# Studies of pentaquark states at LHCb

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# Outline

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- Selected LHCb results
  - Observation of $J/\psi p$ resonances in $\Lambda_b^0 \to J/\psi p K^-$ decays
    Phys. Rev. Lett. 115, 072001 (2015)
    Phys. Rev. Lett. 122, 222001 (2019)
  - Evidence for a $J/\psi p$ resonance in $B_s^0 \to J/\psi p \bar{p}$ decays
    Phys. Rev. Lett. 122, 191804 (2019)
    Phys. Rev. Lett. 128, 062001 (2022)
  - Evidence for a $J/\psi \Lambda$ resonance in $\Xi_b^- \to J/\psi \Lambda K^-$ decays
    Science Bulletin 66 (2021) 1278–1287
  - NEW Observation of a $J/\psi \Lambda$ resonance in $B^- \to J/\psi \Lambda \bar{p}$ decays
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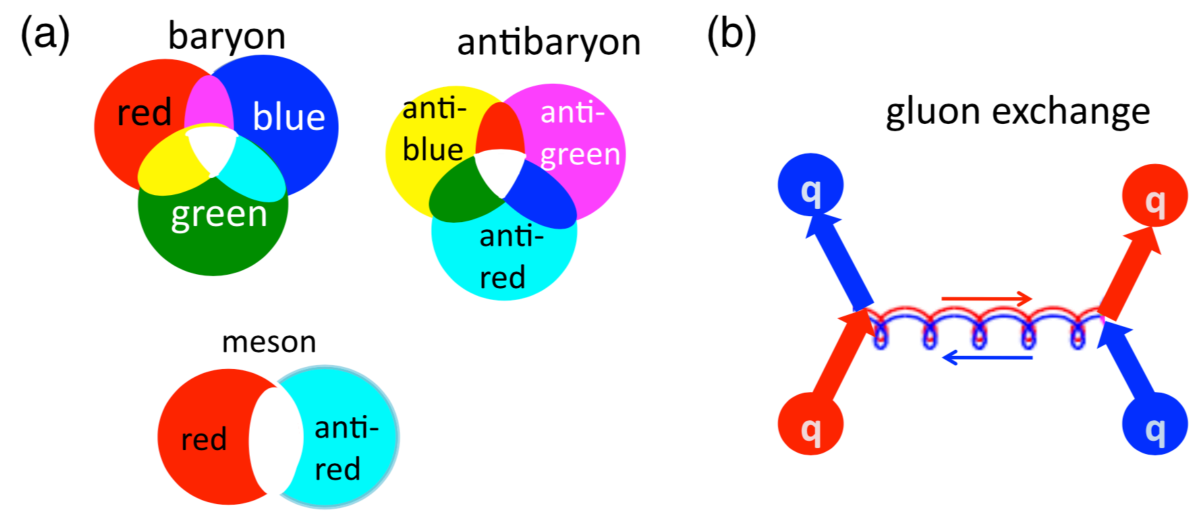
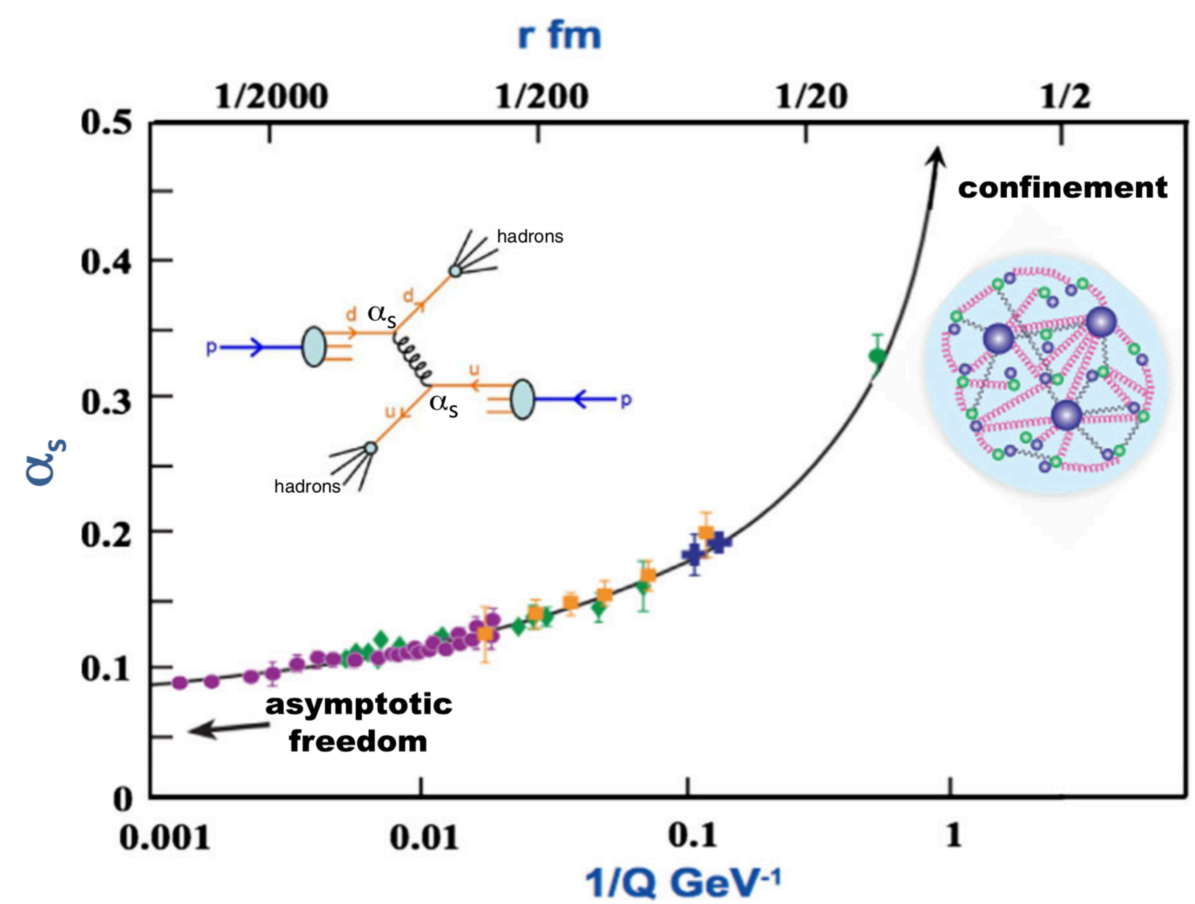
- Summary

# Introduction

- Quantum chromodynamics (QCD) describes interactions of quarks and gluons. Accepted theory of strong interactions
- Quark and gluon composition of observed hadrons in experiments is very complex: "QCD dilemma"
- Understanding QCD (long-distance) is also very important for improving sensitivity in new physics searches, e.g. flavour physics, muon *g-2*

Rev. Mod. Phys. 90, 15003 (2018)



# Pentaquark ("exotic") baryons

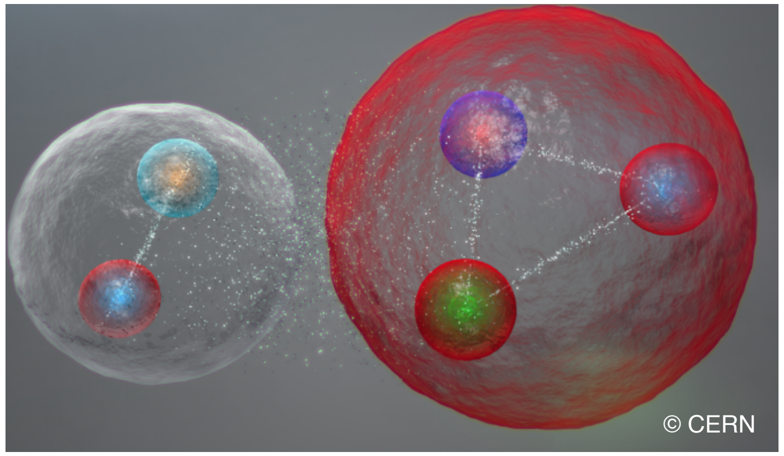
- Pentaquark baryons $(qqqq\bar{q})$ already present in original Gell-Mann, Zweig formulation of quark model (1964)

- Discovery of pentaquark candidates at LHCb in 2015 after 50 years of experimental searches. Renaissance of hadron spectroscopy

- Different models proposed for quark composition and binding mechanisms of pentaquark "exotic" states

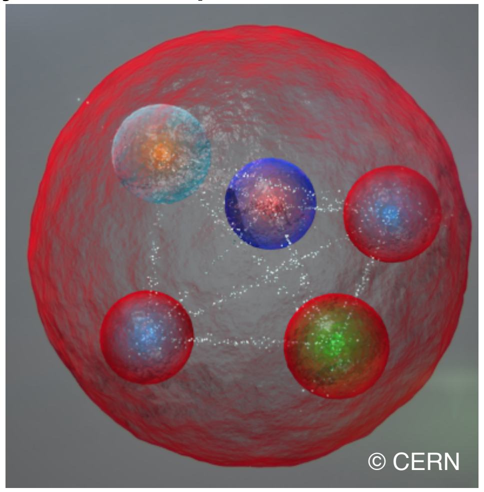
- Precise measurements of mass, width $J^P$ quantum numbers, and identification of isospin multiplets are needed to understand their nature

Molecule model - nuclear forces



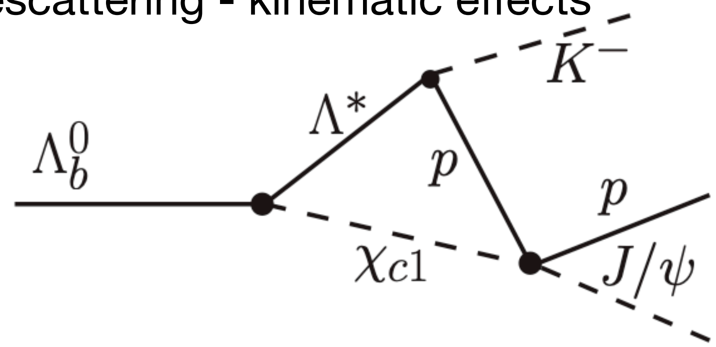

F.-K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004

Tightly bound quarks - color forces




A. Esposito, A Pilloni, A. D. Polosa, Phys. Rept. 668 (2017) 1
J.-M. Richard, Few Body Syst. 57 (2016) 1185

Rescattering - kinematic effects




F. Guo et al., Phys. Rev. D 92, 071502 (2015)

# Selected LHCb results

- Other LHCb results not discussed in this talk

Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ decays Phys. Rev. Lett. 117 (2016) 082003

Model-independent evidence for $J/\psi p$ contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ decays Phys. Rev. Lett. 117 (2016) 082002

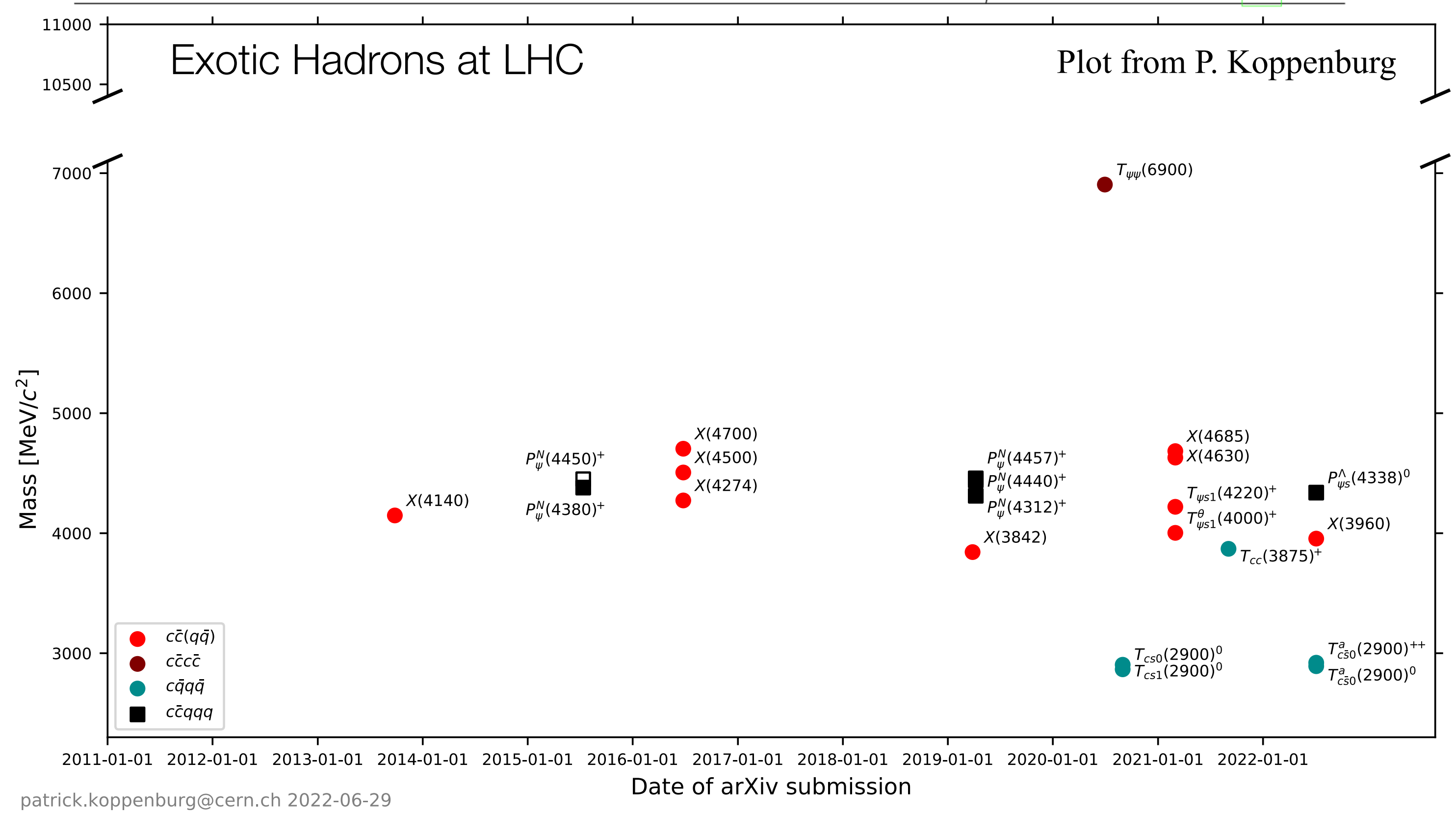
Search for weakly decaying $b$-flavored pentaquarks Phys. Rev. D97 (2018) 032010

# New exotic hadron naming convention

- New scheme for consistent naming convention for new exotic states
- Pentaquarks are labelled as $P$, tetraquarks are labelled as $T$
- For $P$ states
  - superscript indicates isospin (i.e. $\Lambda, N, \Sigma, \Delta$ for $I = 0, 1/2, 1, 3/2$
  - subscripts $\Upsilon, \psi, \phi$ denote hidden beauty, charm, strangeness; $b, c, s$ denote the open flavour quantum numbers
  - Ex: $P_{\psi}^{N}(4312)^{+}$ for $c\bar{c}uud$, $P_{\psi s}^{\Lambda}(4338)^{0}$ for $c\bar{c}uds$

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] |
| $c\bar{c}u\bar{d}$ | $Z_c(3900)^+$ | $I^G = 1^+$, $J^P = 1^+$ | $T_{\psi 1}^{b}(3900)^+$ | [26–28] |
| $c\bar{c}u\bar{d}$ | $X(4100)^+$ | $I^G = 1^-$ | $T_{\psi}(4100)^+$ | [29] |
| $c\bar{c}u\bar{d}$ | $Z_c(4430)^+$ | $I^G = 1^+$, $J^P = 1^+$ | $T_{\psi 1}^{b}(4430)^+$ | [30, 31] |
| $c\bar{c}(s\bar{s})$ | $\chi_{c1}(4140)$ | $I^G = 0^+$, $J^{PC} = 1^{++}$ | $\chi_{c1}(4140)$ | [32–35] |
| $c\bar{c}u\bar{s}$ | $Z_{cs}(4000)^+$ | $I = \frac{1}{2}$, $J^P = 1^+$ | $T_{\psi s1}^{\theta}(4000)^+$ | [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] |
| $b\bar{b}u\bar{d}$ | $Z_b(10610)^+$ | $I^G = 1^+$, $J^P = 1^+$ | $T_{\Upsilon 1}^{b}(10610)^+$ | [36] |
| $c\bar{c}uud$ | $P_c(4312)^+$ | $I = \frac{1}{2}$ | $P_{\psi}^{N}(4312)^+$ | [3] |
| $c\bar{c}uds$ | $P_{cs}(4459)^0$ | $I = 0$ | $P_{\psi s}^{\Lambda}(4459)^0$ | [20] |

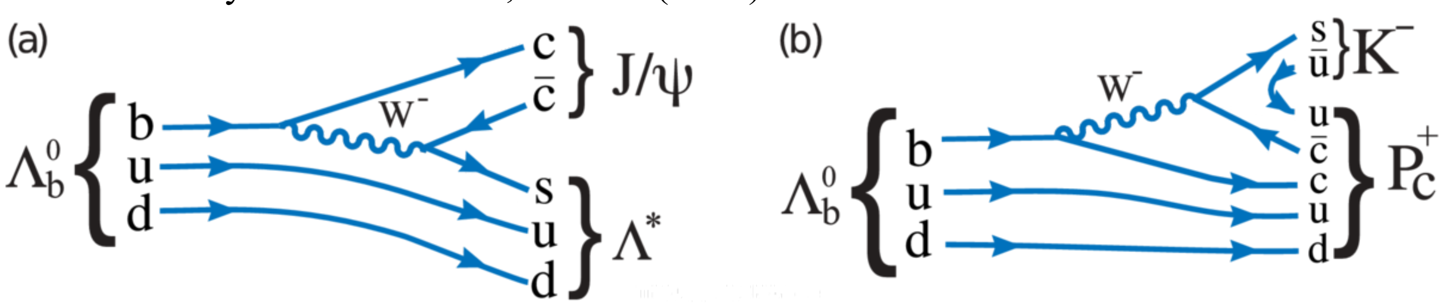


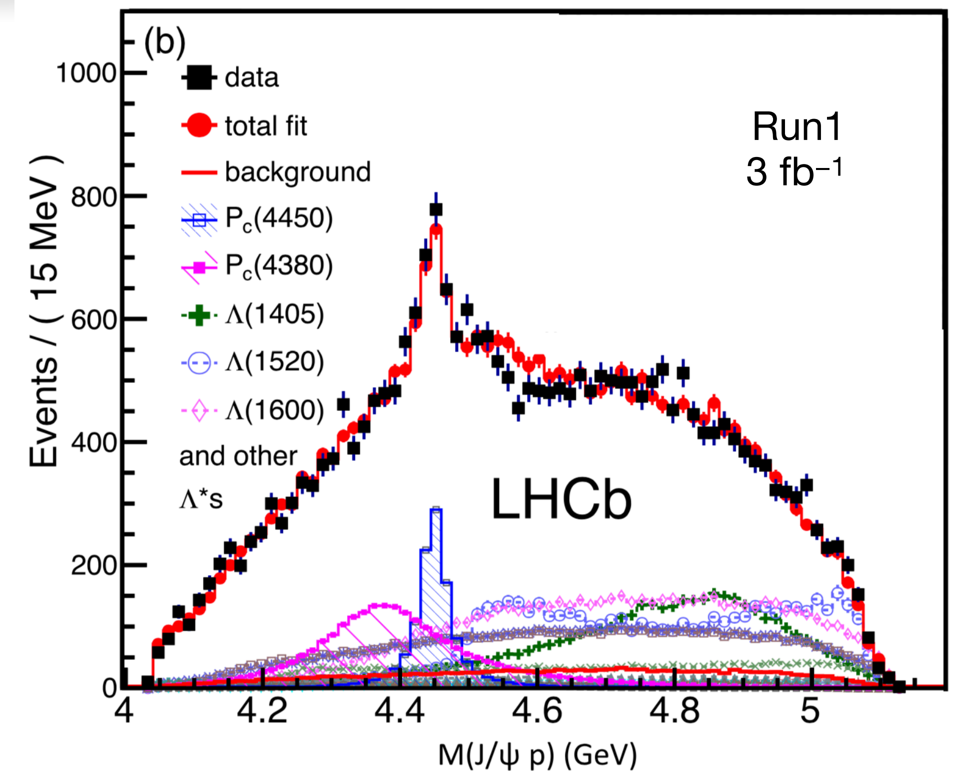
# Discovery of $J/\psi p$ pentaquark candidates at LHCb

- Observation of pentaquark candidates in $J/\psi p$ system in $\Lambda_b^0 \to J/\psi p K^-$ decays
  6D amplitude analysis, 26000 signal yield

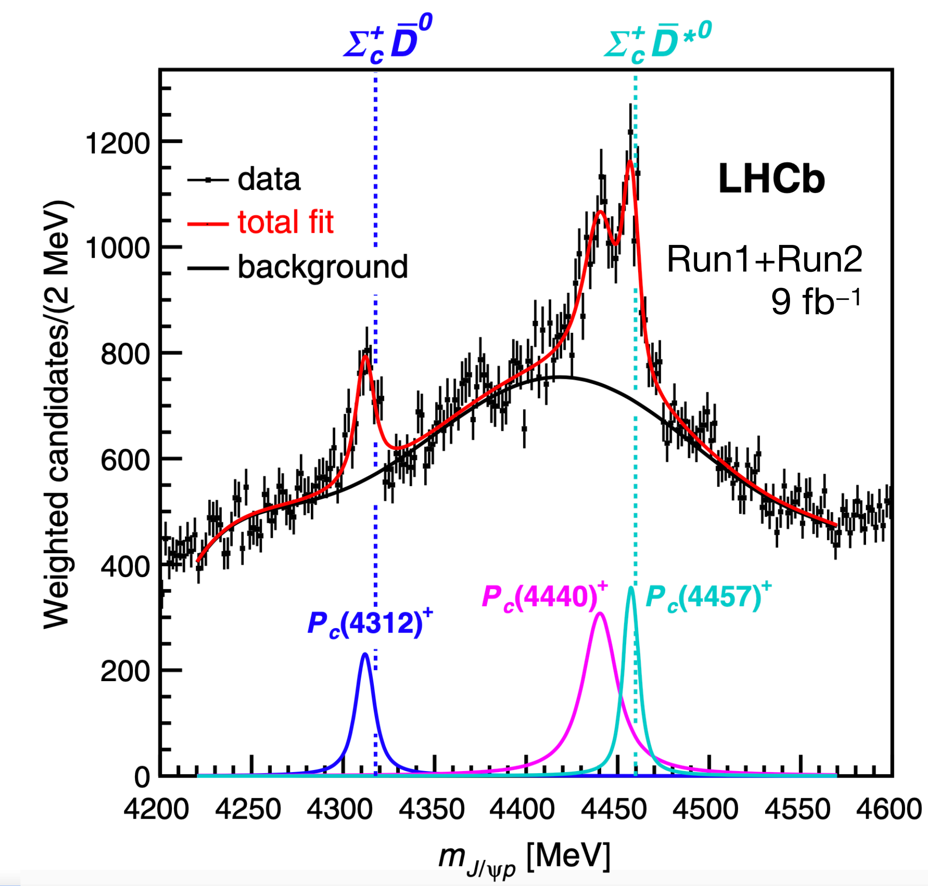
- Pentaquark candidates $P_\psi^N(4380)^+$ and $P_\psi^N(4450)^+$

  Phys. Rev. Lett. 115, 072001 (2015)




- Update of the analysis using Run1+Run2 data
  1D fit, 246000 signal yield  Phys. Rev. Lett. 122, 222001 (2019)
  - found a new state $P_\psi^N(4312)^+$
  - resolved 2 peaks $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$
  - analysis technique not sensitive to broad states such as $P_\psi^N(4380)^+$
  - $J^P$ quantum numbers not measured

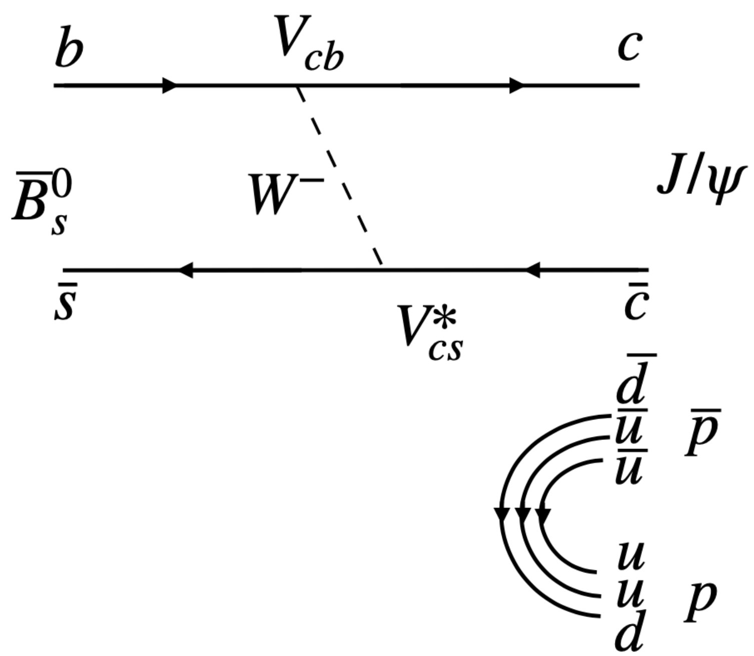


# Evidence for a $J/\psi p$ resonance in $B_s^0 \to J/\psi p\bar{p}$ decays

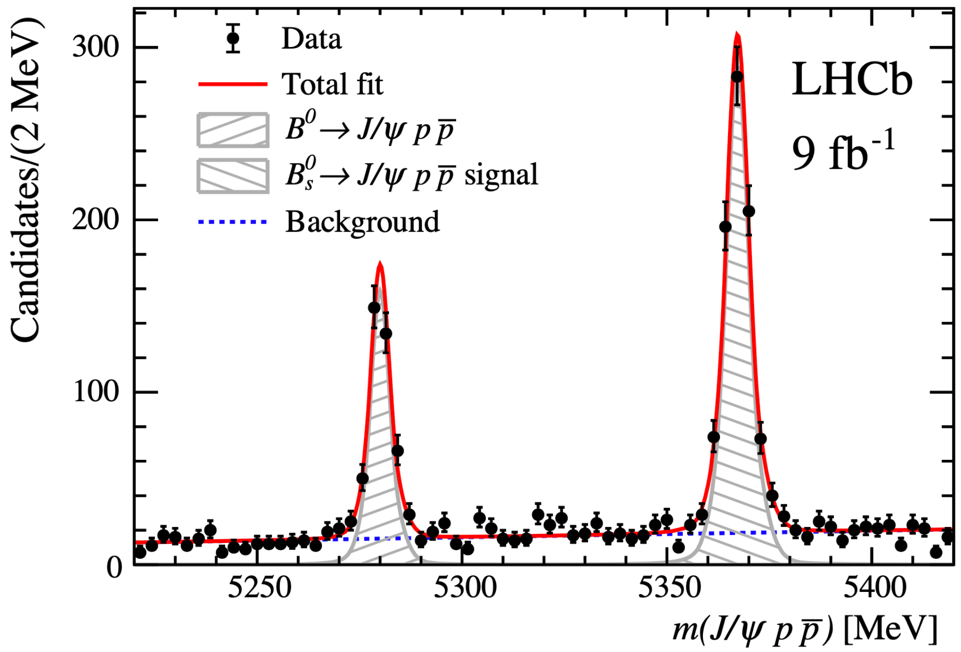
- OZI suppressed decay: 800 signal yield

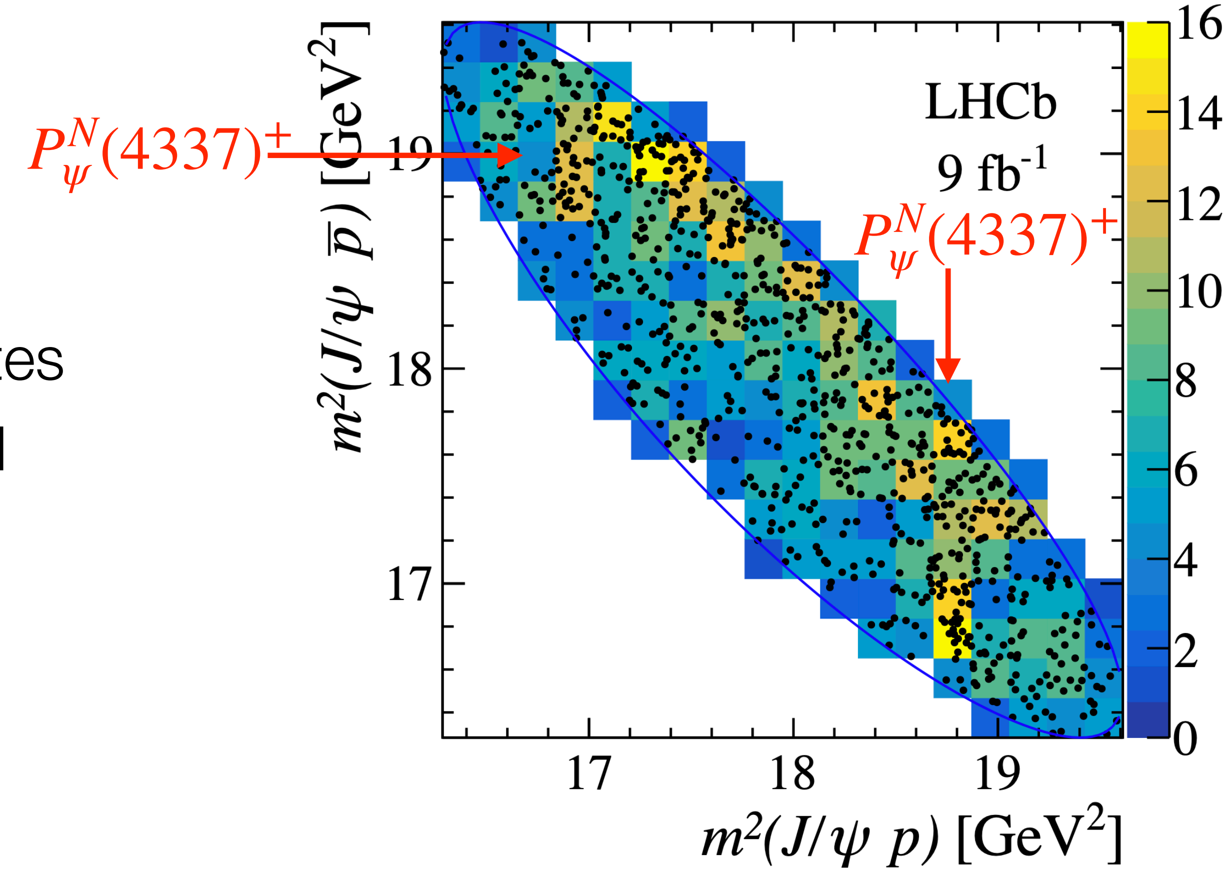
$$\mathcal{B}(B_s^0 \to J/\psi p \bar{p}) = [3.58 \pm 0.19(\text{stat}) \pm 0.39(\text{syst})] \times 10^{-6},$$

Phys. Rev. Lett. 122, 191804 (2019)




Phys. Rev. Lett. 128, 062001 (2022)



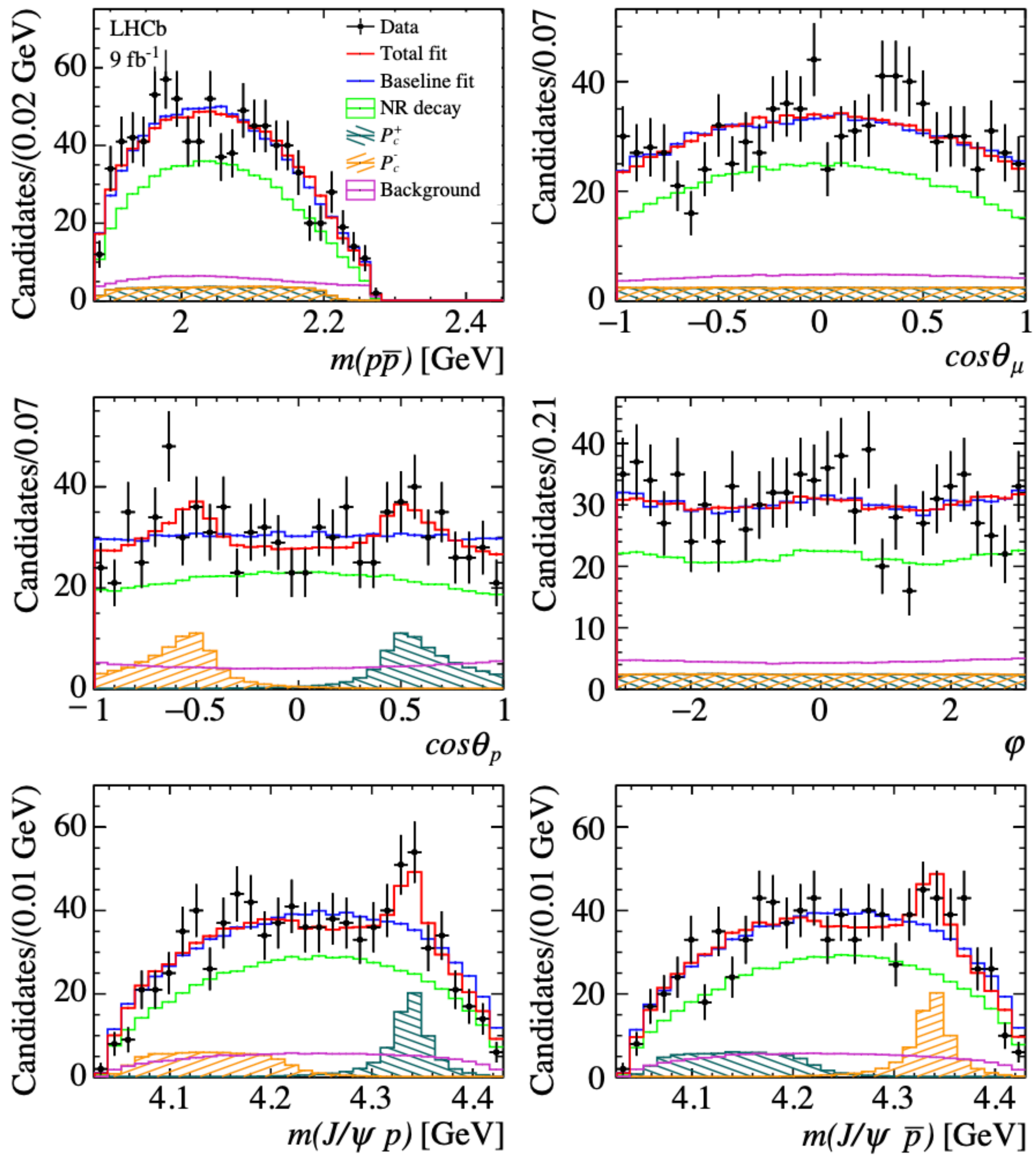

- Sensitive to $J/\psi p$ pentaquark candidates and $f_J(2220) \to p\bar{p}$ process mediated via glueball

- Small $Q$-value $\approx 393$ MeV provides excellent invariant mass resolution

# Evidence for a $J/\psi p$ resonance in $B_s^0 \to J/\psi p\bar{p}$ decays

Phys. Rev. Lett. 128, 062001 (2022)

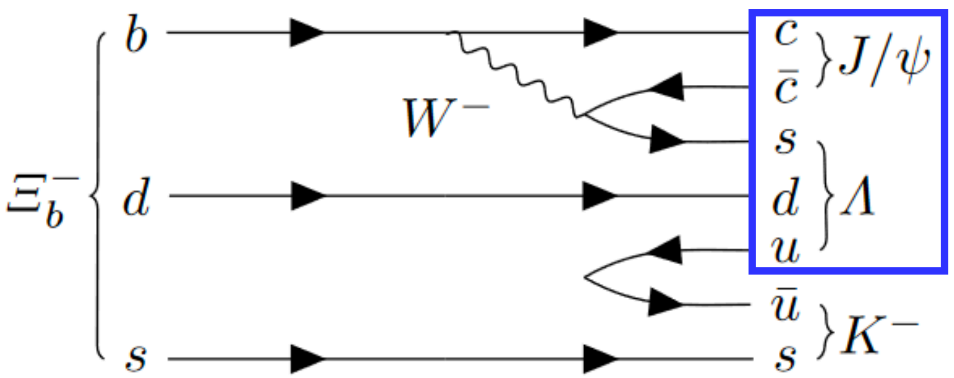
- 4D amplitude analysis of flavour untagged $B_s^0 \to J/\psi p\bar{p}$ decays
- No conventional resonances expected. Clean environment to search for new structures
- No threshold enhancement in $m(p\bar{p})$ spectrum
- Evidence for $P_\psi^N(4337)^+$ at $3.1\sigma$
  $J^P$ not determined
- Breit-Wigner parameters
  $M = 4337^{+7+2}_{-4-2}$ MeV
  $\Gamma = 29^{+12+14}_{-26-14}$ MeV

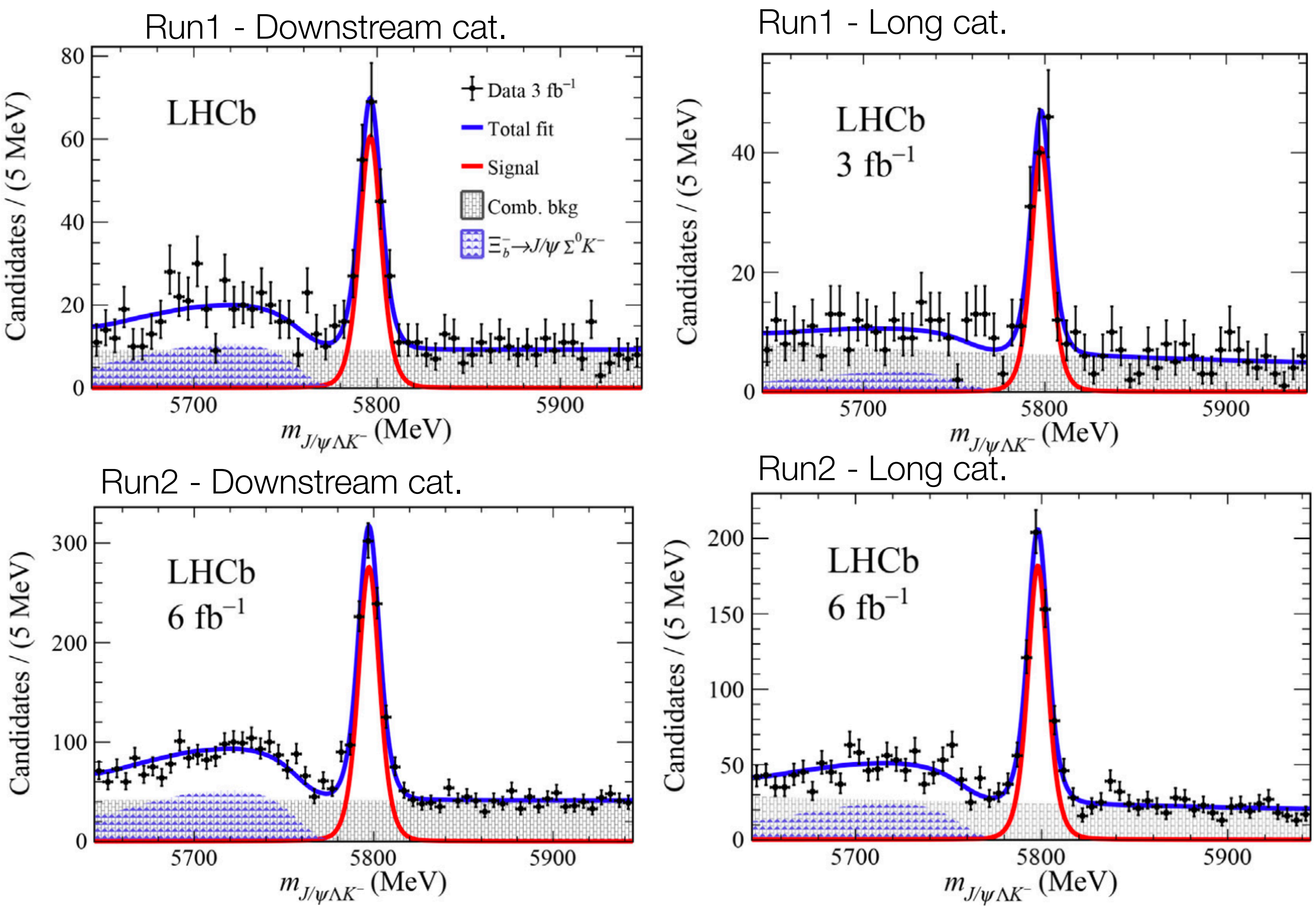


# Evidence for a $J/\psi\Lambda$ resonance in $\Xi_b^- \to J/\psi\Lambda K^-$ decays

Science Bulletin 66 (2021) 1278–1287

- Predicted $J/\psi\Lambda$ strange counterpart of $J/\psi p$ pentaquark candidates



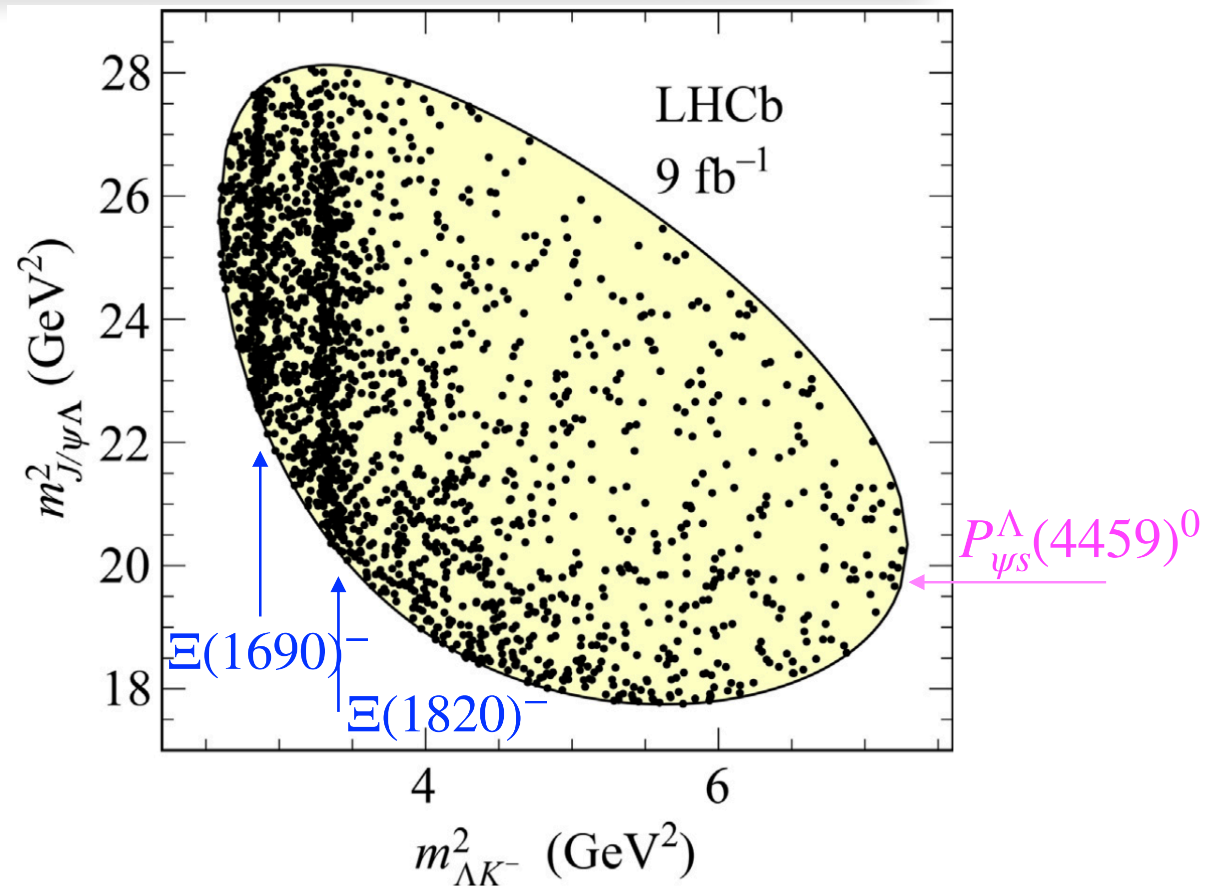



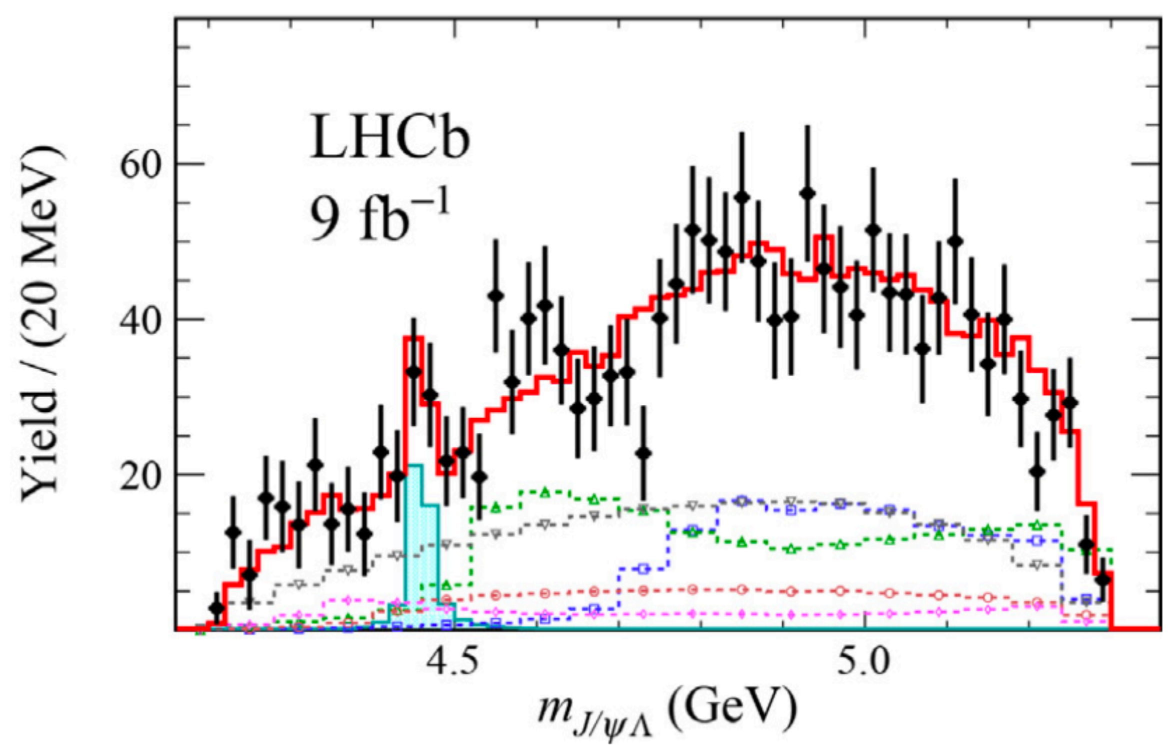

- $\Lambda \to p\pi^-$ decays reconstructed in 2 categories: i) Downstream - decay downstream of the vertex detector; ii) Long - decay inside the vertex detector
- Signal yield about 1750

# Evidence for a $J/\psi\Lambda$ resonance in $\Xi_b^- \to J/\psi\Lambda K^-$ decays

Science Bulletin 66 (2021) 1278–1287

- 6D amplitude analysis of $\Xi_b^- \to J/\psi\Lambda K^-$ decays
- Evidence for $P_{\psi s}^{\Lambda}(4459)^0$ state at $3.1\sigma$ level, $J^P$ not determined
- $M = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV
  $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV
  18 MeV below $\Xi_c^0 \overline{D}^{*0}$ threshold
- Observation of new $\Xi(1690)^-$, $\Xi(1820)^-$ resonant states.
  $J^P = 3/2^-$ for $\Xi(1820)^-$



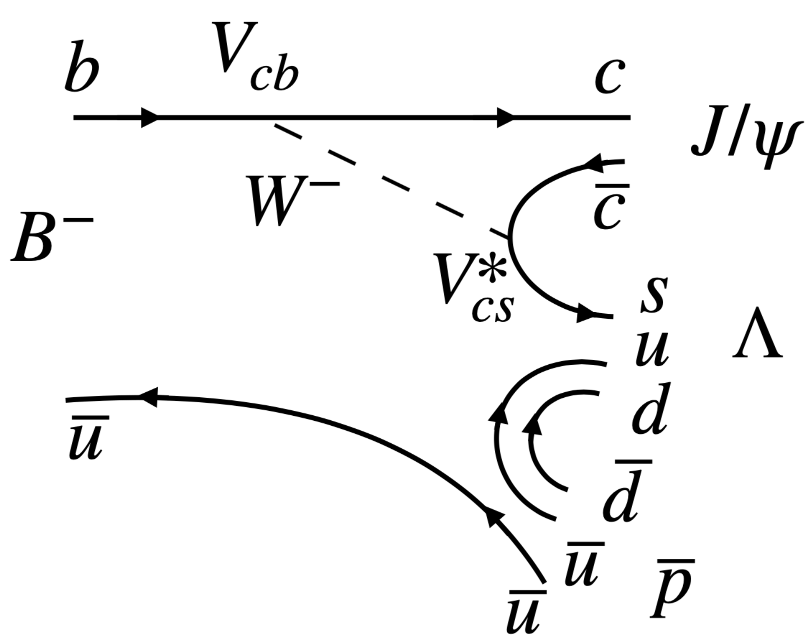
# Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decays

NEW

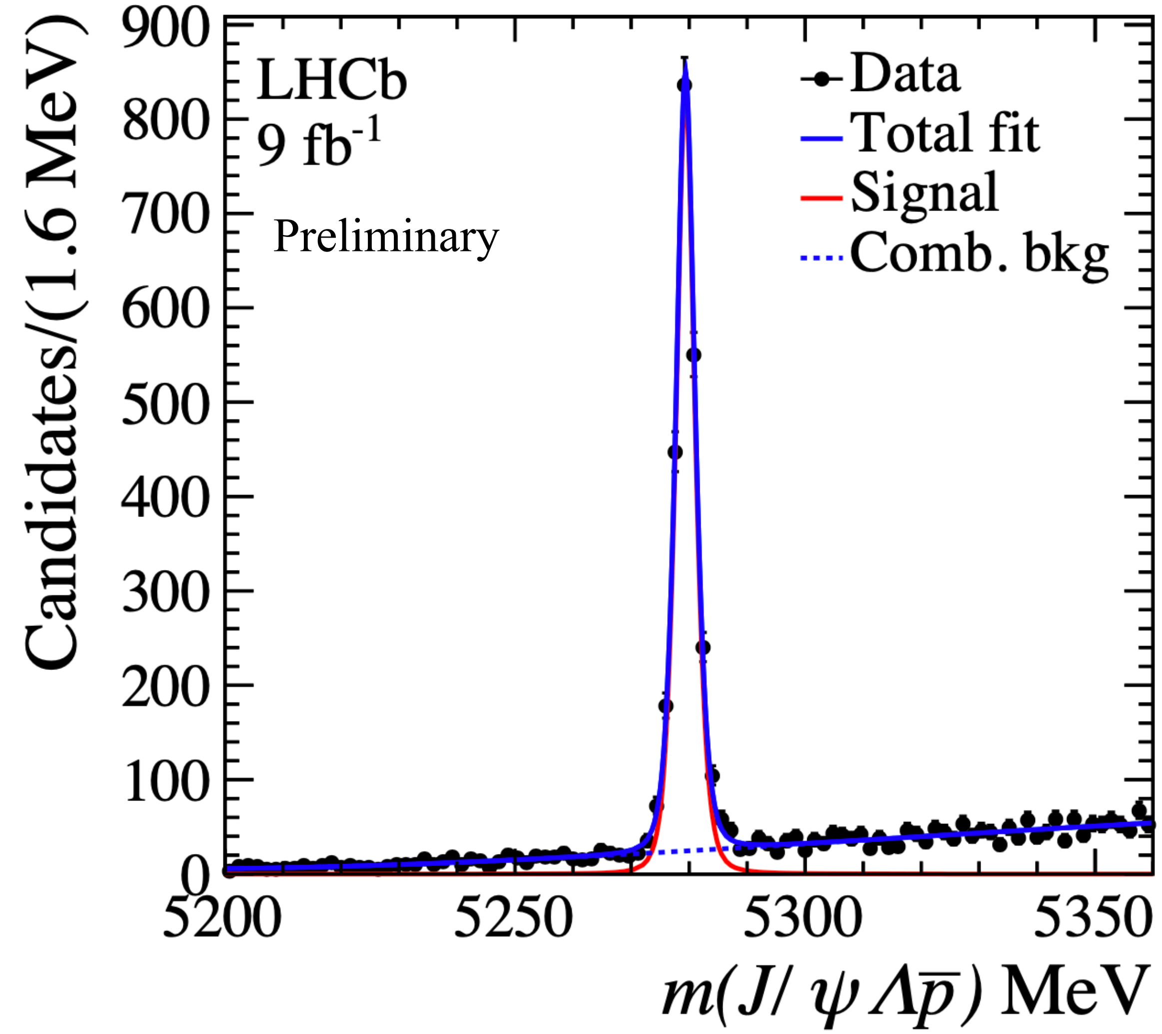
- $B$ decay studied at CMS: inconsistent with pure phase space JHEP12(2019)100

  $BR(B^- \to J/\psi\Lambda\bar{p}) = (1.46 \pm 0.12) \times 10^{-5}$

  PDG 2022




LHCb-PAPER-2022-031 (in preparation)




- Signal yield 4400. High purity 93%. $\Lambda$ as Downstream + Long categories

- Small $Q$-value $\approx 128$ MeV. Resolution on $m(J/\psi\Lambda\bar{p})$, $\sigma \approx 2$ MeV

- Most precise $B^-$ mass measurement

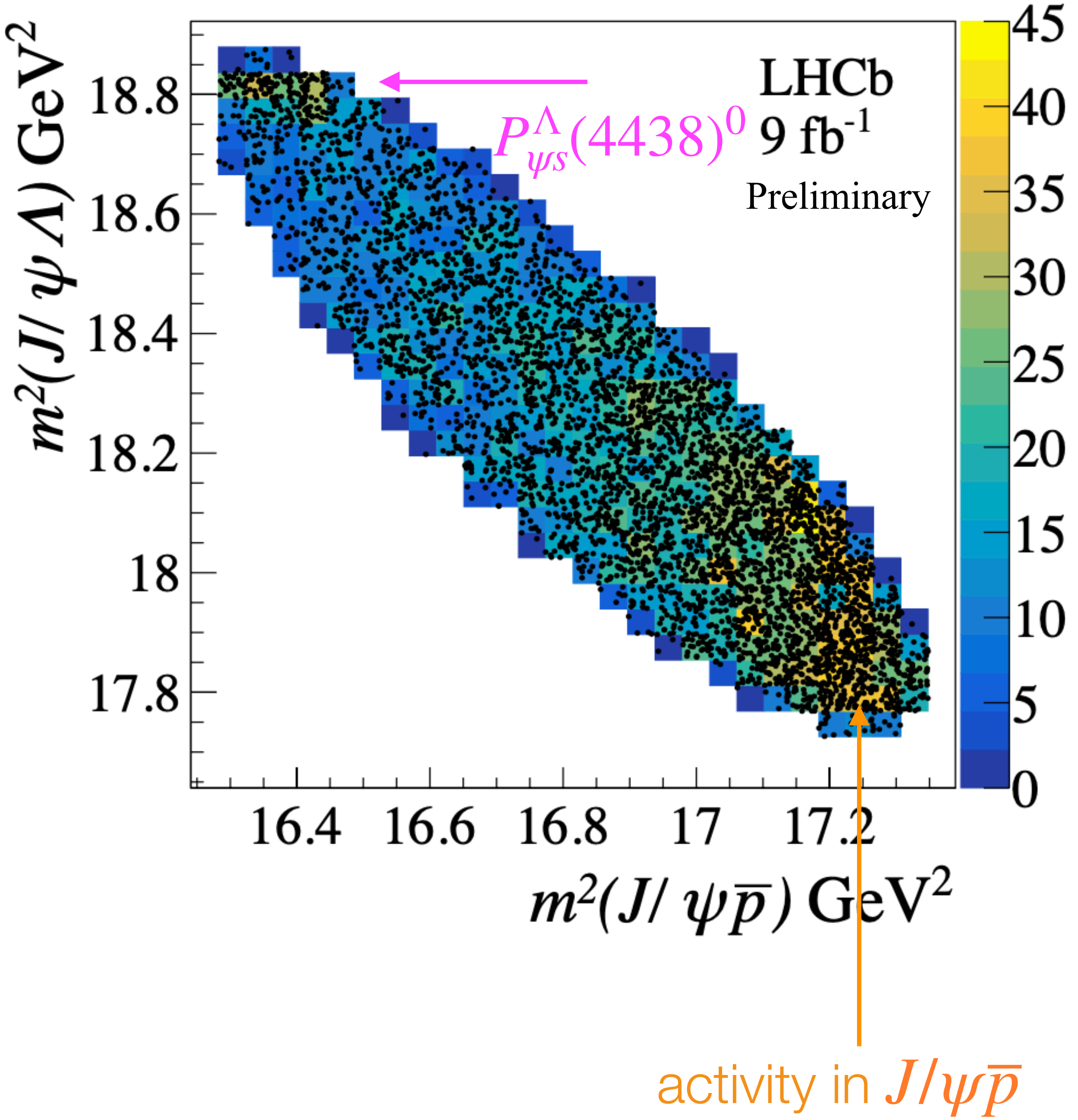
  $m(B^-) = 5279.44 \pm 0.05\ (\text{stat}) \pm 0.07\ (\text{syst})$ MeV

# Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decays

NEW

- $B^- \to J/\psi\Lambda\bar{p}$ decays: excellent laboratory to search for new pentaquark candidates
  - access to $J/\psi\Lambda$, $J/\psi\bar{p}$ systems
  - excellent $m(J/\psi\Lambda)$, $m(J/\psi\bar{p})$ resolution $\approx 0.5 - 1.0$ MeV allows to search for narrow resonances
  - no predicted $\Lambda\bar{p}$ resonances inside phase space

LHCb-PAPER-2022-031 (in preparation)

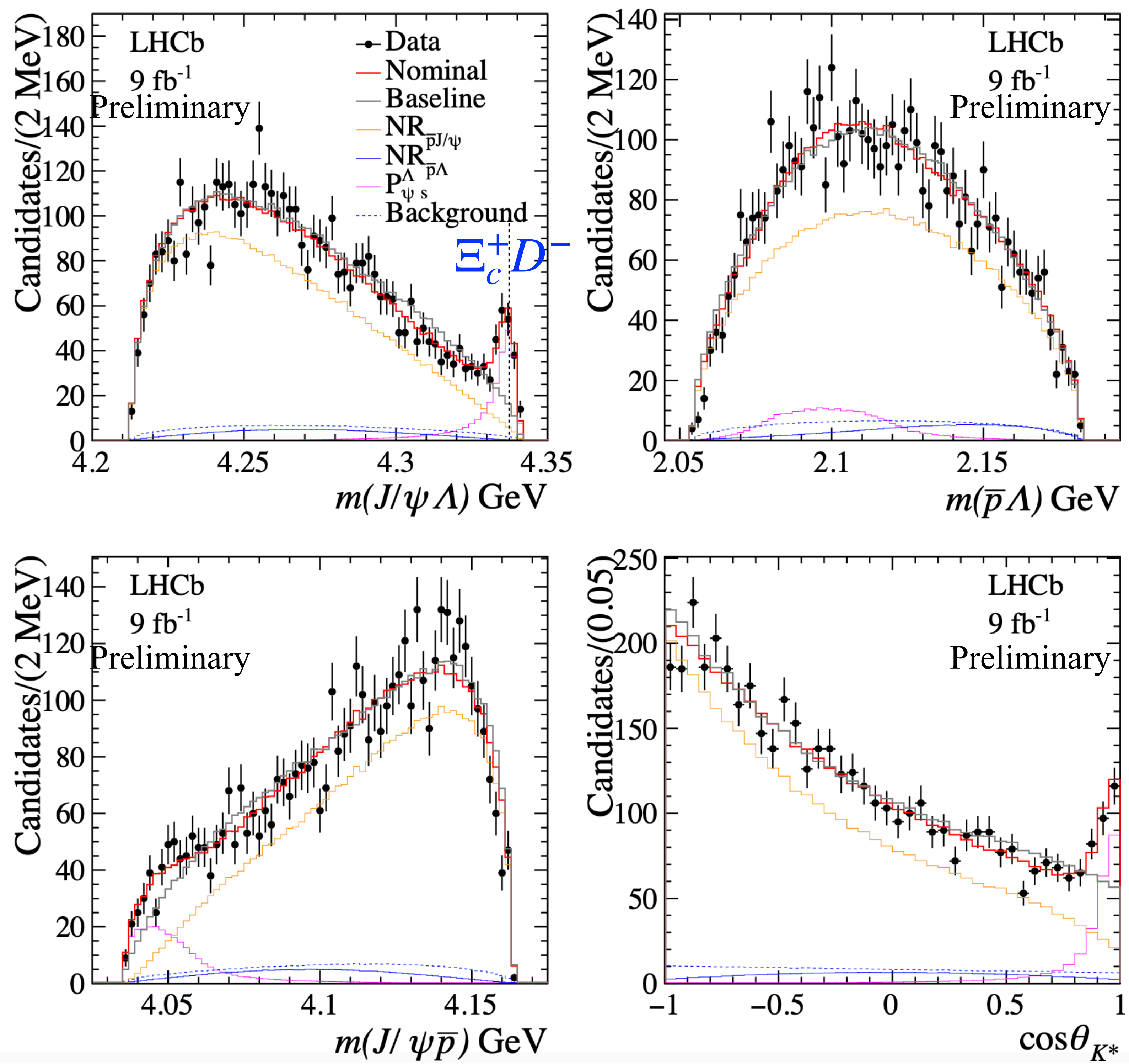


# Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decays

NEW

- 6D amplitude fit:
  $m(\Lambda\bar{p}), \cos\theta_{K^*}, \cos\theta_{\psi}, \phi_{\mu^-}, \cos\theta_{\Lambda}, \phi_p$
  - GoF test: $\chi^2/\mathrm{ndf} = 55.3/39$, $p - \mathrm{value} = 4.4\,\%$
- Amplitude contributions, fit fractions, and results
  - $\mathrm{NR}(J/\psi\bar{p})$ 2nd order polyn.
    $f(\mathrm{NR}(J/\psi\bar{p})) = 84.0 \pm 2.2\,\%$
  - $\mathrm{NR}(\bar{p}\Lambda)$ constant
    $f(\mathrm{NR}(\bar{p}\Lambda)) = 11.3 \pm 1.3\,\%$
  - $P_{\psi s}^{\Lambda}(J/\psi\Lambda)$ Rel. Breit-Wigner
    $f(P_{\psi s}^{\Lambda}) = 12.5 \pm 0.7\,\%$
    $m(P_{\psi s}^{\Lambda}) = 4338.2 \pm 0.7$ MeV
    $\Gamma(P_{\psi s}^{\Lambda}) = 7.0 \pm 1.2$ MeV

LHCb-PAPER-2022-031 (in preparation)



# Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decays

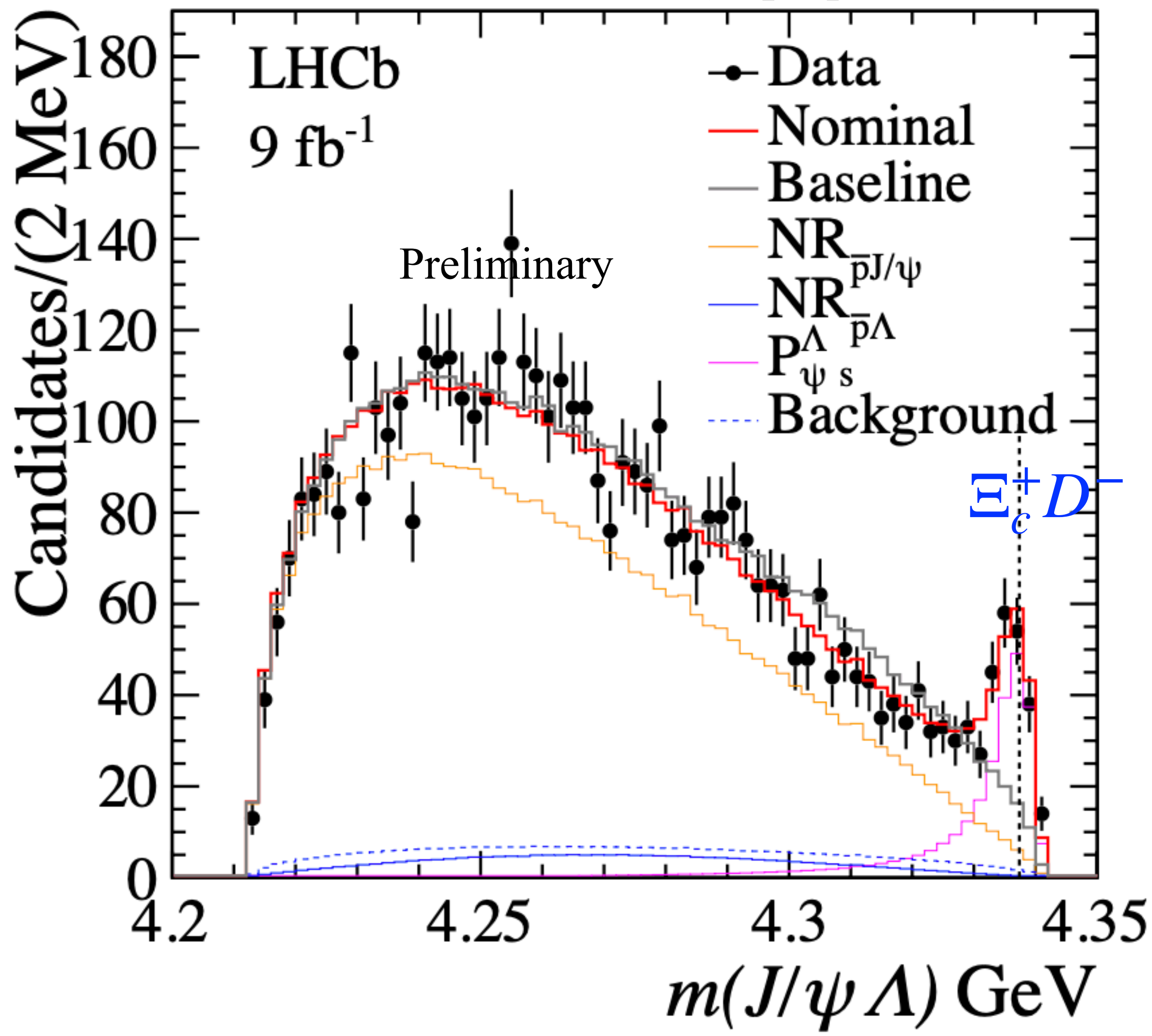
NEW

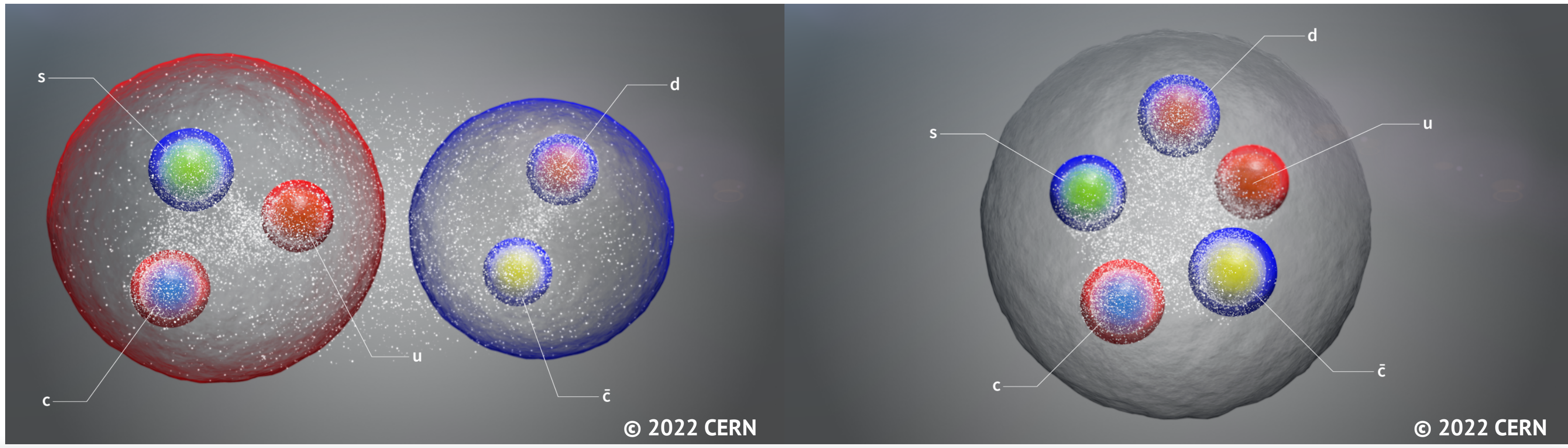
- Observation of $P^{\Lambda}_{\psi s}(J/\psi\Lambda)$ with strange quark content $c\bar{c}uds$ close to $\Xi_c^+ D^-$ threshold ( $> 10\sigma$ significance)
  $m(P^{\Lambda}_{\psi s}) = 4338.2 \pm 0.7 \pm 0.4$ MeV
  $\Gamma(P^{\Lambda}_{\psi s}) = 7.0 \pm 1.2 \pm 1.3$ MeV

- $J = 1/2$ is assigned. $J^P = 1/2^-$ preferred. $J^P = 1/2^+$ excluded at 90% C.L.

- Is it a baryon-meson molecule or a tightly bound five-quark state?

LHCb-PAPER-2022-031 (in preparation)



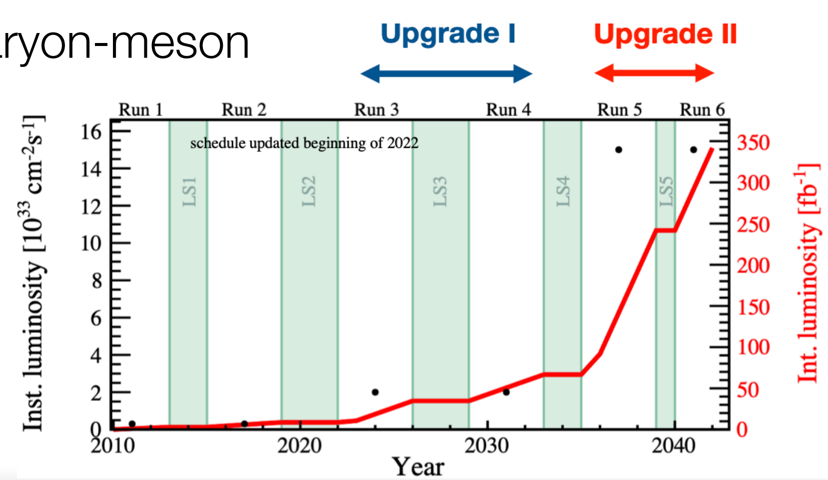
# Summary

- The study of $b$-hadron decays at LHCb continues to provide exciting results for pentaquark candidates. However, no consensus yet on theory models
  - Pentaquark candidates discovery in $\Lambda_b^0 \to J/\psi p K^-$ decays
    - $J/\psi p$ structures with minimal quark content $c\bar{c}uud$ close to $\Sigma_c^+\bar{D}^0, \Sigma_c^+\bar{D}^{*0}$ baryon-meson thresholds. $J^P$ not determined yet. $P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$
  - Evidence for new pentaquark candidates: $P_{\psi s}^\Lambda(4459)^0$ with strangeness in $\Xi_b^- \to J/\psi \Lambda K^-$ decays, $P_\psi^N(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays
  - First pentaquark candidate $P_{\psi s}^\Lambda(4338)^0$ with strangeness observed in $B^- \to J/\psi \Lambda \bar{p}$ decays

NEW

    - $J/\psi\Lambda$ structure with minimal quark content $c\bar{c}uds$ close to $\Xi_c^+ D^-$ baryon-meson thresholds. $J^P = 1/2^-$ spin assigned, $-$ parity preferred

- Exciting times ahead of us: Run3 data and close exchange between theory and experiments will help understanding the nature of exotic pentaquark candidates



# Backup slides

# Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decays

NEW

- Results are robust against cross checks and systematic uncertainties
  - Fit with only $K^{*-}(\to \Lambda\bar{p})$ resonances, $\chi^2/\mathrm{ndf} = 123/33$. Rejected
  - Fit with baseline model (null hypothesis) $\mathrm{NR(J/\psi\bar{p})}$, $\mathrm{NR(\bar{p}\Lambda)}$ only, $\chi^2/\mathrm{ndf} = 121/39$. Rejected. Significance of $P^{\Lambda}_{\psi s}(J/\psi\Lambda) > 10\sigma$ from $2\Delta\log\mathscr{L} = 243,\ \Delta\mathrm{ndf} = 4$ wrt nominal model
  - Fit with resonant $J/\psi\bar{p}$ Breit-Wigner, $2\Delta\log\mathscr{L} = 80$ wrt nominal model. Disfavoured
  - Spin-parity $J = 1/2$ is assigned. $J^P = 1/2^-$ for $P^{\Lambda}_{\psi s}(J/\psi\Lambda)$ is preferred. $J^P = 1/2^+$ excluded at 90% C.L. using the $\mathrm{CL}_s$ method.
  - Fit with $m(P^{\Lambda}_{\psi s})$ allowed to go outside of phase space. Consistent results
  - Main syst. uncertainties: $J^P$ assignment, model with additional $LS$ couplings

# CMS results

JHEP12(2019)100

Invariant mass resolution:
-CMS: m(pπ)~3.7 MeV,
-LHCb: m(B)~2 MeV, $m(J/\psi\Lambda) = 0.5 - 1.0$ MeV

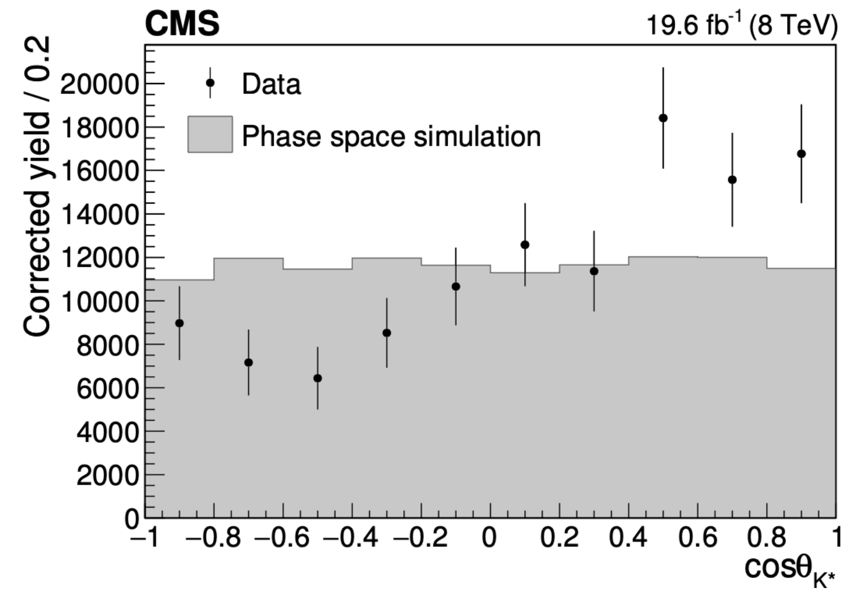
Statistics: 10x larger yield LHCb analysis, 4400 vs 450

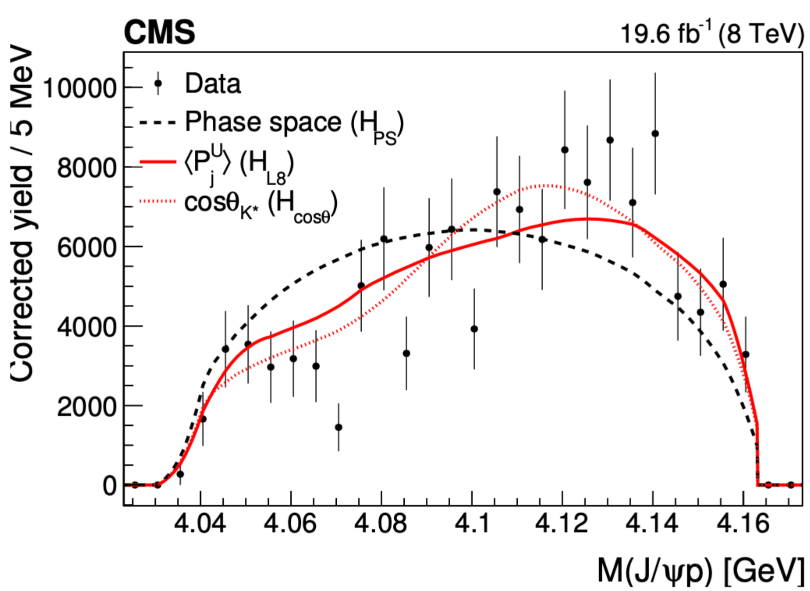
Trigger and selection cuts, in particular on $p_T$:
-CMS: $p_T(J/\psi)$>7 GeV, $p_T(\Lambda)$>1 GeV, $p_T(p)$>1 GeV
-LHCb: $p_T(\mu)$ > 500 MeV, no $p_T$ cut on Λ and p

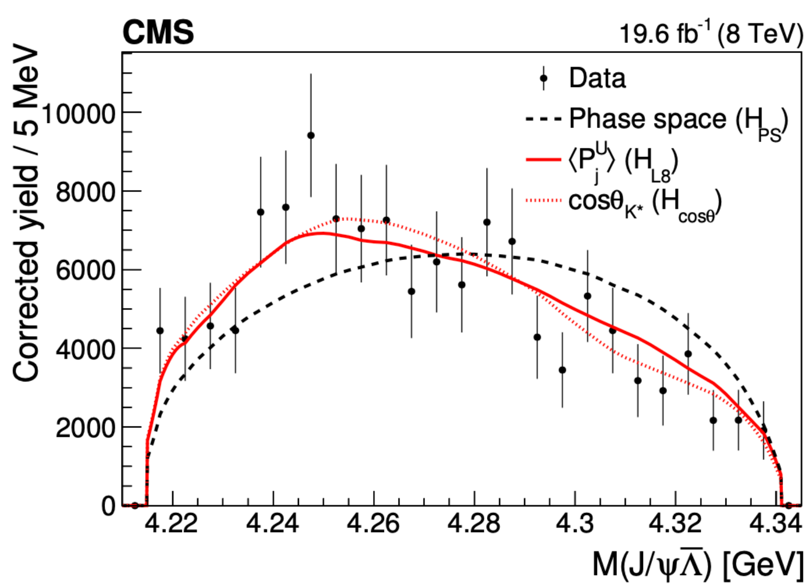
| Resonance | Mass (MeV) | Natural width (MeV) | $J^P$ |
|---|---|---|---|
| $K_4^*(2045)^+$ | $2045 \pm 9$ | $198 \pm 30$ | $4^+$ |
| $K_2^*(2250)^+$ | $2247 \pm 17$ | $180 \pm 30$ | $2^-$ |
| $K_3^*(2320)^+$ | $2324 \pm 24$ | $150 \pm 30$ | $3^+$ |

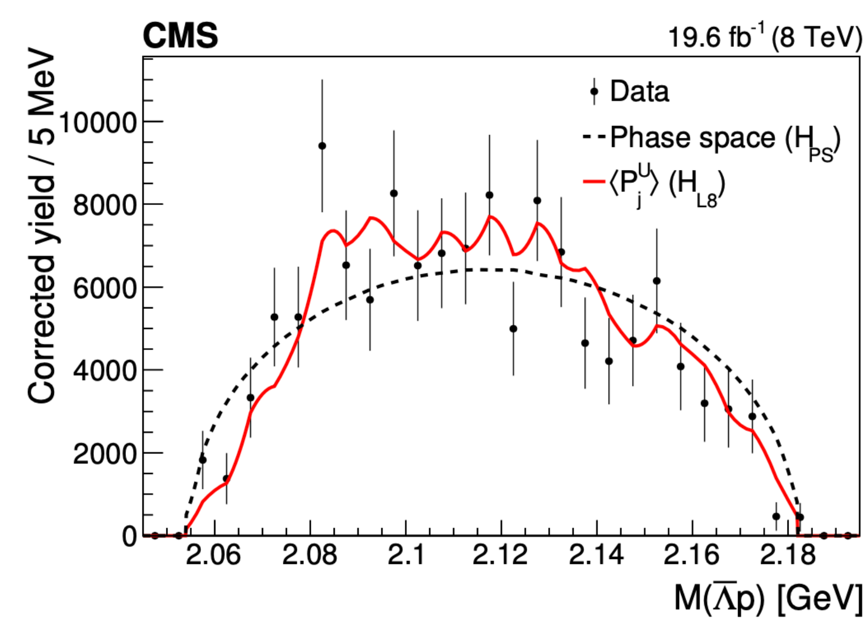
Spectra are not compatible with pure phase space distributions. Efficiency corrected plot in $m(\overline{\Lambda}p), \cos\theta_{K^*}$

Considered possible contributions of known K*+ resonances to improve the agreement

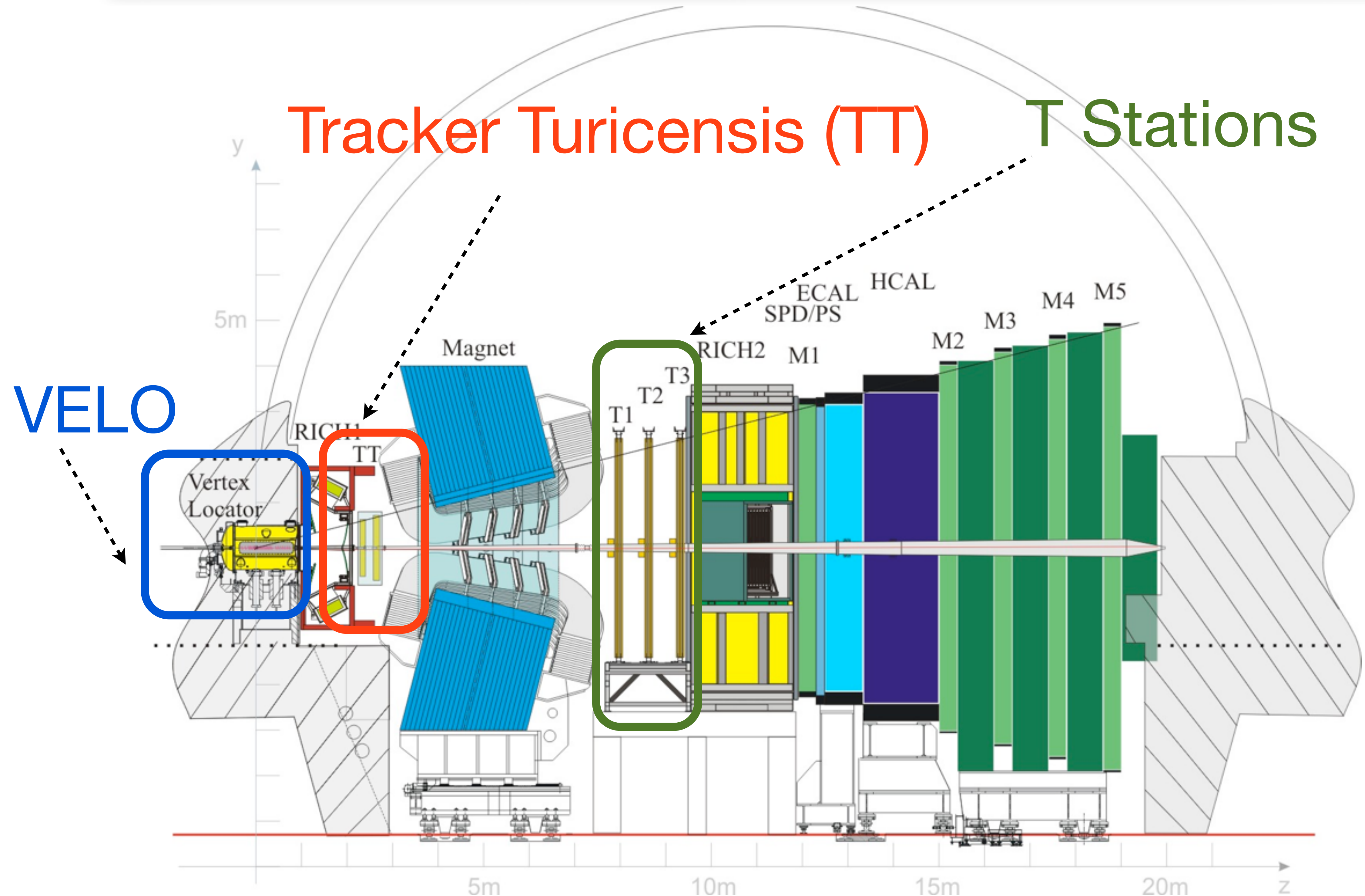


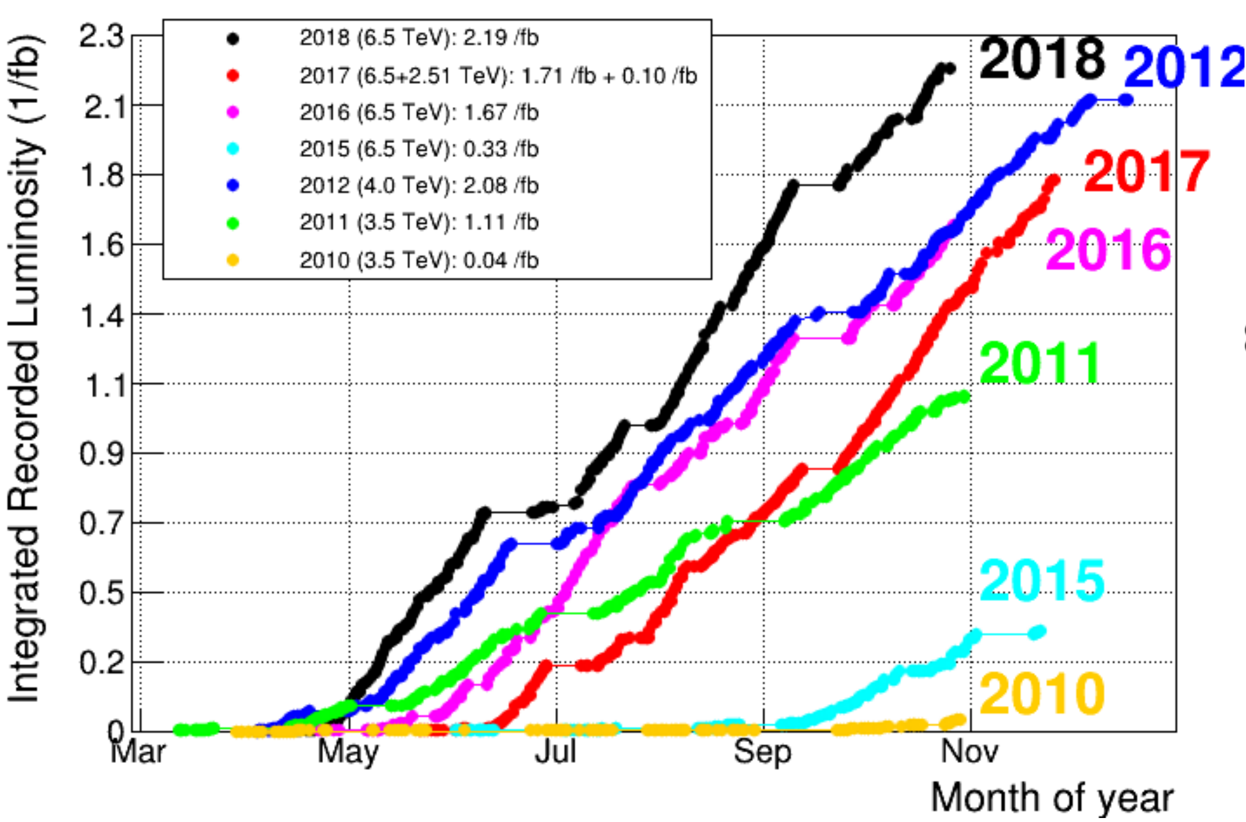



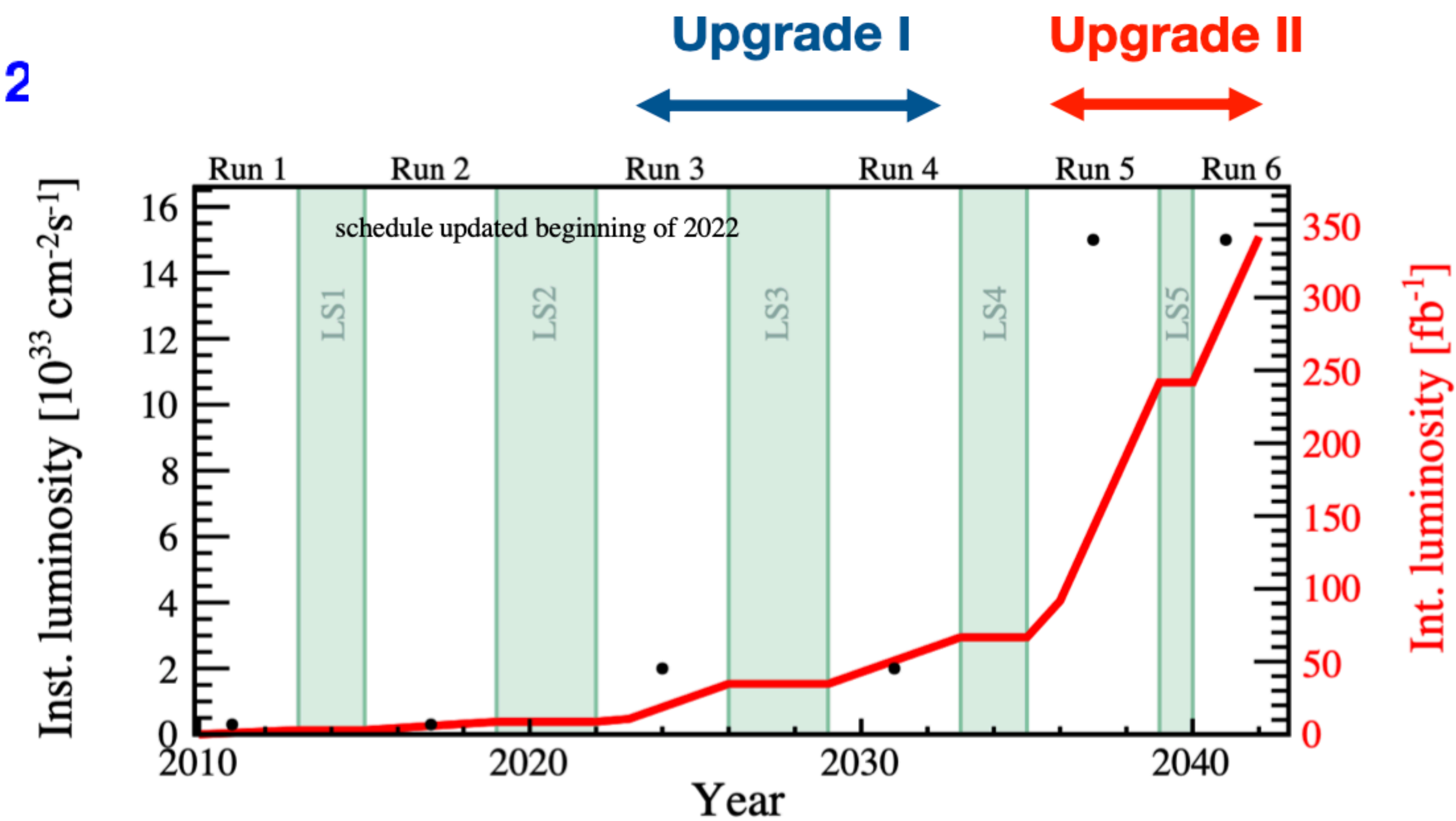



# LHCb detector at CERN



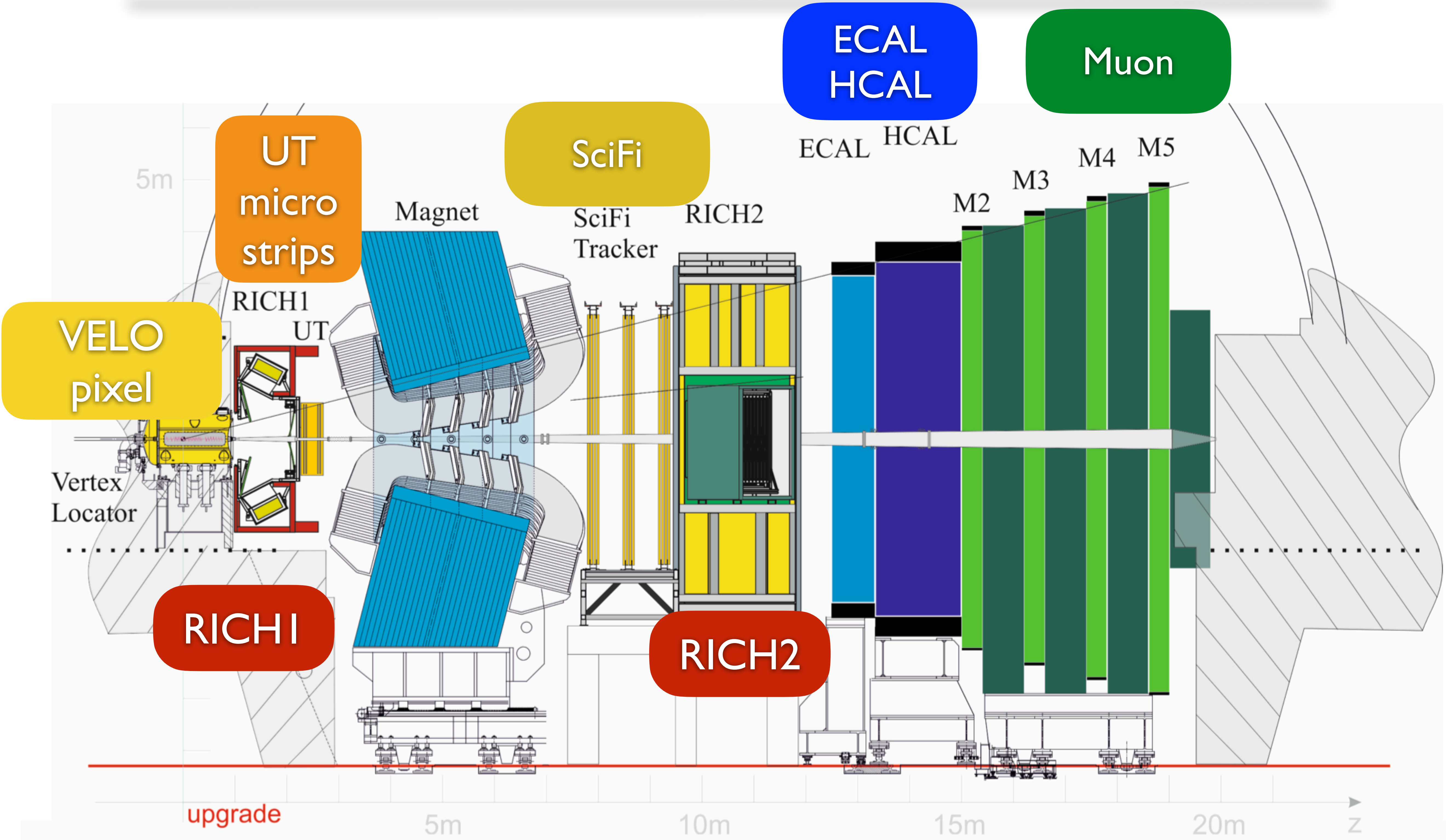
# LHCb data sample and plans




- Collected >9 fb$^{-1}$ in 2010-2018. Major detector upgrade during LS2 (Upgrade I). Aim at 50 fb$^{-1}$ before 2033
- Major detector upgrade during LS4 (Upgrade II - 2033). Aim at >300 fb$^{-1}$ after 2035 - ….

# LHCb Upgrade detector




- Major detector upgrade during Long Shutdown 2 (LS2)