Pentaquark candidates at LHCb

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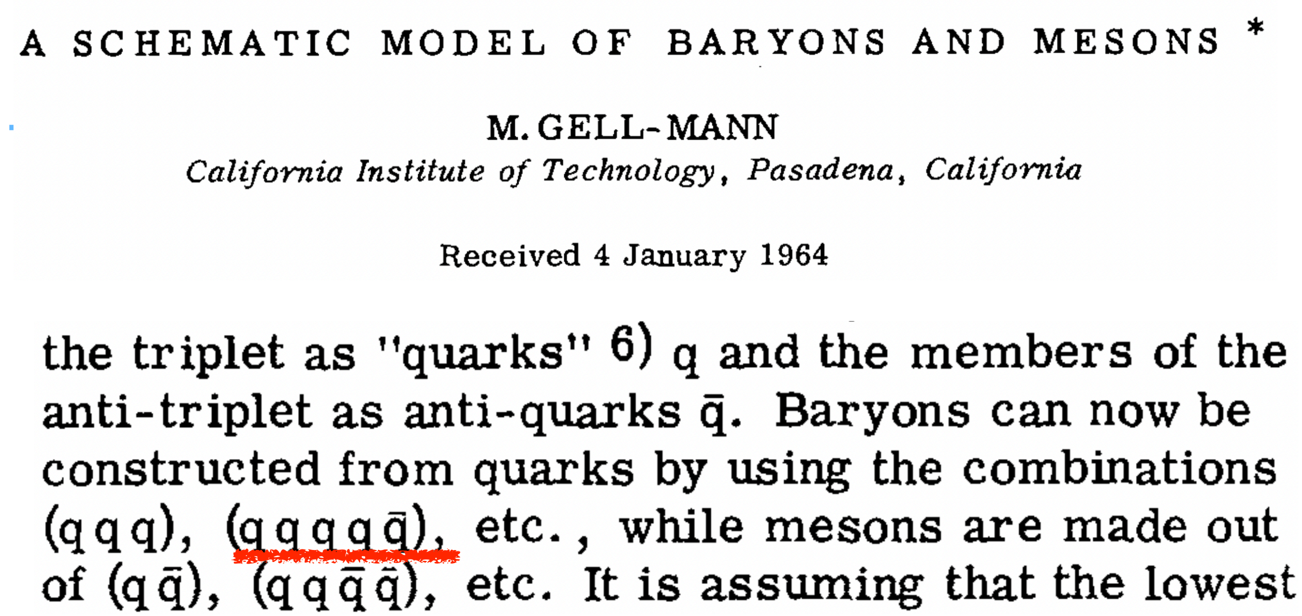
2023年10月14日 华中师范大学

Pentaquark state

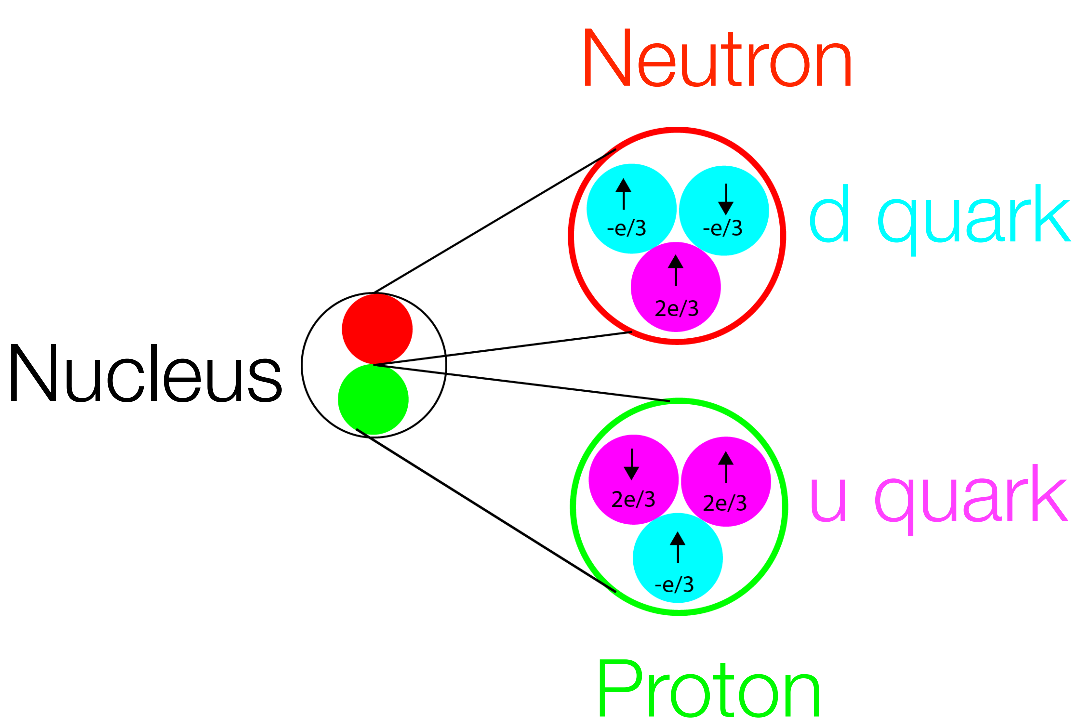

A SCHEMATIC MODEL OF BARYONS AND MESONS *

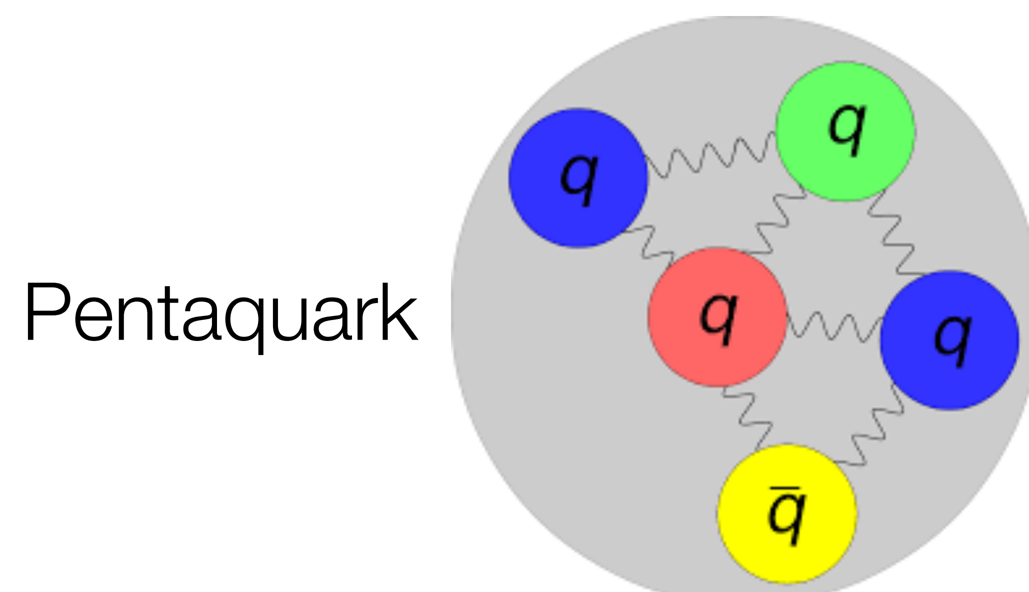
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

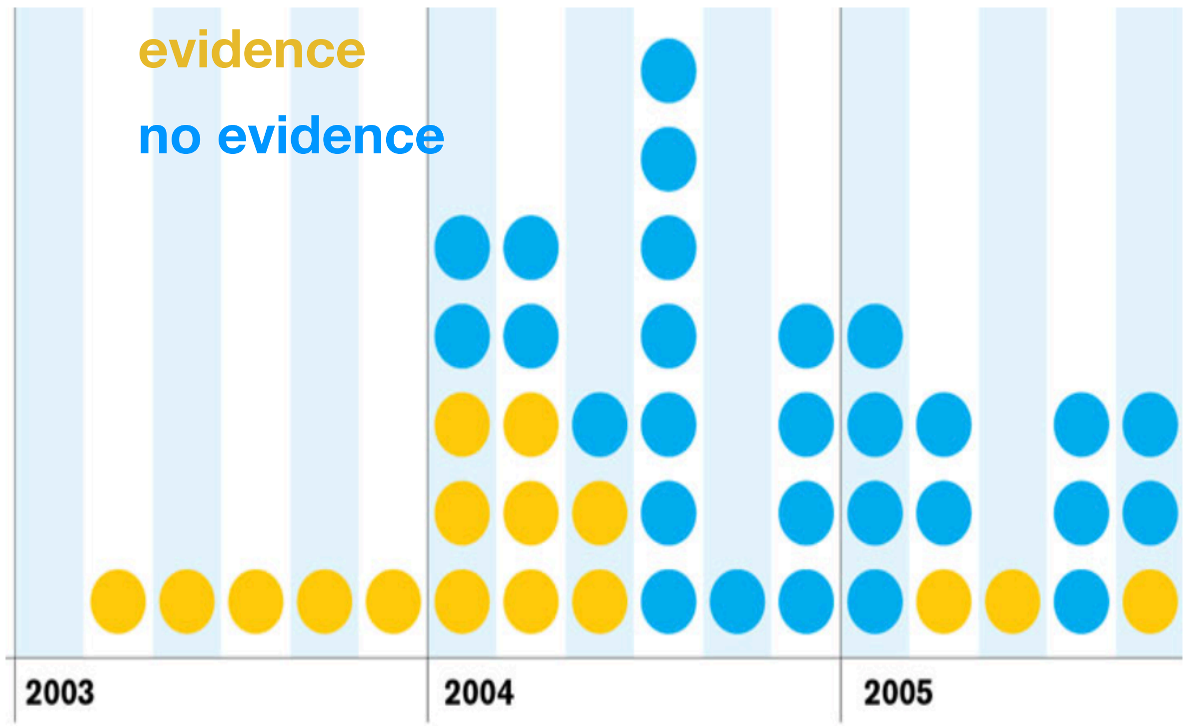
the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

- Predicted in the quark model in 1964, with minimal content $qqqq\bar{q}$
- Multiquark states also allowed in QCD





Searches from 2003 to 2005



(PANIC'05), 2005, nucl-ex/0512042

- In 1997, Maxim Polyakov, Dmitri Diakonov, Victor Petrov predicted pentaquark named "Θ^+" $(uudd\bar{s})$
- In 2003, hints from Spring-8, Jefferson Lab, ITEP, ELSA
- Increasing number of experiments rule out the pentaquarks

PDG2008

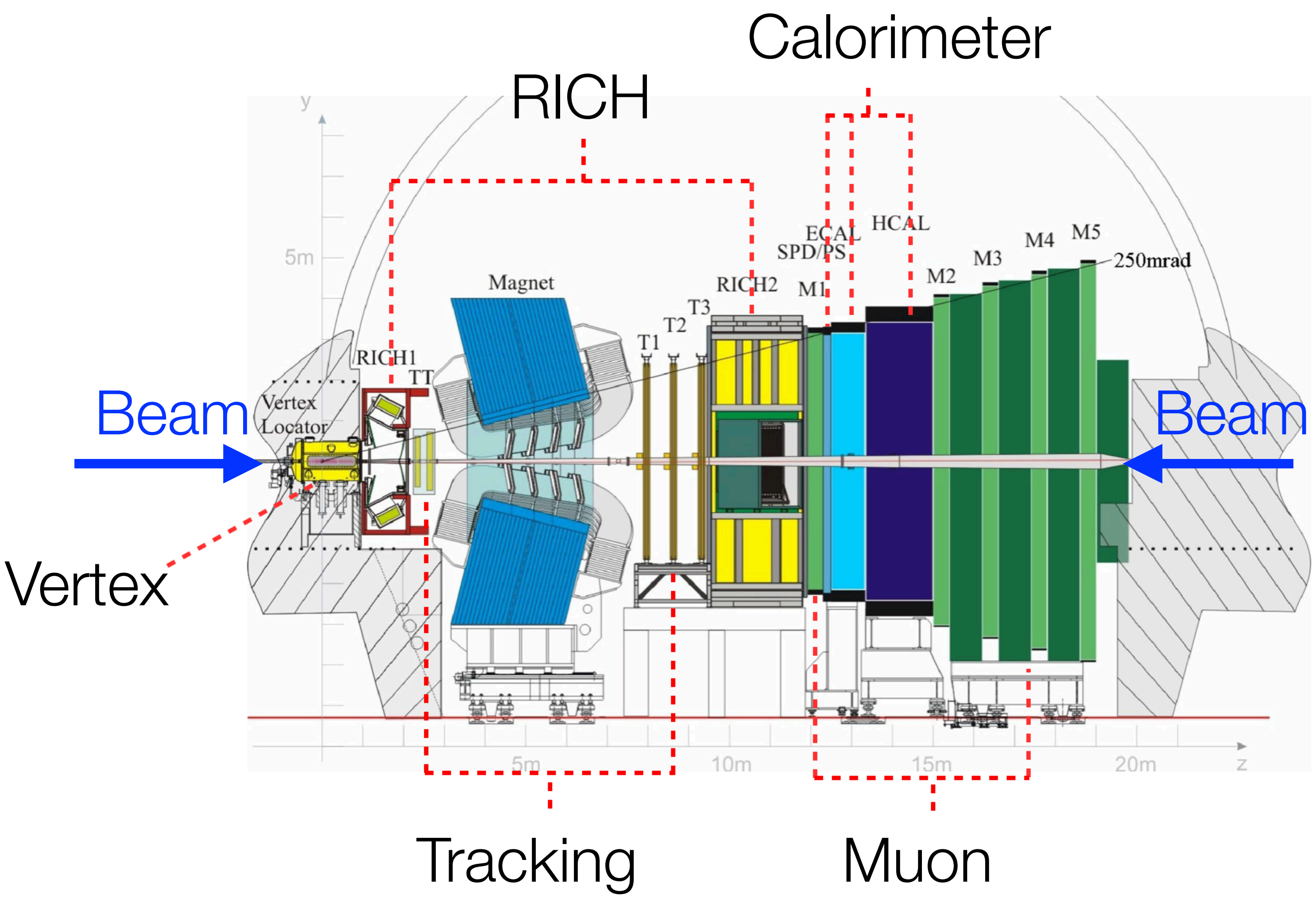
There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist. The only

LHCb detector and performance

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

JINST3(2008)S08005

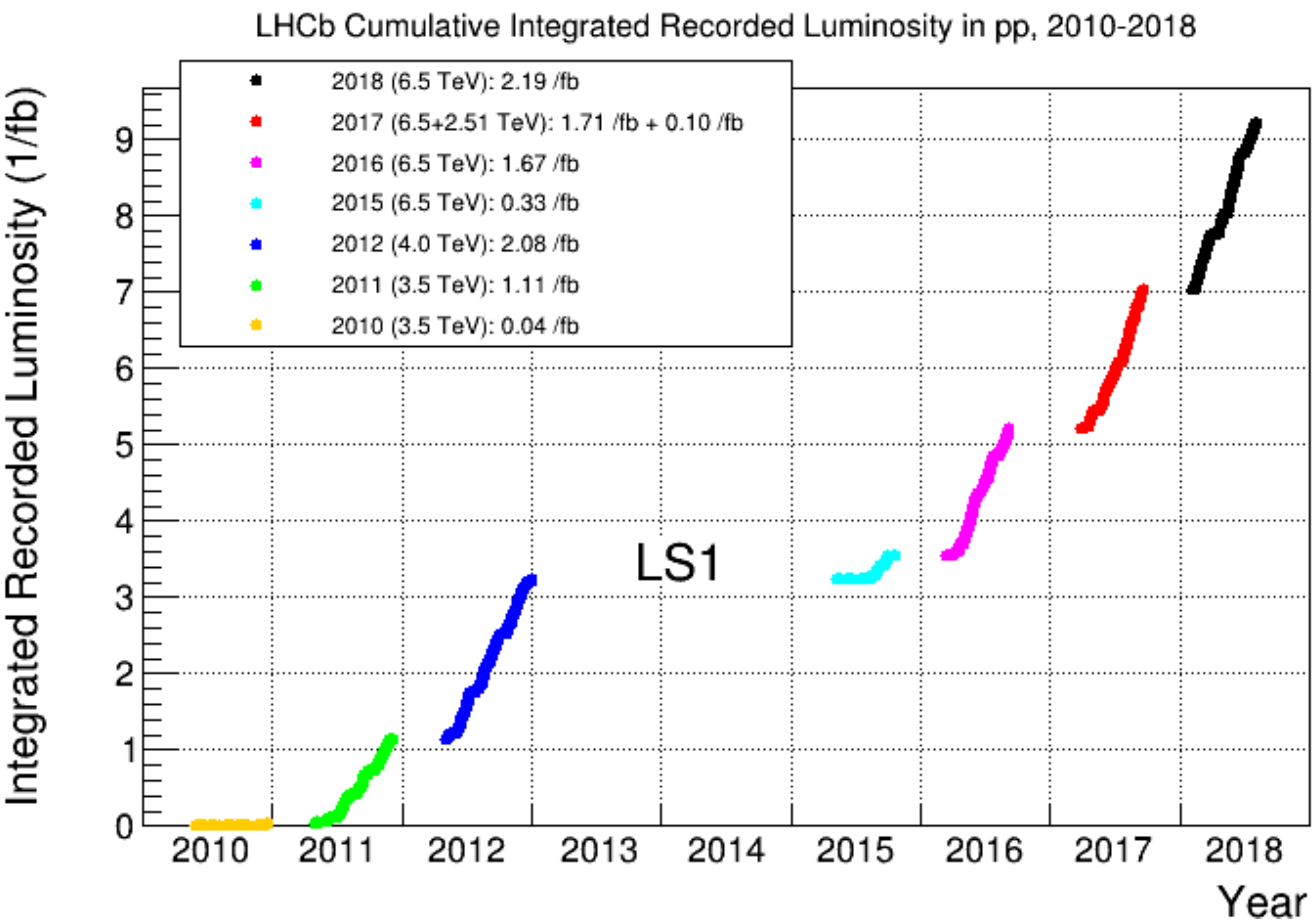
LHCb is a forward spectrometer



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

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

LHCb collected luminosity



Run1: @7/8 TeV

2010-12, 3fb^{-1}

Run2: @13TeV

2015-18, 6fb^{-1}

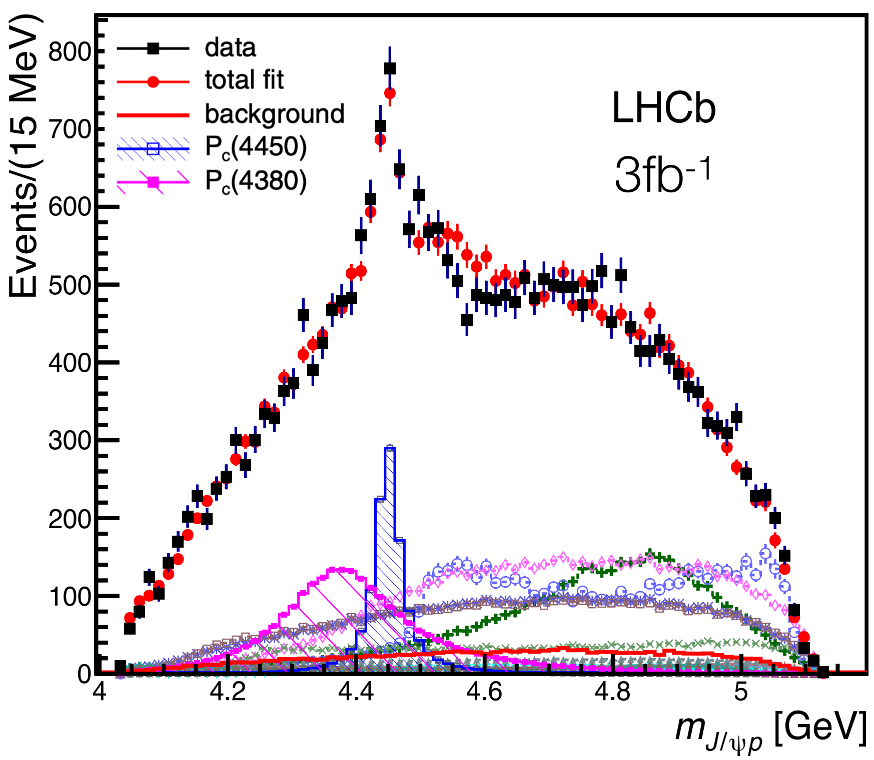
- 9fb^{-1} pp collision sample collected in run1+run2
- Large b hadrons produced

$$\boldsymbol{B^+ : B^0 : B_s^0 : \Lambda_b^0}$$
$$\boldsymbol{(u\bar{b})\ (d\bar{b})\ (s\bar{b})\ (udb)}$$
$$\boldsymbol{4 : 4 : 1 : 2}$$

First discovery of pentaquark candidates at LHCb

First observation of P_{ψ}^{N+}s in $\Lambda_b^0 \to J/\psi p K^-$ decays

In 2015, 26k signal yield, amplitude analysis



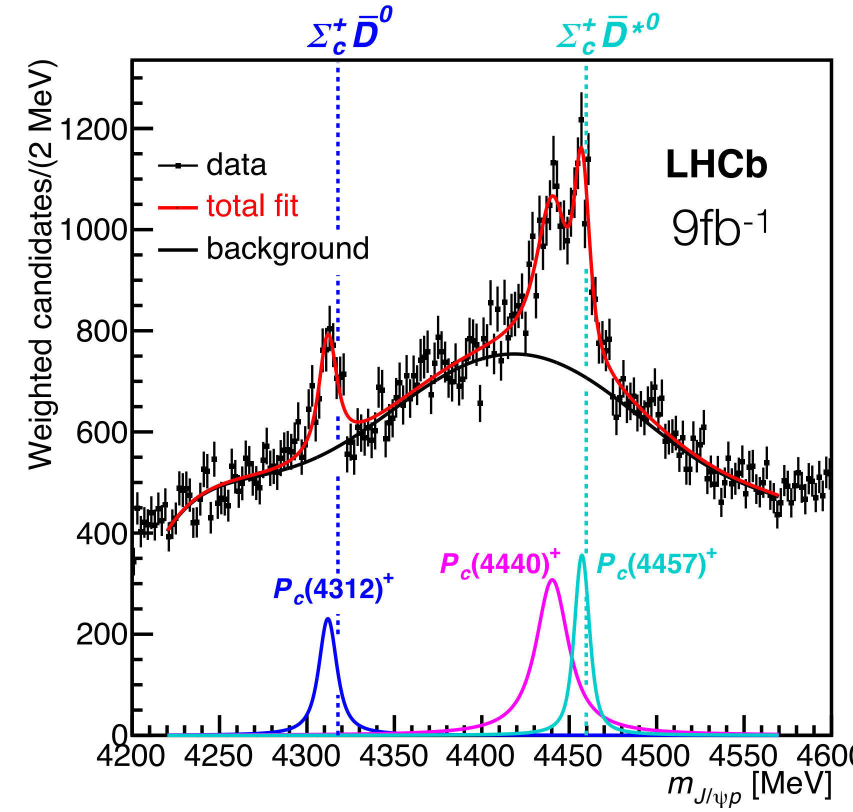
PRL115(2015)072001

pentaquark candidates:

$P_{\psi}^{N}(4450)^+$

$P_{\psi}^{N}(4380)^+$

In 2019, 246k signal yield, 1D mass fit



PRL122(2019)222001

Fine structures $P_{\psi}^{N}(4440)^+$, $P_{\psi}^{N}(4457)^+$

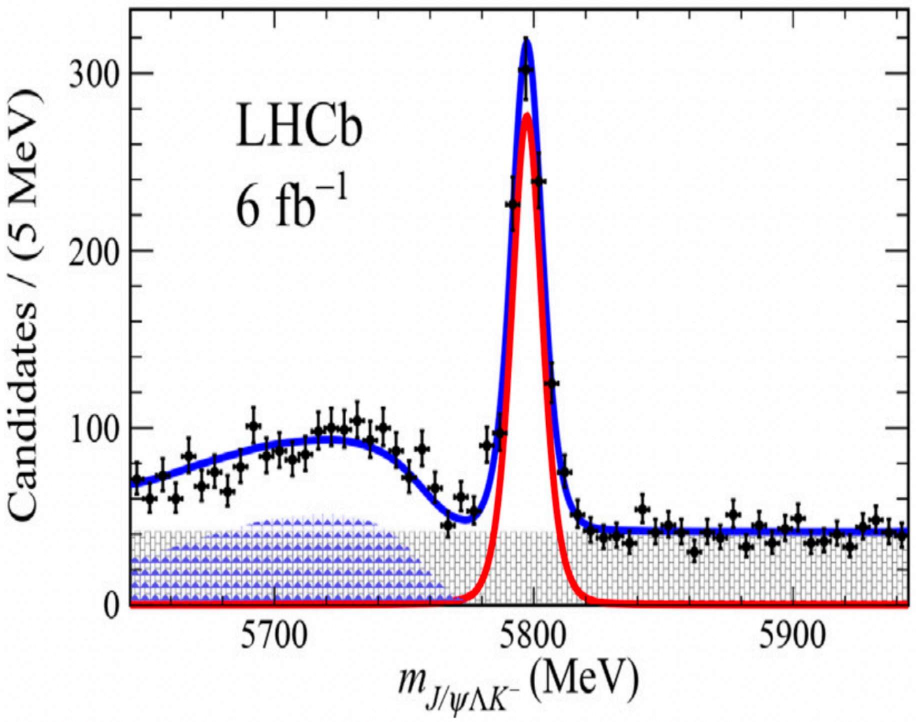
New pentaquark state $P_{\psi}^{N}(4312)^+$

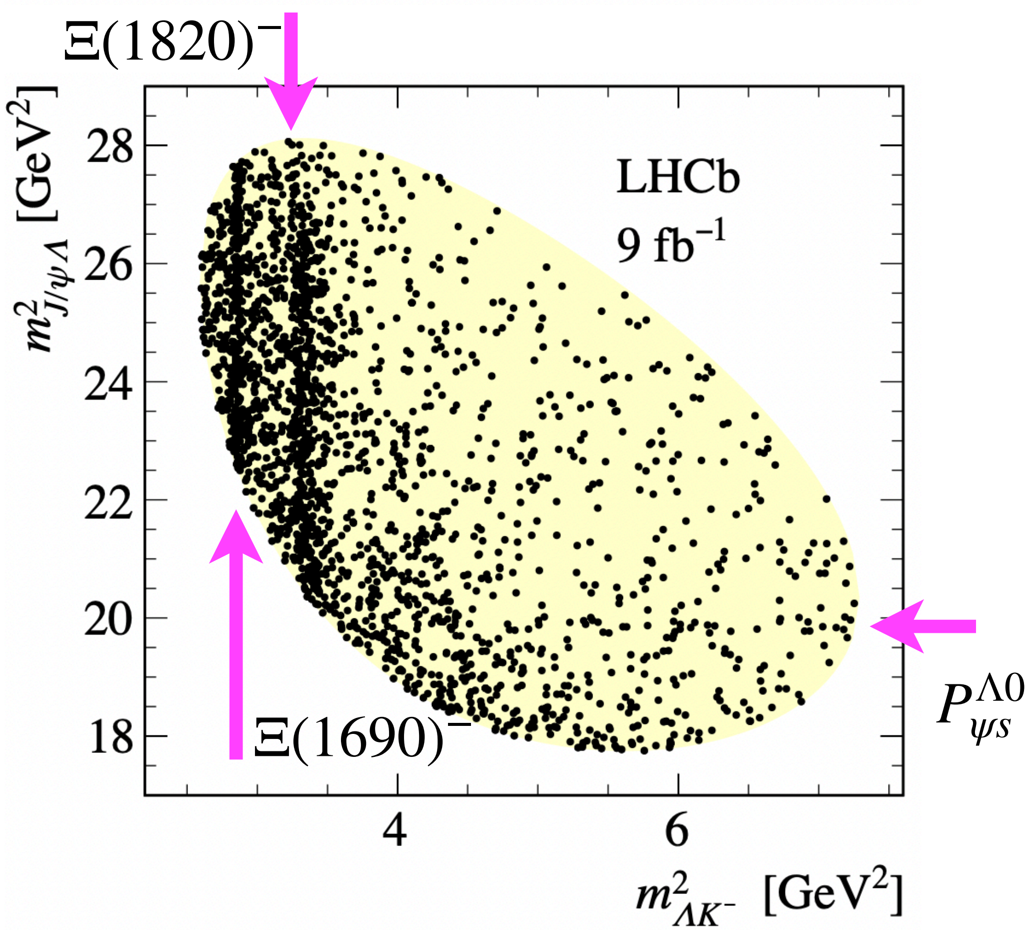
Not sensitive to broad state $P_{\psi}^{N}(4380)^+$

J^P not determined

Evidence for $P_{\psi s}^{\Lambda}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays

Sci.Bull.66(2021)1278

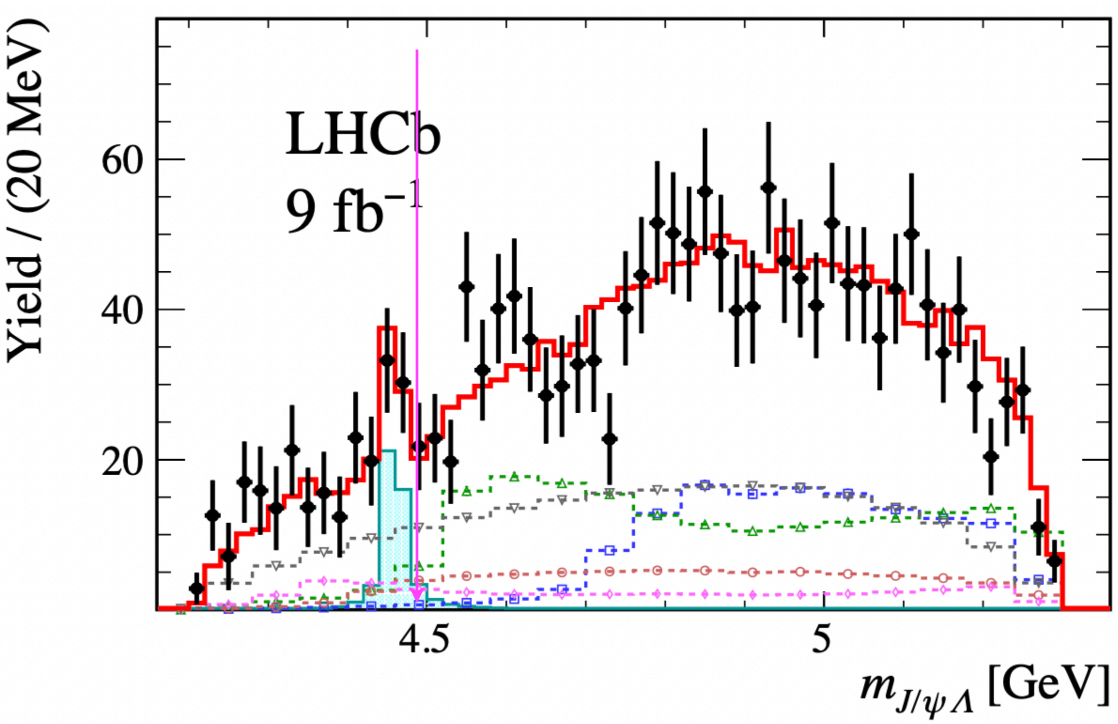


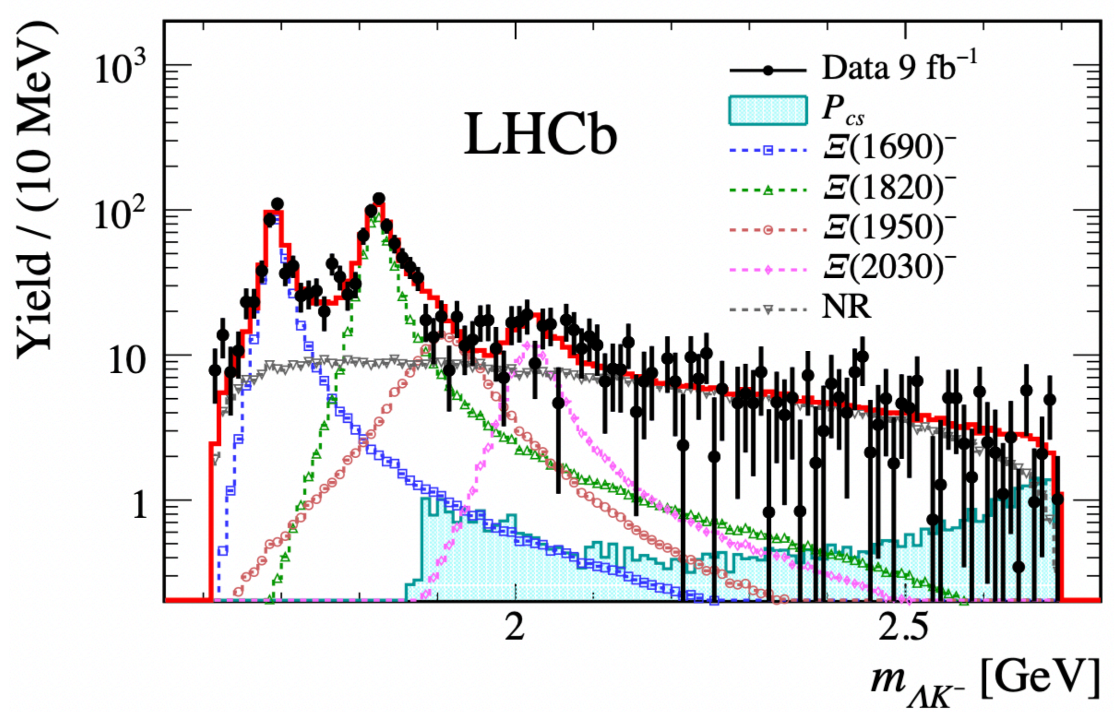


- Pentaquark candidate predicted with p replaced by Λ
- Λ decays inside/downstream of vertex detector
- 1750 signal candidates using 9fb^{-1} data, purity ~80%
- Clear structures of Ξ^{*-}
- Hint of structures in Dalitz plot

Evidence for $P_{\psi s}^{\Lambda}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays

Sci.Bull.66(2021)1278





- amplitude analysis
- Evidence for $P_{\psi s}^{\Lambda}(4459)^0$ near threshold of $\Xi_c^0 \overline{D}^{*0}$
- Significance: 3.1σ

Breit-Wigner parameters:

$m(P_{\psi s}^{\Lambda})$=4458.8 $\pm$ 2.9$^{+4.7}_{-1.1}$ MeV

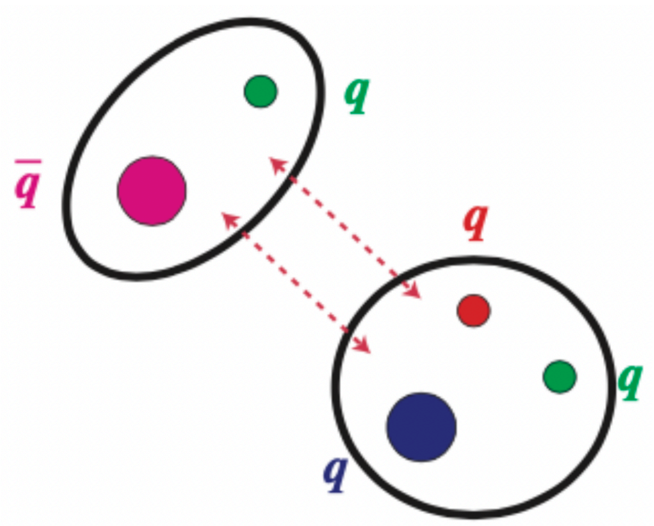
$\Gamma(P_{\psi s}^{\Lambda})$=17.3 $\pm$ 6.5$^{+8.0}_{-5.7}$ MeV

- More precise mass measurement of $\Xi(1690)^-$ and $\Xi(1820)^-$

Interpretations

Their nature is still largely unknown, various interpretations including:

Hadronic Molecules

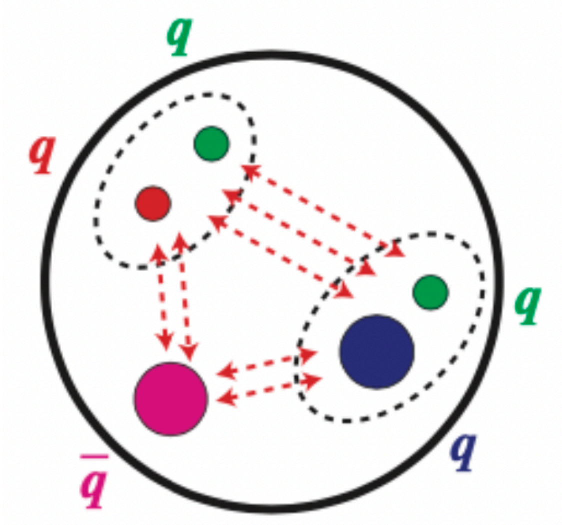


Rev. Mod. Phys. 90(2018)015004

PRD103(2021)112006

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

Compact pentaquark



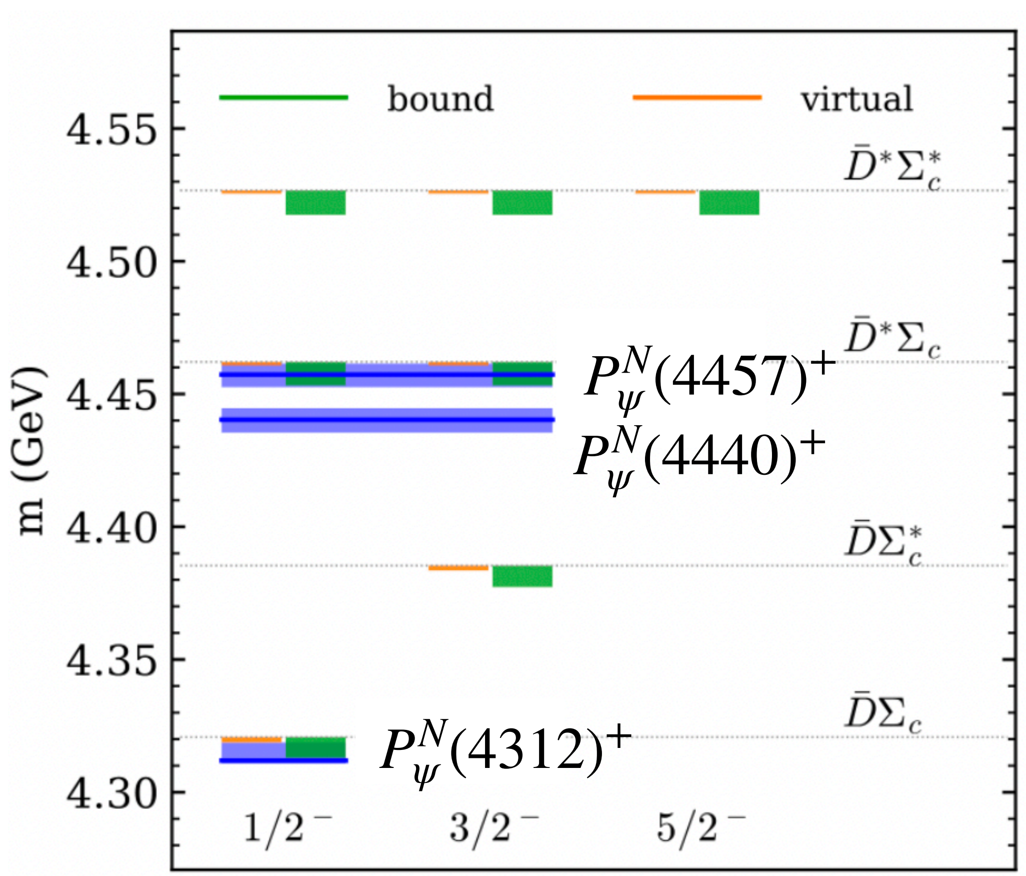
Phys. Rept. 668(2017)1

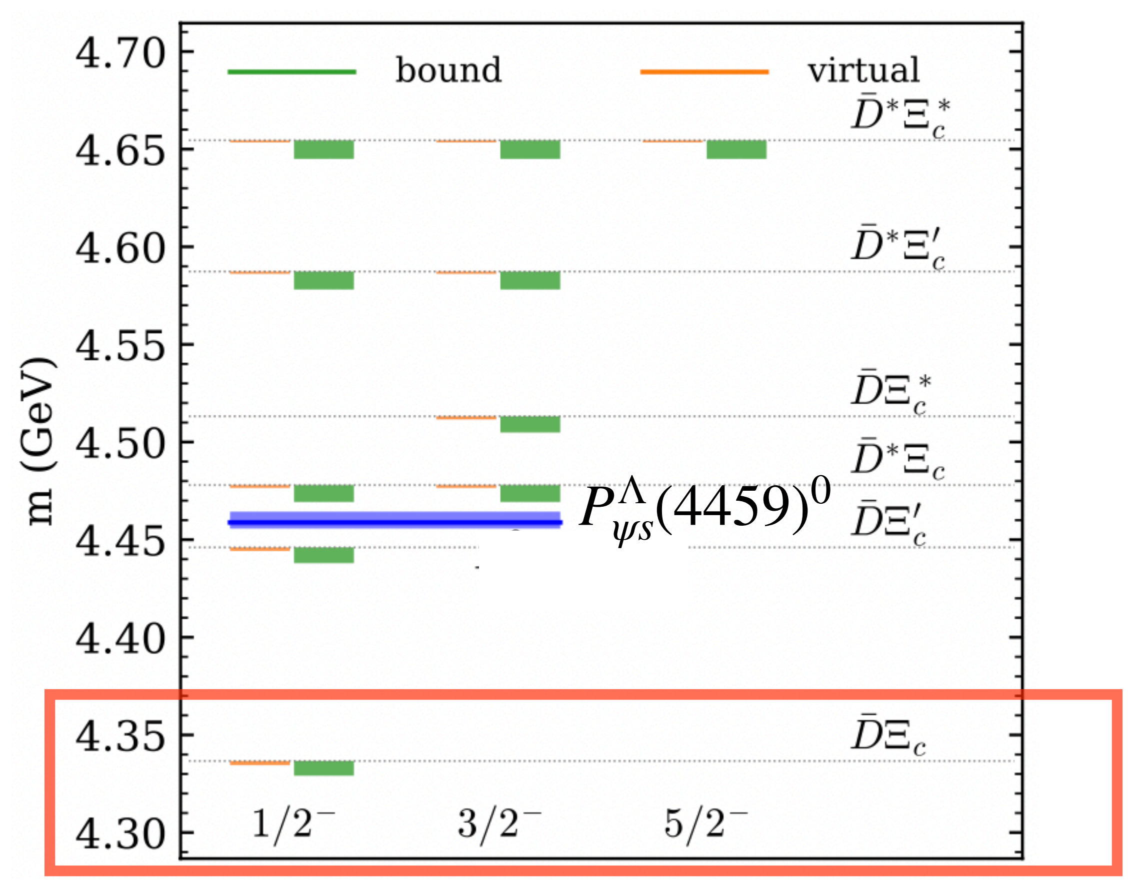
Few Body Syst. 57 (2016)1185

More pentaquark 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





Advantage of B-meson decays

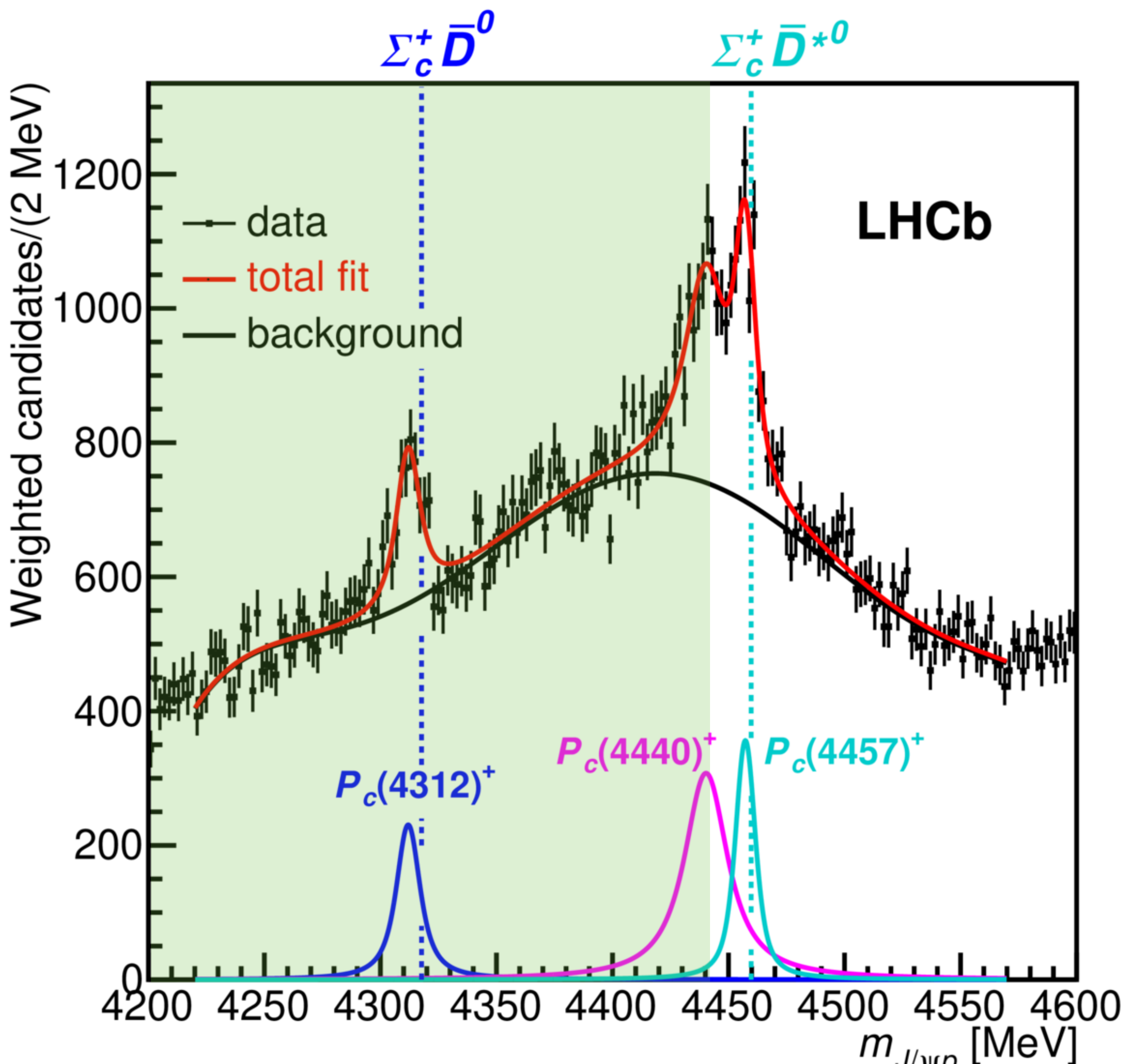
- Small Q-value, providing excellent mass resolution, allows to search for narrow structures

- Search for pentaquark and anti-pentaquark states at the same time

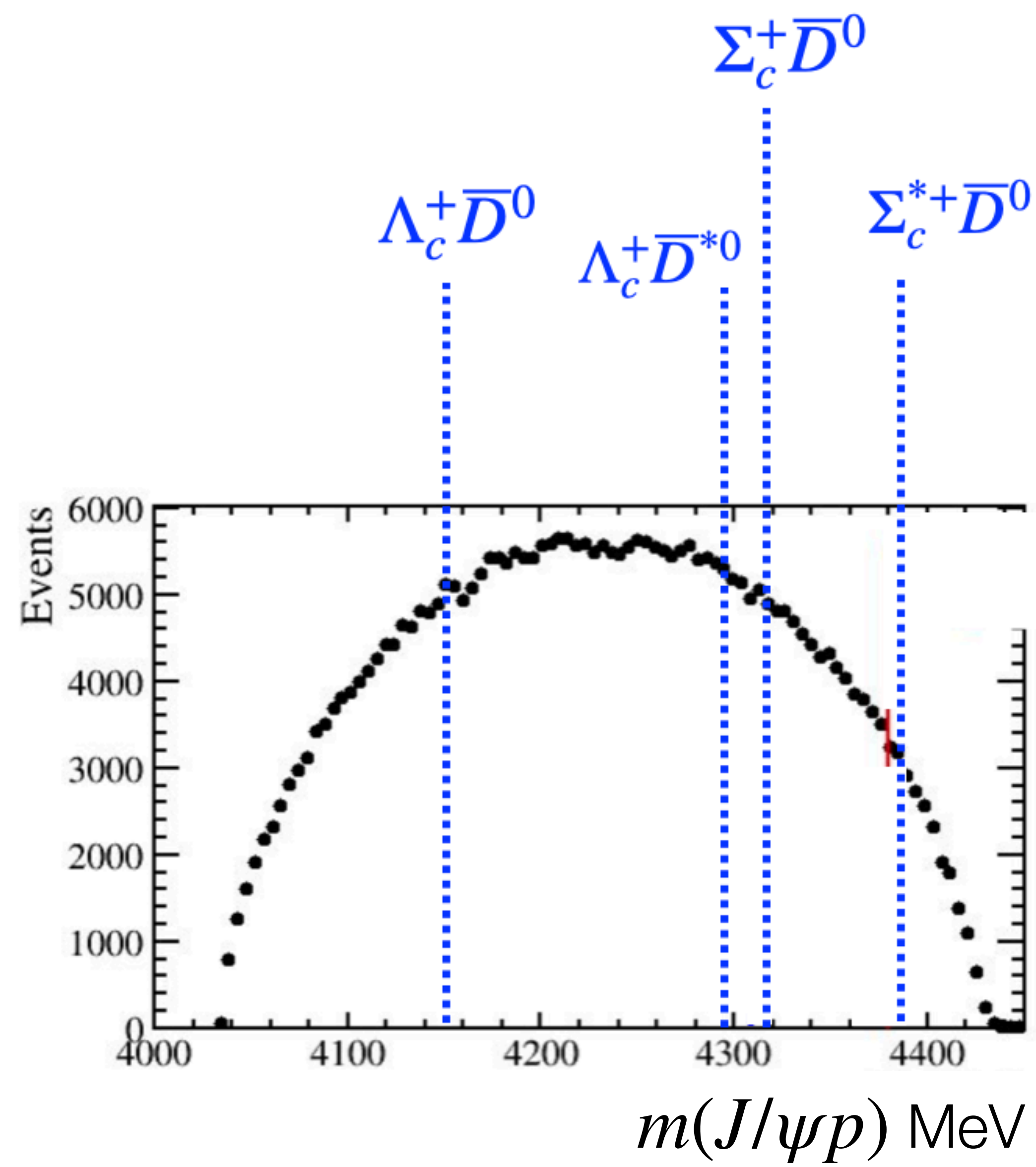
- Sensitive to structures in baryon and anti-baryon system

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

- Q-value ~393MeV and four thresholds
- Check $P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$



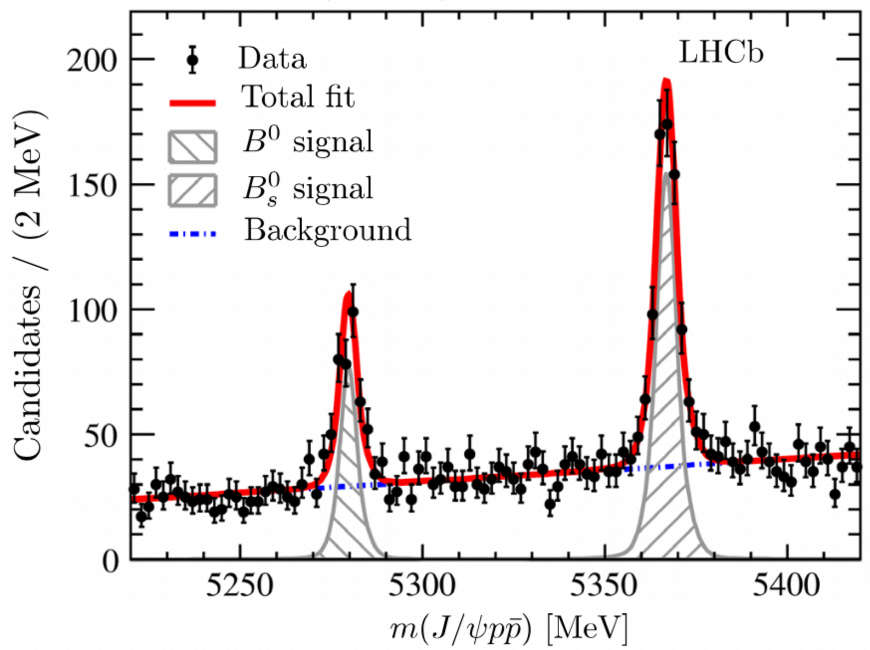
$\Lambda_b^0 \to p K^- J/\psi$



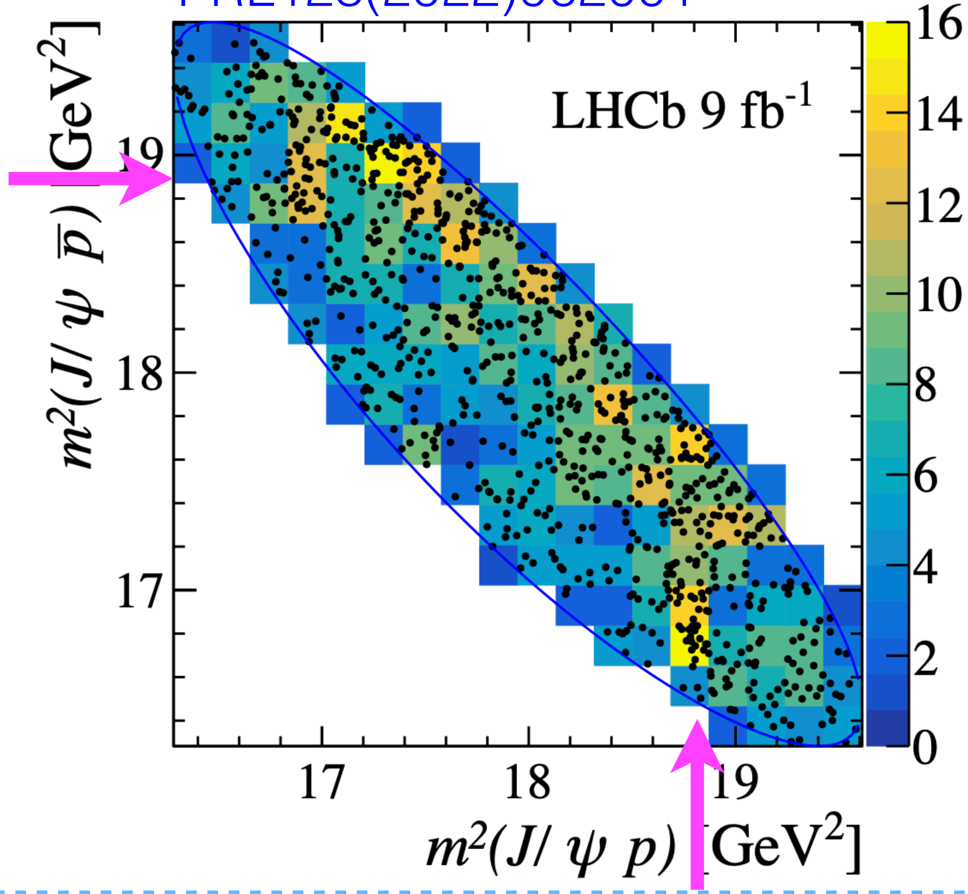
$B_s^0 \to J/\psi p\bar{p}$

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

PRL 122(2019)191804



PRL128(2022)062001



- First observed at LHCb in 2019

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

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

800 candidates

85% purity

B mass resolution 3.5MeV

- Hints of structures in Dalitz plot

- Full amplitude analysis using 9fb^{-1} data

Evidence for $P_\psi^N(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays

PRL128(2022)062001

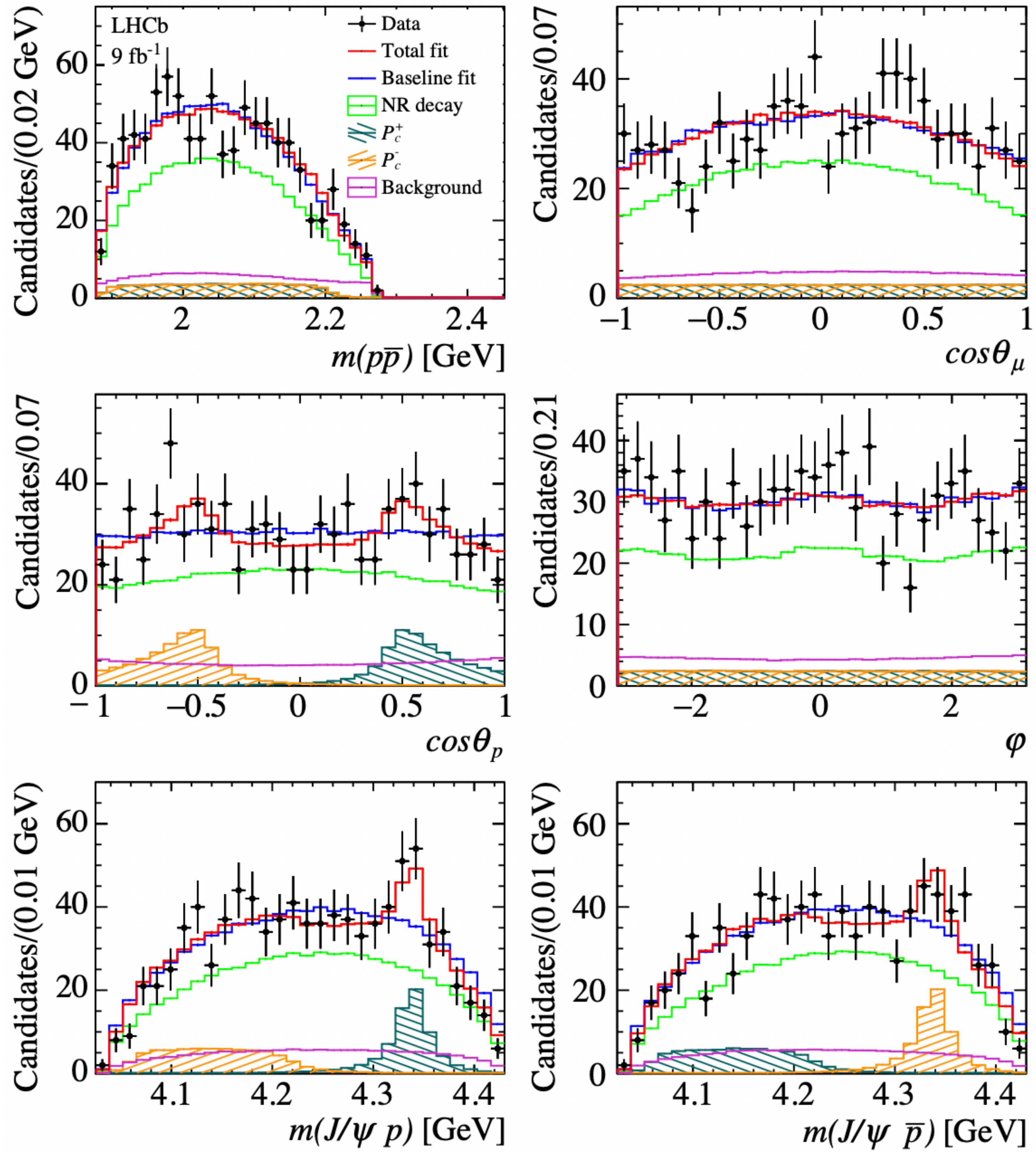
- Two amplitude models

  Baseline: NR($p\bar{p}$)

  With $P_\psi^{N\pm}$: NR($p\bar{p}$) + RBW($P_\psi^{N\pm}$)

- The same mass, width and couplings for $P_\psi^{N\pm}$

- Improvement in mass and helicity distributions



Evidence for $P_\psi^N(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays

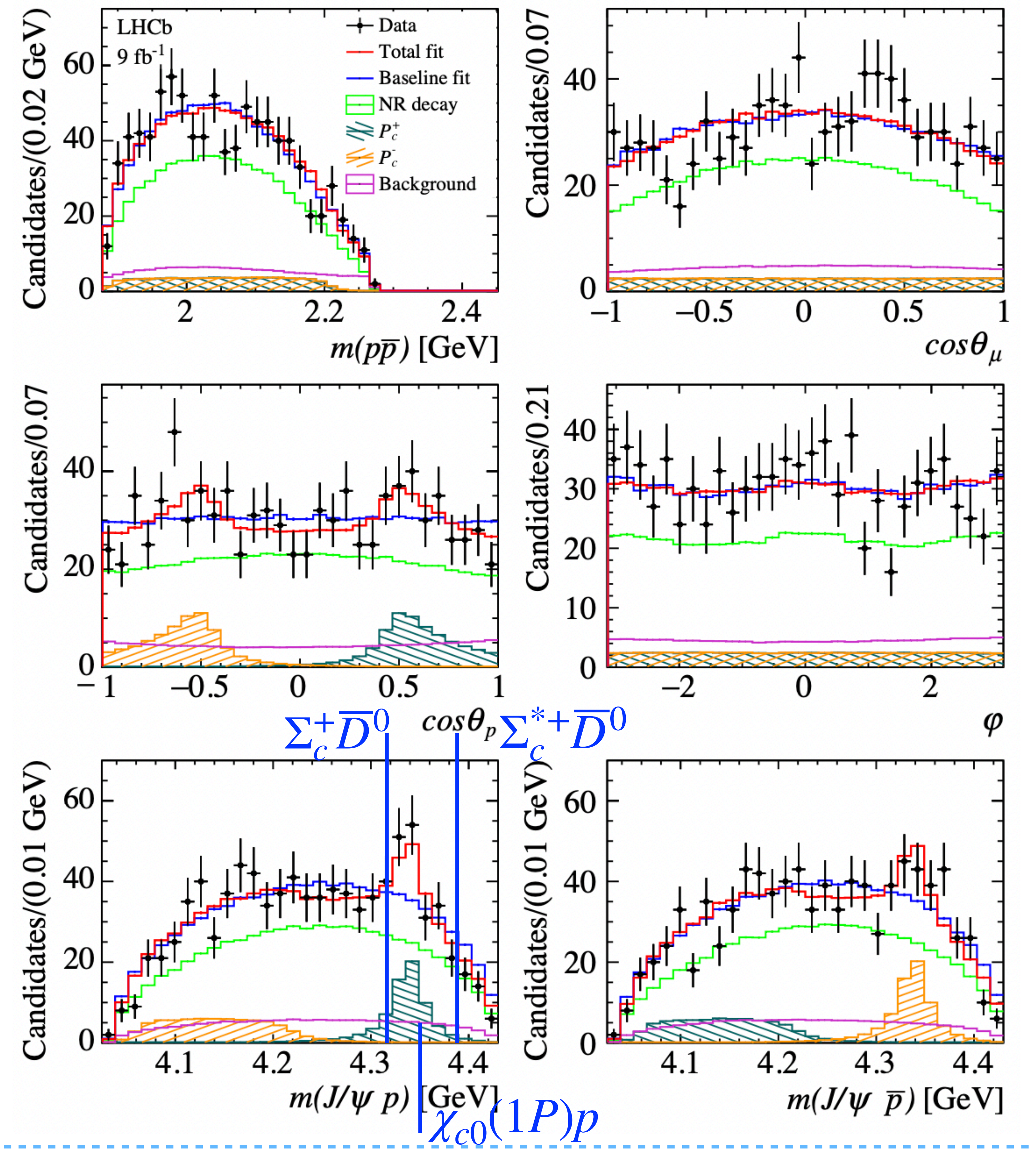
PRL128(2022)062001

- Evidence for a charged pentaquark candidate $P_\psi^N(4337)^\pm$
- Significance: 3.1~3.7σ for $J^P(1/2^\pm, 3/2^\pm)$

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

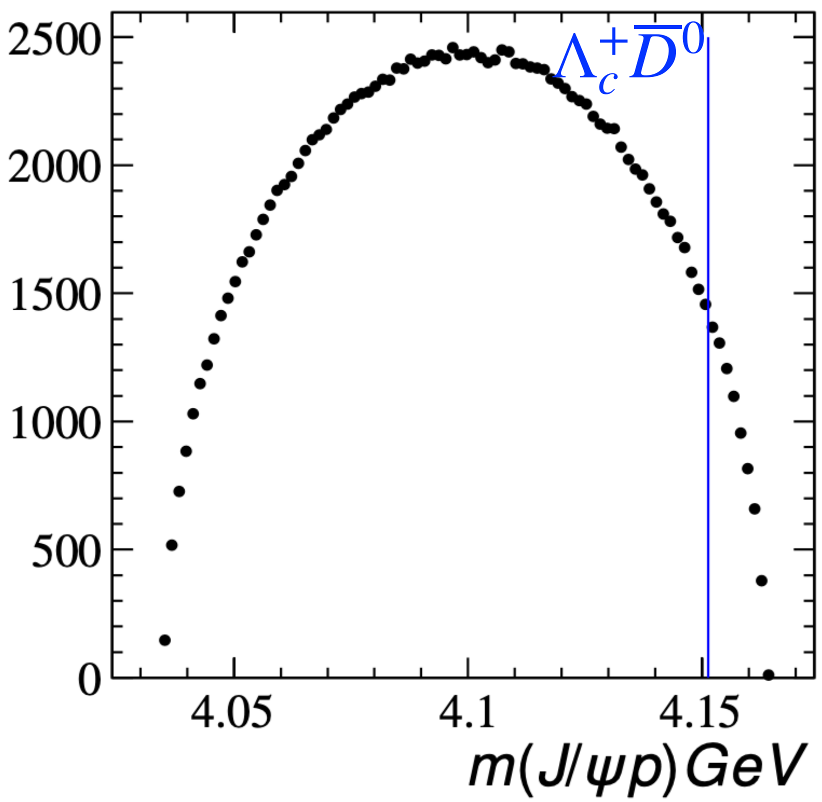
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$

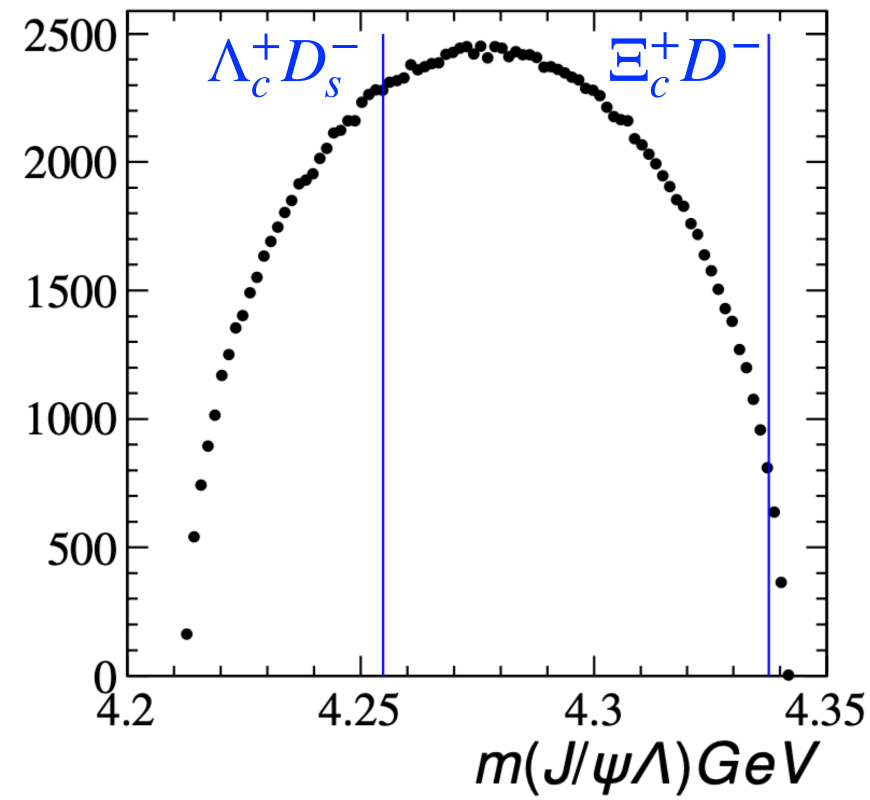
- No evidence for $P_\psi^N(4312)^+$ and $P_\psi^N(4440)^+$



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

- Q-value ~128MeV
- Thresholds: $\Lambda_c^+\overline{D}^0$ in $m(J/\psi\overline{p})$, $\Lambda_c^+D_s^-$ and $\Xi_c^+D^-$ in $m(J/\psi\Lambda)$

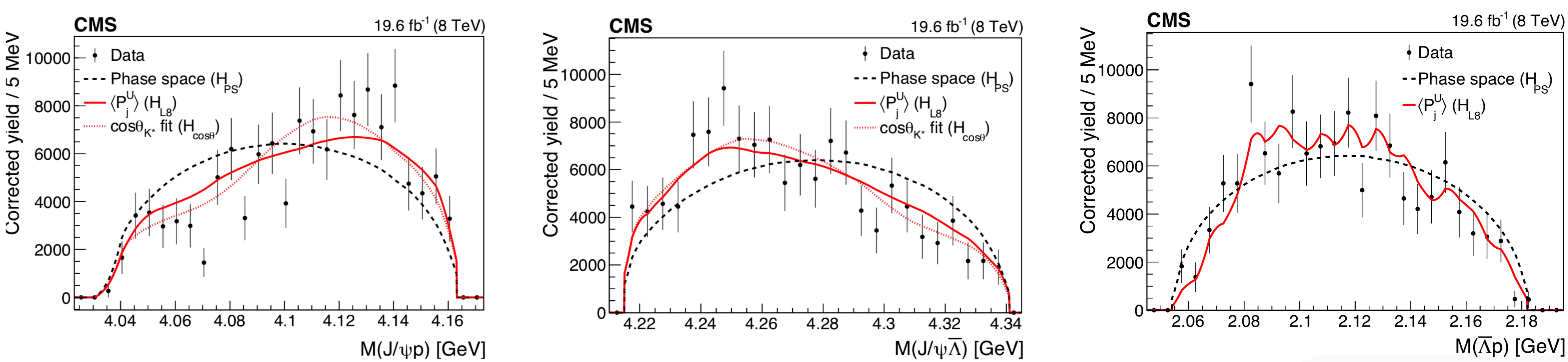




$B^- \to J/\psi\Lambda\bar{p}$ @CMS

JHEP12(2019)100

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



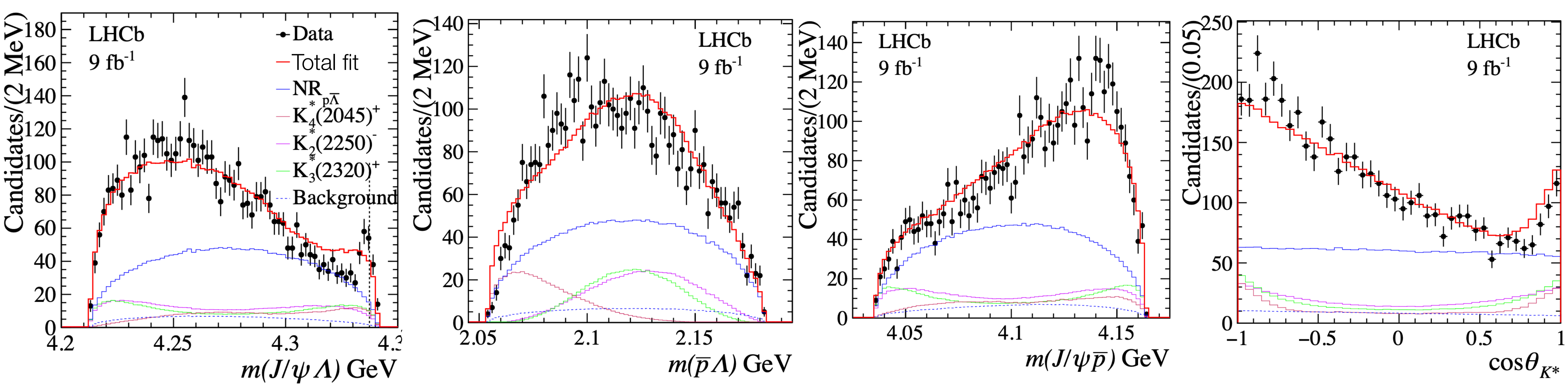
Model with only K^{*-}

- $K^{*-}_{2,3,4}$ peak out of phsp, and contribution not obvious in $\bar{p}\Lambda$ 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^+

- Amplitude model with $K^{*-}_{2,3,4}$ + NR($\bar{p}\Lambda$), can not describe date.

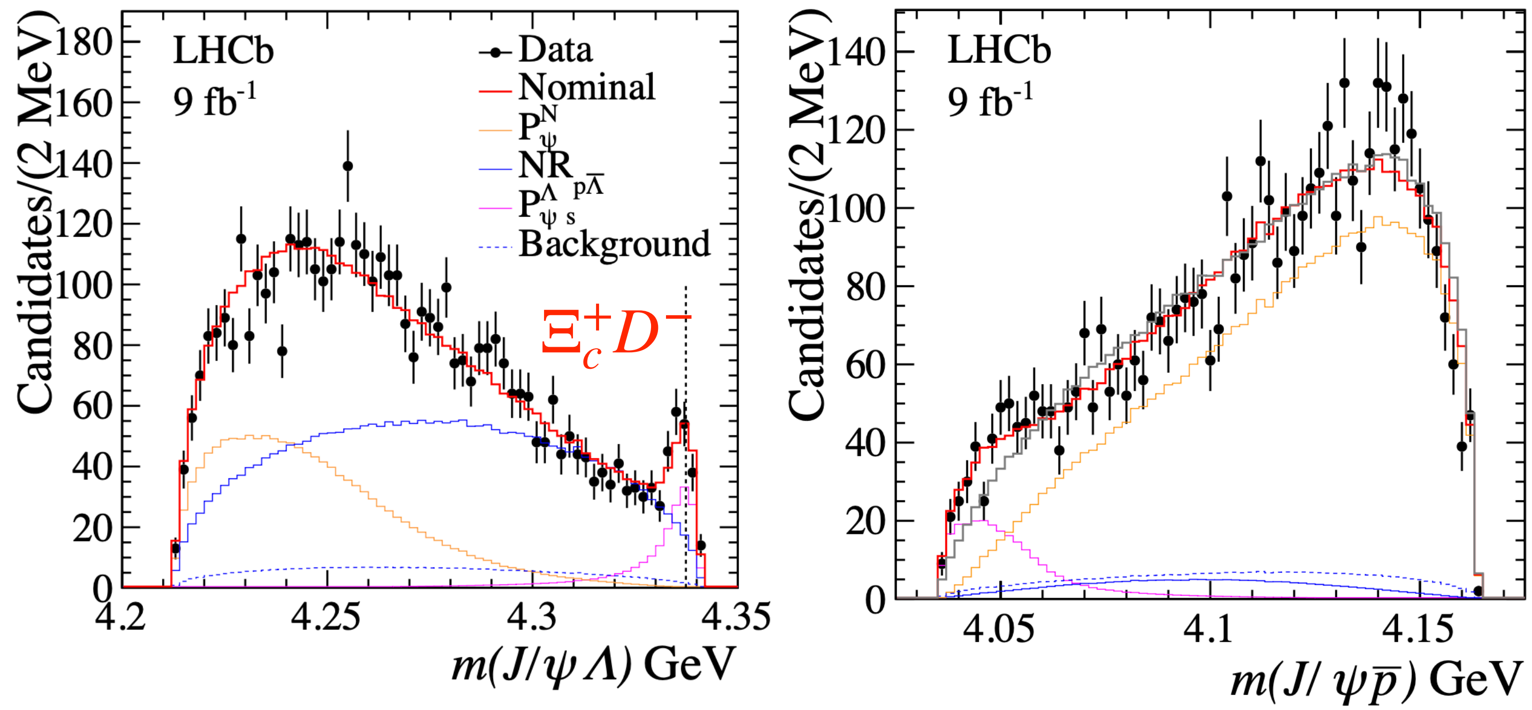
$\chi^2_{max}/ndof$=123/46



Observation of $P_{\psi s}^{\Lambda}(4338)^0$ in $B^- \to J/\psi \Lambda \bar{p}$ decays

Phys.Rev.Lett.131(2023) 031901

- First pentaquark candidate $P_{\psi s}^{\Lambda}(4338)^0$ with strangeness near threshold of $\Xi_c^+ D^-$
- Significance: >10σ wrt null-hyp. model



Breit-Wigner parameters:

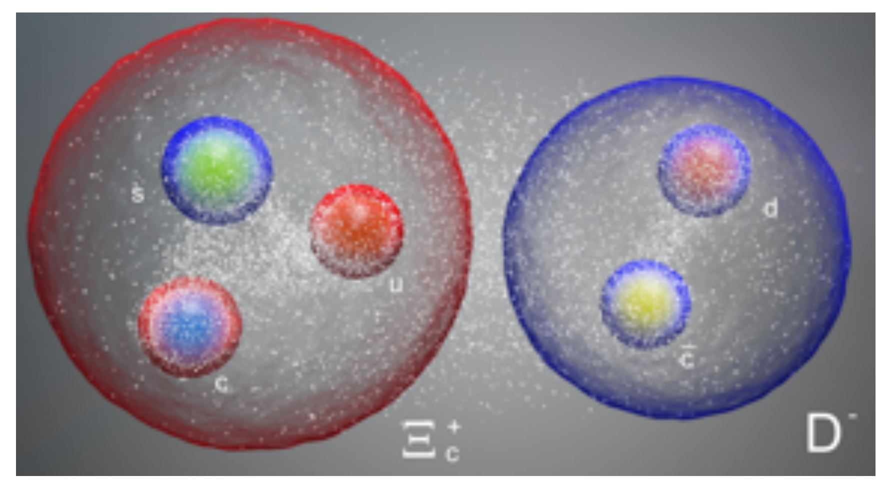
$m(P_{\psi s}^{\Lambda})$=4338.3±0.7±0.4 MeV

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

Spin 1/2 assigned

$1/2^-$ preferred

$1/2^+$ excluded at 90% C.L.



attractive by ρ/ω exchange

Structure around $\Lambda_c^+\overline{D}^0$

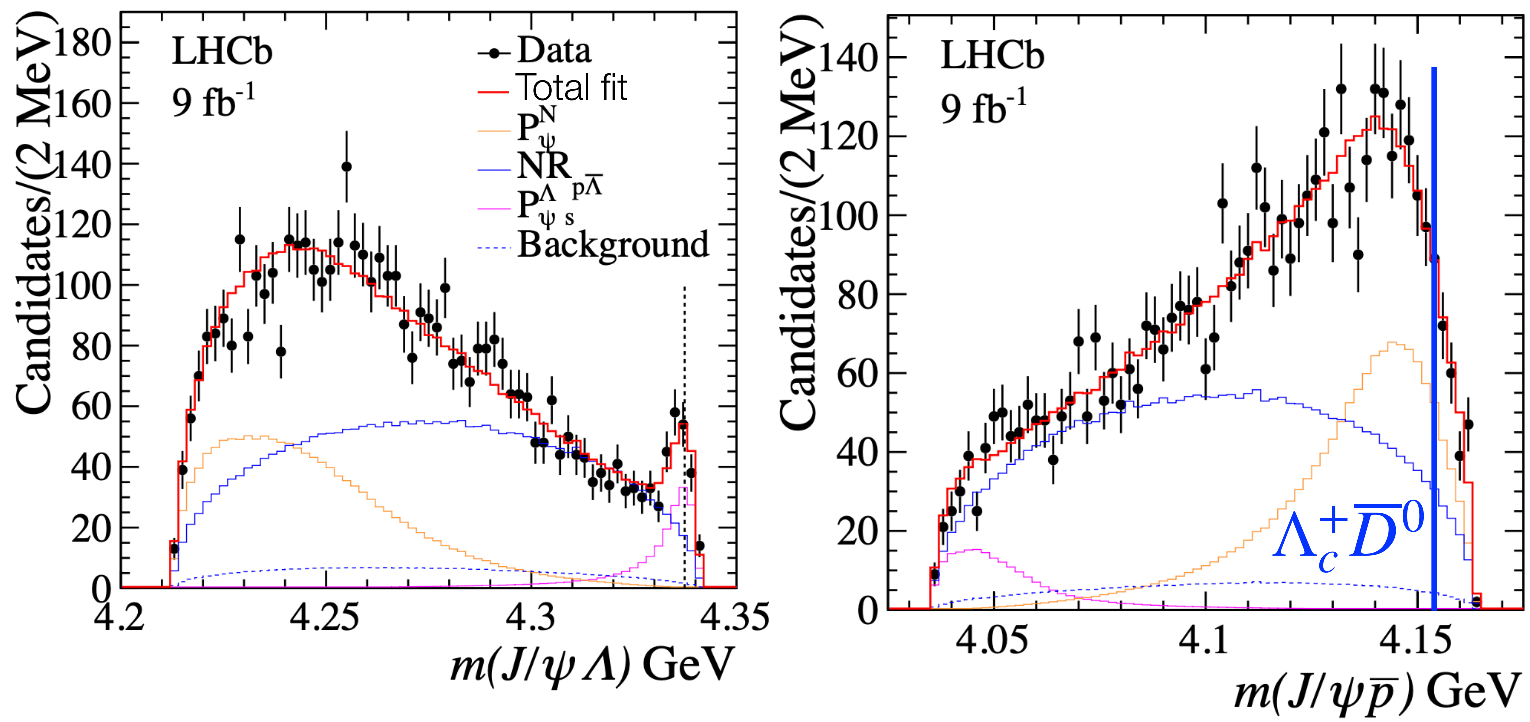
Phys.Rev.Lett.131(2023) 031901

- Amplitude fit with RBW(P_ψ^N) for possible resonance around $\Lambda_c^+\overline{D}^0$

  Breit-Wigner parameters:

  $m(P_{\psi s}^\Lambda)$=4338.8±1.1 MeV
  $\Gamma(P_{\psi s}^\Lambda)$=8.4±1.6 MeV

  $m(P_\psi^N)$=4152.3±2.0 MeV
  $\Gamma(P_\psi^N)$=41.8±6.0 MeV



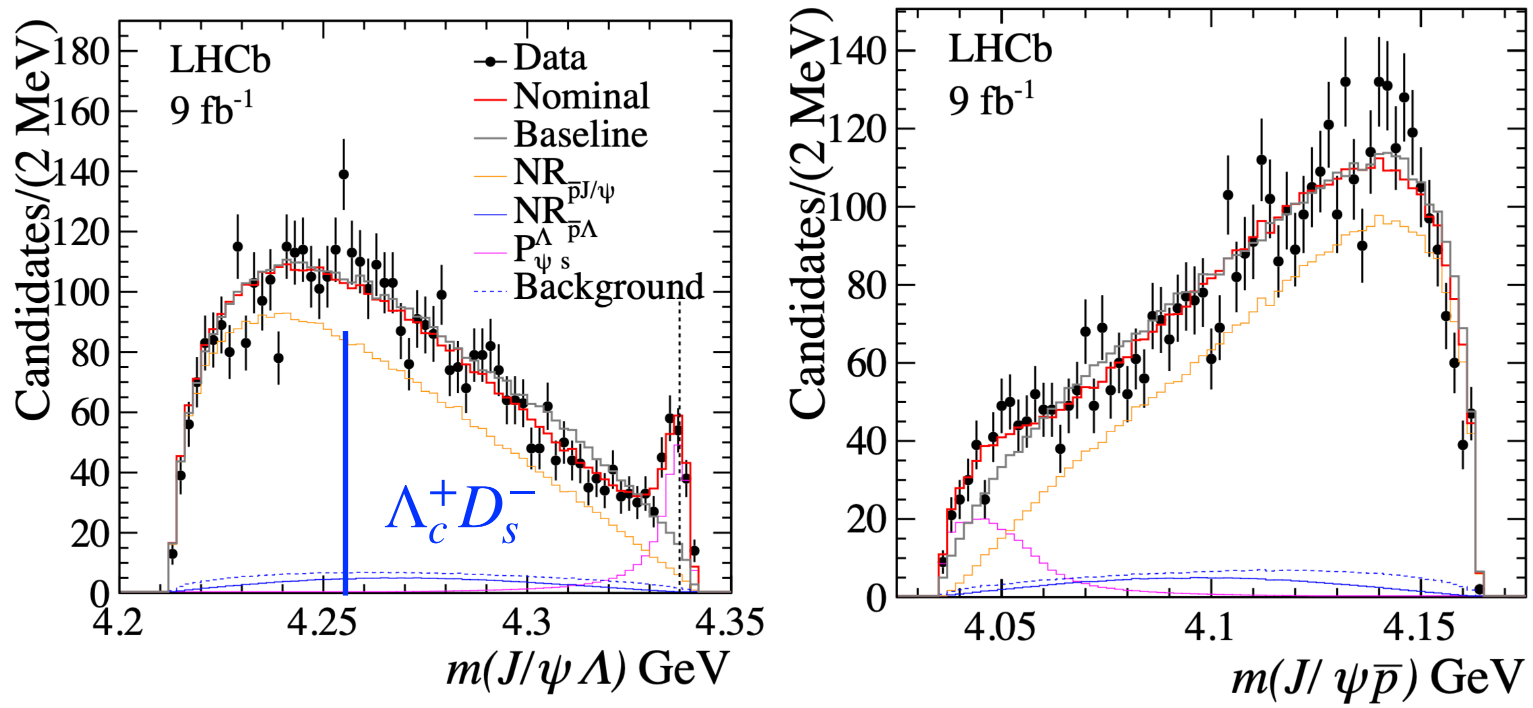
- BUT, -2$\Delta\log L$~80, worse than nominal fit

  2nd polynomial is preferred => no evidence for $P_\psi^N(4152)^+$

Structure around $\Lambda_c^+ D_s^-$

Phys.Rev.Lett.131(2023) 031901

- Few events excess around threshold of $\Lambda_c^+ D_s^-$
- A second RBW($P_{\psi s}^{\Lambda 0}$) added to the nominal model



- A p-value of 20% determined from toys => no evidence for $P_{\psi s}^{\Lambda}(4255)^0$

Summary

- Pentaquark candidates observed at LHCb:

  $c\bar{c}uud$: $P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$ in $\Lambda_b^0 \to J/\psi p K^-$ decays

  near thresholds of $\Sigma_c^+\overline{D}^0$, $\Sigma_c^+\overline{D}^{*0}$, J^P not determined

  $c\bar{c}uds$: $P_{\psi s}^\Lambda(4338)^0$ in $B^- \to J/\psi \Lambda \bar{p}$ decays

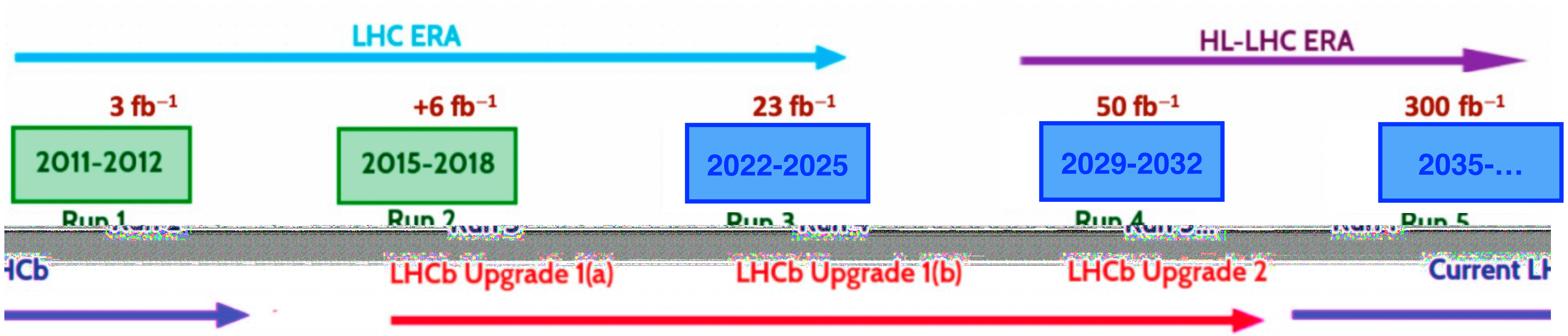
  near threshold of $\Xi_c^+ D^-$, J=1/2 assigned, P=-1 preferred

- Evidence for pentaquark candidates

  $c\bar{c}uud$: $P_\psi^N(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays, near threshold of $\chi_{c0}(1P)p$

  $c\bar{c}uds$: $P_{\psi s}^\Lambda(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays, near threshold of $\Xi_c^0\overline{D}^{*0}$

- Run3 is coming, expect to have more structures in the following years



Thank you!