varepsilon(\Lambda_c^+ \bar{D}^0) \times \mathcal{B}(\Lambda_c^+ \to pK\pi)\mathcal{B}(\bar{D}^0 \to K\pi) / \varepsilon(J/\psi p) \times \mathcal{B}(J/\psi \to \mu\mu) \sim 1/280$$

  - Low reconstruction efficiency due to more particles and $\mathcal{B}$ of double charm decays
- Assuming $\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0}\right) \approx 5 \times \mathcal{B}(P_c^+ \to J/\psi p)$, we expect

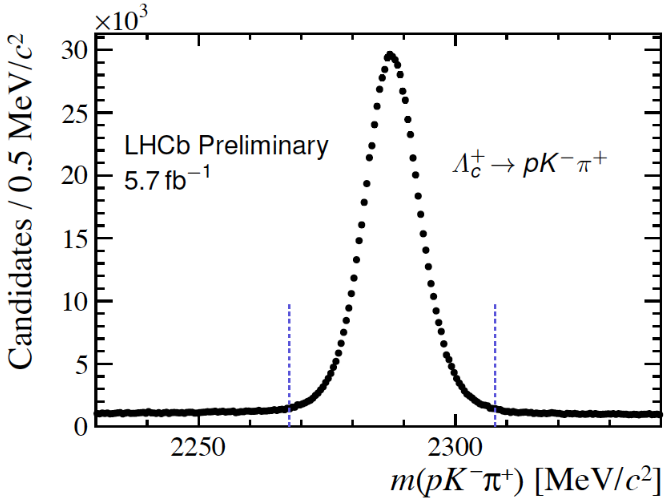
	$P_c^+ \to J/\psi p$ observed in 9 fb^{-1}	$P_c^+ \to \Lambda_c^+ \bar{D}^{(*)}$ expected in 5.4 fb^{-1}
$P_c(4312)^+$	700	9
$P_c(4440)^+$	2700	34
$P_c(4457)^+$	1300	16

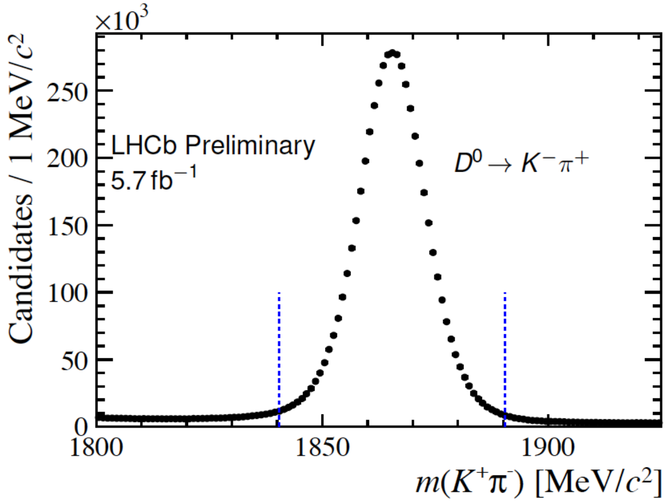
- So current data should still have some sensitivity for $\mathrm{R} = \frac{\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0}\right)}{\mathcal{B}\left(P_c^+ \to J/\psi p\right)}$
- Run3 data will add 5 times data, can get sensitivity of 1 for R

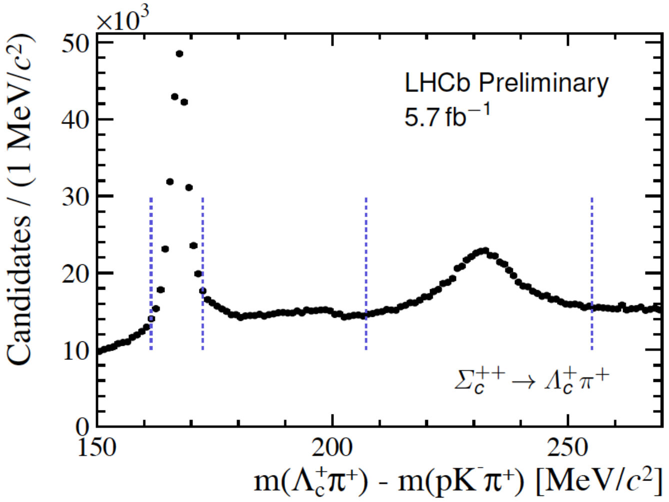
Search for pentaquarks via open charm

- Prompt production with 32 final states
  - $\Lambda_c^+\overline{D}$, $\Lambda_c^+\overline{D}^*$, $\Lambda_c^+\pi\overline{D}$, $\Sigma_c^{(*)}\overline{D}^{(*)}$ and Λ_c^+D, $\Lambda_c^+D^*$, $\Lambda_c^+\pi D$, $\Sigma_c^{(*)}D^{(*)}$
- Scan to search for pentaquarks with narrow width (0-15 MeV)
- No significant narrow peak is found for all the modes
- Upper limits are set on the production rates related to Λ_c^+

LHCb-PAPER-2023-018 in preparation



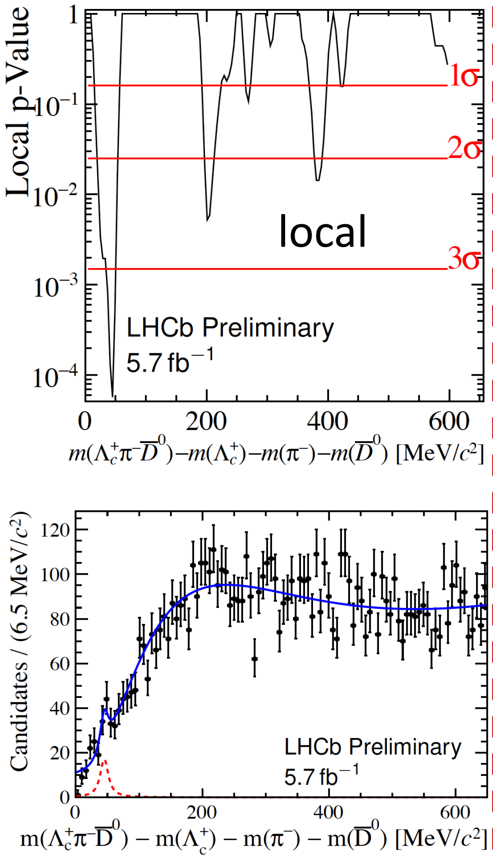




Results

[LHCb-PAPER-2023-018]

- Upper limits set on $R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \rightarrow \frac{\sigma(P_c)\times\mathcal{B}\left(P_c\rightarrow\Lambda_c^+ D(\pi)\right)\times\mathcal{B}(D)}{\sigma(\Lambda_c^+)}$



$c\bar{c}udd$

$M\sim 4335.87$ MeV

preliminary

Decay Mode	Significance (σ) Local	Significance (σ) Global	Corresponding Mass (MeV/c^2)	Signal Yield	Upper Limit ($\times 10^{-3}$) 90% CL	Upper Limit ($\times 10^{-3}$) 95% CL
$\Lambda_c^+\bar{D}^0$	2.85	1.01	349	46.8 ± 23.4	1.16	1.21
$\Lambda_c^+ D^{*-}$	2.32	0.00	365	15.0 ± 10.3	2.16	2.39
$\Lambda_c^+\pi^+ D^-$	2.82	0.99	225	68.6 ± 13.3	1.95	2.40
$\Sigma_c^0\bar{D}^0$	1.90	0.00	65	4.7 ± 4.2	1.02	1.15
$\Lambda_c^+\pi^-\bar{D}^0$	3.86	2.56	45	60.1 ± 25.9	1.40	1.70
$\Sigma_c^0 D^-$	2.03	0.00	261	7.0 ± 2.6	0.71	0.89
$\Lambda_c^+\pi^- D^-$	3.67	2.35	249	82.8 ± 14.3	2.23	2.67
$\Lambda_c^+\pi^- D^{*-}$	2.31	0.00	409	23.6 ± 23.0	2.79	3.28
$\Sigma_c^{*++} D^{*-}$	1.74	0.00	453	3.3 ± 2.4	1.24	1.43
$\Sigma_c^{*0} D^-$	1.86	0.00	109	10.7 ± 29.1	1.32	1.59
$\Lambda_c^+ D^+$	2.52	0.59	169	14.9 ± 9.6	1.34	1.50
$\Lambda_c^+\pi^+ D^0$	3.21	1.72	45	24.8 ± 39.3	0.98	1.18
$\Lambda_c^+\pi^+ D^{*+}$	3.37	1.99	165	13.8 ± 3.5	0.97	1.22
$\Lambda_c^+\pi^- D^{*+}$	2.70	0.58	73	5.8 ± 71.3	1.70	1.94
$\Sigma_c^{*++} D^0$	2.11	0.00	113	3.9 ± 2.8	0.87	0.99
$\Sigma_c^{*0} D^+$	2.18	0.00	69	4.7 ± 4.6	1.13	1.32

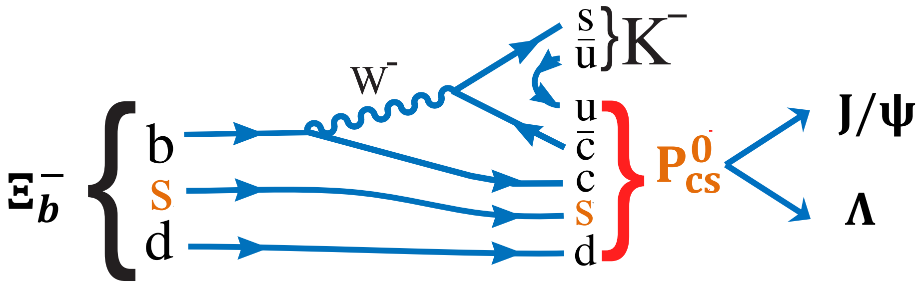
Largest significance

Known P_c^+ states tested and yields all agree with 0

$$P_{cs} \to J/\psi\Lambda$$

Motivation

- SU(3) partner P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi \Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]



- According to the P_c results in 2019, ten possible molecular states are predictions for P_{cs}

System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]^\sharp_{\frac{5}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

[Bo Wang PRD 101 (2020) 034018]

M	4436.7	4580.96	4580.96	4506.99	4650.86	4650.58	4650.56	4276.59	4429.84	4429.52

[CW Xiao PLB 799 (2019) 135051]

More than P_c

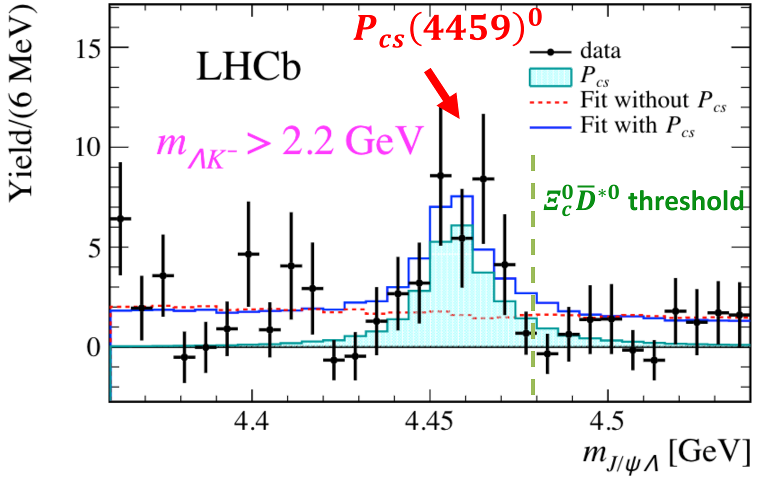
Evidence of $J/\psi\Lambda$ structure

[Science Bulletin 66 (2021) 1278]

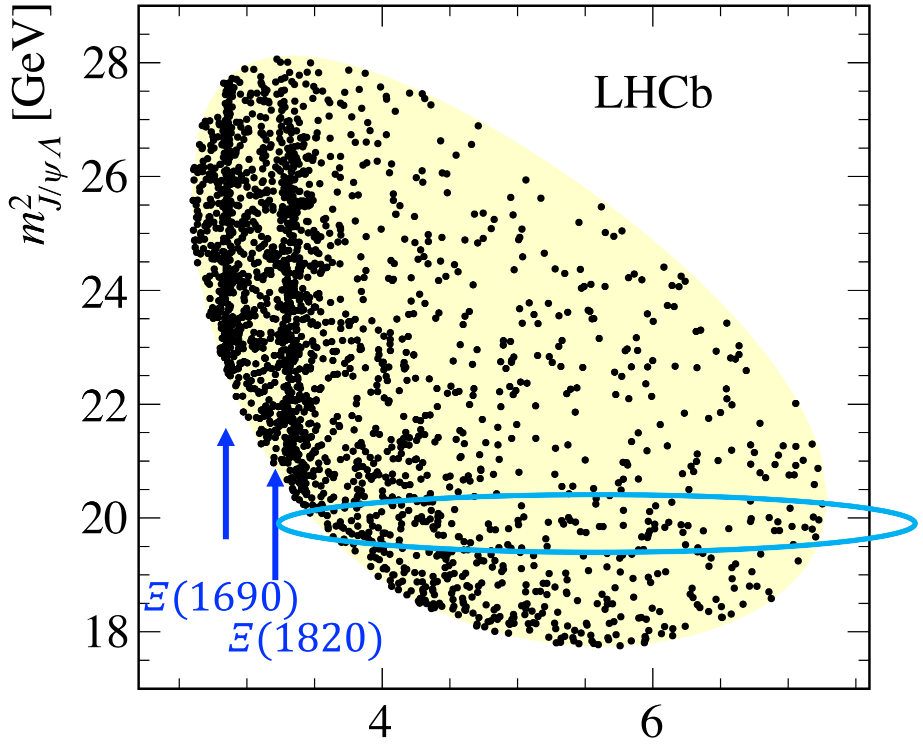
- P_{cs} is suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]
- Amplitude analysis with improved helicity formalism
  - $P_{cs}(4459)^0$ found, significance >3.1σ

Mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold

State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$



$\sim$1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)

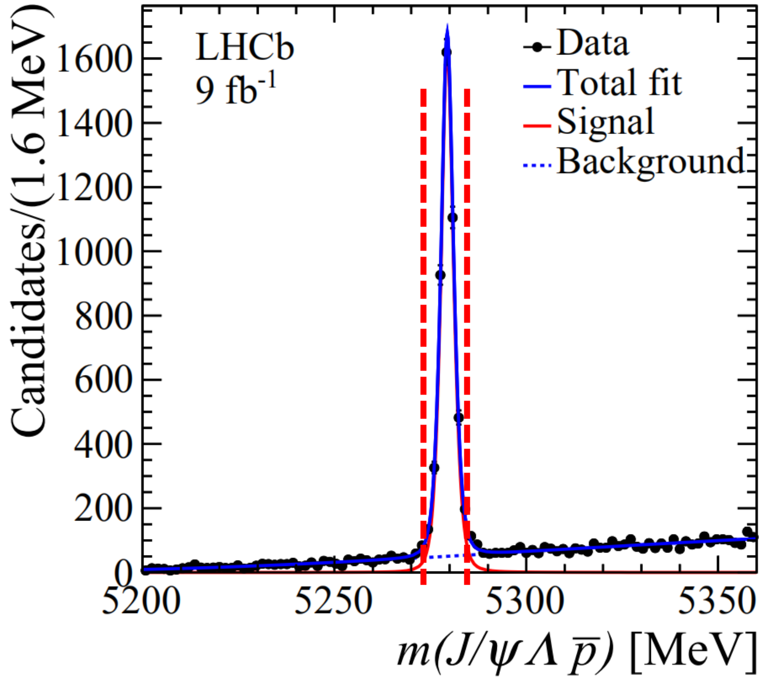


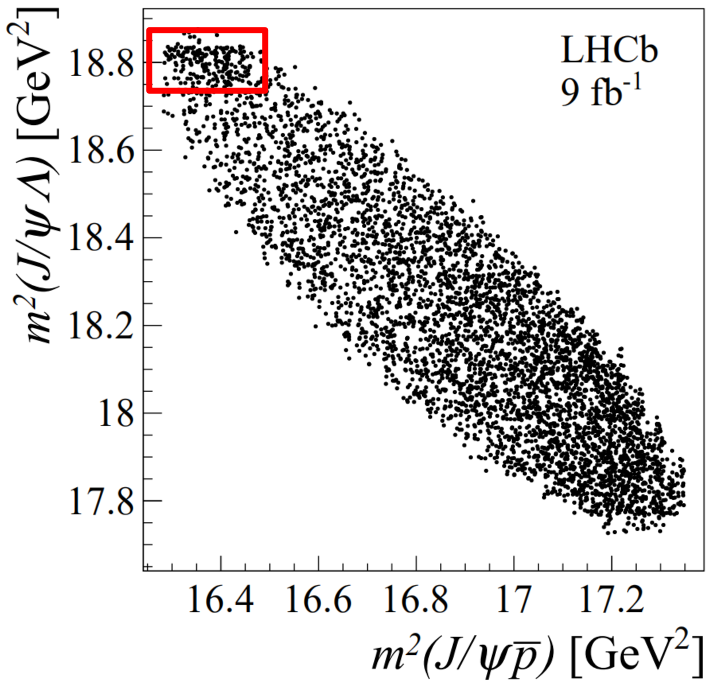
Potential P_{cs}^0 structure?

P_{cs} in $B^- \to J/\psi \Lambda \bar{p}$

[PRL 131 (2023) 031901]

- Can search for pentaquark both in $J/\psi p$ & $J/\psi \Lambda$
  - Limited range: $m(J/\psi p) < 4.16$ GeV, $m(J/\psi\Lambda) < 4.34$ GeV, Cover thresholds of $\Lambda_c^+ \bar{D}$ and $\Xi_c \bar{D}$





$N_{\rm sig} = \mathbf{4617 \pm 73}$

Purity in signal region : 93%

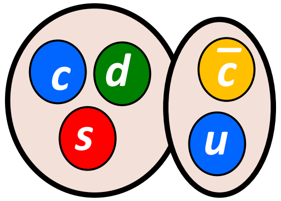
Horizontal band at $m^2(J/\psi\Lambda) \sim 18.8 \mathrm{GeV}^2$

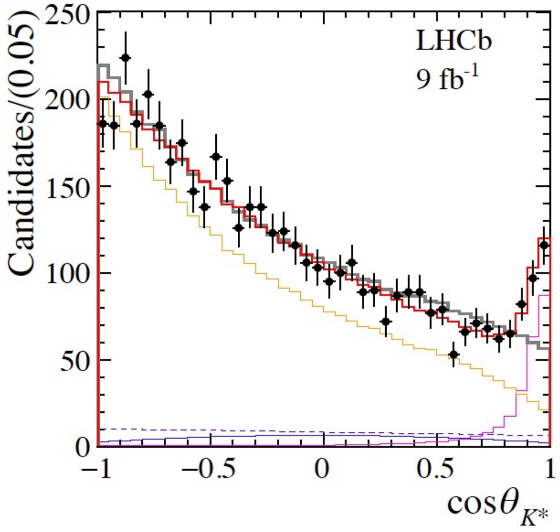
Further confirmed by amplitude analysis

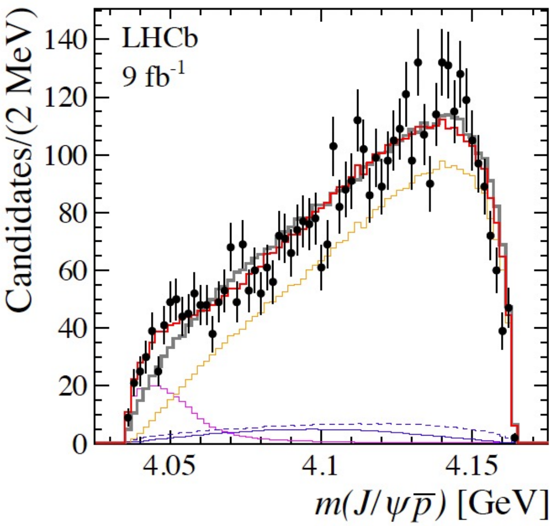
Pentaquark with strangeness

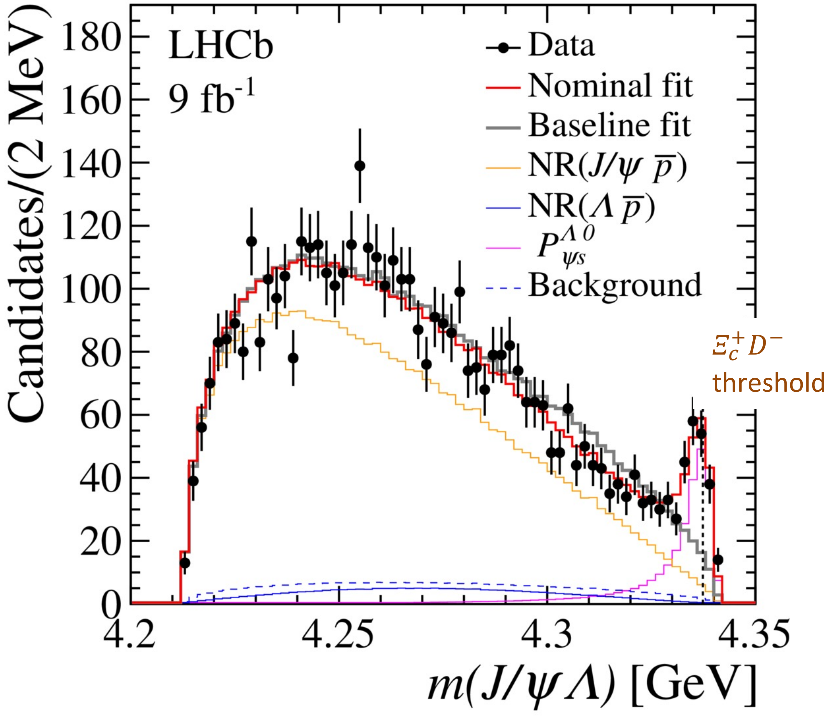
[PRL 131 (2023) 031901]

- A new pentaquark with strangeness $P_{\psi s}^{\Lambda}(4338)^0$ ($c\bar{c}sud$) observed in the $B^- \to J/\psi\Lambda\bar{p}$ decay
  - **At $\Xi_c^+ D^-$ threshold**
  - $\boldsymbol{m = 4338.2 \pm 0.7 \pm 0.4}$ **MeV**
  - $\boldsymbol{\Gamma = 7.0 \pm 1.2 \pm 1.3}$ **MeV**
  - **Fit fraction** $= \boldsymbol{(12.5 \pm 0.7 \pm 1.9)\%}$
  - $\boldsymbol{J^P = (1/2)^-}$ **preferred**, $\boldsymbol{J^P = \frac{1}{2}^+}$ **rejected under 90%** $\boldsymbol{CL_s}$



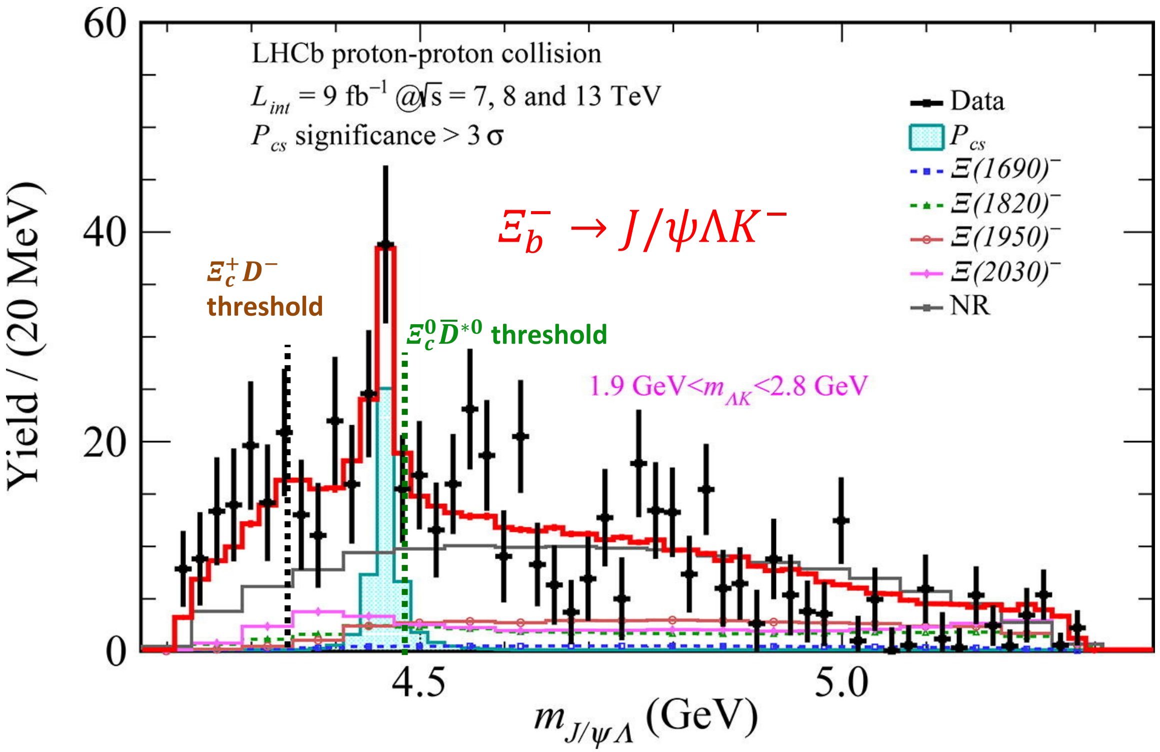






Summary of $P_{cs} \to J/\psi\Lambda$

State	M_0 [MeV]	Γ [MeV]	FF (%)	Threshold
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$	$\Xi_c \bar{D}^*$
$P_{cs}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	$12.5 \pm 0.7 \pm 1.9$	$\Xi_c \bar{D}$



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

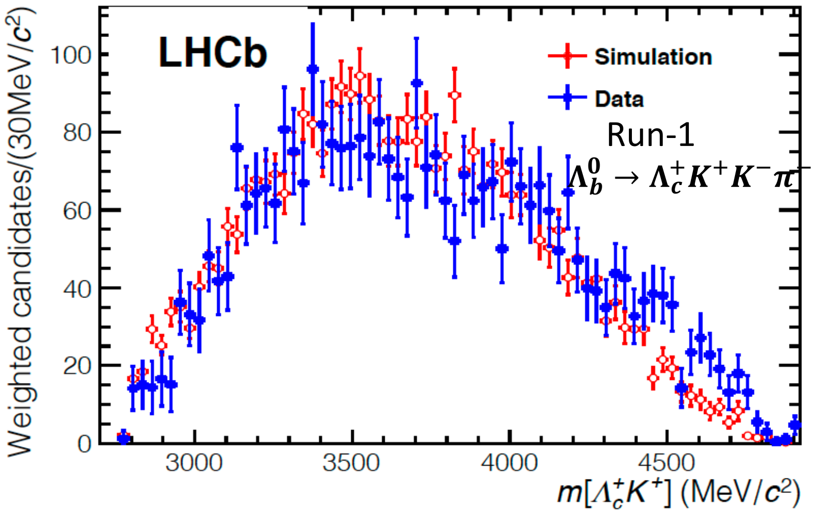
Summary of $P_{cs} \to J/\psi\Lambda$

$\Xi_c^+ D^-$ threshold

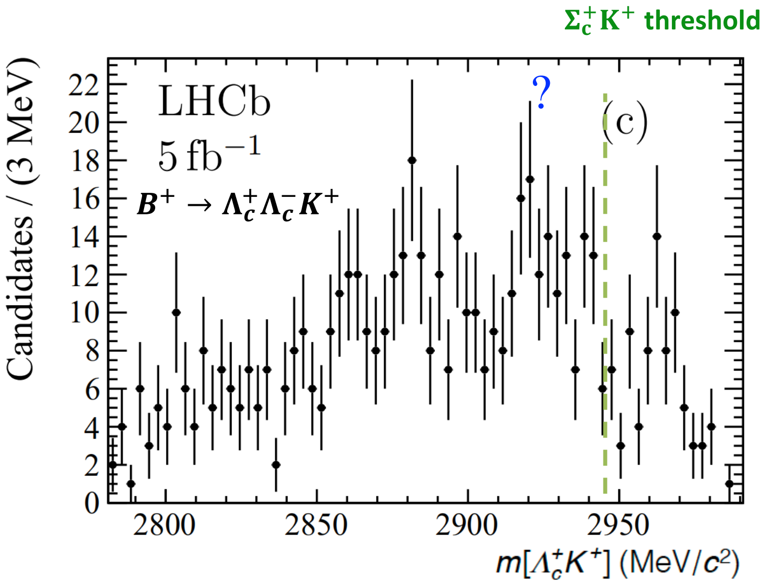
Other studies

Search for open-charm pentaquark

- Potential open-charm pentaquark $[c\bar{s}uud]$ decay to $\Lambda_c^+ K^+$
- **Modes:**
  - $\boldsymbol{\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-}$
  - $\boldsymbol{B^+ \to \Lambda_c^+ \Lambda_c^- K^+}$
- Potential hint in the B^+ decays, more data and amplitude analysis needed



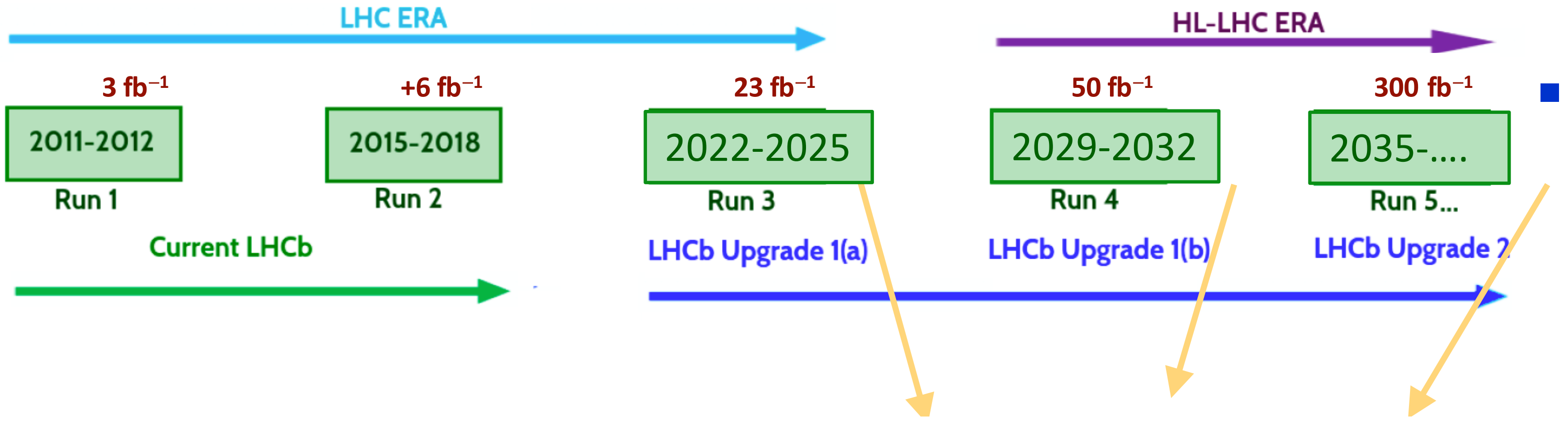
[Phys. Lett. B 815 (2021) 136172]



[PRD 108 (2023) 012020]

Prospects

[arXiv:1808.08865]



Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^+$	23k	58k	390k

- **LHCb is now boosting the data to a new level**
  - Expect to 3x data (5x hadronic events) by 2025
  - Opportunity for decays with hadronic final state, such as $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^+$

$\chi_{c1}(3872)$ lineshape from multi-channels

Z_c(4430)

Doubly-charmed tetraquark $\mathcal{T}_{cc\bar{s}}^+ \to D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result

Summary

- We have observed narrow pentaquark states $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$, and SU(3) partner $P_{cs}(4338)^0$
- We also have evidences for $P_{cs}(4459)^0$, and $P_c(4337)^+$
- Except for $P_c(4337)^+$, all states are just below or at the corresponding thresholds of charm-baryon and anti-charm meson

- Many studies performed, but statistics are limited

- Run-3 data is essential, more information will be given
  - **More decay modes, $\Lambda_c^+\bar{D}^{(*)0}$, $\Sigma_c^{++}D^{(*)-}$, $J/\psi p\pi$?**
  - **$P_{cs}(4459)^0$ and $P_c(4337)^+$, more P_{cs}?**
  - **Open-charm pentaquarks?**

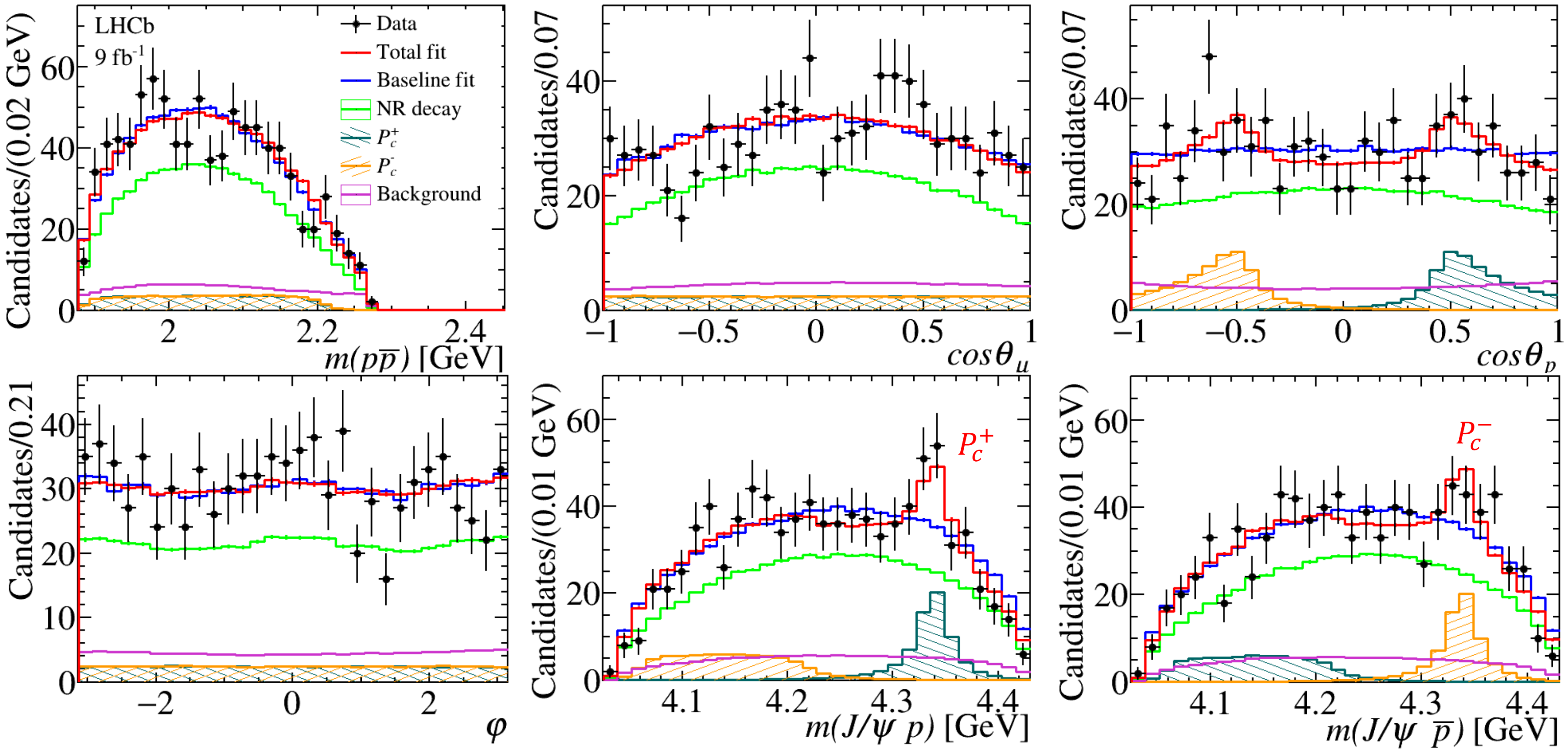
Your suggestions/comments are highly welcome

Thanks!

4D amplitude analysis

[PRL 128 (2022) 062001]

- Untagged B decay, assuming CP conservation, the same mass, width and couplings for $P_c^{\pm}$
- Significance 3.1σ~3.7σ for J^P $(\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm})$, after considering syst. uncertainties and look-elsewhere effect



No $P_c^{\pm}$ fit

W/ $P_c^{\pm}$ fit

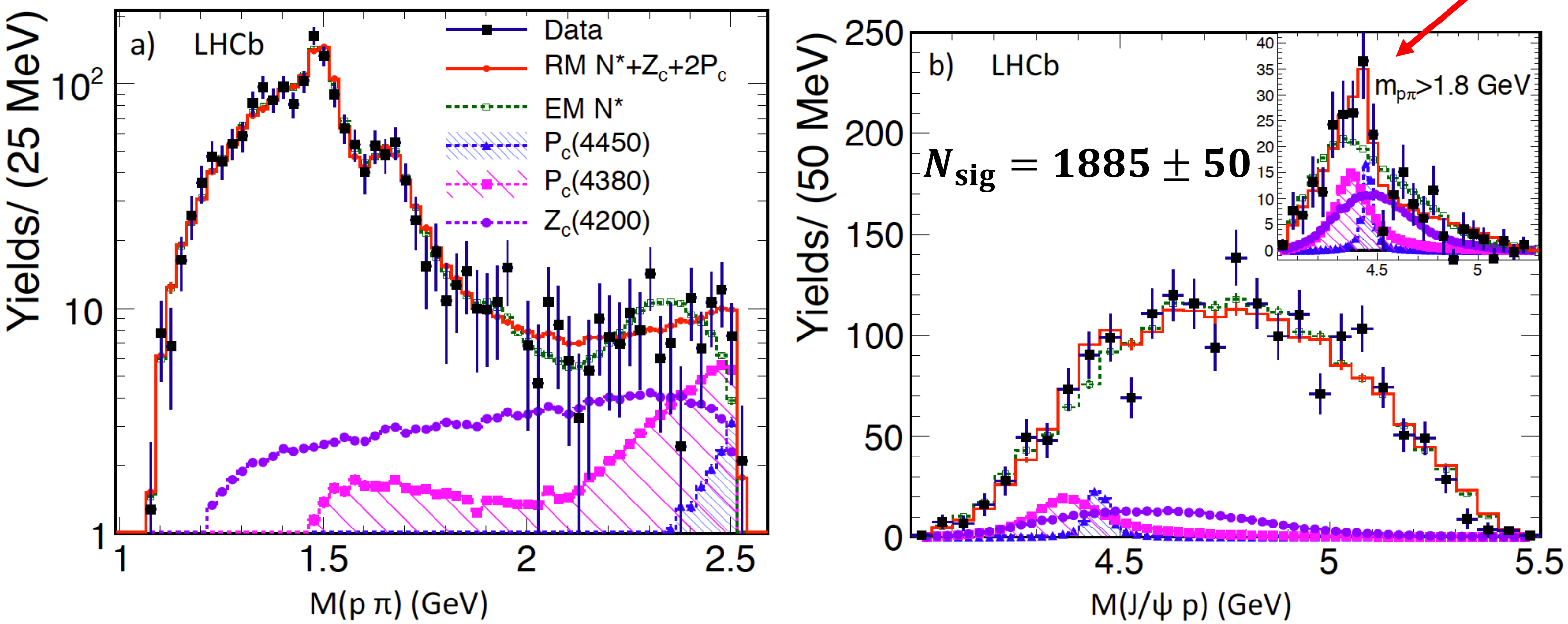
Adding $P_c^{\pm}$ → better description of data distributions

Pentaquarks in $\Lambda_b^0 \to J/\psi p \pi^-$ decays

- Finding the same P_c^+ in other decays may suggest P_c^+ is not a triangle singularity
- Run-1 data shows evidence of exotic hadron contributions in this channel
  - Possible contribution from P_c^+'s and $Z_c(4200)^-$
- **~10k signal events are expected in Run1+2 data,**
  May need to wait for Run3 data to see the fine structure

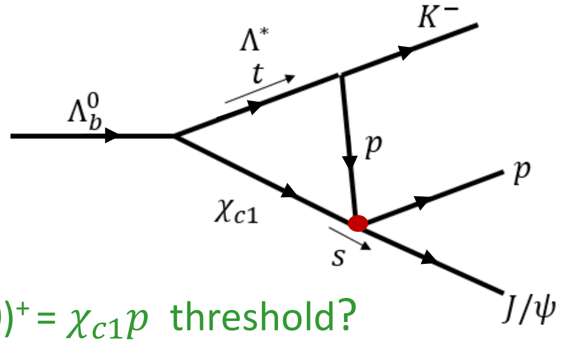
PRL 117 (2016) 082003

$P_c^+?$

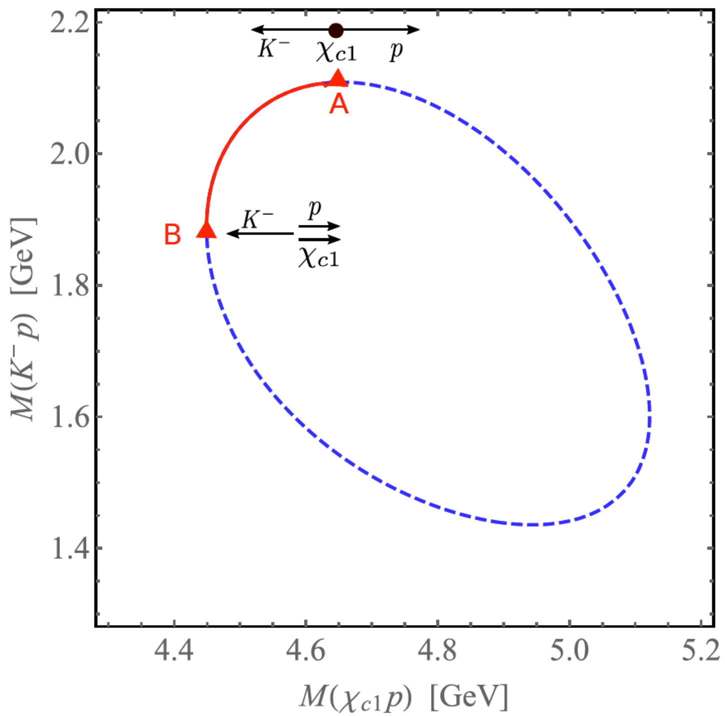


Triangle diagram

Guo *et al*, PRD 92 (2015) 071502



$P_c(4450)^+ = \chi_{c1}p$ threshold?



Requirements:

- All the intermediate states are on shell
- The proton emitted from the decay of the Λ^* moves along the same direction as the χ_{c1} and can catch up with it to rescatter
- Can only happen on the red line of the Dalitz-plot boundary

Triangle diagrams?

PRL 122 (2019) 222001

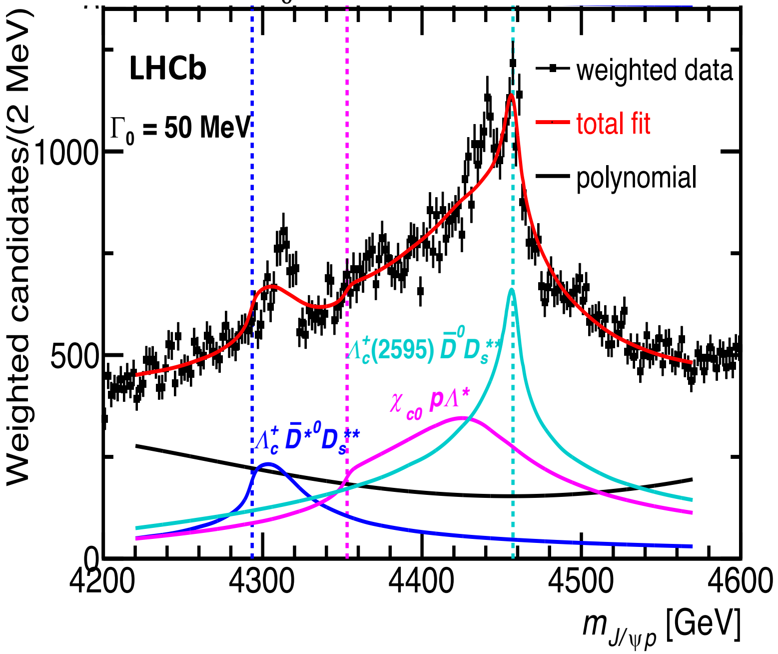
- Can produce peaking structure at or above mass threshold, but not below
- Cannot rule out $P_c(4457)^+$ as a triangle effect

$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds

3 triangle-diagram amplitudes + polynomial

More realistic Γ_0

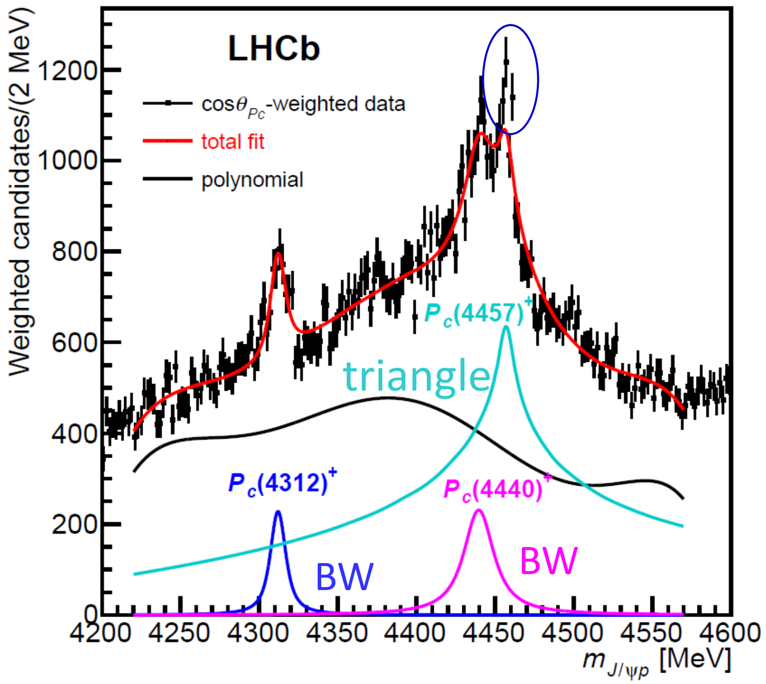
$D_s^{**} = D_s(2860)$

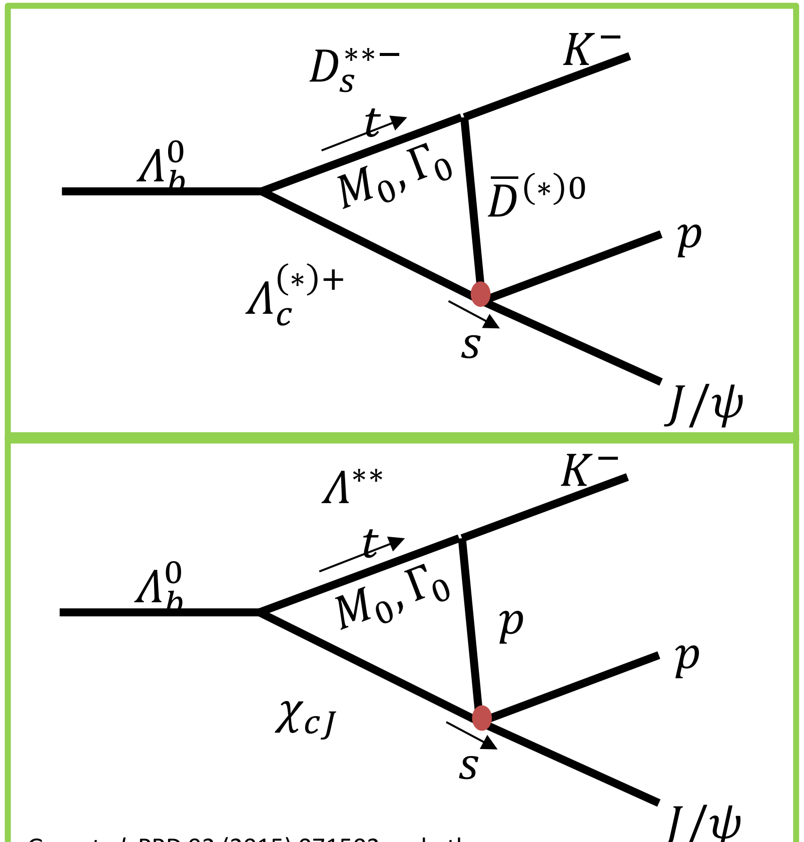


$P_c(4457)^+$ is right at the $\Lambda_c(2595)^+\bar{D}^0$ threshold

2BW + 1 triangle-diagram amplitudes + polynomial

$D_s(2860)$ $\Gamma_0 = 159$ MeV [PDG]





Guo *et al*, PRD 92 (2015) 071502 and others

Summary of $J/\psi\Lambda$ structures

- **$P_{cs}(4459)^0$ mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold**

State	M_0 [MeV]	Γ[MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

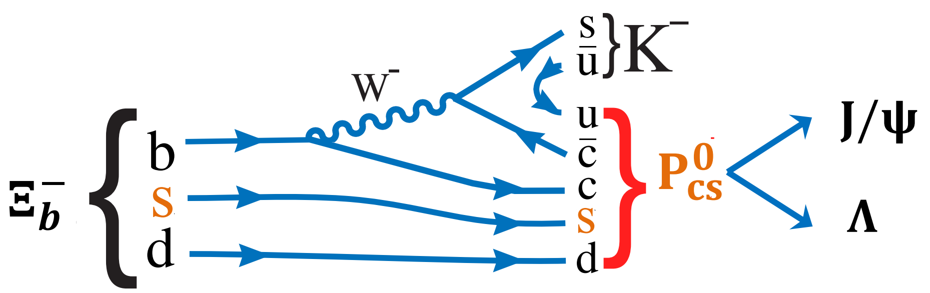
- The peak position is consistent with $\Xi_c^0\bar{D}^{*0}$ molecule model prediction
- **More P_{cs} states are expected**; Molecular model predicted 10 states

System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]^\sharp_{\frac{5}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

[Bo Wang, PRD 101 (2020) 034018]

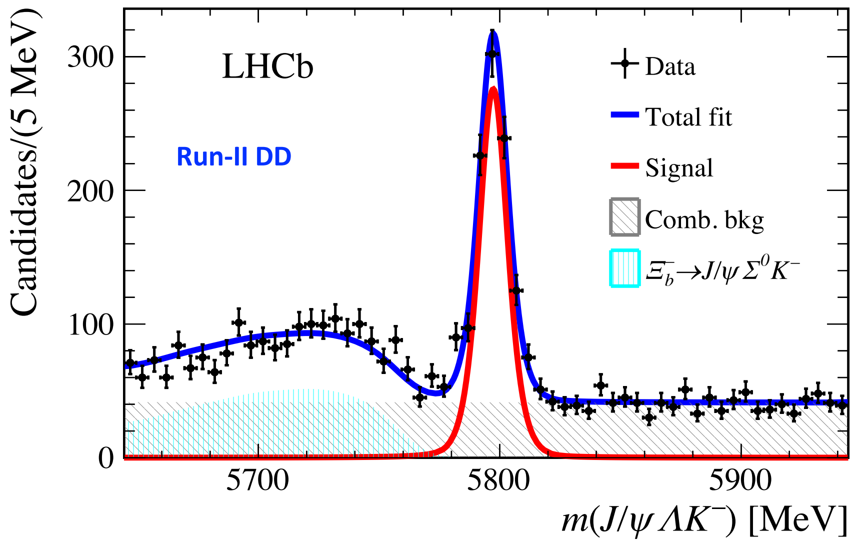
$\Xi_b^- \to J/\psi \Lambda K^-$ Data sample

[Science Bulletin 66 (2021) 1278]



- Reconstruction at LHCb

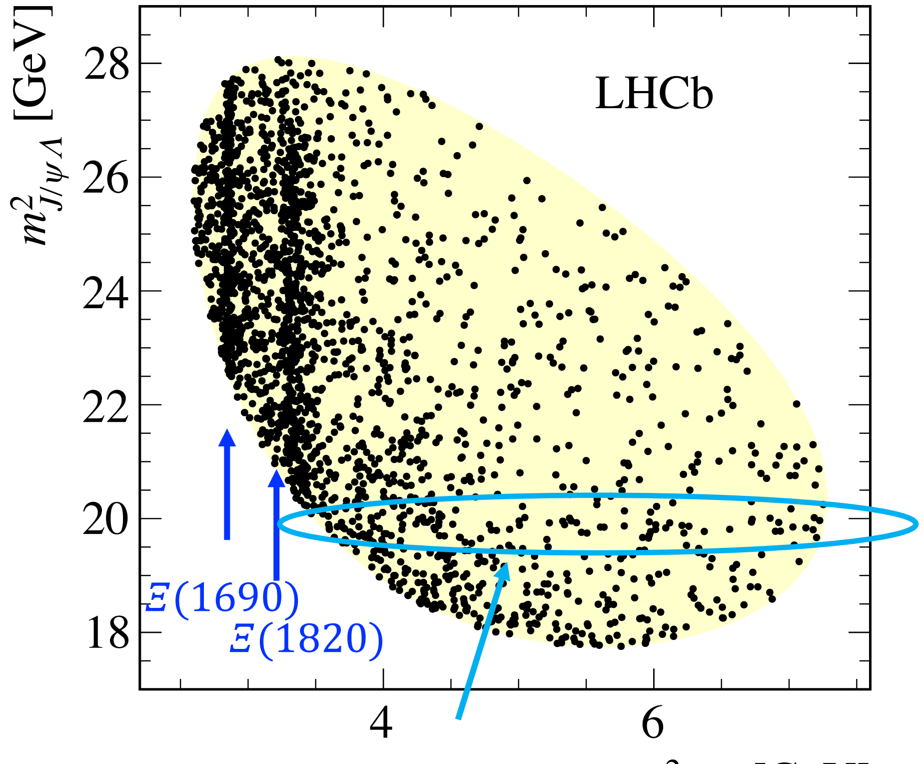
~1750 $\Xi_b^- \to J/\psi \Lambda K^-$ signals (purity ~80%)



$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8\,\mathrm{TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2} \quad [\sqrt{s} = 13\,\mathrm{TeV}].$$

[PRD 99 (2019) 052006]



$m^2_{\Lambda K^-}$ [GeV]

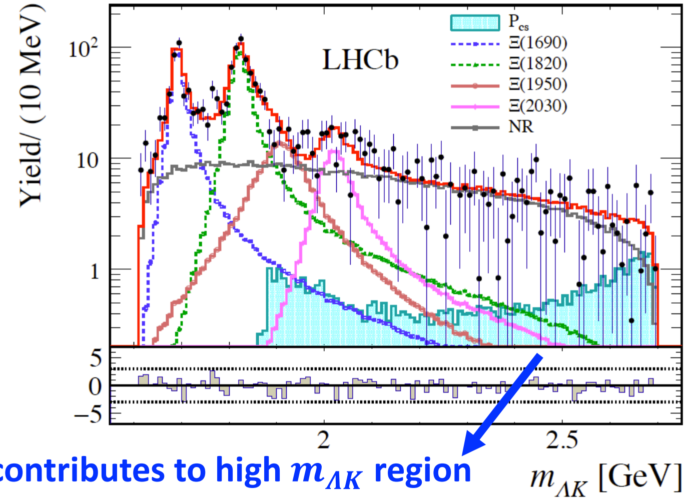
Potential P_{cs}^0 structure?

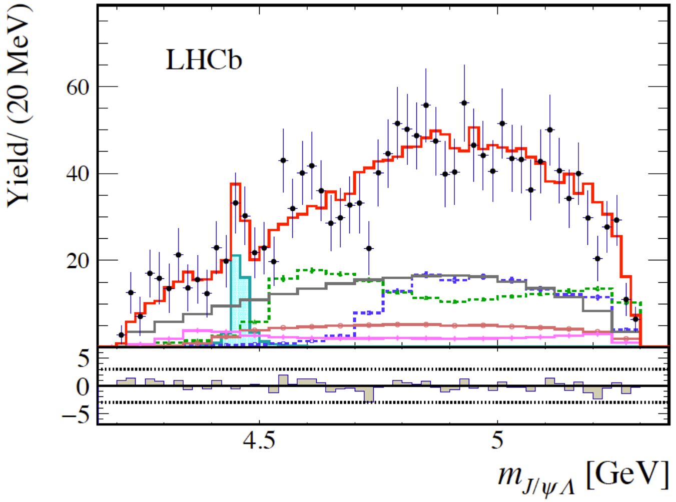
Full amplitude analysis is required

Evidence of $J/\psi\Lambda$ structure

[Science Bulletin 66 (2021) 1278]

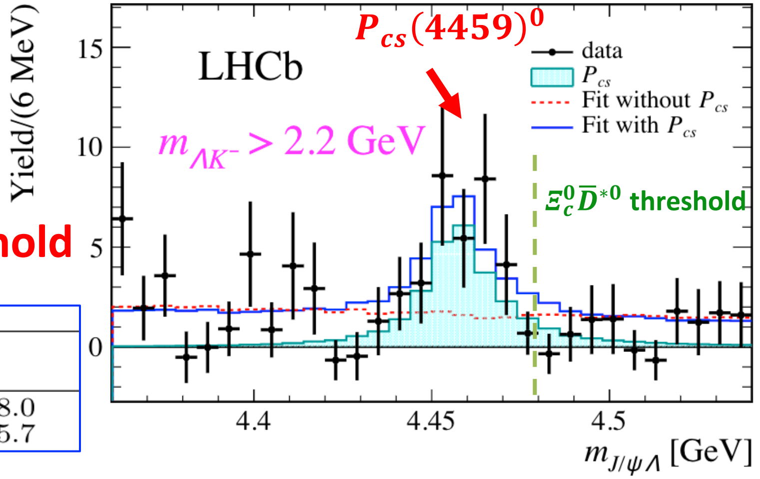
- Adding one P_{cs}^0 improves the fit significantly
  - Adding a P_{cs} improves $2\ln\mathcal{L}$ by 43 units (**4.3σ**)
  - Including various syst. uncertainty, significance >3.1σ
  - Look-elsewhere effect is included in both cases

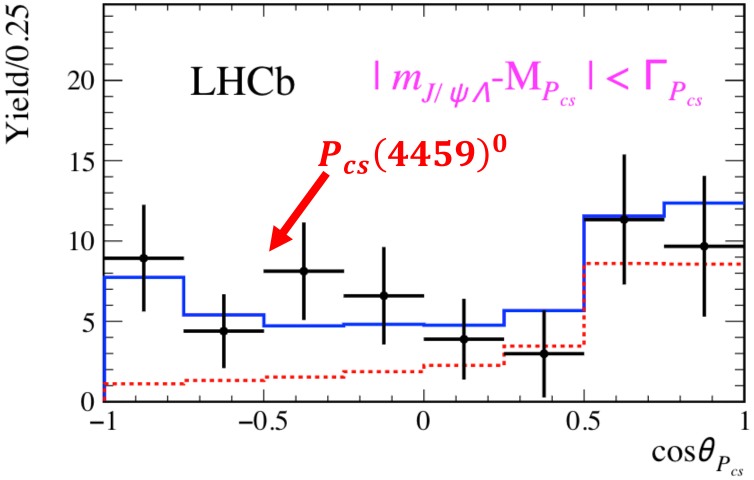




P_{cs}^0 contributes to high $m_{\Lambda K}$ region

Zoom in to P_{cs} signal region. Visible improvement.



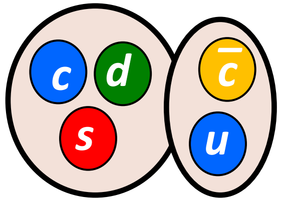


Mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold

State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$

Evidence of $J/\psi\Lambda$ resonance: discussion

- The peak position is consistent with $\Xi_c^0\bar{D}^{*0}$ molecule model prediction



Predicts **two states** with J^P 1/2(3/2)^−

System	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

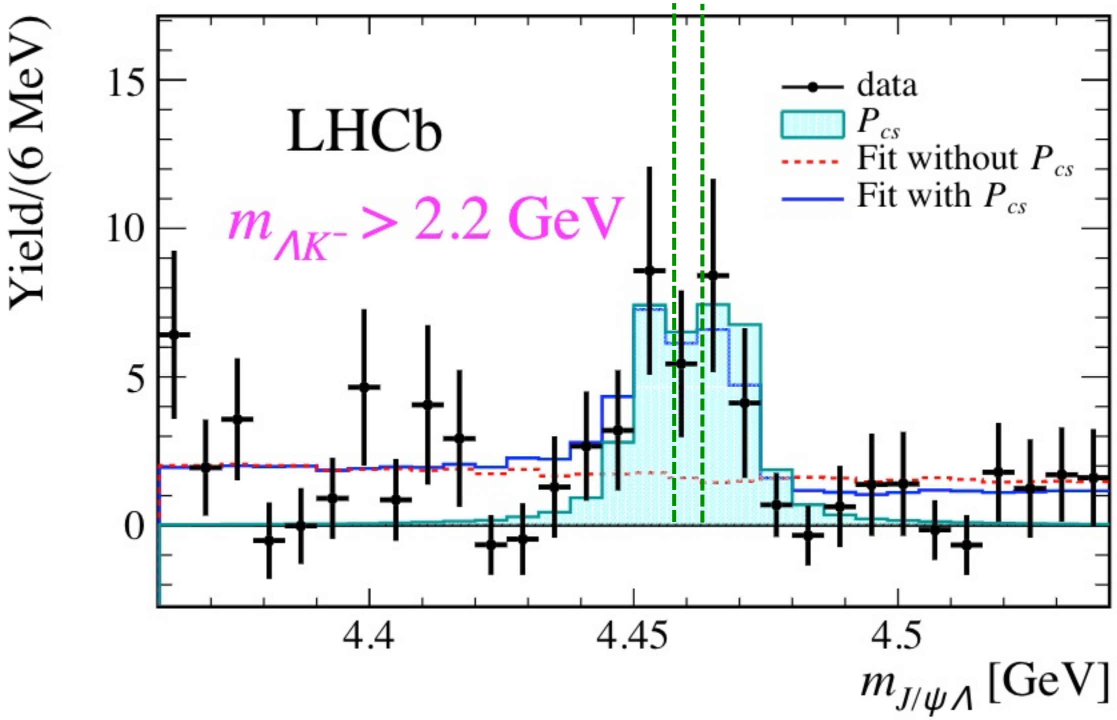
- Two-peak hypothesis is allowed
  - More data is required to distinguish one-peak vs two-peak
- $\Xi_c^0\bar{D}^{*0}$ SU(3) partner is $\Lambda_c^+\bar{D}^{*0}$, not $\Sigma_c\bar{D}^*$ for observed $P_c(4440)^+$ and $P_c(4457)^+$
  - Indict $\Lambda_c^+\bar{D}^{*0}$ molecule exist?
  - The theory paper disfavors it, but should be examined by experiments

Mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold

State	M_0 [MeV]	Γ[MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

[Bo Wang, PRD 101 (2020) 034018]

Fit with two BW (Predicted two states)



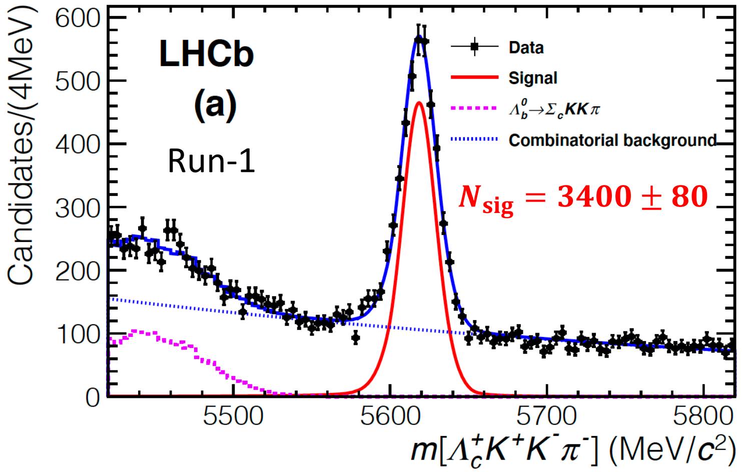
[Science Bulletin 66 (2021) 1278]

Search for open-charm pentaquark

- Potential open-charm pentaquark $[c\bar{s}uud]$ decay to $\Lambda_c^+ K^+$
- **1st observation of $\boldsymbol{\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-}$ (run1)**

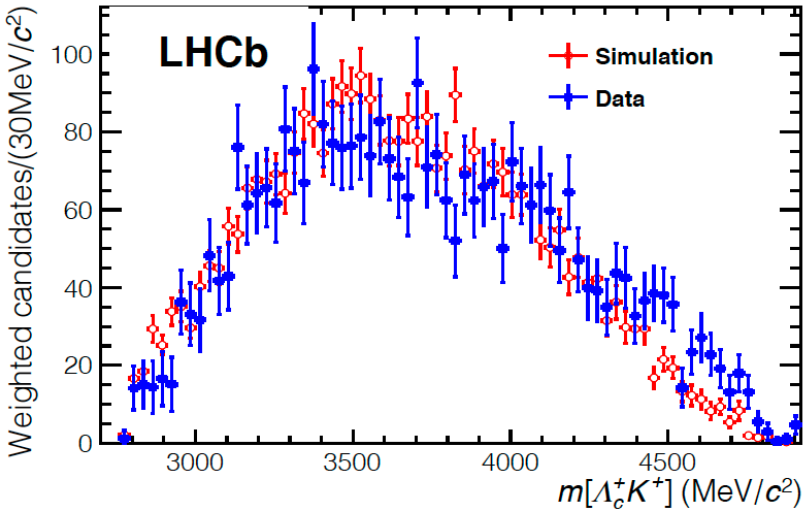
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (9.26 \pm 0.29 \pm 0.46 \pm 0.26) \times 10^{-2},$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-) = (1.02 \pm 0.03 \pm 0.05 \pm 0.10) \times 10^{-3}$$



- No excess observed in $m(\Lambda_c^+ K^+)$ spectrum
- Will search with more data and can also look for pentaquark $[c\bar{s}udd]$ in $\Lambda_c^+ K^+ \pi^-$ system

[Phys. Lett. B 815 (2021) 136172]



Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \boxed{\chi_{c(1,2)} p} K^-$ decays **PRD 92 (2015) 071502**
  $\Rightarrow$ Test hypothesis of kinematic rescattering effect

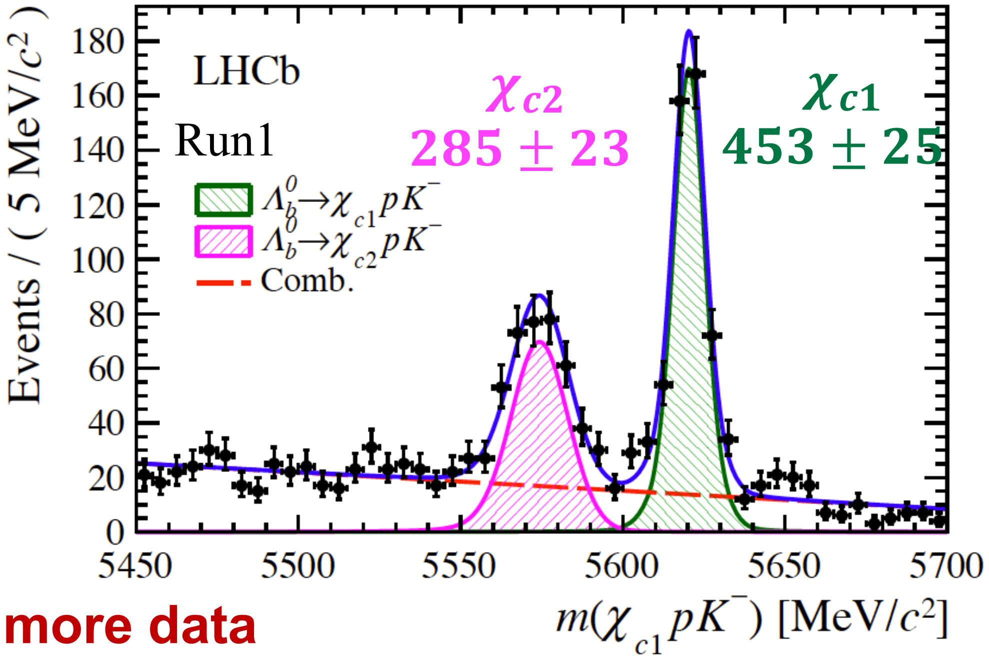
- Expect ~2000 signal in run1+2 data

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

$\mathcal{B}(\chi_{cJ})$

PRL 119 (2017) 062001



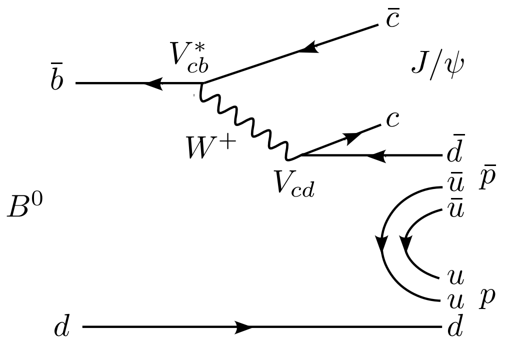
Next step: full amplitude analysis with more data

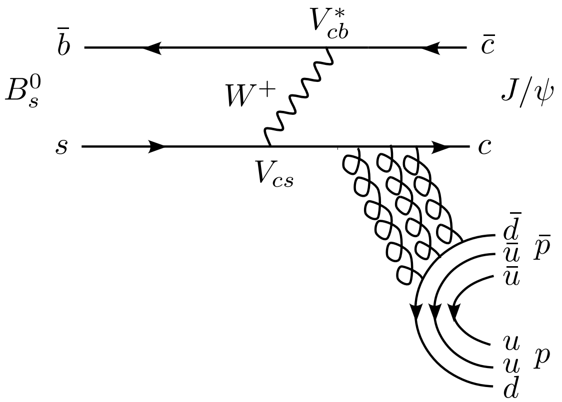
$B^0_{(s)} \to J/\psi p\bar{p}$ decays

[PRL 122 (2019) 191804]

Decay modes are suppressed

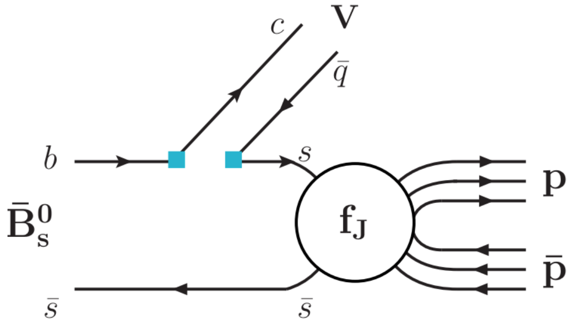
B^0: Cabibbo suppressed **B^0_s: "OZI" suppressed**



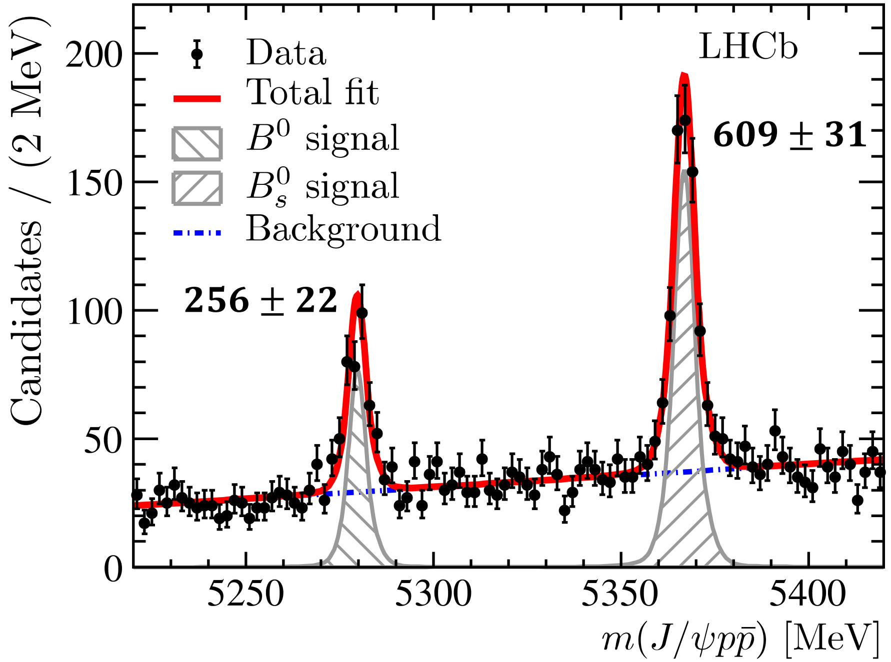


Can be enhanced through

- **Exotic states** in $J/\psi p$ system
- **Glueballs** in $p\bar{p}$ system [Y. K. Hsiao and C. Q. Geng, EPJ C75 (2015) 101, arXiv:1412.4900]



First observed with $\mathcal{L} = 4.7\text{fb}^{-1}$, 2011-2016 data



$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = (3.58 \pm 0.19 \pm 0.31)\times 10^{-6}$

larger than predicted value $\sim 10^{-9}$
May indicate exotic hadron contributions

$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.51 \pm 0.40 \pm 0.43)\times 10^{-7}$

Prospects

Ongoing Analyses in in advanced stage

- $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis
  - Lots of improvements: K-matrix model, formalism, resolution included
- $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-$ partial reconstruction
  - Search for $P_c^+ \to \Lambda_c^+ \overline{D}^{*0}$

More interesting ideas

- Open charm baryon meson final state, eg. $\Sigma_c^{++} D^-$?
- **Open-charm pentaquarks?**

Most need more data