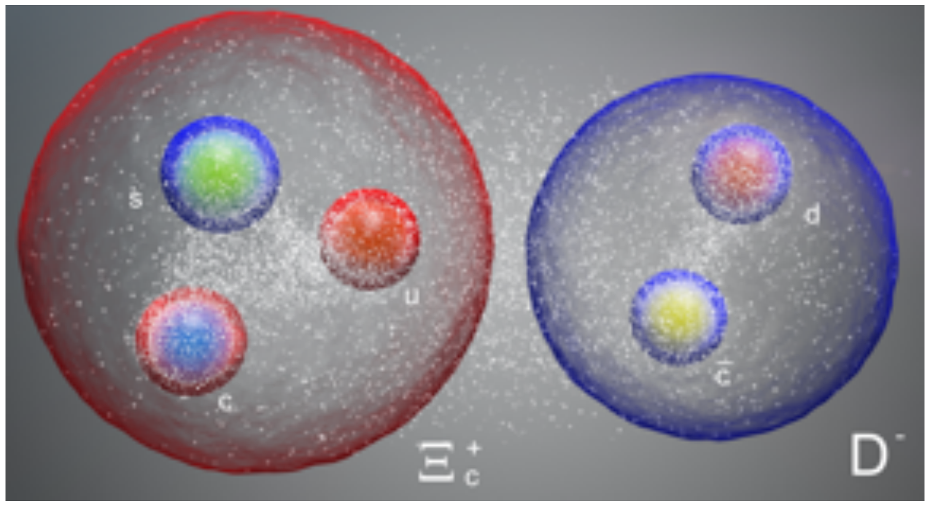
Hadron Physics Online Forum (HAPOF)
https://indico.itp.ac.cn/category/5/
强子物理在线论坛

Observation of a neutral pentaquark candidate in B-meson decays

傅金林
中国科学院大学

2022年7月8日

Outline



- Observation of first neutral pentaquark in $B^- \to J/\psi \Lambda \overline{p}$ decays

  LHCb-PAPER-2022-031 in preparation

- Evidence for a charged pentaquark in $B_s^0 \to J/\psi p \overline{p}$ decays

  PRL128(2022)062001

Pentaquark in the quark model

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 (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), 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".

- Predicted in the quark model
- Minimal content $qqqq\bar{q}$

Exotic hadron naming convention

LHCb-PUB-2022-013, arXiv:2206.15233

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]

- P for pentaquarks, T for tetraquarks
- P states: i.e. $P^N_{\psi}(4312)^+$, $P^{\Lambda}_{\psi s}(4459)^0$

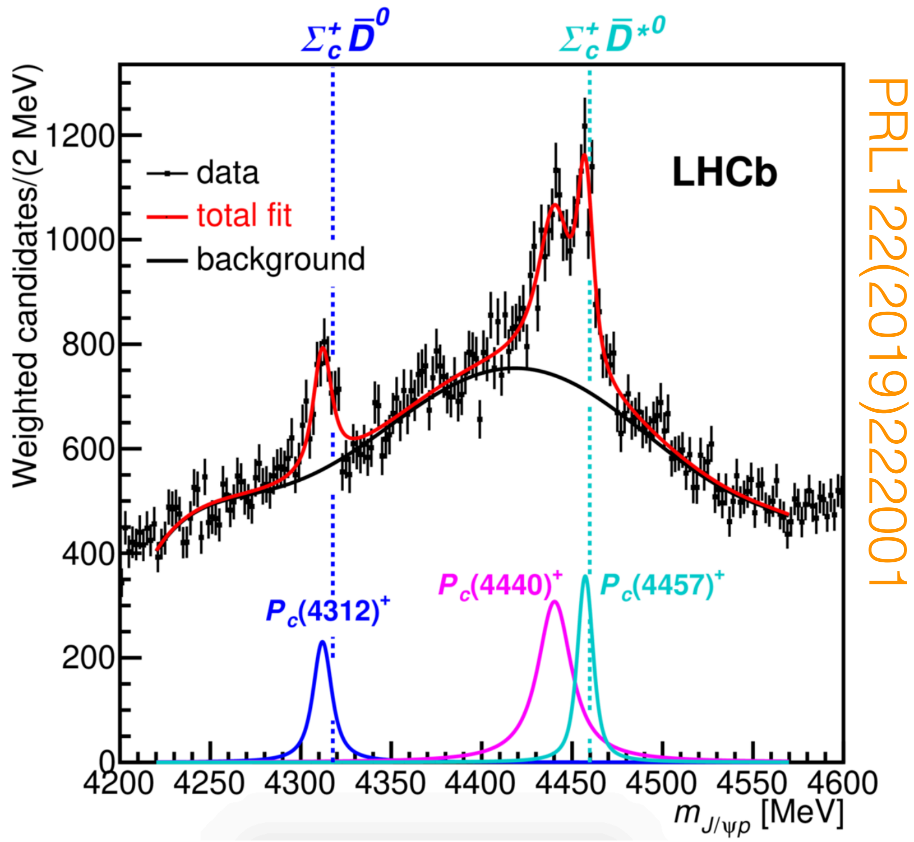
  Superscript: denotes isospin: $\Lambda, N, \Sigma, \Delta$ for I= 0,1/2,1,3/2

  Subscript: Υ, ψ, ϕ for hidden beauty, charm, strangeness; b, c, s for open flavor quantum numbers

Pentaquark candidates in B-baryon decays

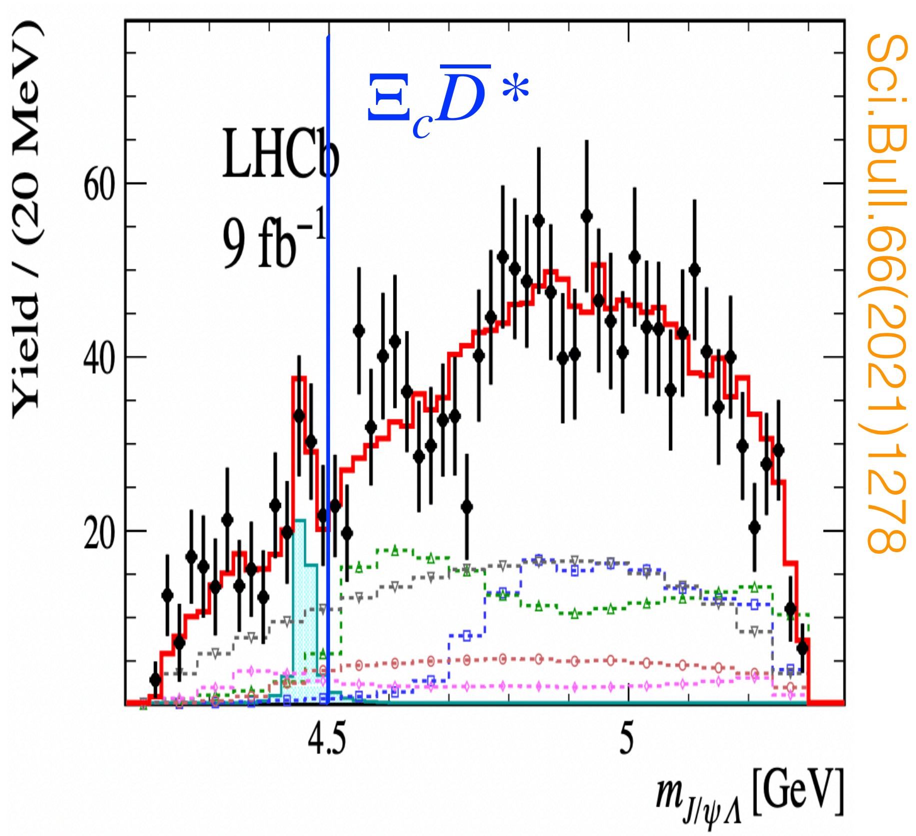
Observation in $\Lambda_b^0 \to pK^- J/\psi$

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



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

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

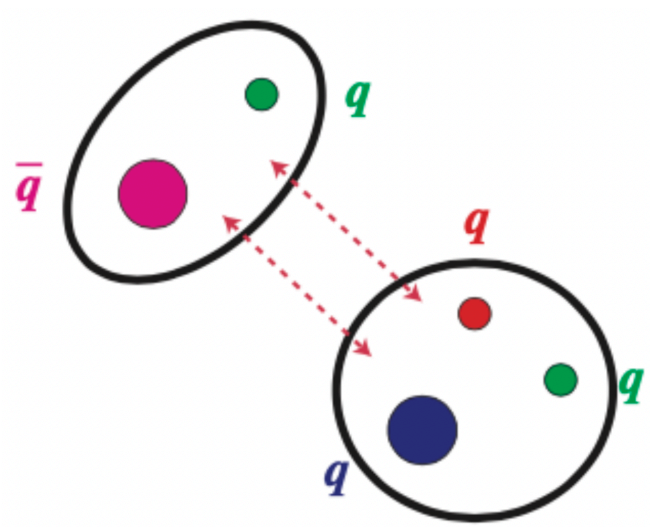


- Narrow structures require excellent mass resolution
- Interesting physics related to thresholds
- Spin and parity not determined

Interpretations

Their nature is still largely unknown, various interpretations including:

Hadronic Molecules

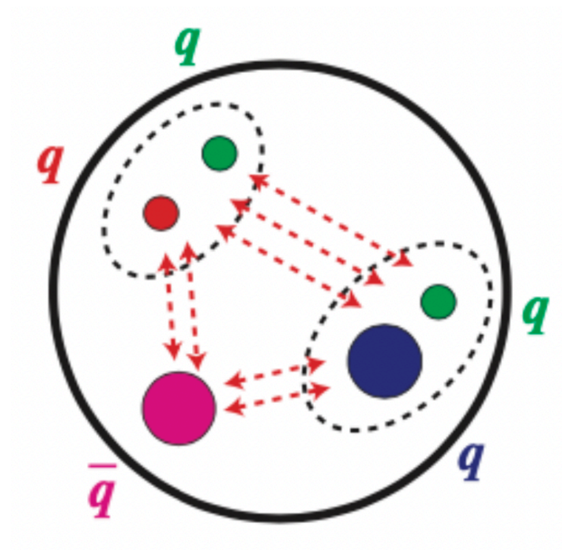


Rev. Mod. Phys. 90(2018)015004

PRD103(2021)112006

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

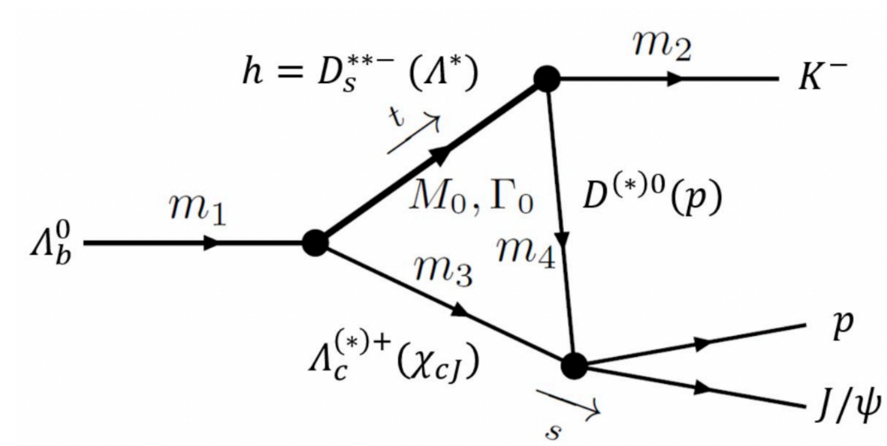
Compact pentaquark



Phys. Rept. 668(2017)1

Few Body Syst. 57 (2016)1185

Rescattering effects

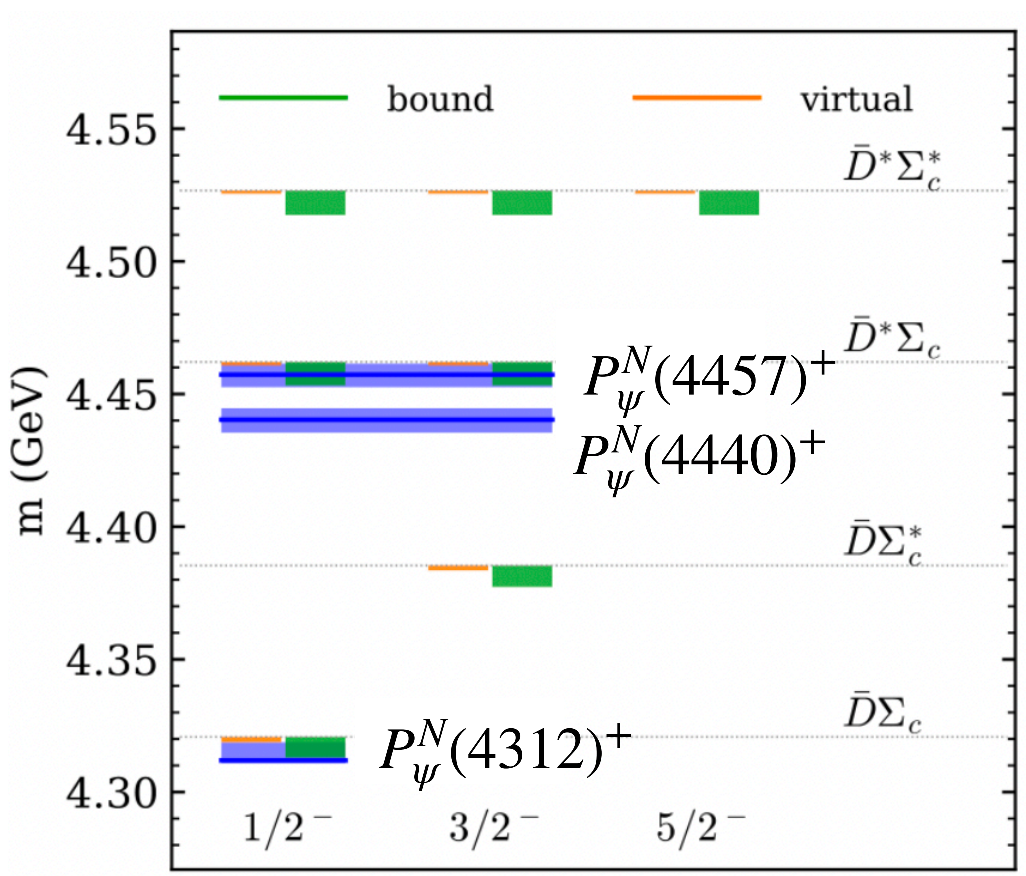


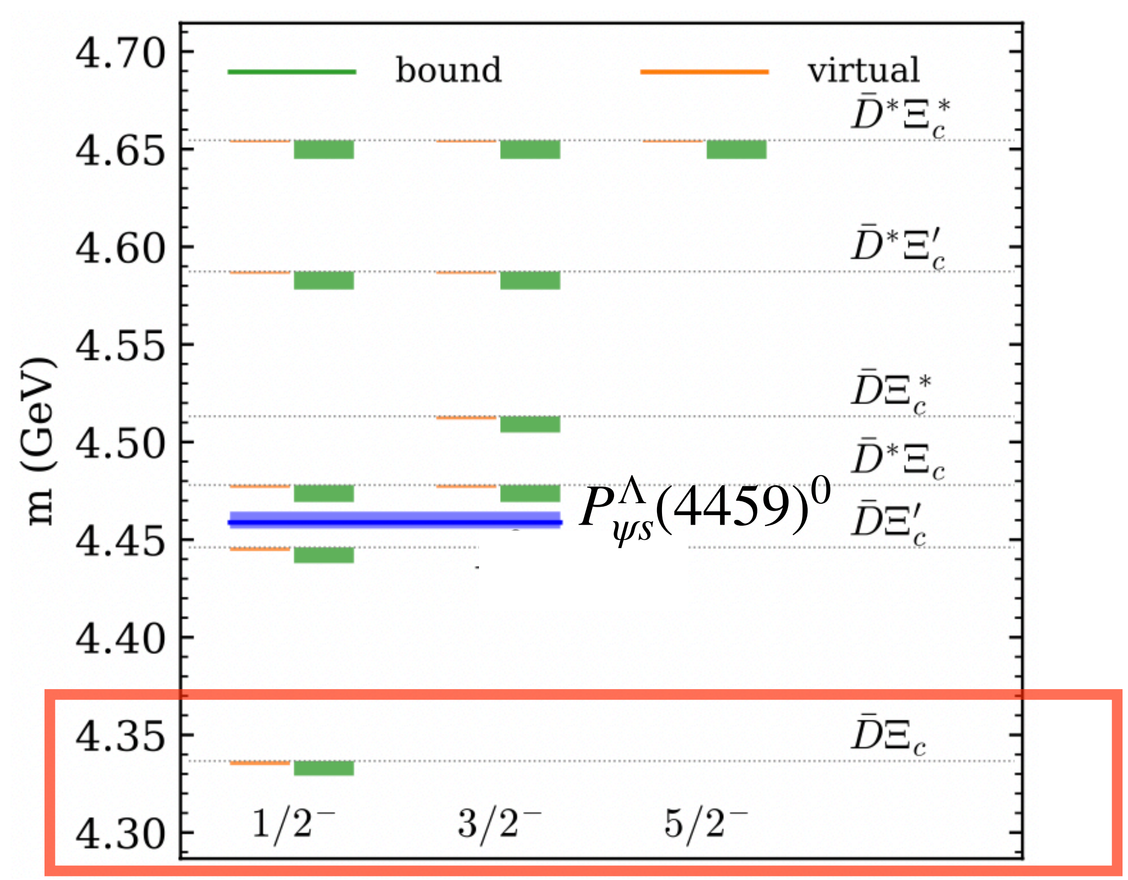
Prog. Part. Nucl. Phys. 112 (2020)103757

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



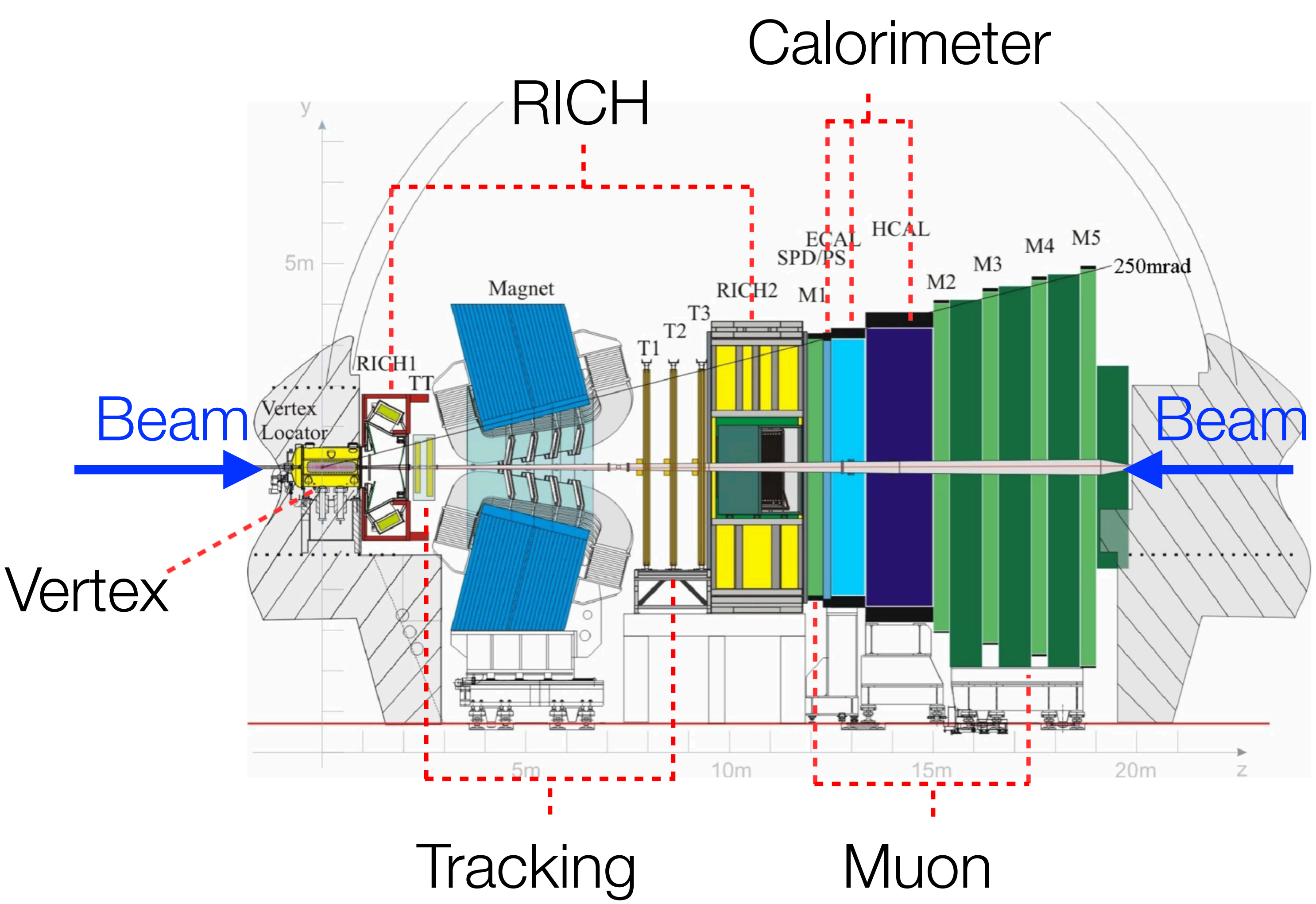


LHCb detector and performance

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

JINST3(2008)S08005

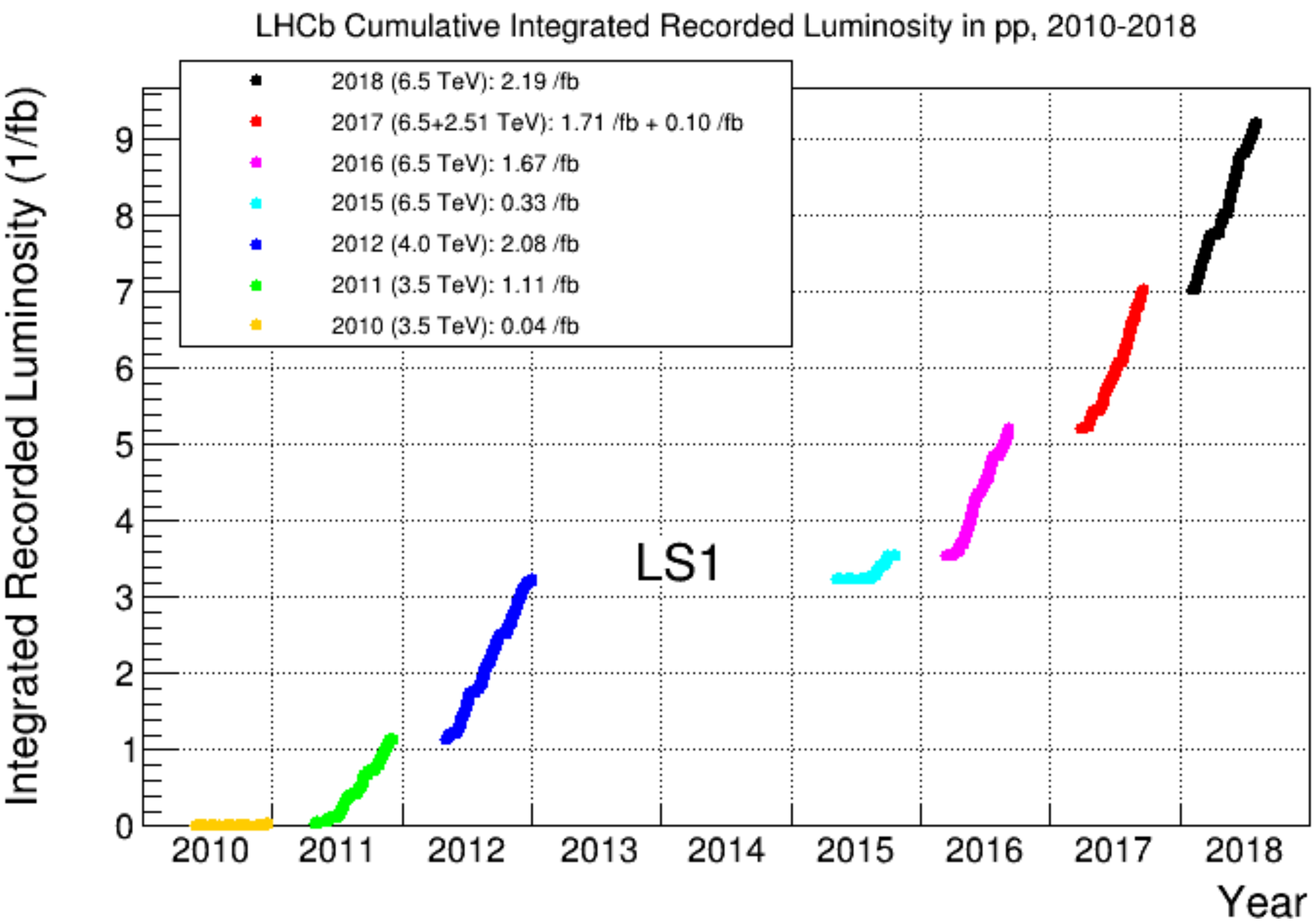
LHCb is a forward spectrometer



$2 < \eta < 5$, 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

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

Why in B-meson decays

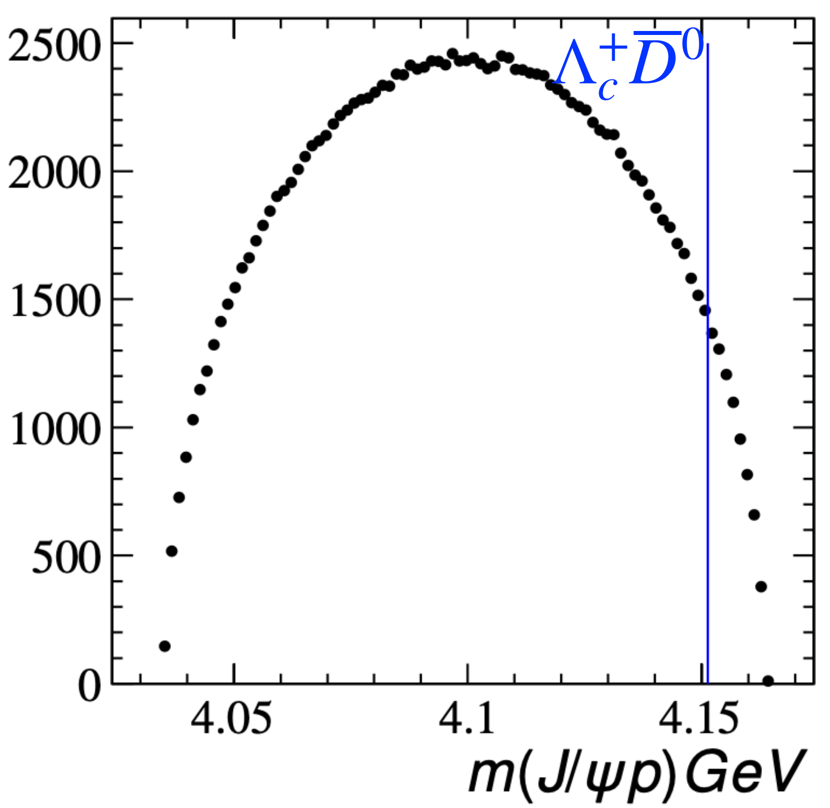
- Small Q-value, providing excellent mass resolution, allows to search for narrow structures
- Search for pentaquark and anti-pentaquark states at the same time
- Sensitive to structures in baryon and anti-baryon system

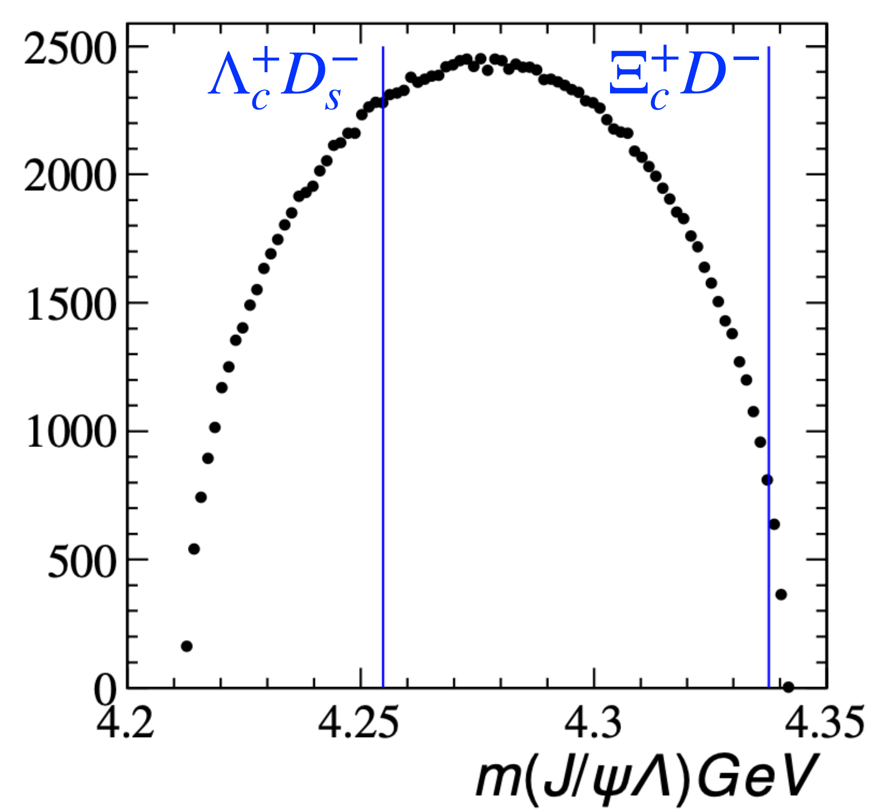
Amplitude analysis in $B^- \to J/\psi \Lambda \overline{p}$ decays

LHCb-PAPER-2022-031 in preparation

$B^- \to J/\psi\Lambda\overline{p}$ 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 $m(J/\psi\Lambda)$

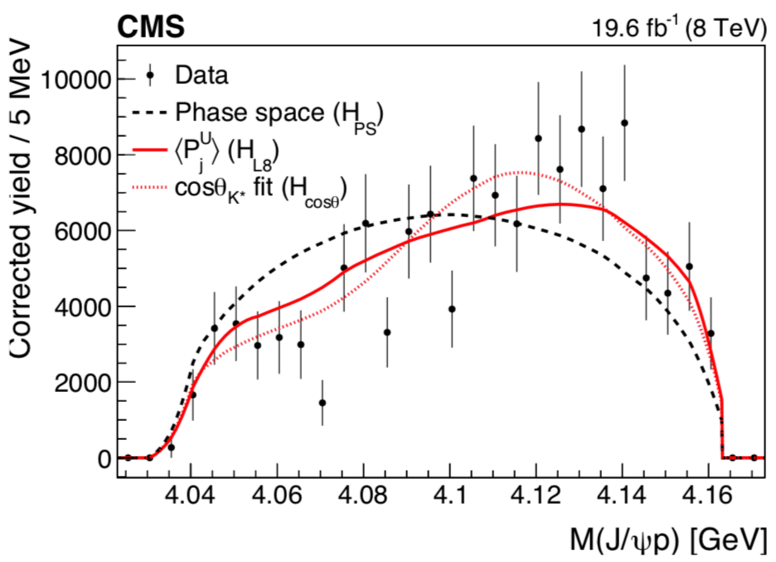


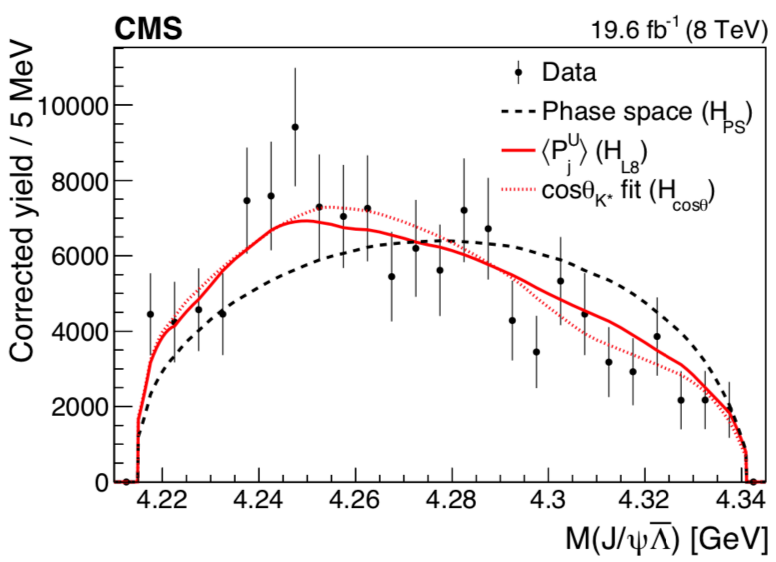


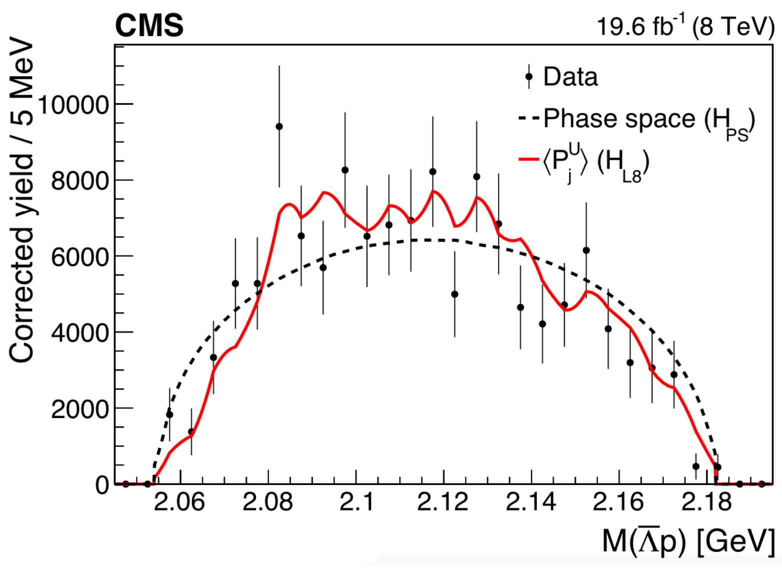
$B^- \to J/\psi\Lambda\bar{p}$ @CMS

JHEP12(2019)100

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

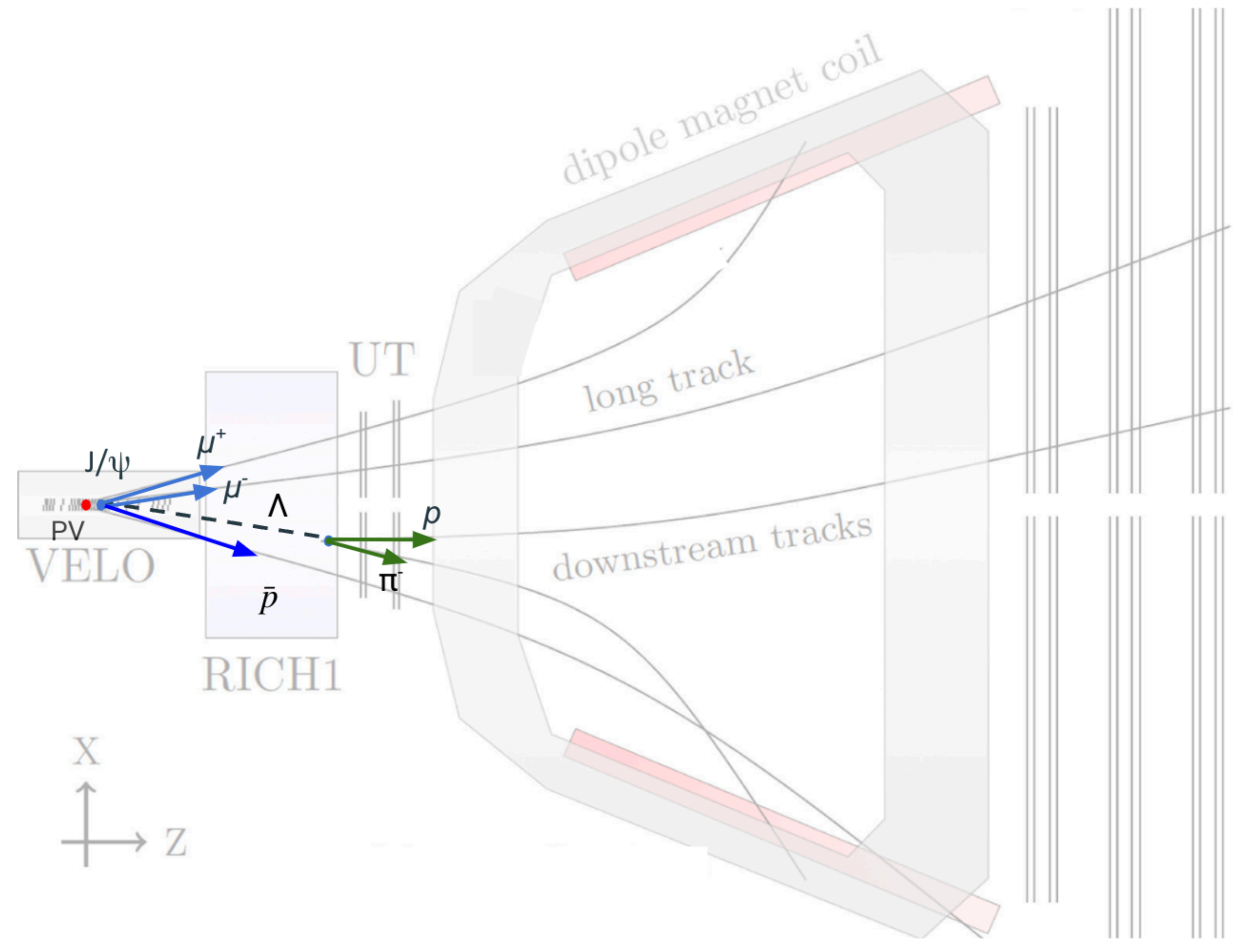






$B^- \to J/\psi \Lambda \overline{p}$ reconstruction

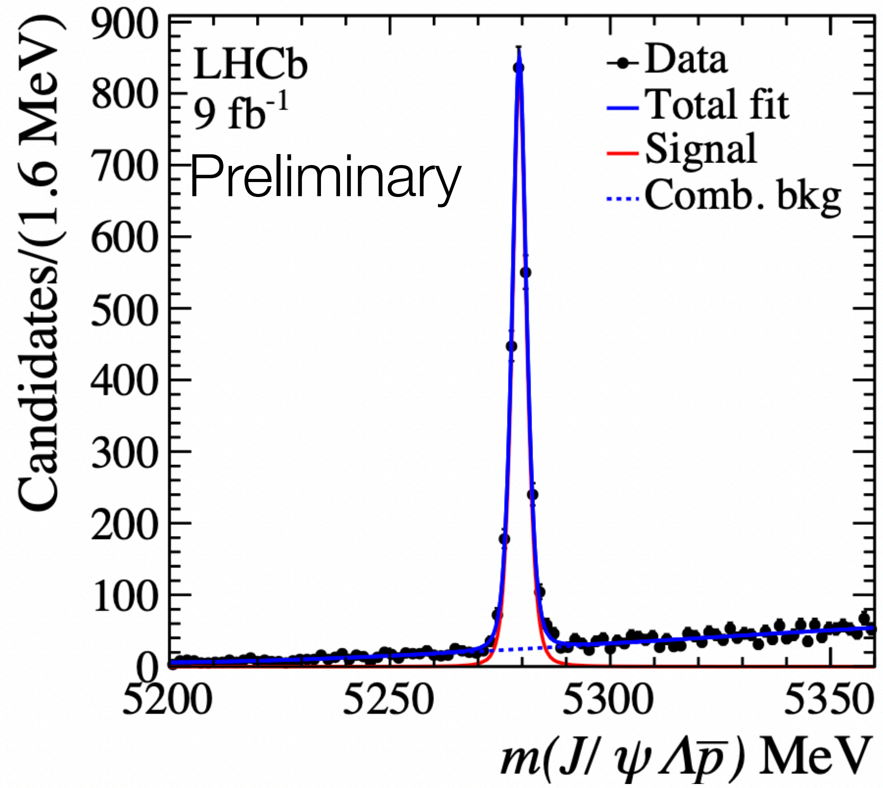
- Trigger on detached $J/\psi \to \mu^+\mu^-$
- $\Lambda \to p\pi^-$ reconstruction:
  - Λ decay inside VELO
  - Λ decay after VELO



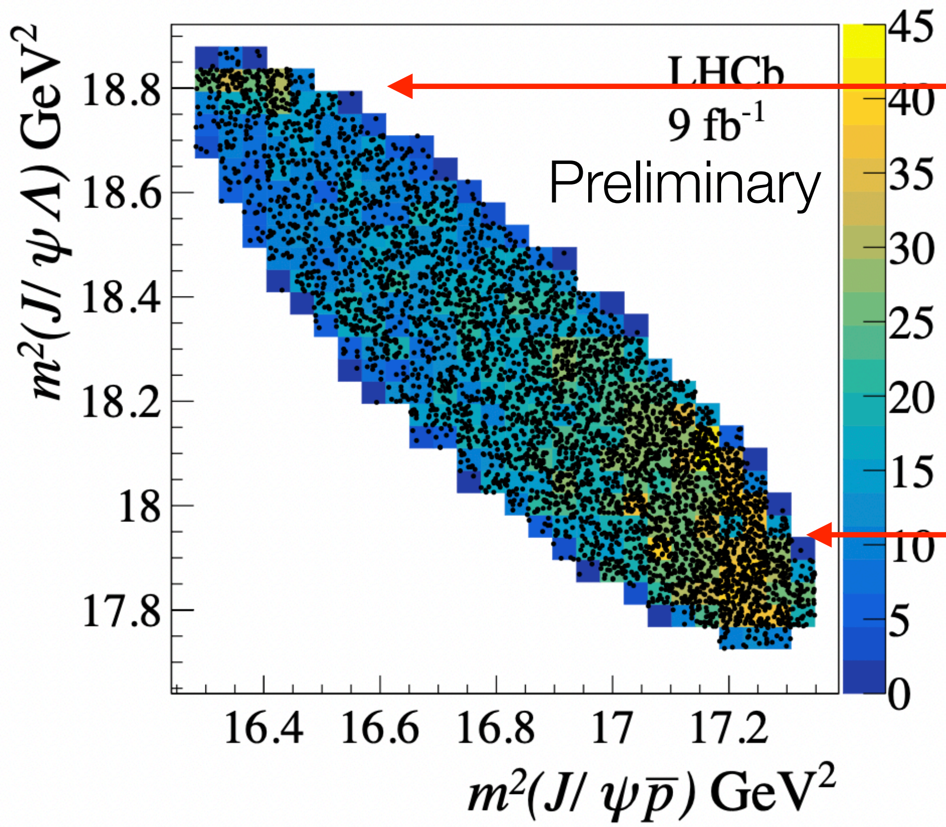
- PID for bachelor anti-proton
- Good-quality vertex for Λ, J/ψ and B^-
- BDT optimization

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

LHCb-PAPER-2022-031 in preparation



- LHCb run1 and run2, 9fb^{-1} dataset
  - Signal window $\pm 2.5\sigma$
  - 4400 candidates
  - 93% purity
  - B mass resolution 2MeV



- Narrow structure in $J/\psi\Lambda$
- Activity in the $J/\psi p$ system

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

- Amplitudes developed using helicity formalism, assuming no CPV
- Three decay chains: $J/\psi K^{*-}(\to \Lambda\overline{p})$, $\Lambda P_c^-(\to J/\psi\overline{p})$ and $\overline{p}P_{cs}^0(\to J/\psi\Lambda)$
- Resonant lineshape: Relativistic Breit-Wigner (RBW)
- Non-resonant (NR) lineshape: constant or 2nd order polynomial
- Amplitude fit to data by minimizing

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

Model with only K^{*-}

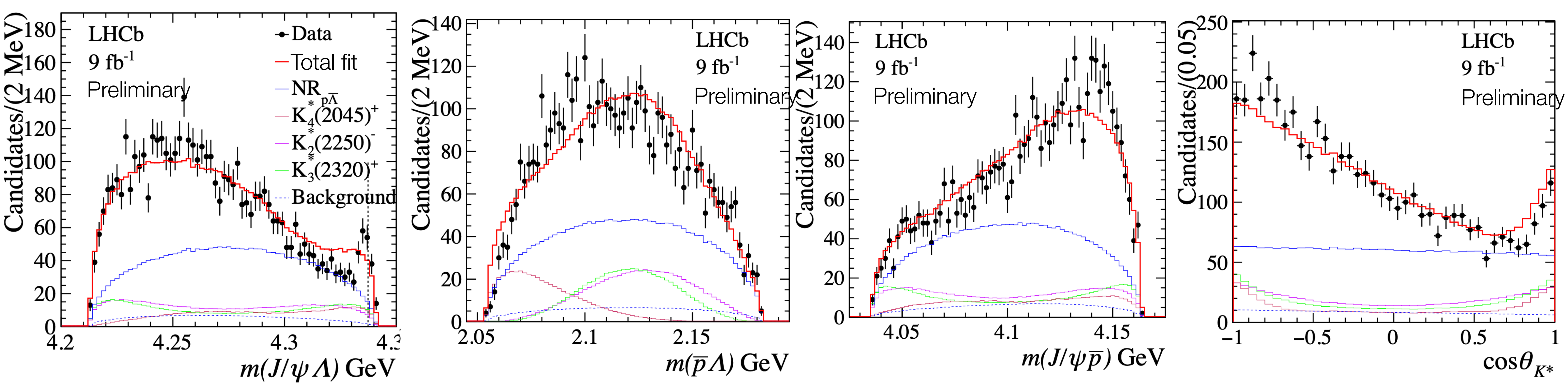
LHCb-PAPER-2022-031 in preparation

- $K^{*-}_{2,3,4}$ 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.

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



Baseline and nominal models

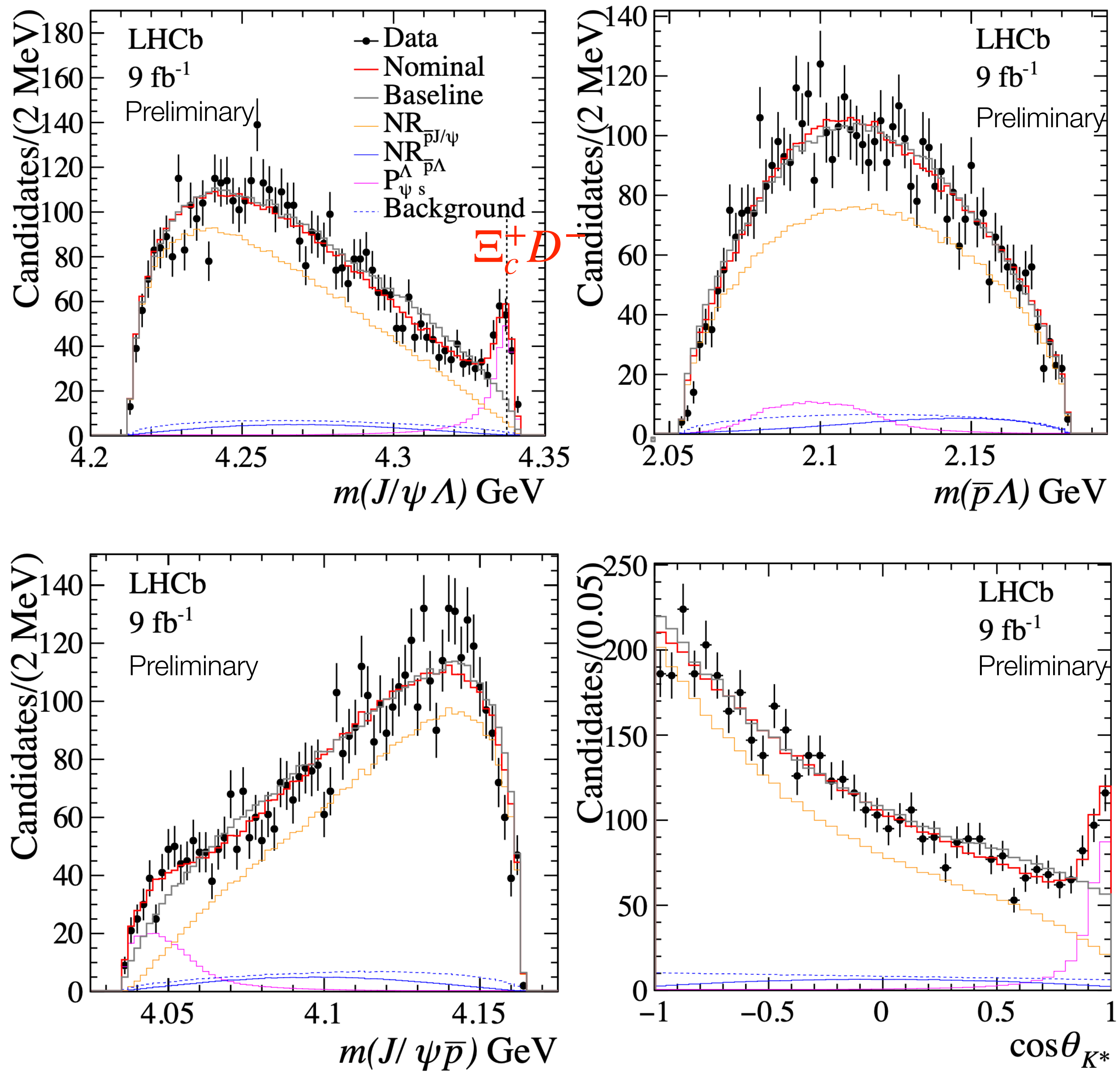
Contributions in two amplitude models

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

Fit results of nominal model

LHCb-PAPER-2022-031 in preparation

- First neutral pentaquark candidate $P_{\psi s}^{\Lambda}(4338)^0$ near threshold of $\Xi_c^+ D^-$
- Significance: $>10\sigma$ wrt baseline model



$m(P_{\psi s}^{\Lambda})$=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.

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

LHCb-PAPER-2022-031 in preparation

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

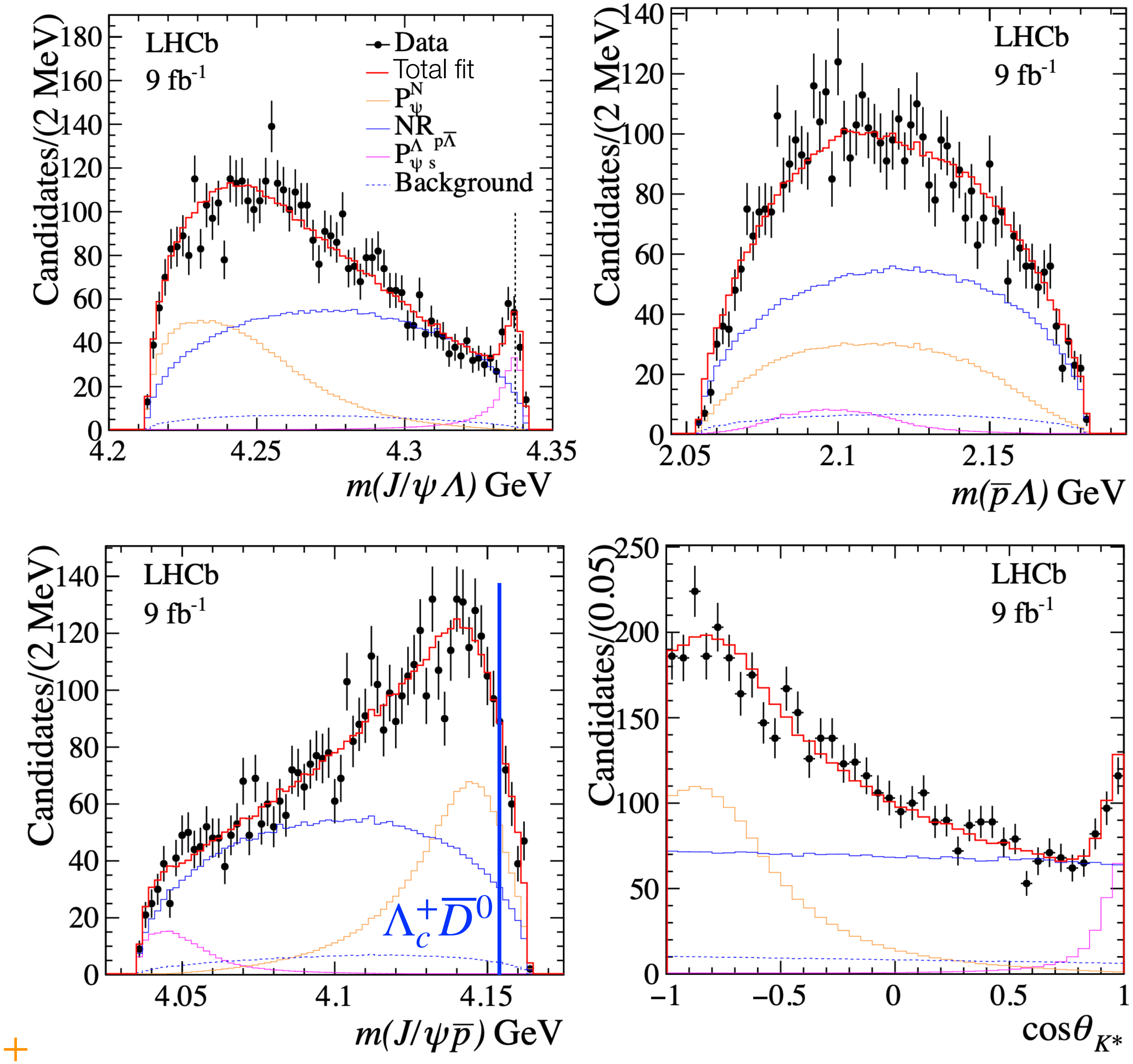
$m(P_{\psi s}^\Lambda)$=4338.8±1.1 MeV
$\Gamma(P_{\psi s}^\Lambda)$=8.4±1.6 MeV

$m(P_\psi^N)$=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 $P_\psi^N(4152)^+$

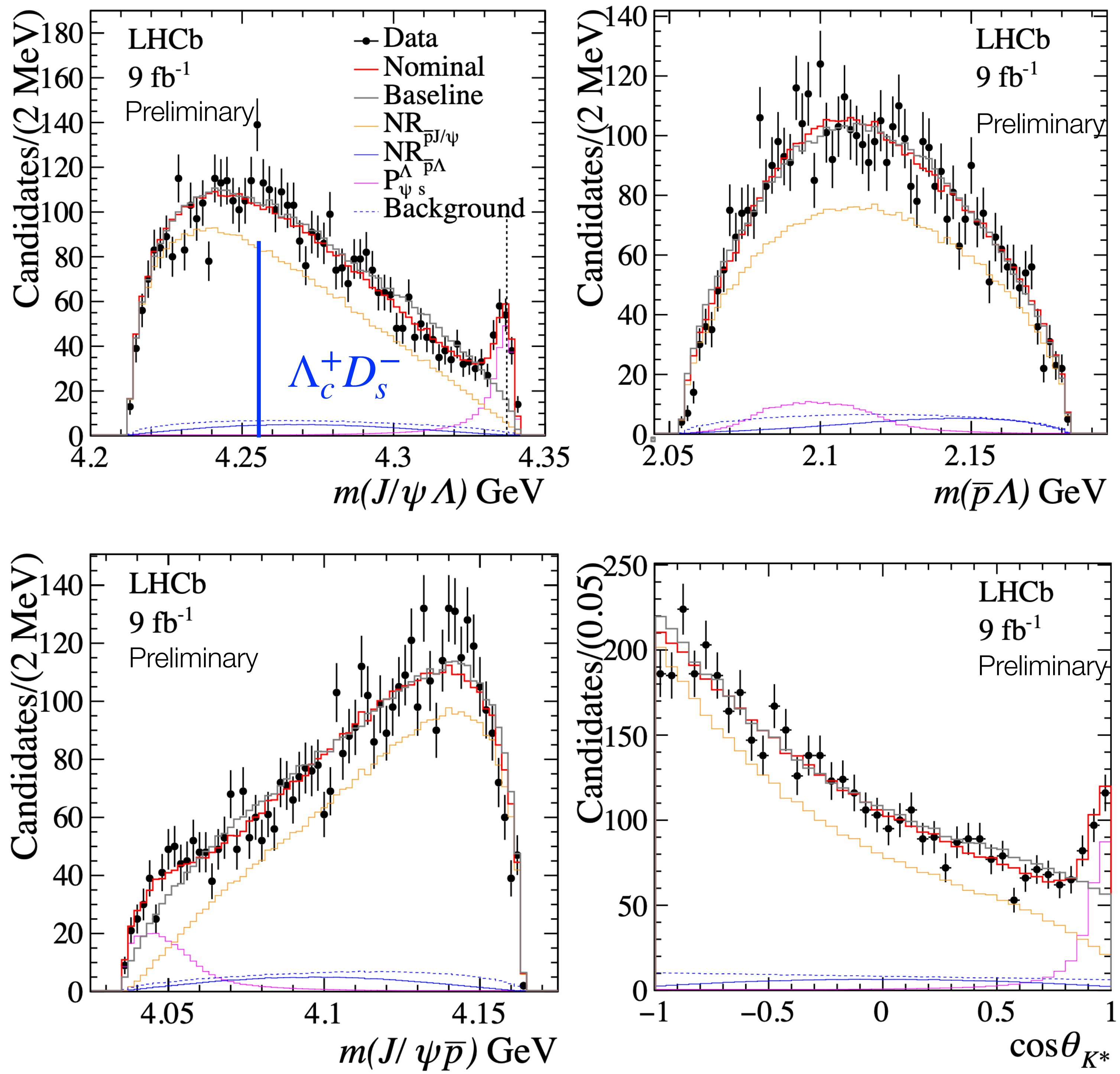


Structure around $\Lambda_c^+ D_s^-$

LHCb-PAPER-2022-031 in preparation

- 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 $P_{\psi s}^{\Lambda}(4255)^0$

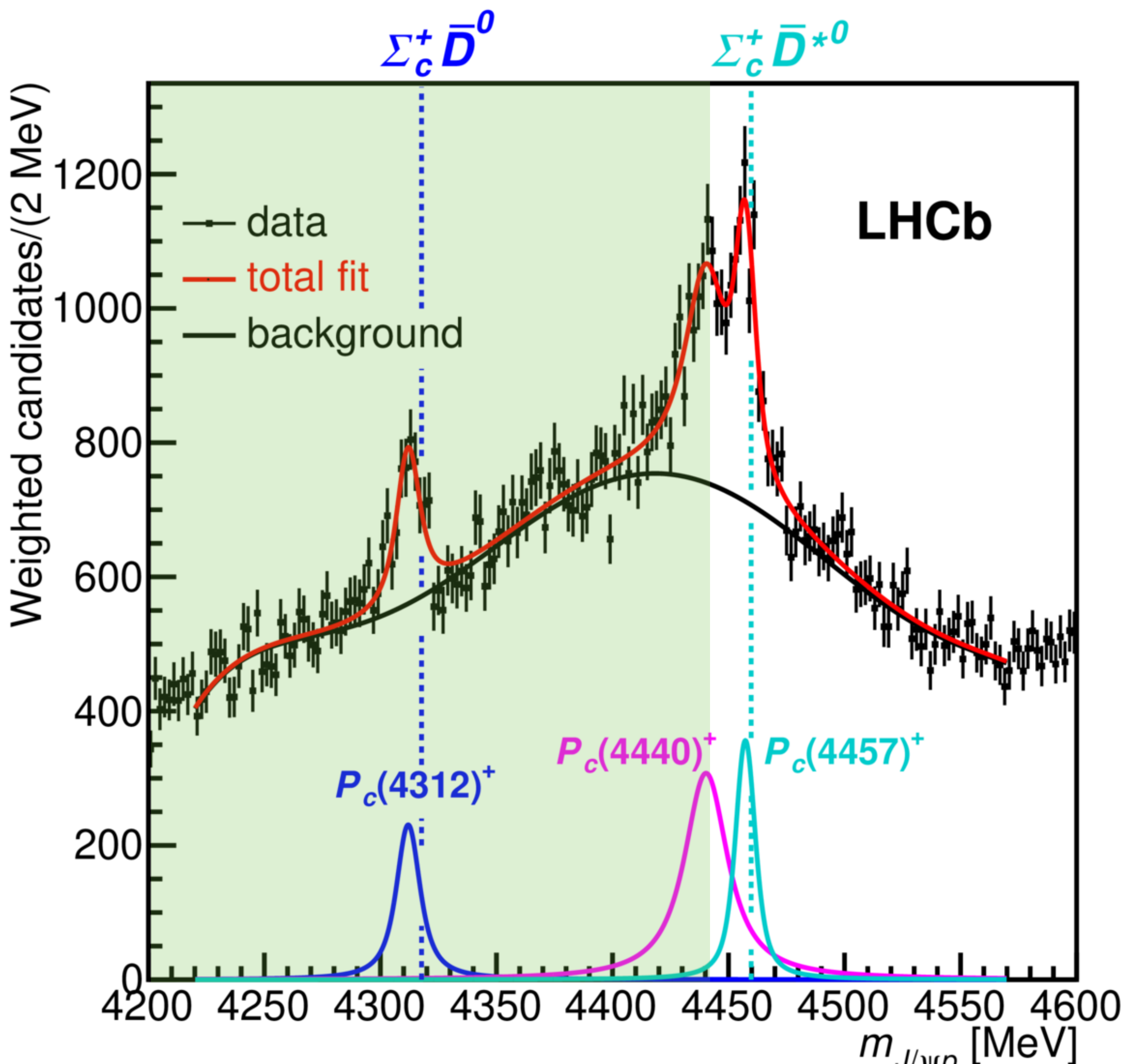


Amplitude analysis in $B_s^0 \to J/\psi p\overline{p}$ decays

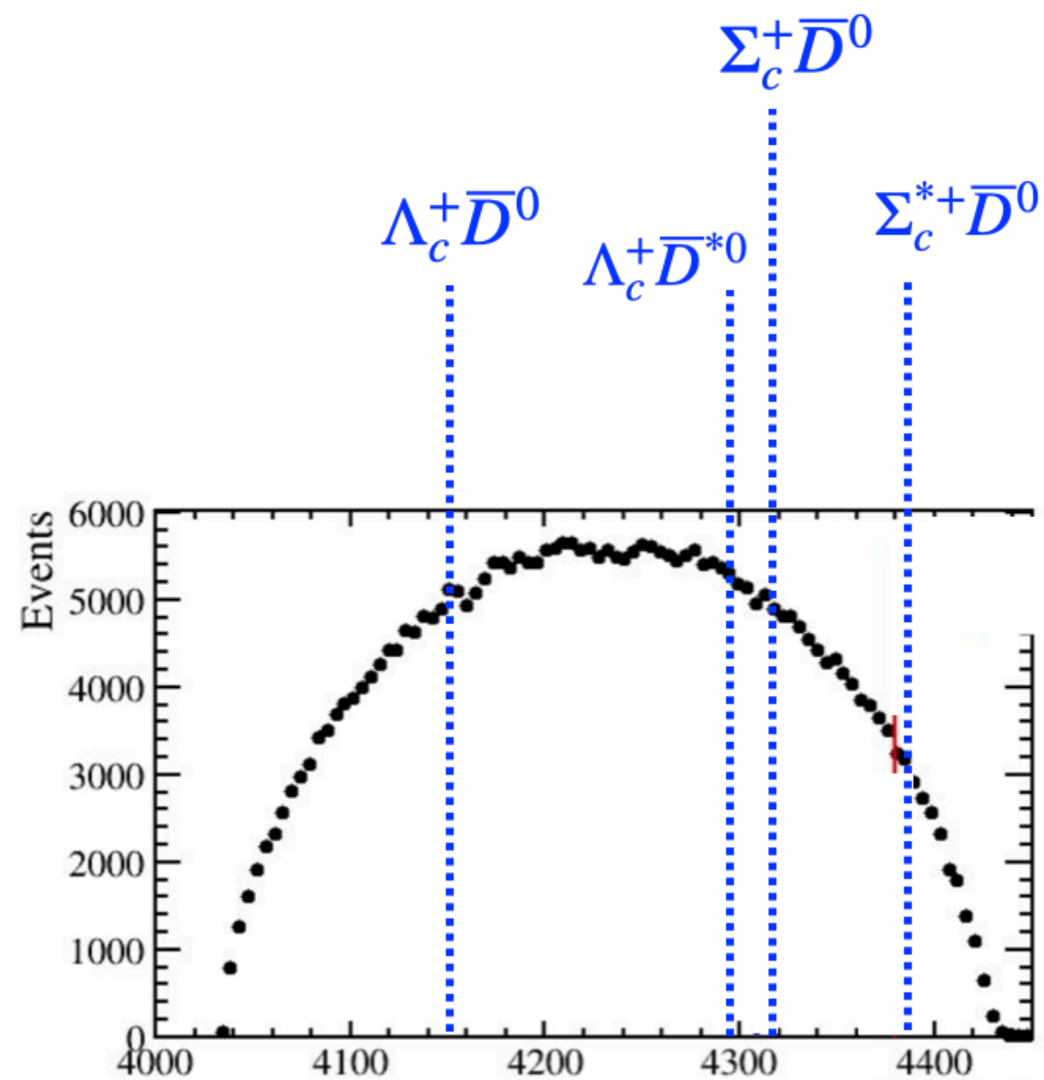
PRL128(2022)062001

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

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



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

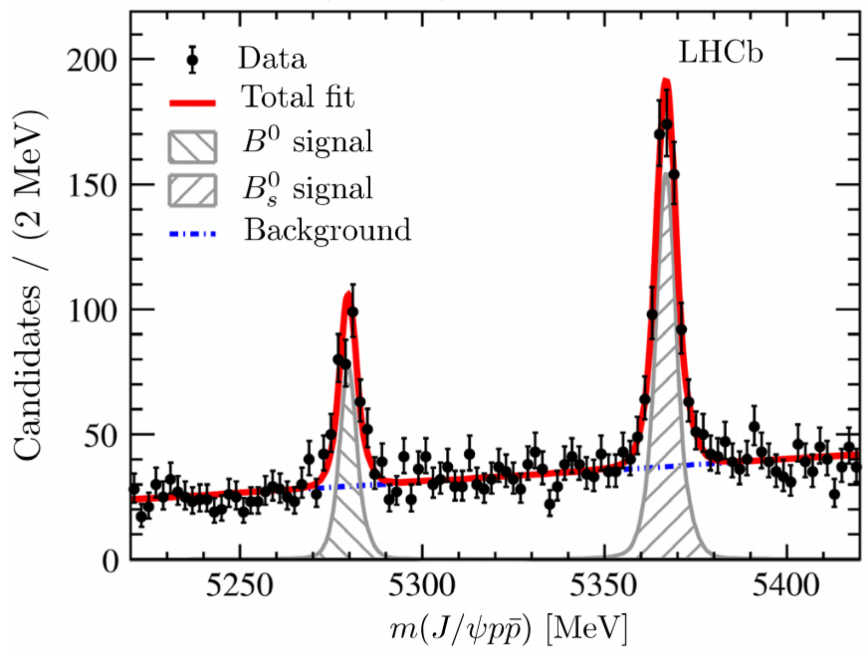


$m(J/\psi p)$ MeV

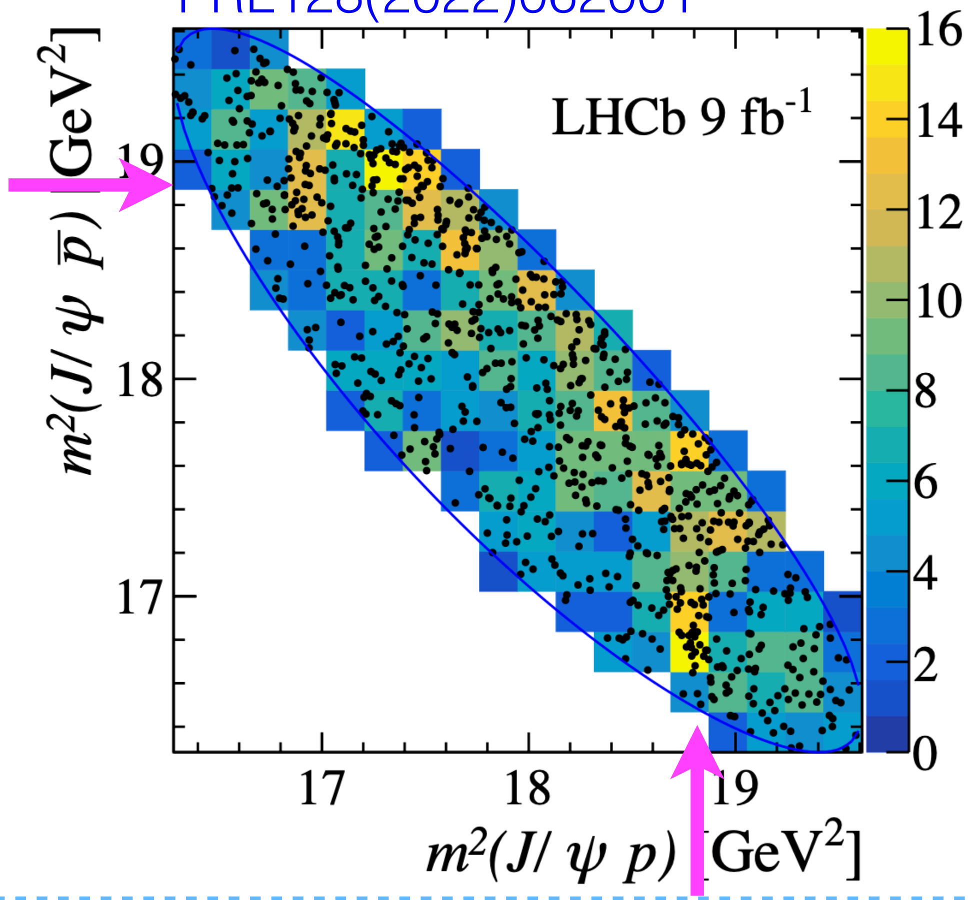
$B_s^0 \to J/\psi p\bar{p}$

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

Amplitude fit

- Amplitudes developed using helicity formalism

- Assuming no CPV

- For untagged B decay, total amplitude

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

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

Amplitude fit

PRL128(2022)062001

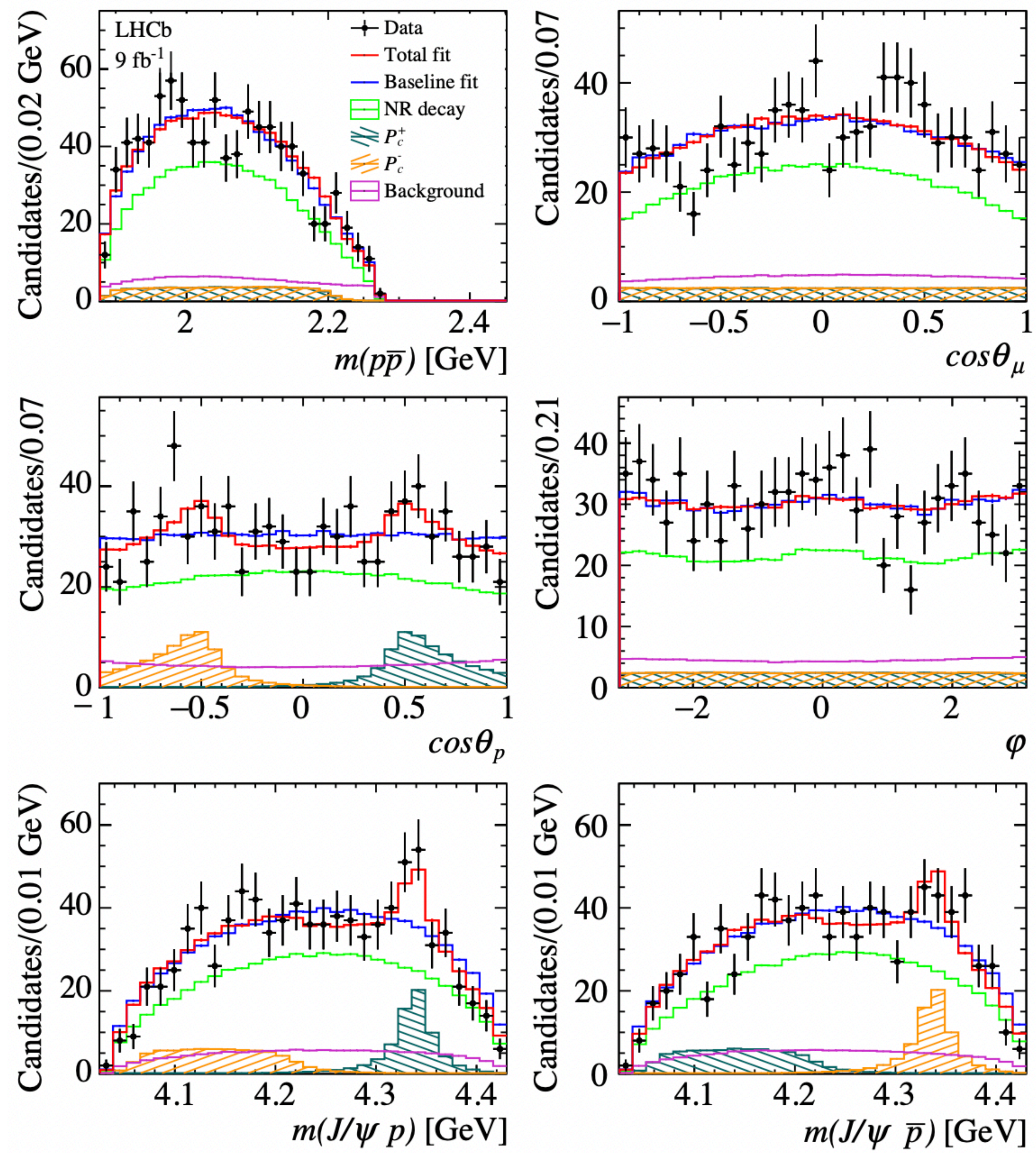
- Two amplitude models

  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



Amplitude fit

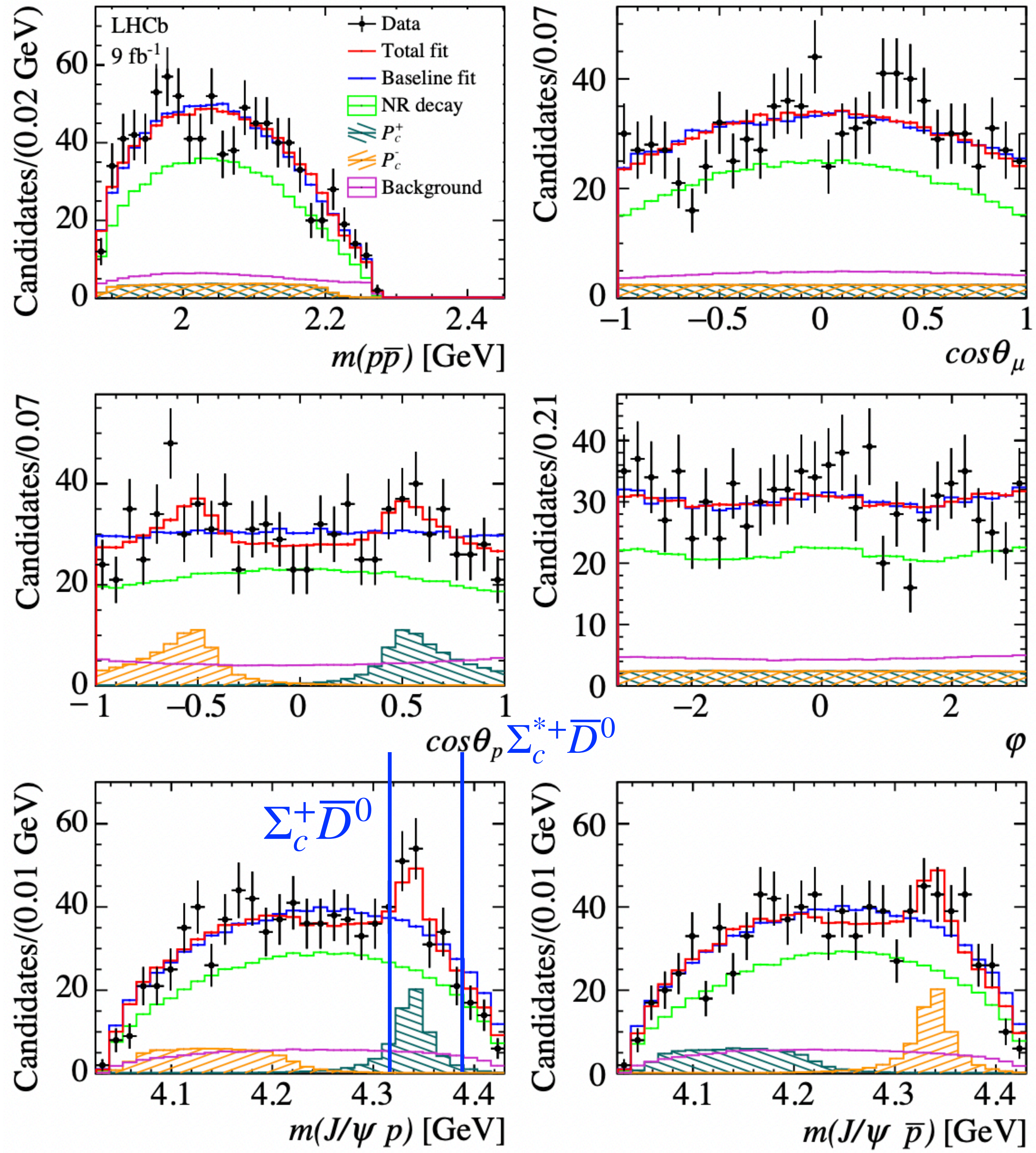
PRL128(2022)062001

- 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 $P_\psi^N(4440)^+$



Summary

- Observation of first neutral pentaquark candidate $P_{\psi s}^{\Lambda}(4338)^0$ with strangeness in $B^- \to J/\psi \Lambda \overline{p}$ decays

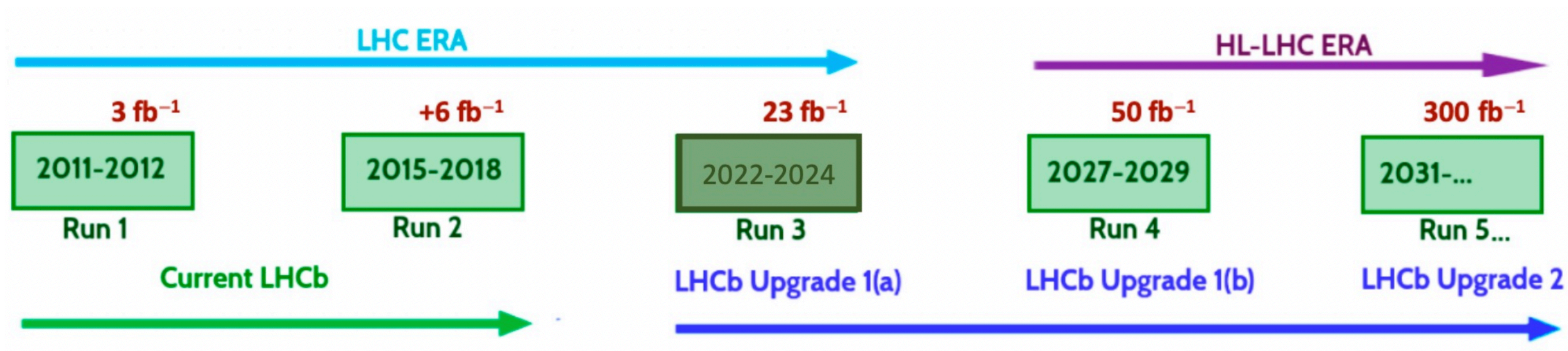
  narrow state close to $\Xi_c^+ D^-$ threshold

  spin 1/2 assigned, negative parity preferred

- Evidence for a charged pentaquark candidate $P_{\psi}^{N}(4337)^+$ in $B_s^0 \to J/\psi p \overline{p}$ 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!

Couplings and lineshapes

- Helicity couplings expressed in LS couplings

$$H^{A\to BC}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C \end{array} \right)$$

- Helicity couplings of Λ decays are fixed according to decay parameters (PDG)

$$H^{\bar{\Lambda}\to\bar{p}\pi^+}_{1/2} = (1,0) \qquad H^{\bar{\Lambda}\to\bar{p}\pi^+}_{-1/2} = \sqrt{\frac{1-\alpha_+}{1+\alpha_+}} e^{-i\phi_+}$$

α_+=-0.758±0.012
ϕ_+=+6.5±3.5°

- Line shape of resonant decay

$$(\frac{p}{p_0})^L B'_L(p, p_0, d) \times (\frac{q}{q_0})^l B'_l(q, q_0, d) \mathrm{BW}(m|m_0, \Gamma_0)$$

$$\mathrm{BW}(m|m_0, \Gamma_0) = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma(m)}$$

$$\Gamma(m) = \Gamma_0 (\frac{q}{q_0})^{2l+1} (\frac{m_0}{m}) B'_l(q, q_0, d)^2.$$

For Non-Resonant (NR), BW replaced by

$$\mathrm{NR} = \begin{cases} 1 & \text{for NR}(\bar{p}\Lambda) \\ c_0 + c_1(m - m_0) + c_2(m - m_0)^2. & \text{for NR}(\bar{p}J/\psi) \end{cases}$$