HADRON 2023

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Studies of pentaquark states with strangeness at LHCb

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On behalf of the LHCb Collaboration

Outline

- Hadron spectroscopy at LHCb and the LHCb detector
- History of pentaquark studies at LHCb
- Possible theoretical interpretations for pentaquark
- Studies of pentaquark states with strangeness at LHCb:

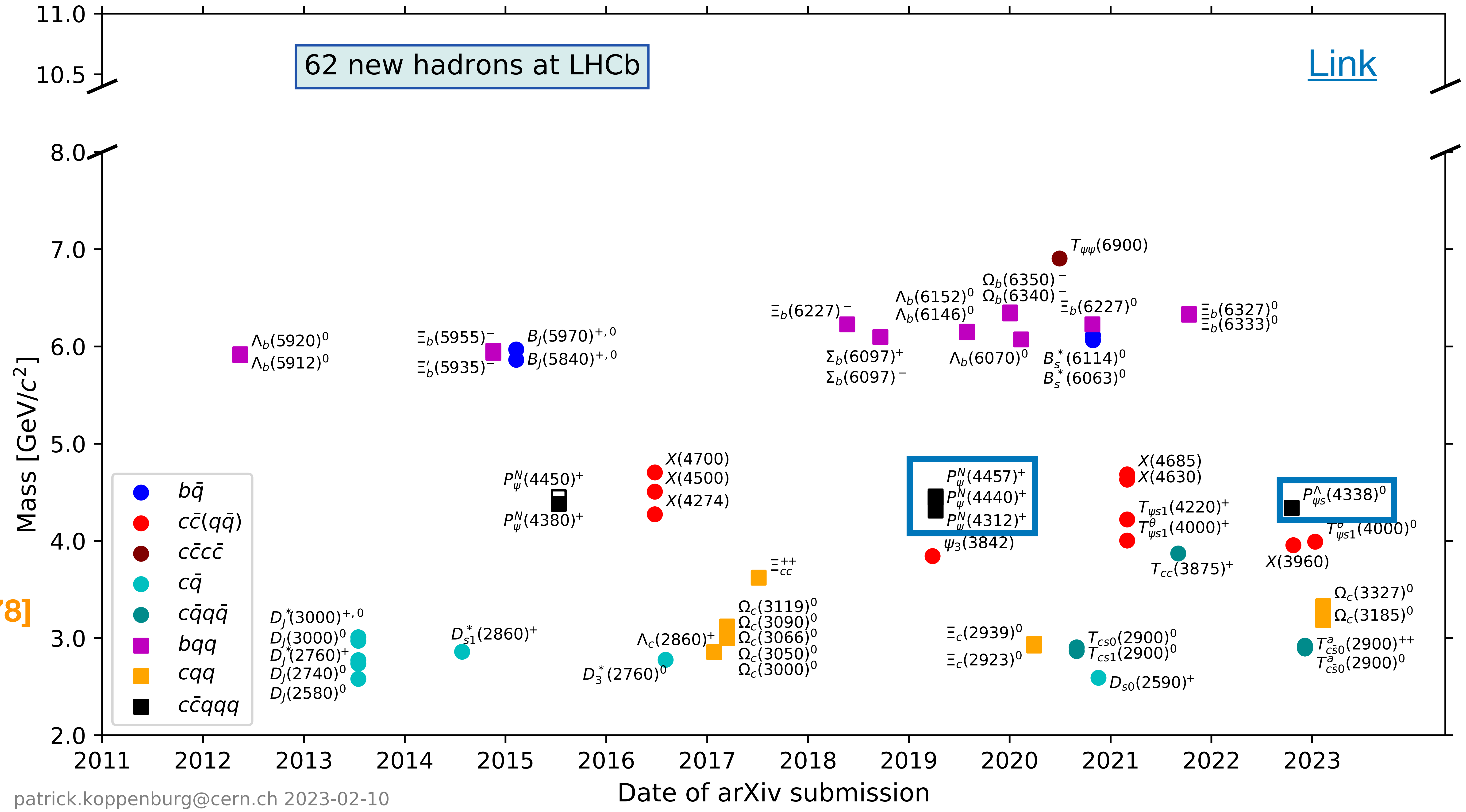
Other exotics@LHCb see Elisabetta's talk

  - Observation of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay [PLB 772 (2017) 265]
  - First evidence of $P_{\psi s}^{\Lambda}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays [Sci. Bull. 66 (2021) 1278]
  - First observation of $P_{\psi s}^{\Lambda}(4338)^0$ in $B^- \to J/\psi \Lambda \bar{p}$ decays [arXiv: 2210.10346] Submitted to PRL
- Prospects and summary

Hadron spectroscopy at LHCb

- So far 70 hadrons have been discovered at the LHC, of which 62 by LHCb

- Observations of 4 pentaquark candidates
  [PRL 122 (2019) 222001, arXiv: 2210.10346]
- Evidences of 2 pentaquark candidates, $P_{\psi}^{N}(4337)^{+}$, $P_{\psi s}^{\Lambda}(4459)^{0}$, need further confirmation
  [PRL 128 (2022) 062001, Sci. Bull. 66 (2021) 1278]
- New naming scheme: [arXiv:2206.15233]

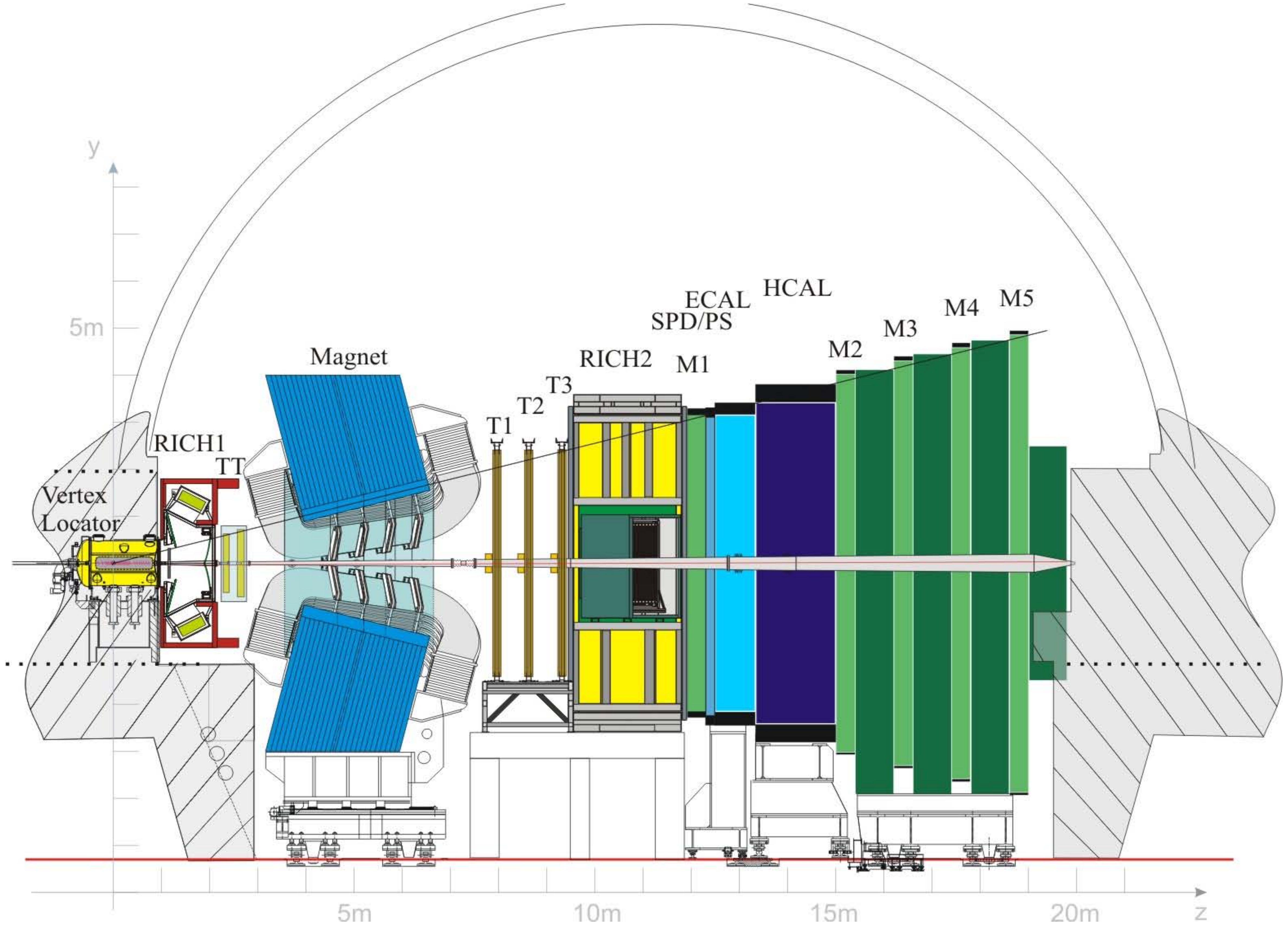


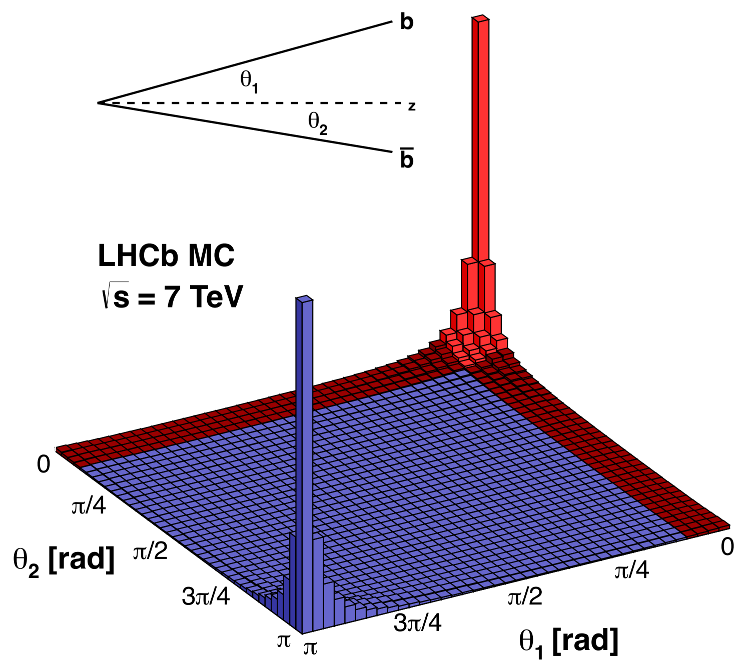
The LHCb detector

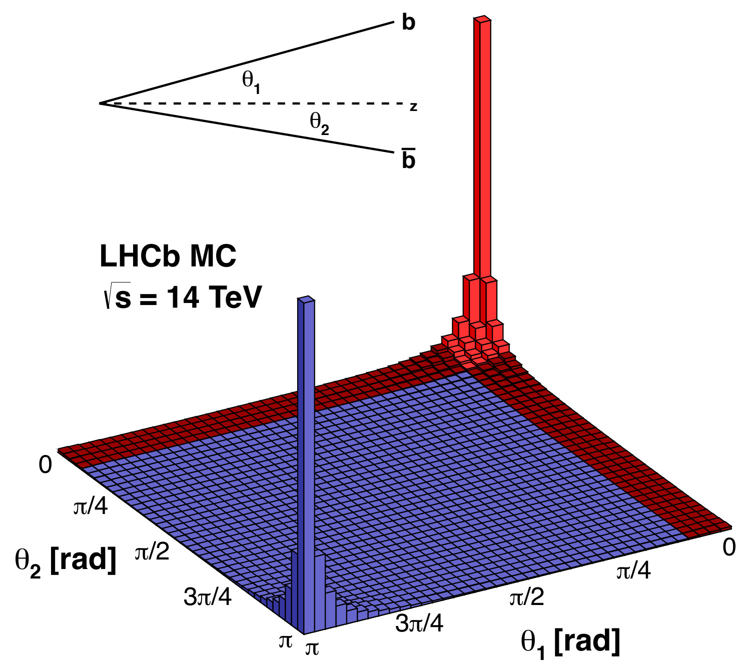
Int. J. Mod. Phys. A 30(2015)153002
JINST 3(2008)S08005

A single-arm forward spectrometer, designed for the study of heavy flavour physics

- Excellent vertex, IP and decay-time resolution
  $\sigma(IP) \approx$ **20** μm **for high-**p_T **tracks**
  $\sigma(\tau) \approx$ **45** fs **for** $B_s^0 \rightarrow J/\psi\phi$ **and** $B_s^0 \rightarrow D_s^- \pi^+$ **decays**
- Very good momentum resolution
  $\delta p/p \approx$ **0.5%-1% for** $p \in$ **(0,200) GeV**
  $\sigma(m_B) \approx$ **24 MeV for two-body B decays**
- Good hadron and muon identification
  $\epsilon_{K\rightarrow K} \approx$ **95% for** $\epsilon_{\pi\rightarrow K} \approx$ **5% up to 100 GeV**
  $\epsilon_{\mu\rightarrow\mu} \approx$ **97% for** $\epsilon_{\pi\rightarrow\mu} \approx$ **1%-3%**







$2 < \eta < 5$ range (LHCb acceptance):

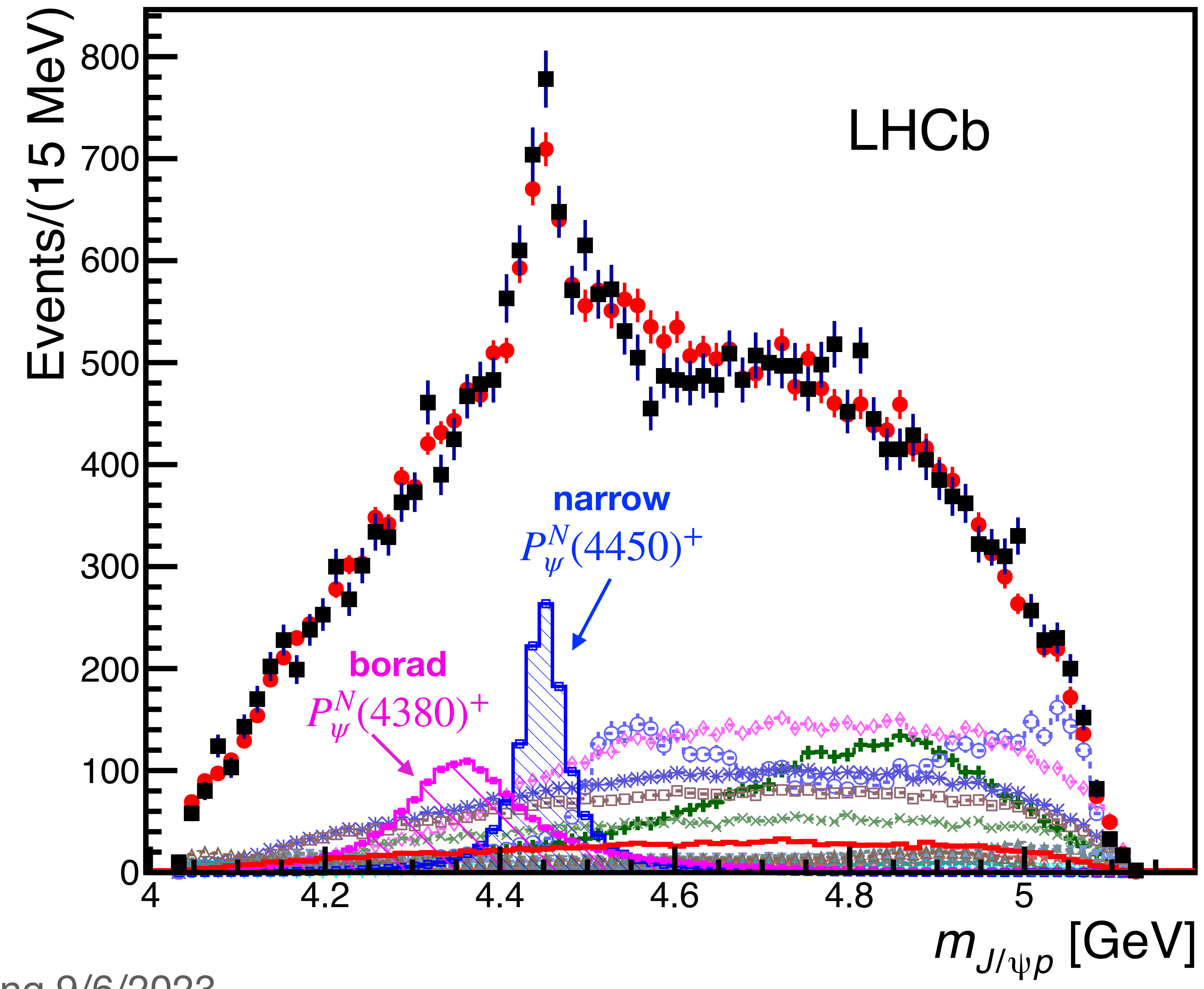
~$3 \times 10^4/s$ $b\bar{b}$ pairs@ 7 TeV ~x2 yield@ 13 TeV

Observation of pentaquark in $\Lambda_b^0 \to J/\psi p K^-$

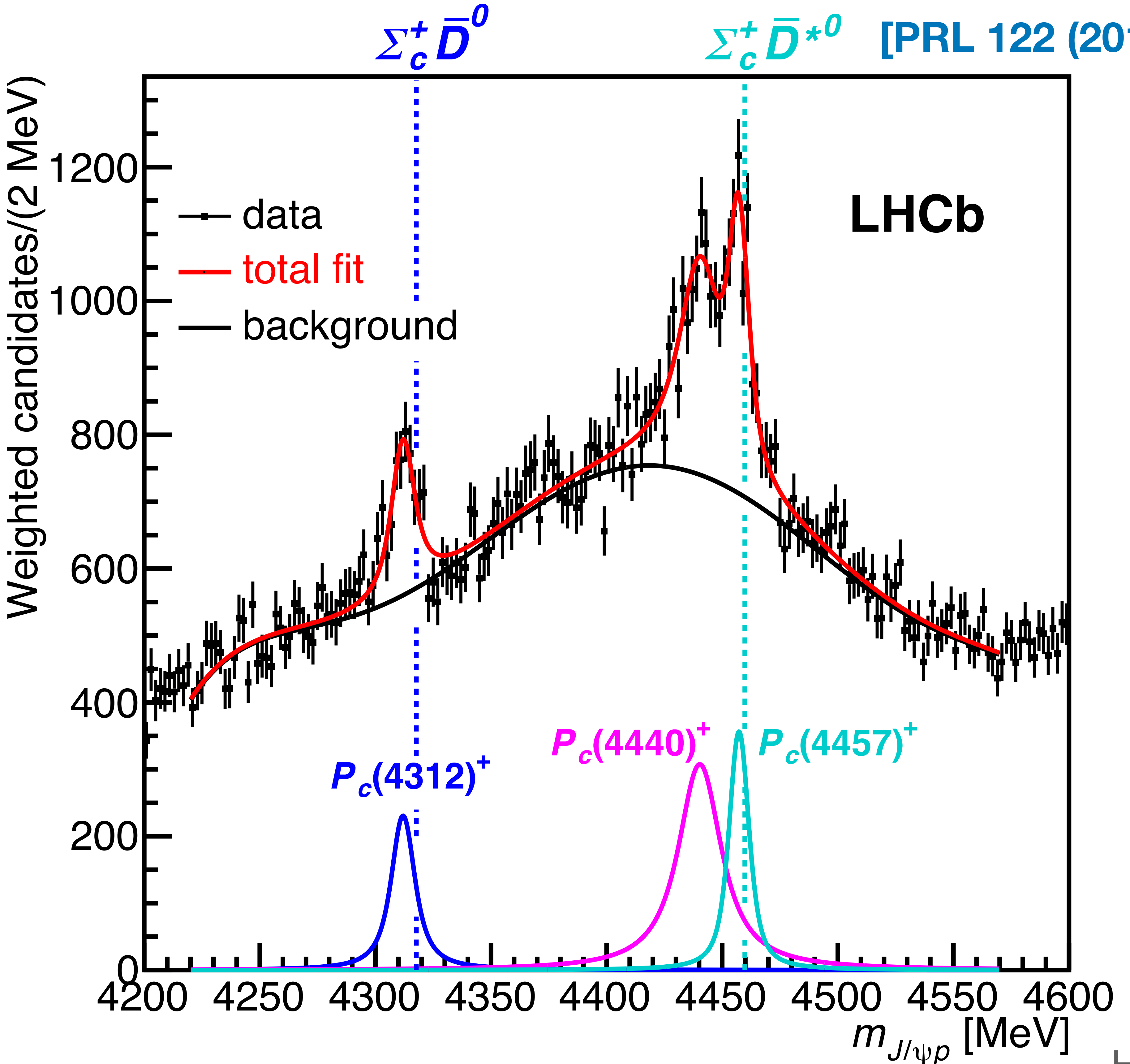
- In 2015, LHCb reported the first observation of pentaquark states P_ψ^N $(c\bar{c}uud)$ in $\Lambda_b^0 \to J/\psi p K^-$ decays using Run1 data

- Later, a new narrow pentaquark state $P_\psi^N(4312)^+$ and two-peak structure of $P_\psi^N(4450)^+$ were observed with the inclusion of LHCb Run2 data

[PRL 115 (2015) 072001]

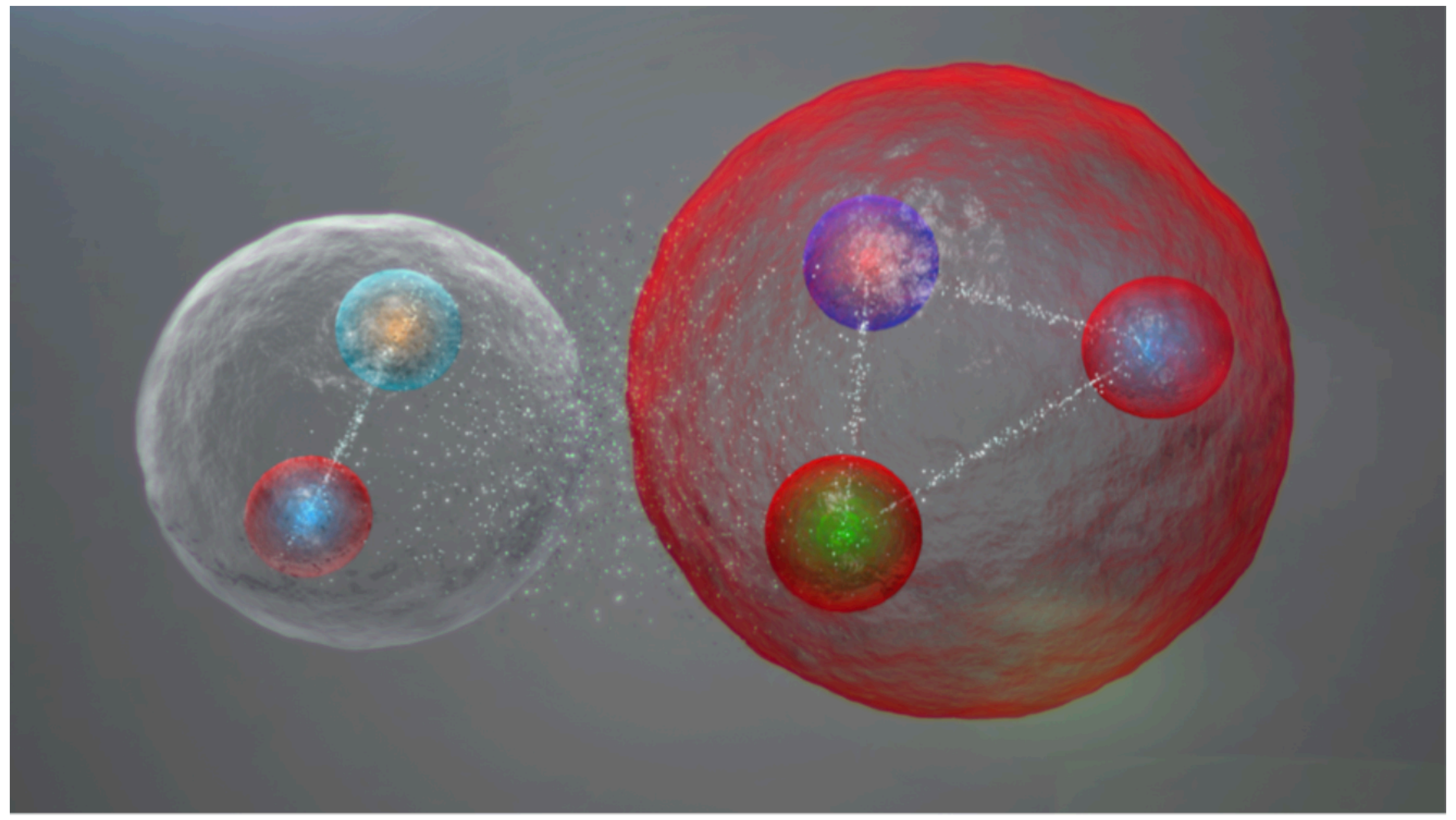


[PRL 122 (2019) 222001]



Possible theoretical interpretations for pentaquark

Hadron molecule

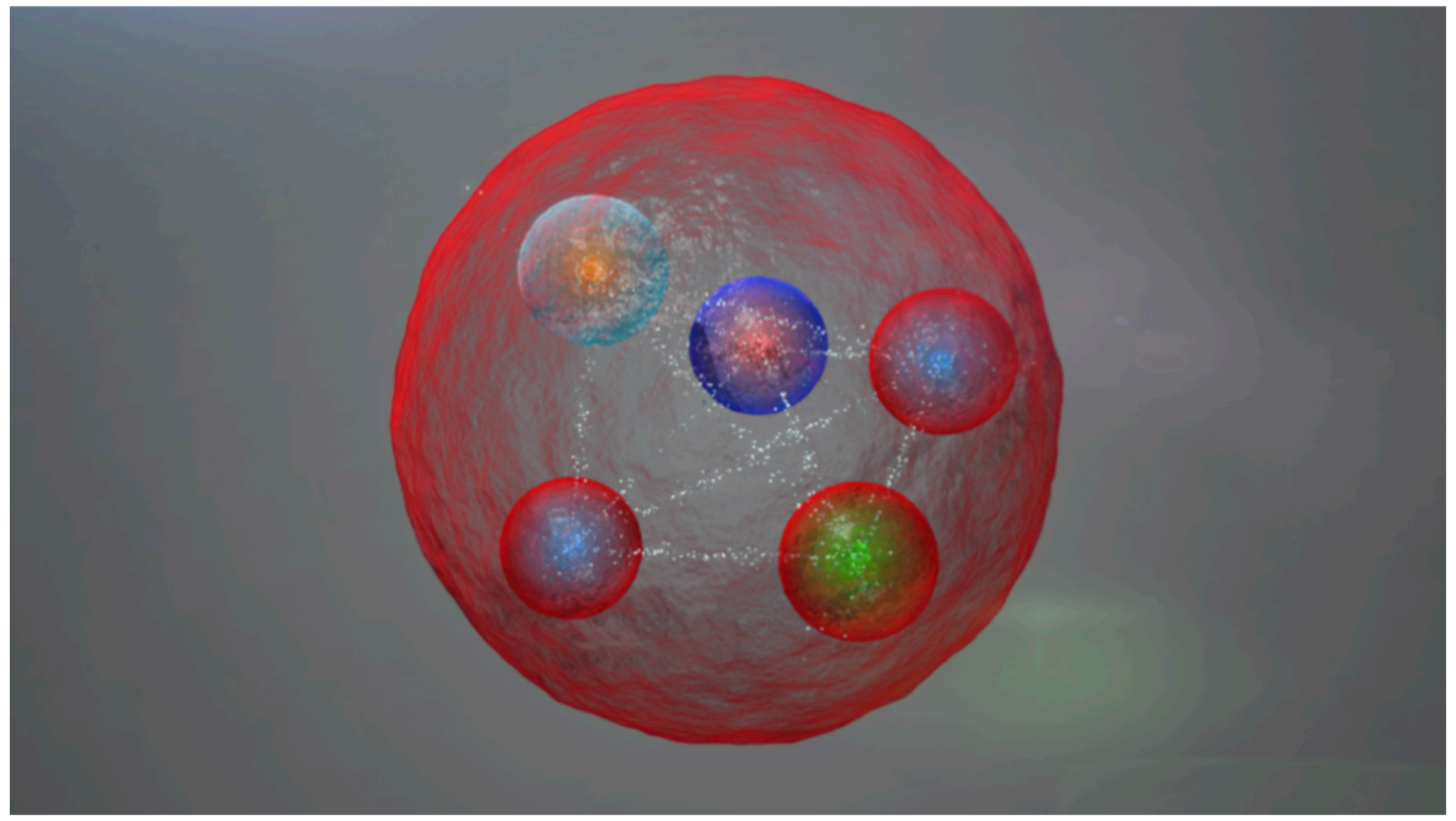


Hadrons bound via mesonic exchange

- J^P combinations highly restricted
- Width is narrow if below threshold

Wu, Molina, Oset, Zou
[**PRL 105 (2010) 232001**]
Karliner, Rosner
[**PRL 115 (2015) 122001**]
Chen, Sun, Liu, Zhu
[**PRD 100 (2019) 011502 (R)**]
and others

Compact state

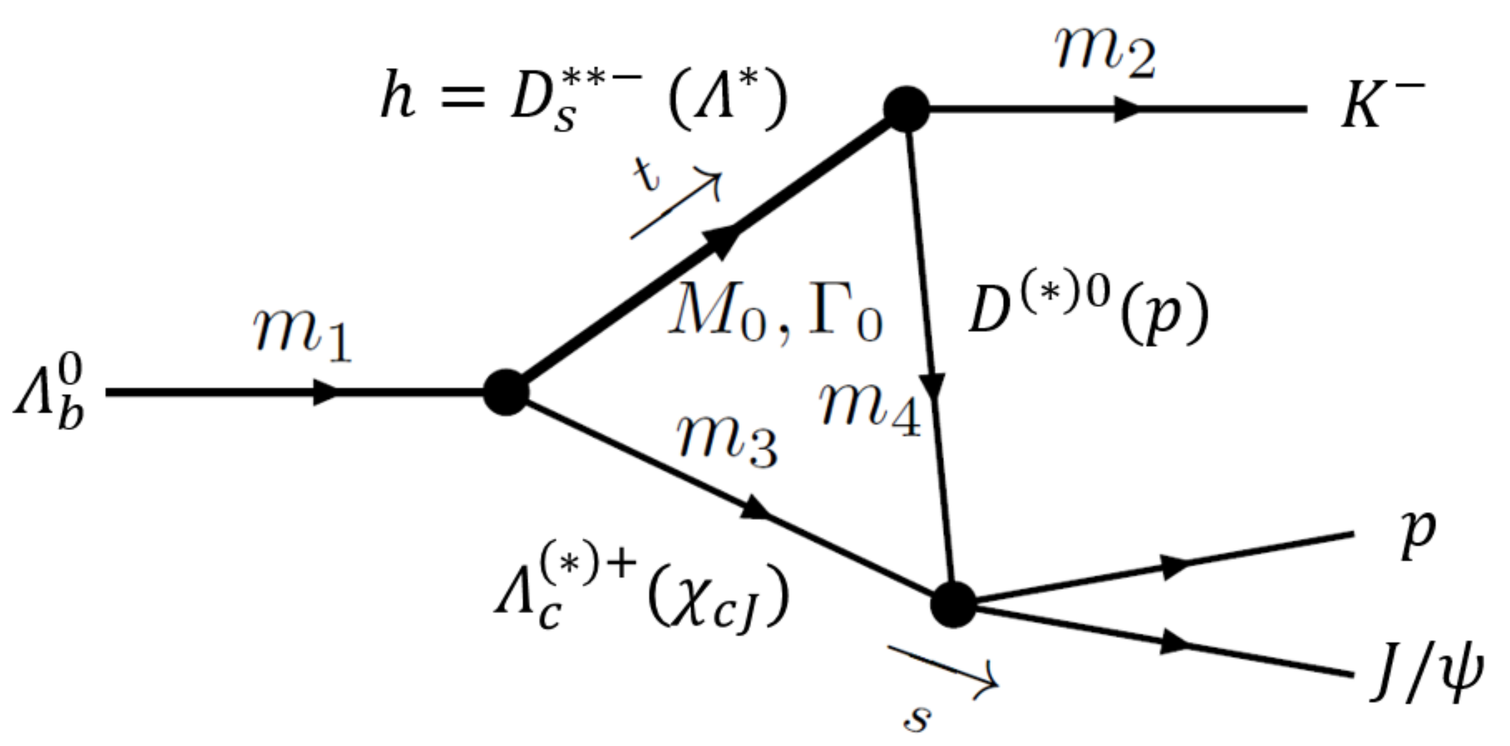


(Di-)quarks bound via colour forces

- J^P and flavour multiplets expected
- Width can be large

Maiani, Polos, Riquer
[**PLB 749 (2015) 289**]
Lebed, [**PLB 749 (2015) 454**]
Santopinto, Giachino
[**PRD 96 (2017) 014014**]
Deng, [**PRD 105 (2022) 116021**]
and others

Triangle diagram



Rescattering effects

- If just kinematical effect, no narrow near-threshold peak in $\chi_{c1}p$ **[JHEP 05 (2021) 95]**

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

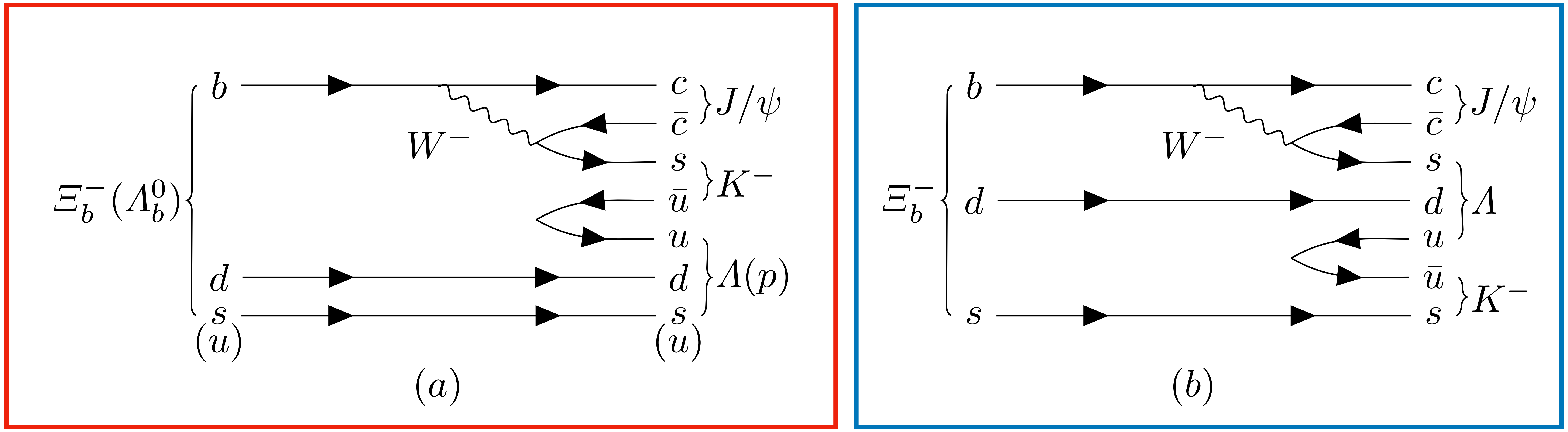
Observation of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay

[PLB 772 (2017) 265]

Motivation for $\Xi_b^- \to J/\psi\Lambda K^-$

[PLB 772 (2017) 265]

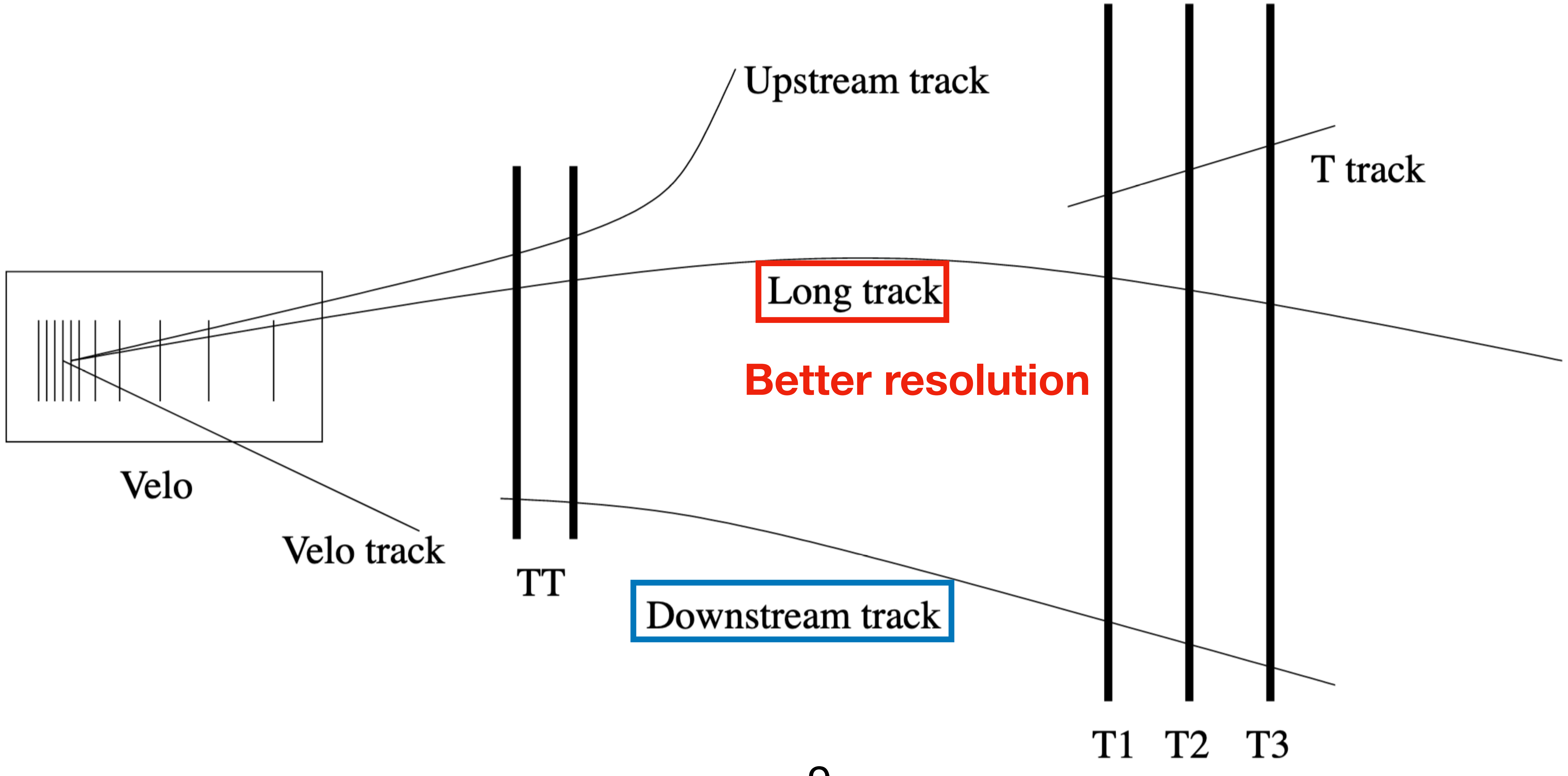
- Similar to $\Lambda_b^0 \to J/\psi p K^-$ decay, with a u quark changed by an s quark
  - An additional diagram can contribute, where the s quark forms K^- instead of Λ
- Suggested to search for pentaquark with open strangeness ($udsc\bar{c}$) in this decay [PRC 93 (2016) 065203]



Dataset and reconstruction

[PLB 772 (2017) 265]

- Run1 data was used, corresponding to an integrated luminosity of 3 fb^{-1}
- Reconstruction of $\Xi_b^- \to J/\psi \Lambda K^-$ decay
  - $J/\psi : \mu^+, \mu^-$ candidates from a common vertex and detached from any primary vertex (PV) of pp collision
  - $\Lambda : p, \pi^-$ candidates, both of either *long* tracks or *downstream* tracks, so called LL or DD



Selection

[PLB 772 (2017) 265]

- General selection criteria:
  - All final-state particles with high transverse momentum
  - $m(\mu^+\mu^-)$ and $m(p\pi^-)$ in known mass range of J/ψ and Λ
  - Require p, π^-, K^- not from any PV
  - Fake Λ candidates from misidentified K_S^0 are vetoed
  - Ξ_b^- associated with appropriate PV
- Further suppress combinatorial background with a multivariate classifier BDTG
  - In total 15 discriminating variables used, such as p_T of p, π^-, K^- and $J/\psi, \chi^2$ of kinematic fit and $cos\theta$...
  - Signal efficiency of 90%(70%) and background rejection rate of 99%(97%) for LL(DD)
- Normalisation channel $\Lambda_b^0 \to J/\psi\Lambda$ with similar selection

Fit results

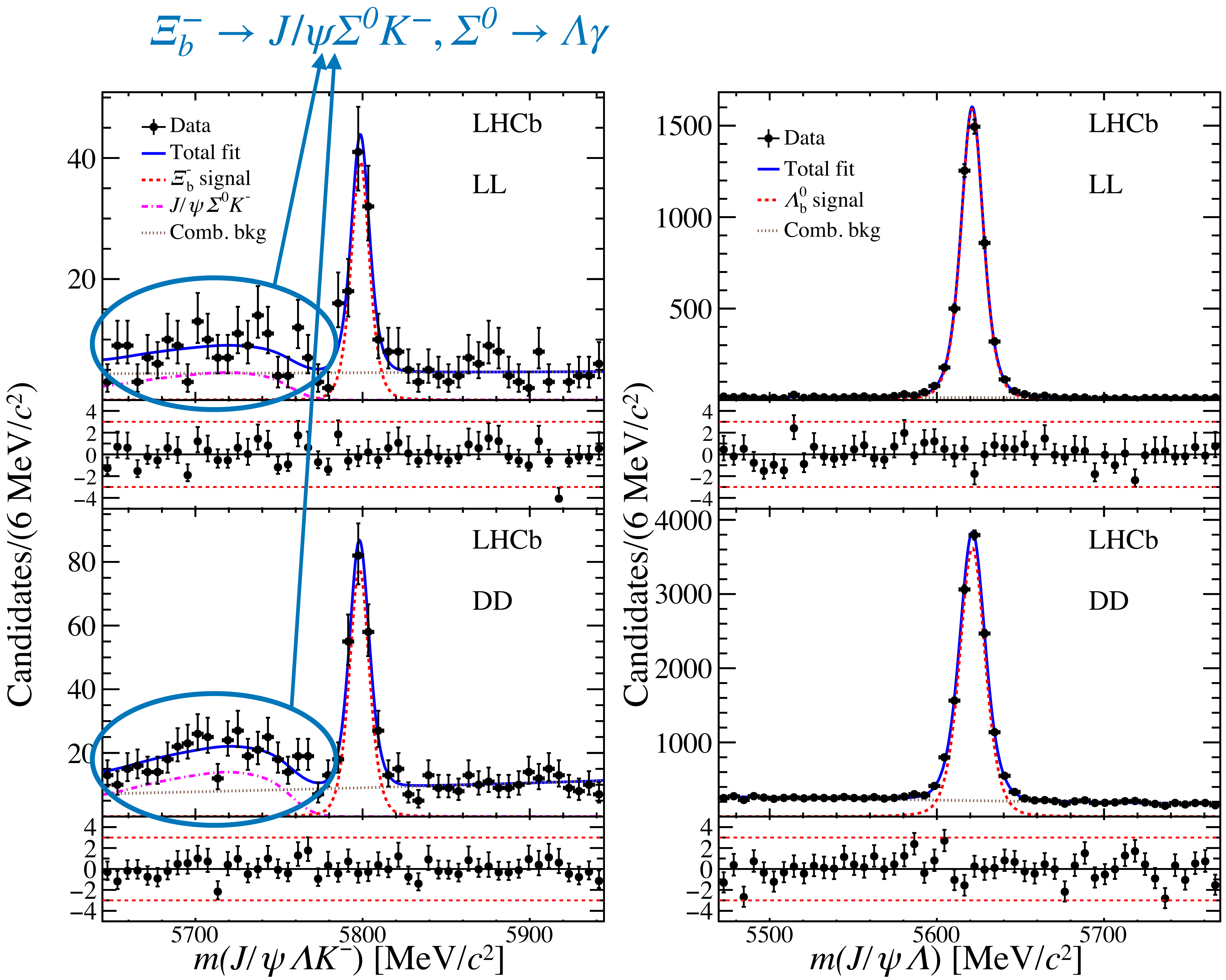
[PLB 772 (2017) 265]

- $\Xi_b^- \to J/\psi \Lambda K^-$ (Run1)
  - ~100 signal for LL
  - ~210 signal for DD
  - combined signal significance ~ 21σ
- Production rate measured

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\frac{\mathcal{B}(\Xi_b^- \to J/\psi\,\Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = (4.19 \pm 0.29\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst})) \times 10^{-2}$$

- Mass difference between Ξ_b^- and Λ_b^0 measured, and combined with previous LHCb result from $\Xi_b^- \to \Xi_c^0\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+\pi^-$

$$M(\Xi_b^-) - M(\Lambda_b^0) = 177.73 \pm 0.33\,(\mathrm{stat}) \pm 0.14\,(\mathrm{syst})\ \mathrm{MeV}/c^2$$



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

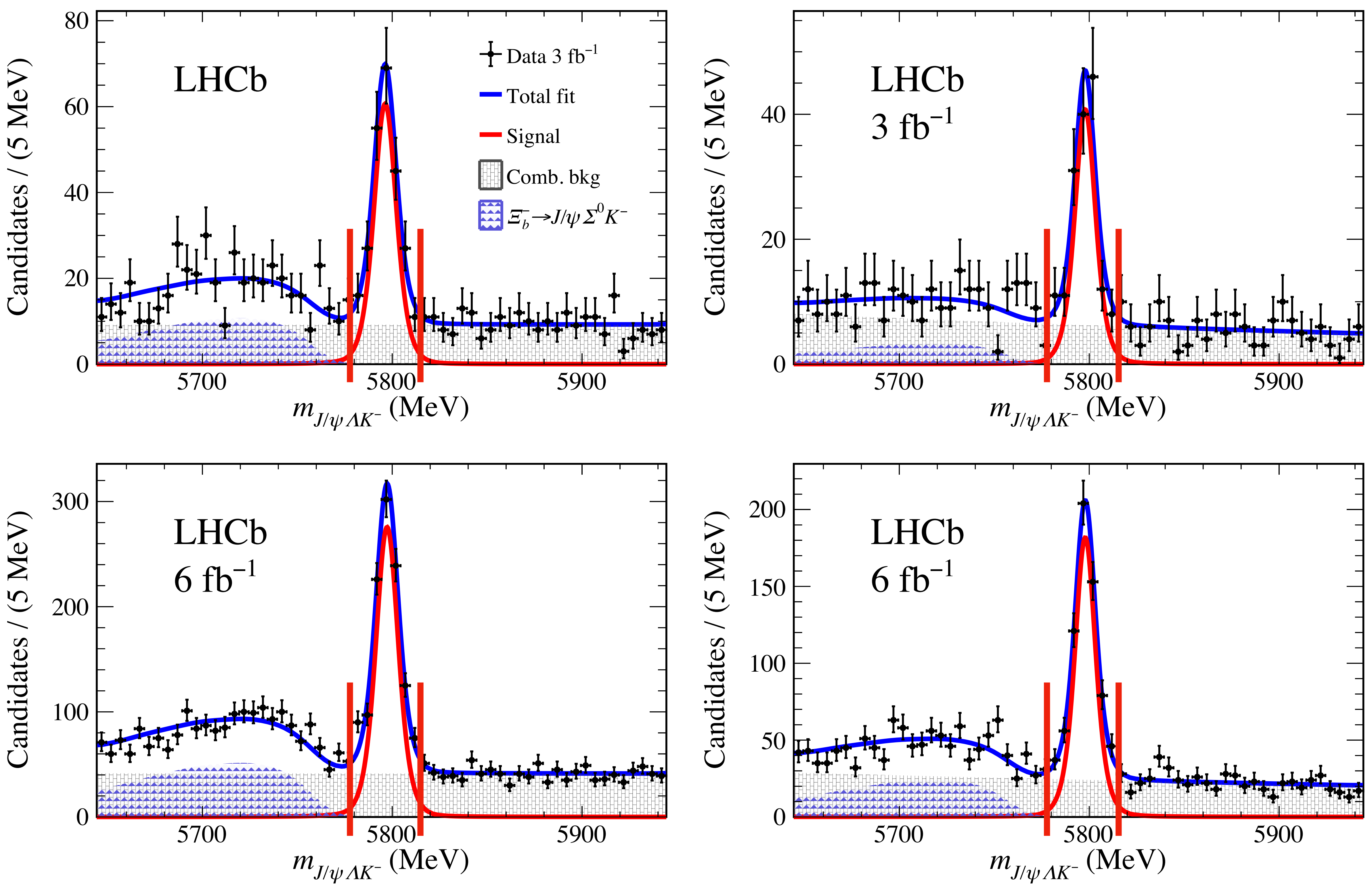
[Sci. Bull. 66 (2021) 1278]

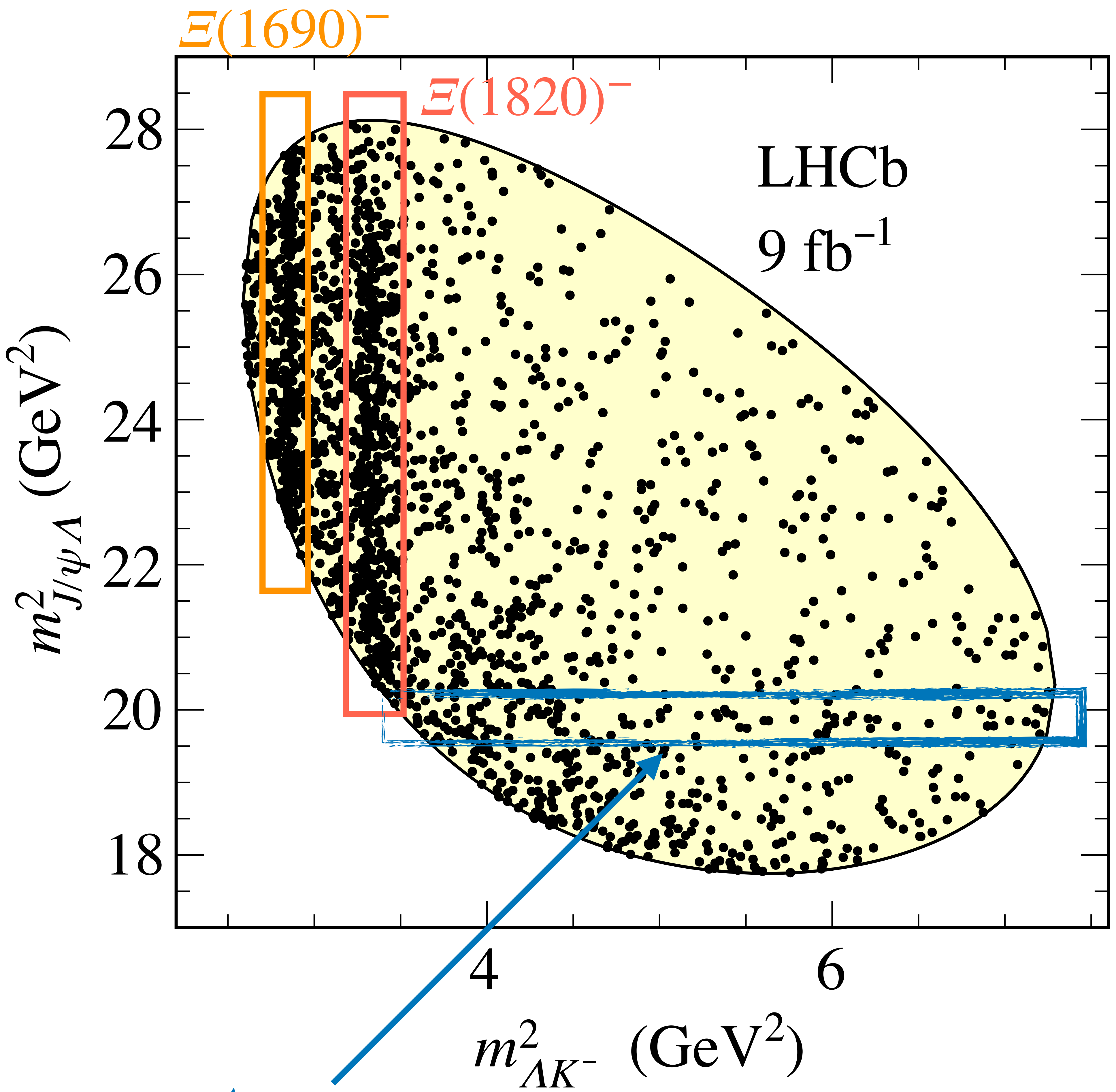
$\Xi_b^- \to J/\psi \Lambda K^-, J/\psi \to \mu^+\mu^-, \Lambda \to p\pi^-$

[Sci. Bull. 66 (2021) 1278]

- This analysis use full Run1+Run2 LHCb data, ~ 9 fb^{-1}
- Selection similar to previous analysis [PLB 772 (2017) 265]
- Signal yield ~1750, purity within 15 MeV of Ξ_b^- peak ~80%

Λ decay inside VELO | **Λ decay outside VELO**



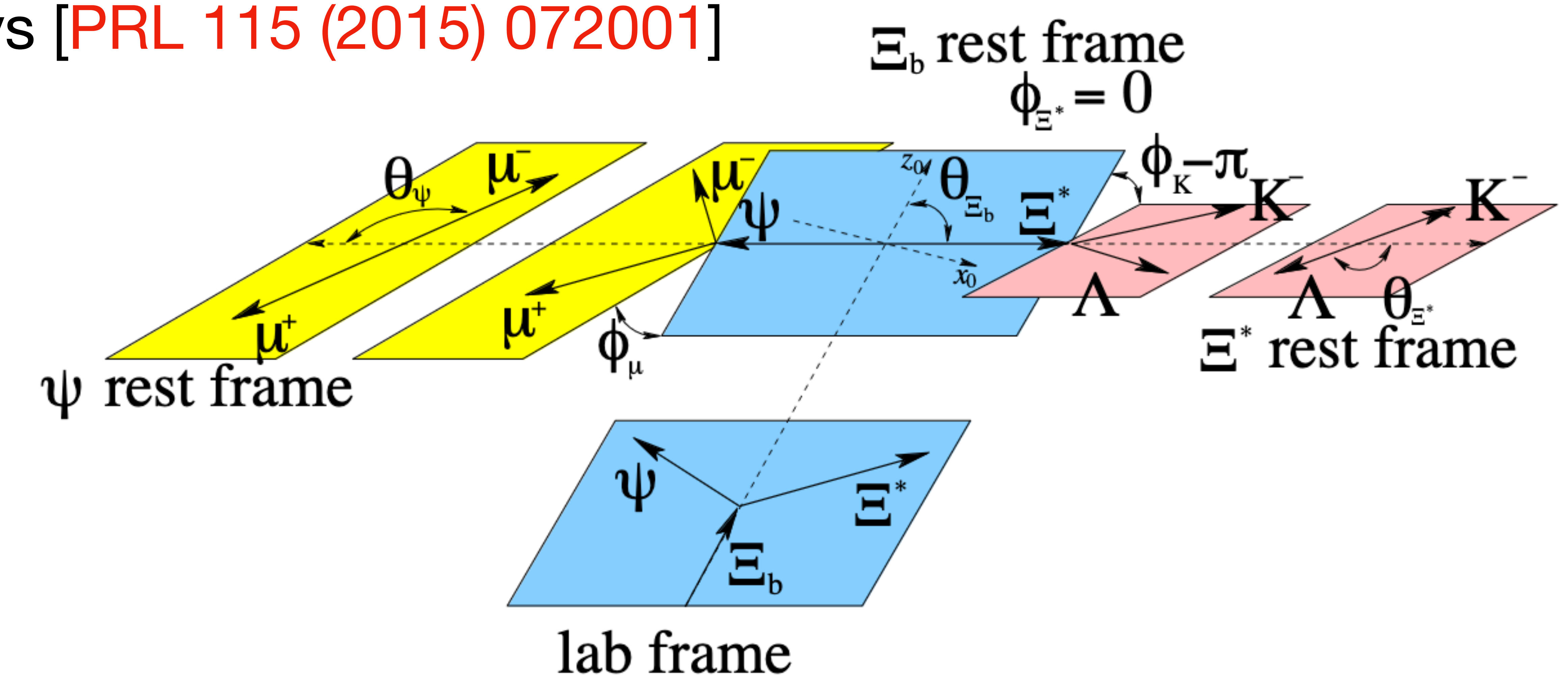


Possible $P^{\Lambda}_{\psi s}$ contribution,
further explored in amplitude analysis

Full 6D amplitude analysis

[Sci. Bull. 66 (2021) 1278]

- Similar to amplitude analysis in $\Lambda_b^0 \to J/\psi p K^-$ decays [PRL 115 (2015) 072001]
- Six dimensions:
  - $m(\Lambda K^-)$
  - three helicity angles $\theta_{\Xi_b^-}, \theta_{\Xi^-}, \theta_{J/\psi}$
  - two azimuthal angles ϕ_K, ϕ_μ



- Formula cross checked with the Dalitz-Plot Decomposition (DPD) formula [PRD 101 (2020) 034033] and updated[CPC 45 (2021) 063103]

More technical details see Mengzhen's talk

States included in nominal model of null hypothesis:

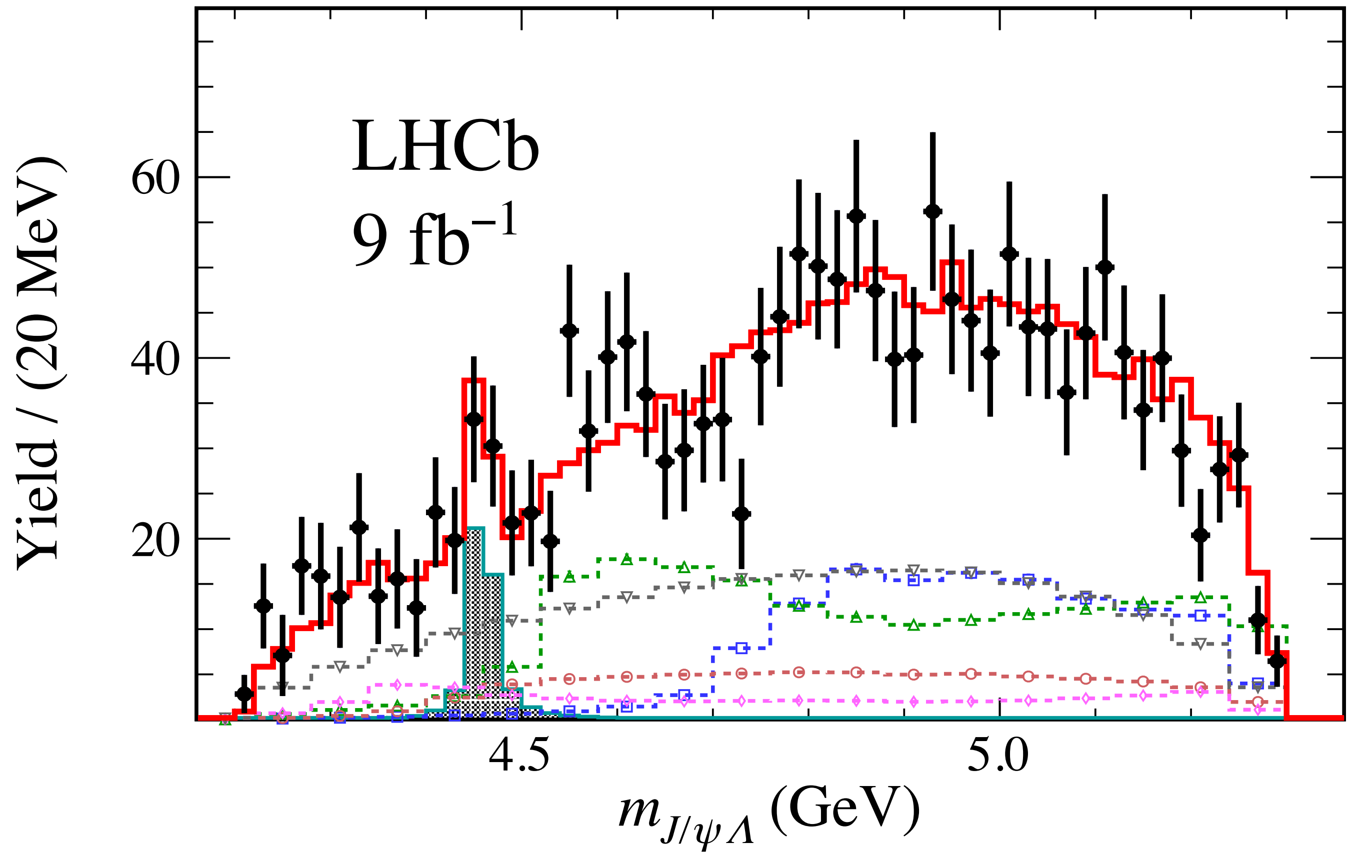
State	M_0 (MeV)	Γ_0 (MeV)	LS couplings	J^P examined
$\Xi(1690)^-$	1690 ± 10	< 30	4 (6)	$(1/2, 3/2)^\pm$
$\Xi(1820)^-$	1823 ± 5	24^{+15}_{-10}	3 (6)	$3/2^-$
$\Xi(1950)^-$	1950 ± 15	60 ± 20	3 (6)	$(1/2, 3/2, 5/2)^\pm$
$\Xi(2030)^-$	2025 ± 5	20^{+15}_{-5}	3 (6)	$5/2^\pm$
NR ΛK^-	-	-	4 (4)	$1/2^-$

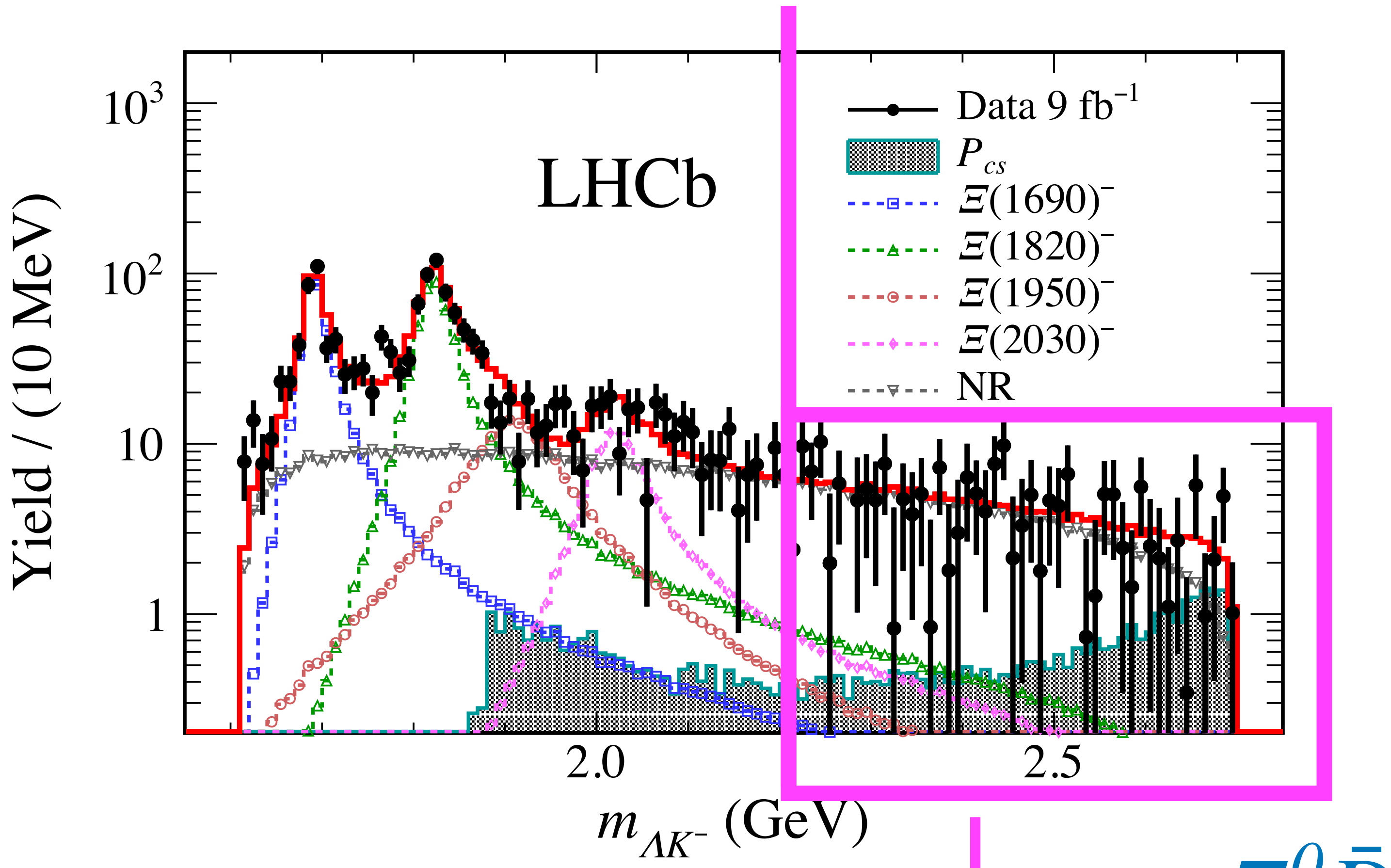
NR: Non-resonance

Amplitude fit results

[Sci. Bull. 66 (2021) 1278]

- After considering syst. uncertainty and look-elsewhere effect, $P_{\psi s}^{\Lambda}(4459)^0$ significance: 3.1σ

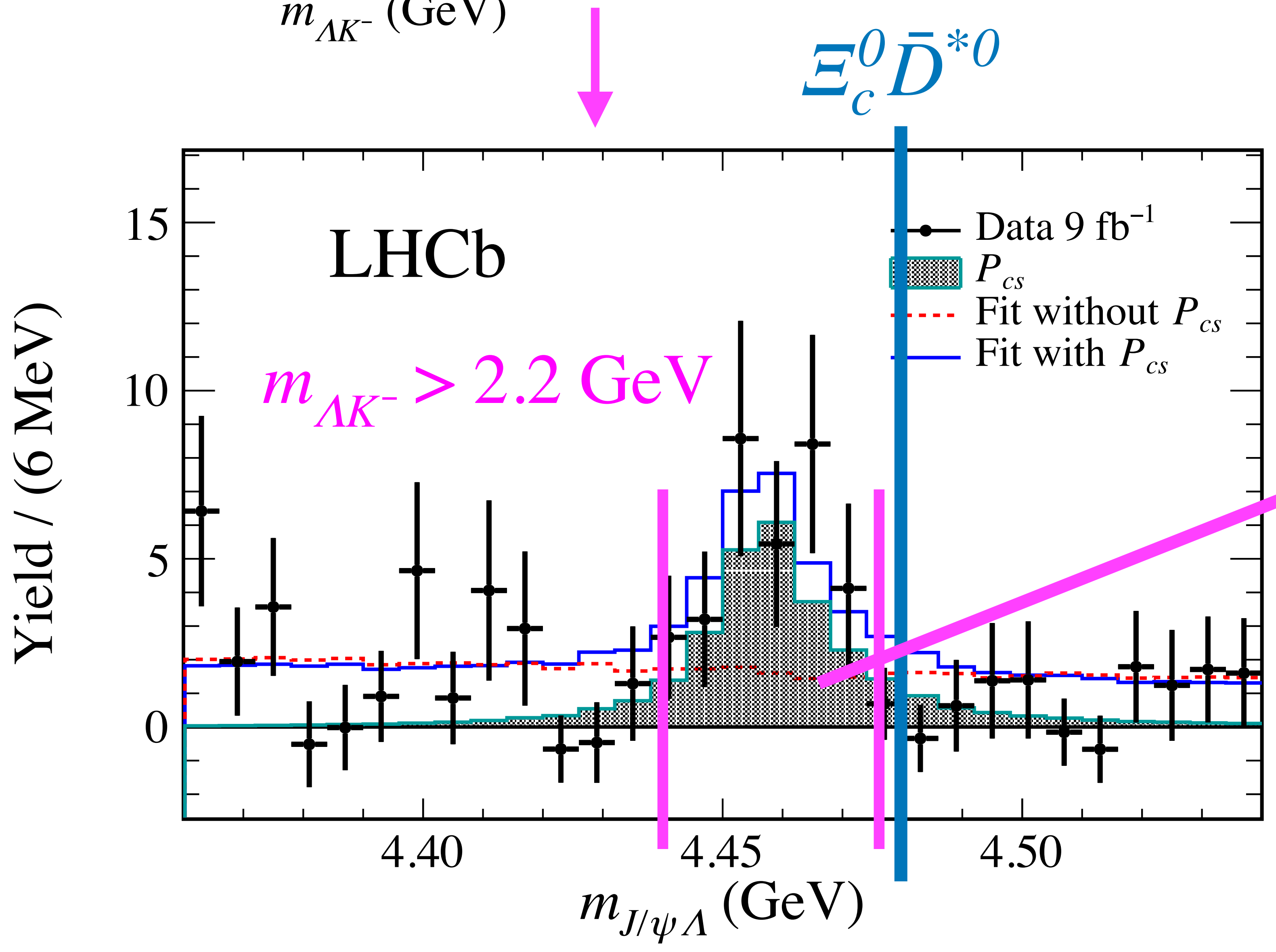


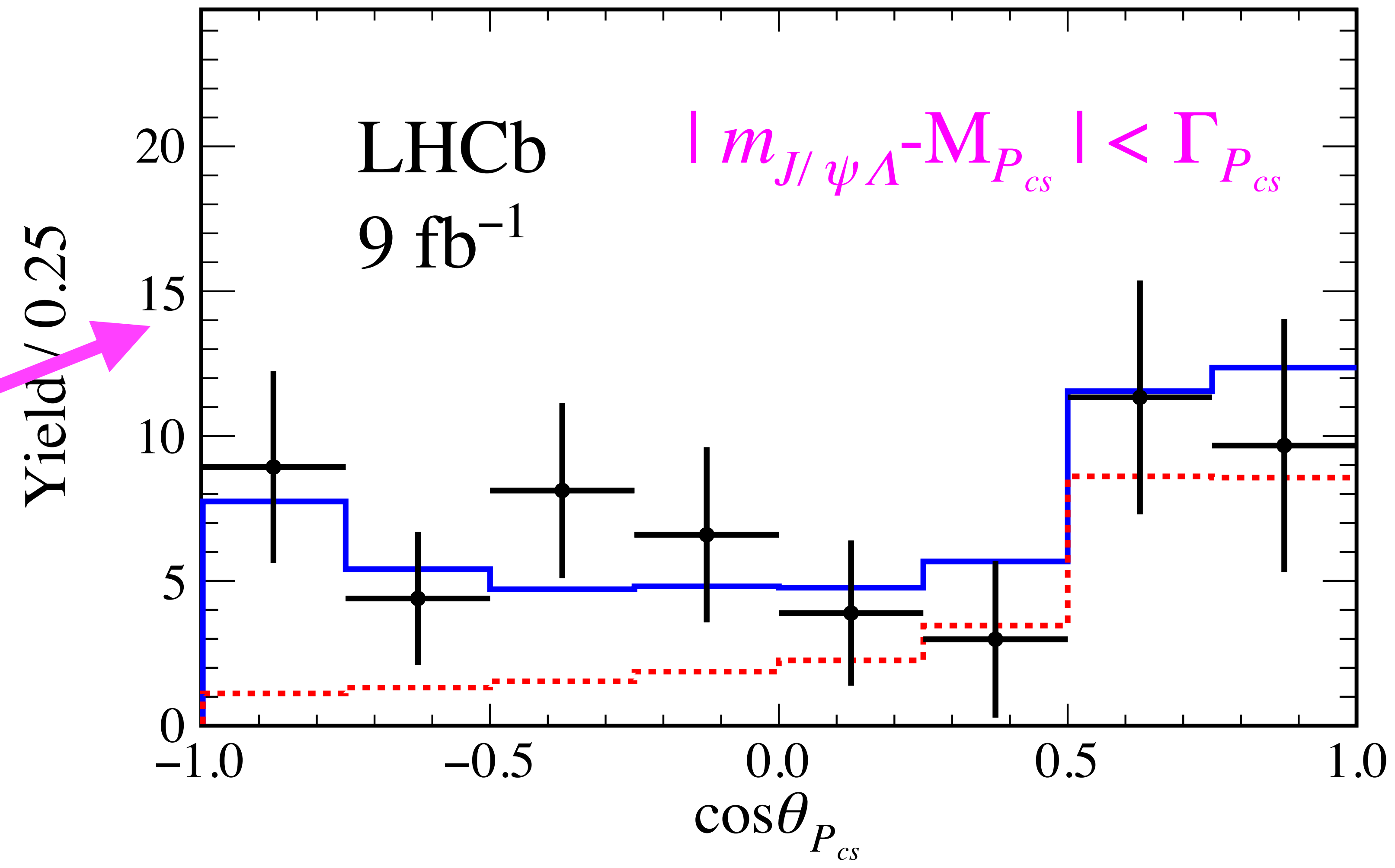


State	M_0 (MeV)	Γ_0 (MeV)	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

- Mass ~19 MeV below $\Xi_c^0 \bar{D}^{*0}$ threshold
- J^P determination needs more data
- Two peak hypothesis cannot be confirmed or refuted

After excluding low-mass Ξ^{*-} contribution, $P_{\psi s}^{\Lambda\,0}$ is more visible



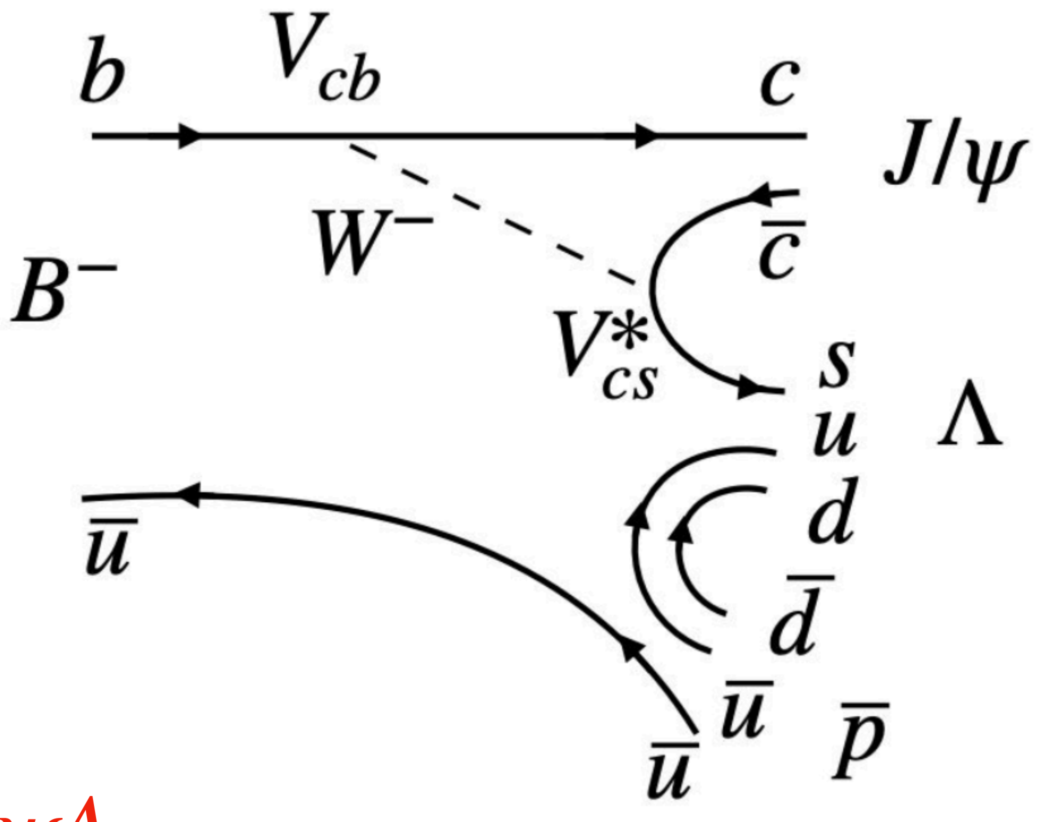


First observation of $P_{\psi s}^{\Lambda}(4338)^0$ in $B^- \to J/\psi \Lambda \bar{p}$ decays

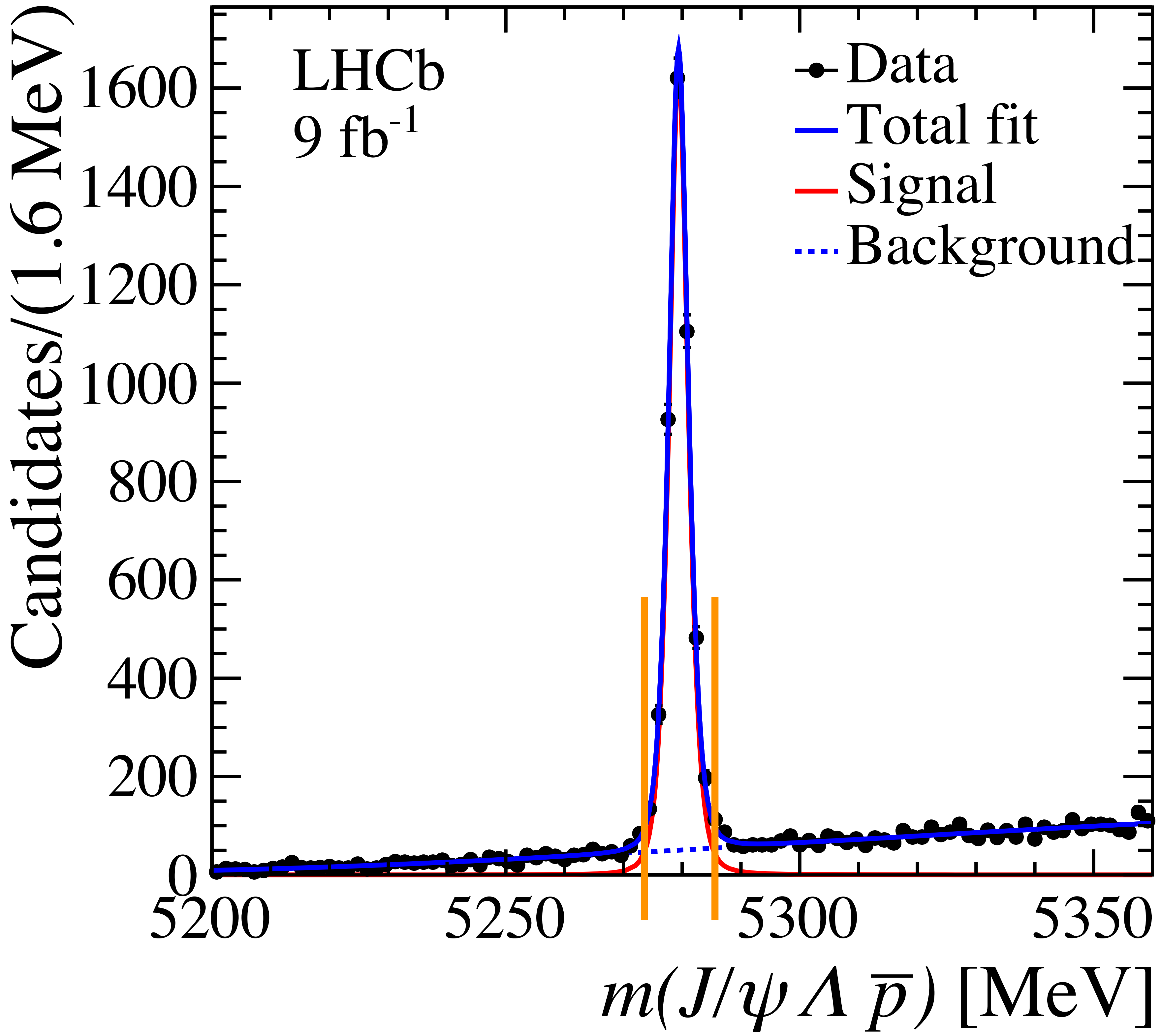
[arXiv: 2210.10346] Accepted by PRL

$B^- \to J/\psi \Lambda \bar{p}, J/\psi \to \mu^+\mu^-, \Lambda \to p\pi^-$

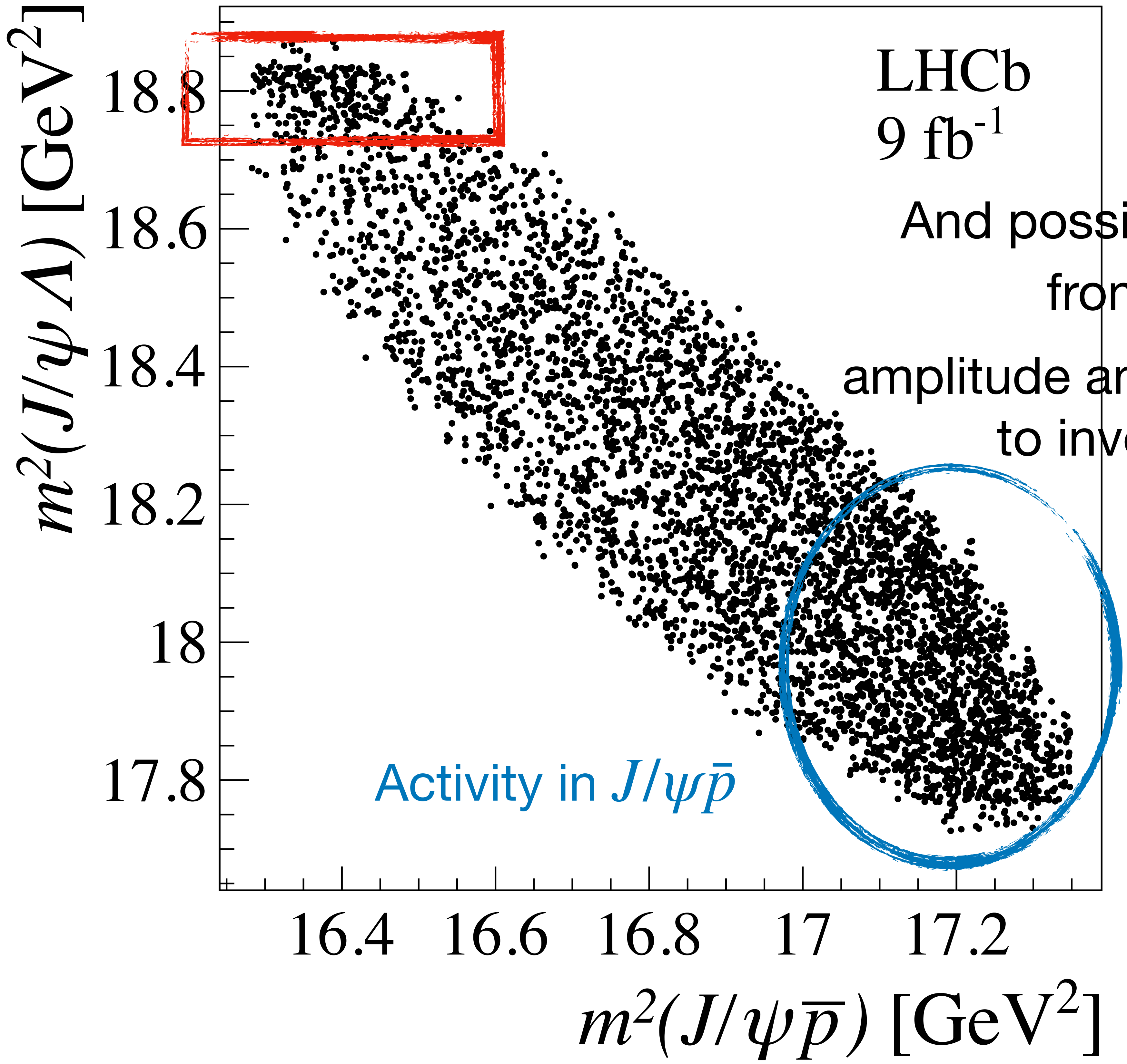
[arXiv: 2210.10346]
Accepted by PRL



- Unique opportunity to simultaneously search for $\bar{P}_{\psi}^{N^-}(J/\psi\bar{p})$ and $P_{\psi s}^{\Lambda\,0}(J/\psi\Lambda)$
- Dataset: full Run1+Run2 LHCb data (9 fb^{-1})
- Signal yield ~4400 with purity of 93% in $\pm 2.5\sigma$ of B^- peak



Narrow structure in $J/\psi\Lambda$



And possible reflections from $K^*_{2,3,4}$, amplitude analysis employed to investigate…

Full 6D amplitude analysis

[arXiv: 2210.10346]
Accepted by PRL

- Following the Dalitz-Plot Decomposition (DPD) formula [PRD 101 (2020) 034033]
- Six dimensions:
  - $m(\Lambda\bar{p})$
  - three helicity angles $\theta_{K^*}, \theta_{J/\psi}, \theta_\Lambda$
  - two azimuthal angles ϕ_p, ϕ_μ

The simplest and
most effective amplitude model

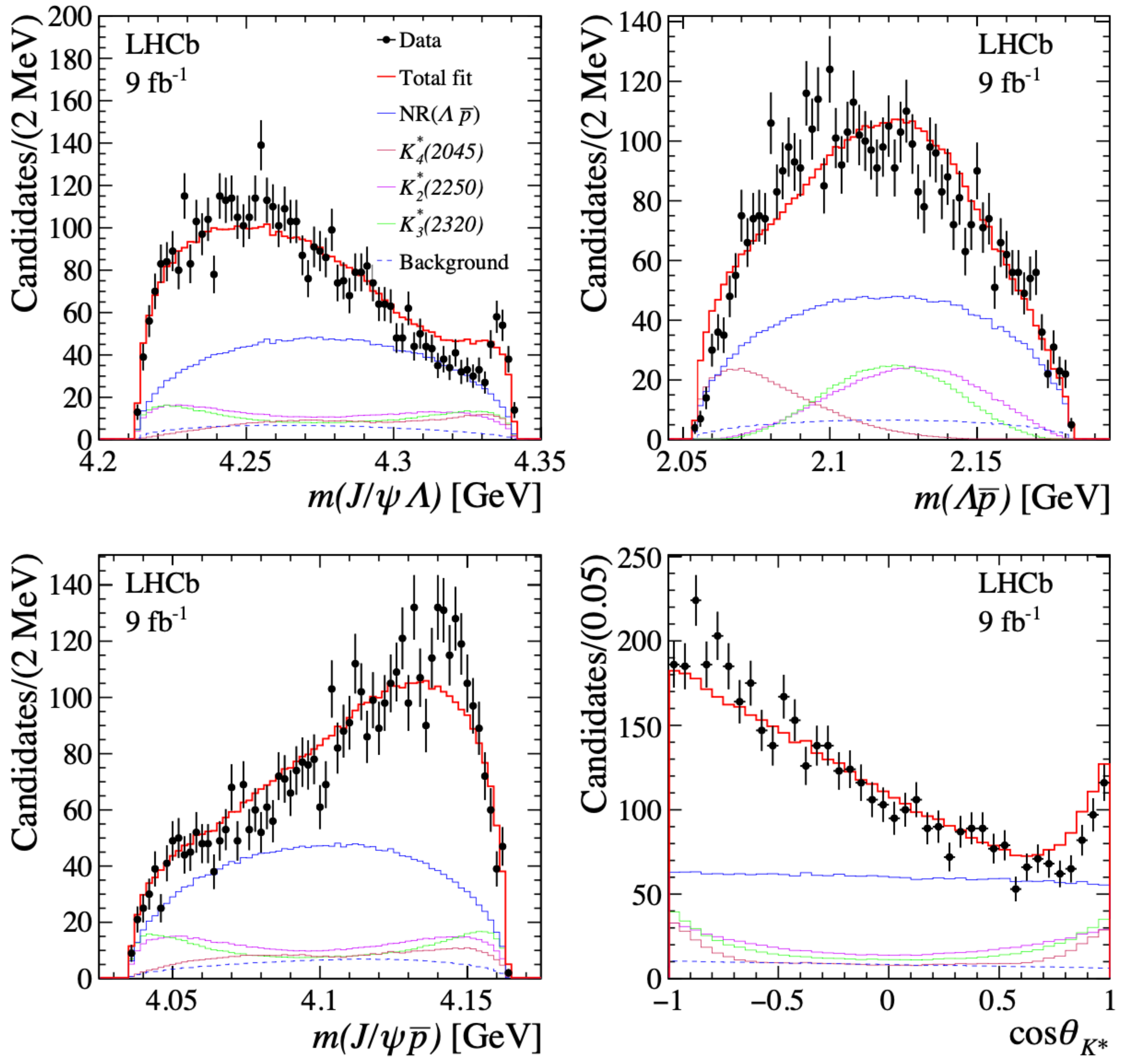
- NR($\bar{p}\Lambda$)
- NR($J/\psi\bar{p}$)
- $P^{\Lambda}_{\psi s}$ (rBW)

First tried a model with only K^{*+}

- NR($\bar{p}\Lambda$)
- $K^{*+}_{2,3,4}$

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^+

Cannot reproduce the data



More technical details see Mengzhen's talk

Amplitude fit results

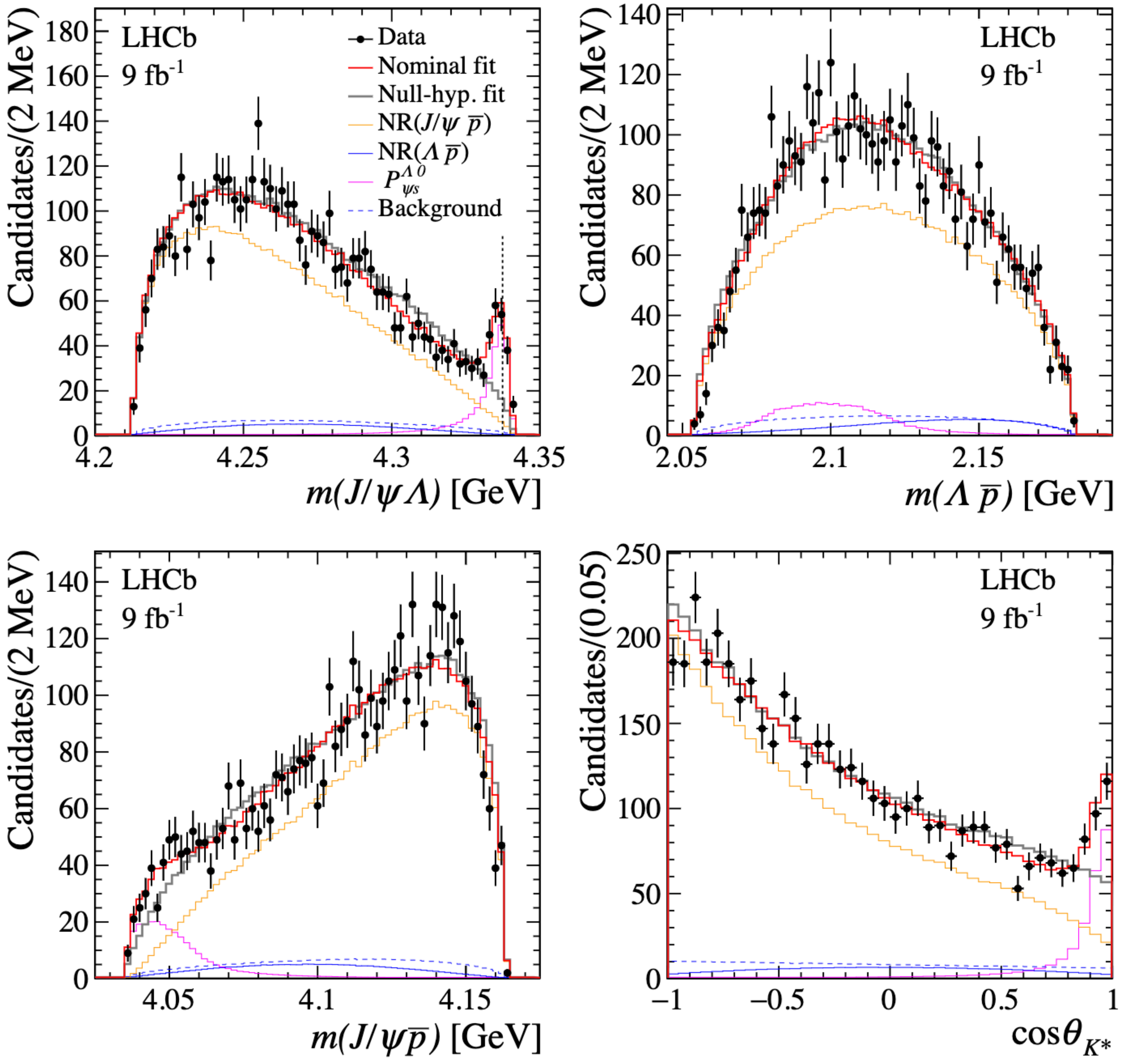
[arXiv: 2210.10346]
Accepted by PRL

- Significance of $P_{\psi s}^{\Lambda}(4338)^0$ > 10σ

- $m(P_{\psi s}^{\Lambda\,0}) = 4338.2 \pm 0.7 \pm 0.4$ MeV
- $\Gamma(P_{\psi s}^{\Lambda\,0}) = 7.0 \pm 1.2 \pm 1.3$ MeV
- Fit fraction for $P_{\psi s}^{\Lambda}(4338)^0$:

  $0.125 \pm 0.007 \pm 0.019$

- Very close to $\Xi_c^+ D^-$ threshold (4337.37 MeV)
- Spin-parity:
  - $J = \dfrac{1}{2}$ determined
  - $P =$ -1 favoured, $+1$ rejected @90% CL



Summary and prospects

Two $P_{\psi s}^{\Lambda\,0}$ candidates from LHCb:

$P_{\psi s}^{\Lambda}(4459)^0$ with significance of 3.1σ: **[Sci. Bull. 66 (2021) 1278]**

- Mass ~ 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold
- Need more data to:
  - Determine J^P
  - Explore possible two-peak structure

$P_{\psi s}^{\Lambda}(4338)^0$ with significance $>10\sigma$: **[arXiv: 2210.10346] Accepted by PRL**

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Summary and prospects

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$P_{\psi s}^{\Lambda}(4338)^0$ with significance $>10\sigma$: **[arXiv: 2210.10346] Accepted by PRL**

- Very close to $\Xi_c^+ D^-$ threshold (4337.37 MeV)
- Spin-parity:
  - $J = \dfrac{1}{2}$ determined
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More modes to look at:

- $\Lambda_b^0 \to J/\psi \Lambda \pi^+ \pi^-$, $\Xi_b \to J/\psi \Lambda K^- \pi^+ (\pi^-)$...
- $B_s^0 \to J/\psi \Lambda \bar{\Lambda}$...
- $\Xi_b^- \to \Xi_c^0 \bar{D}^0 K^-$...
- $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ [arXiv:2211.00812]
- $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ [PLB 815 (2021) 136172]

More data is coming:

- Up to 5x (10x) statistics wrt current data will be collected in Run3 (Run3&4)…

Stay tuned!

Backup

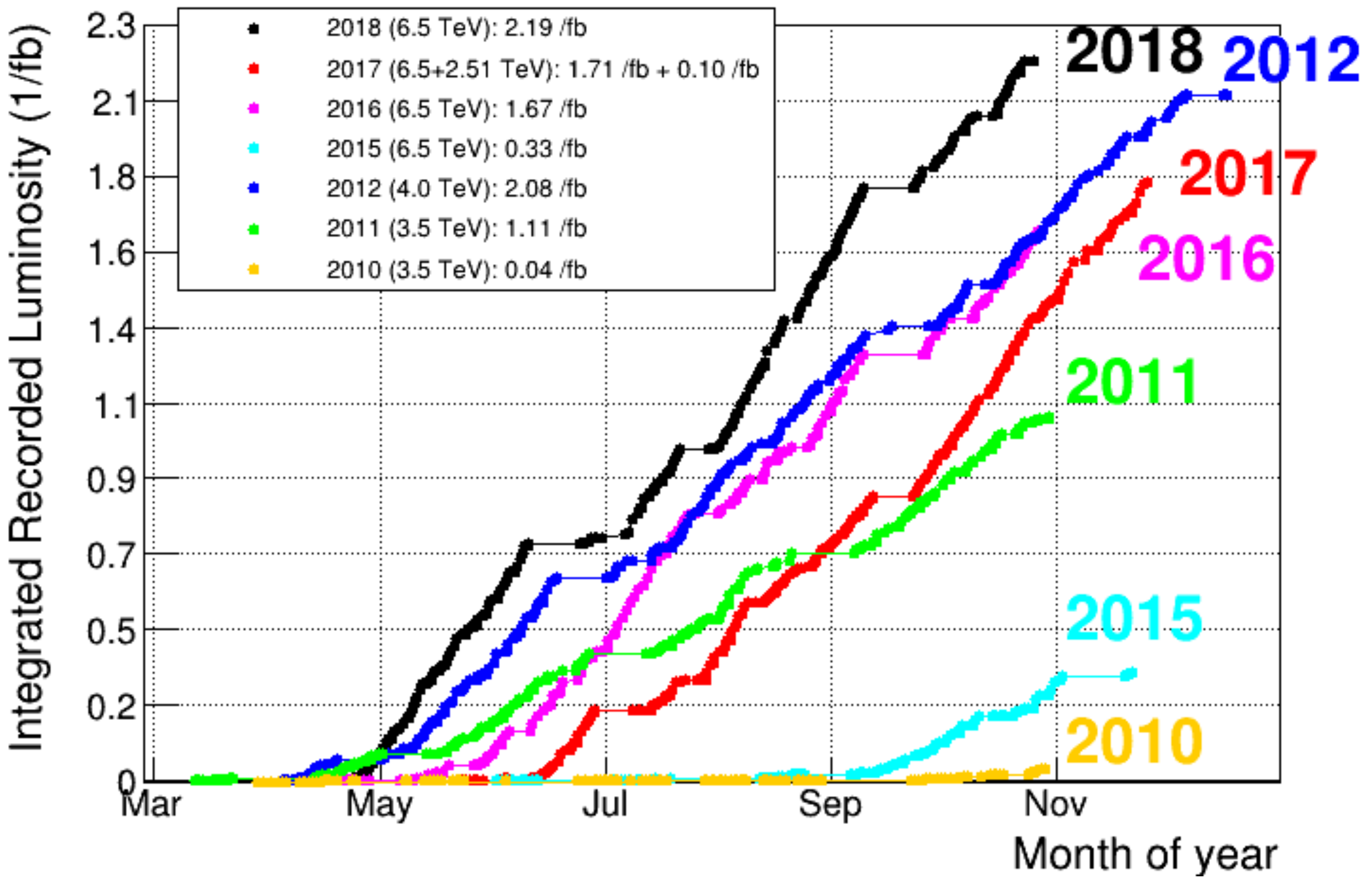
New naming scheme

[arXiv:2206.15233]

Minimal quark content	Current name	$I^{(G)},\ J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+,\ J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(4140)$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2},\ J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2},\ J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+,\ J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$

LHCb data taking

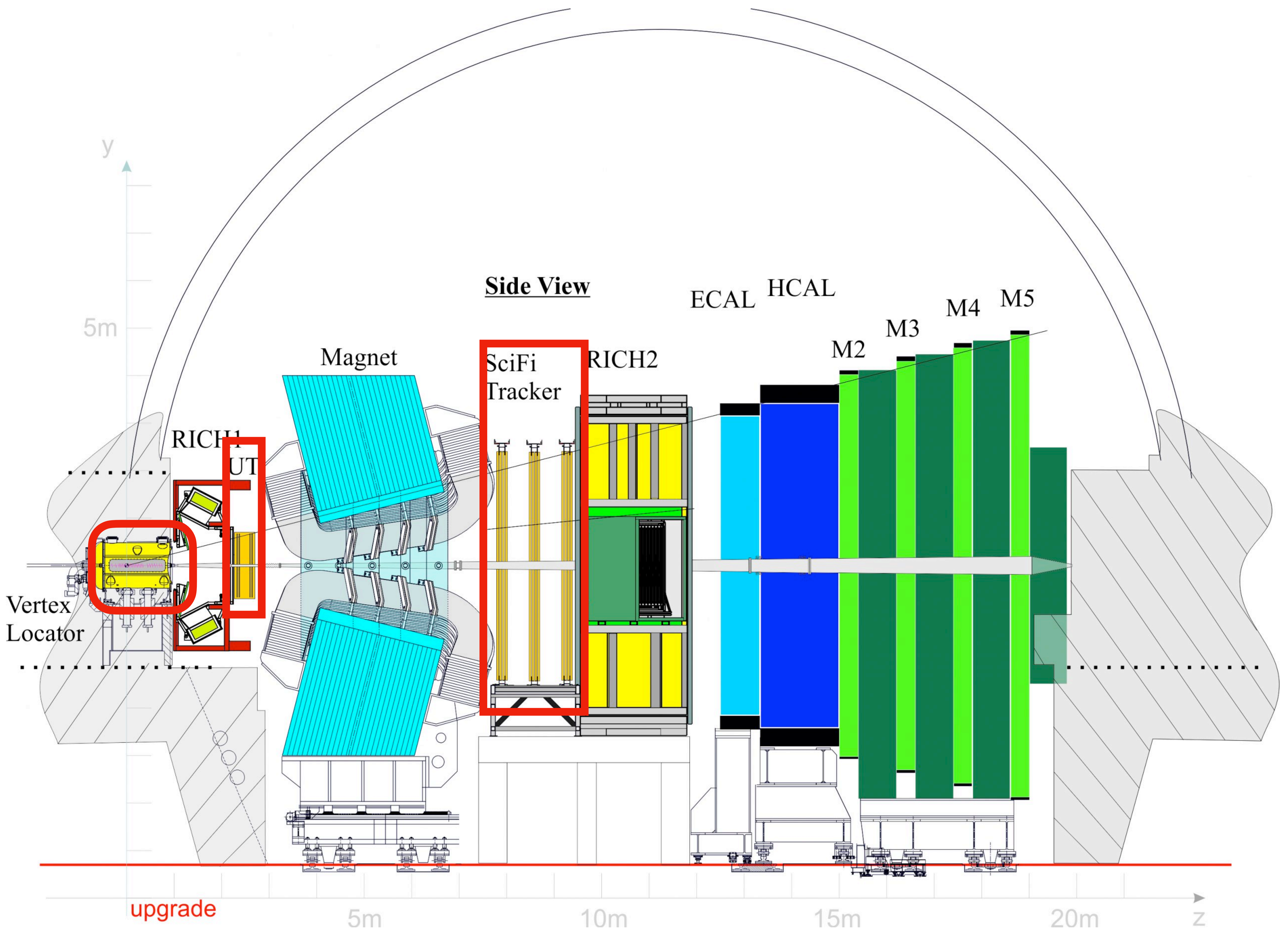
- Run1 (2011-2012): L_{int} = 1 fb^{-1}@ 7 TeV & L_{int} = 2 fb^{-1}@ 8 TeV
- Run2 (2015-2018): L_{int} = 6 fb^{-1} @ 13 TeV



Prospects

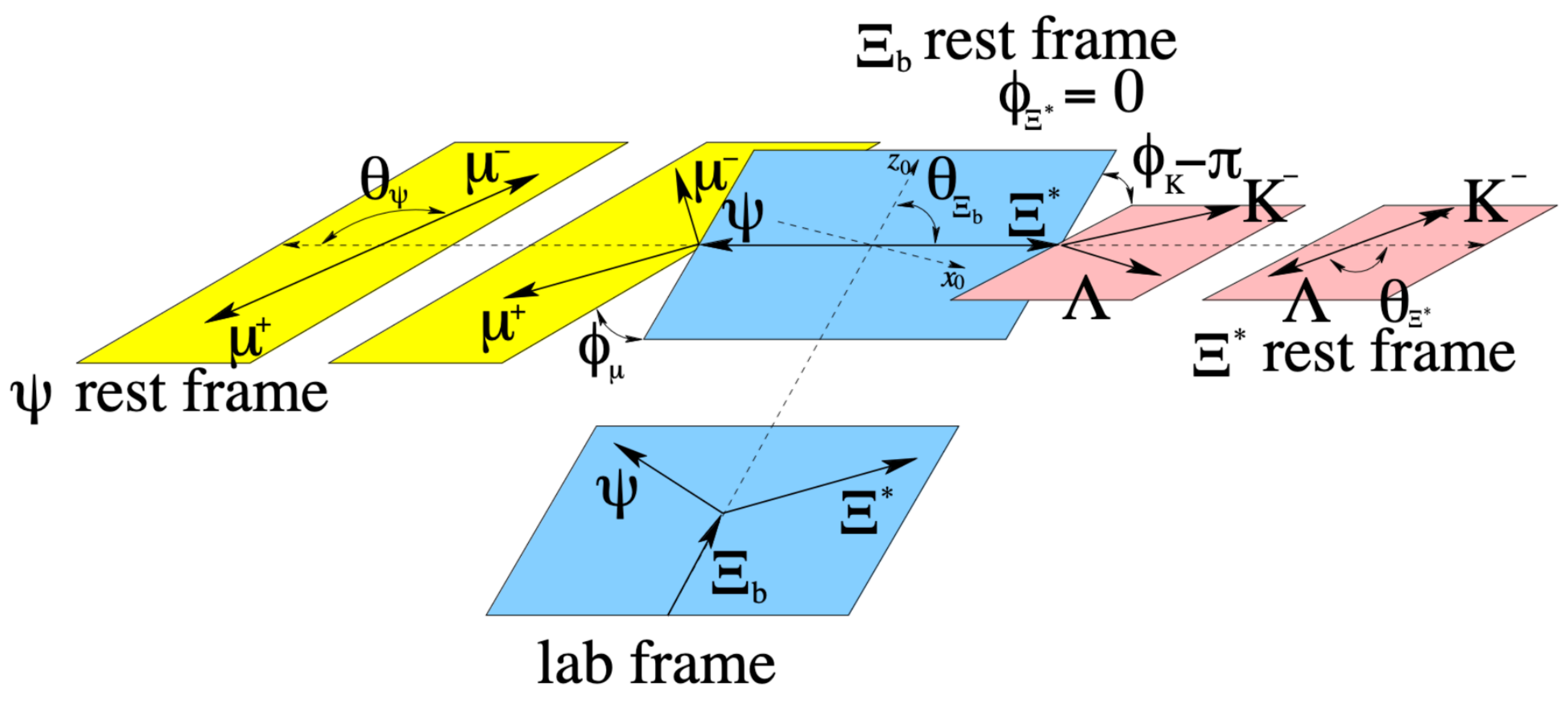
[arXiv: 2305.10515]

- LHCb upgrade1 detector: brand new tracking system
  - VErtex LOcator
  - Upstream Tracker
  - Scintillating Fiber Tracker
- Full software trigger, higher efficiency and more flexibility
- Run3&Run4: target L_{int} ~ 50fb^{-1}

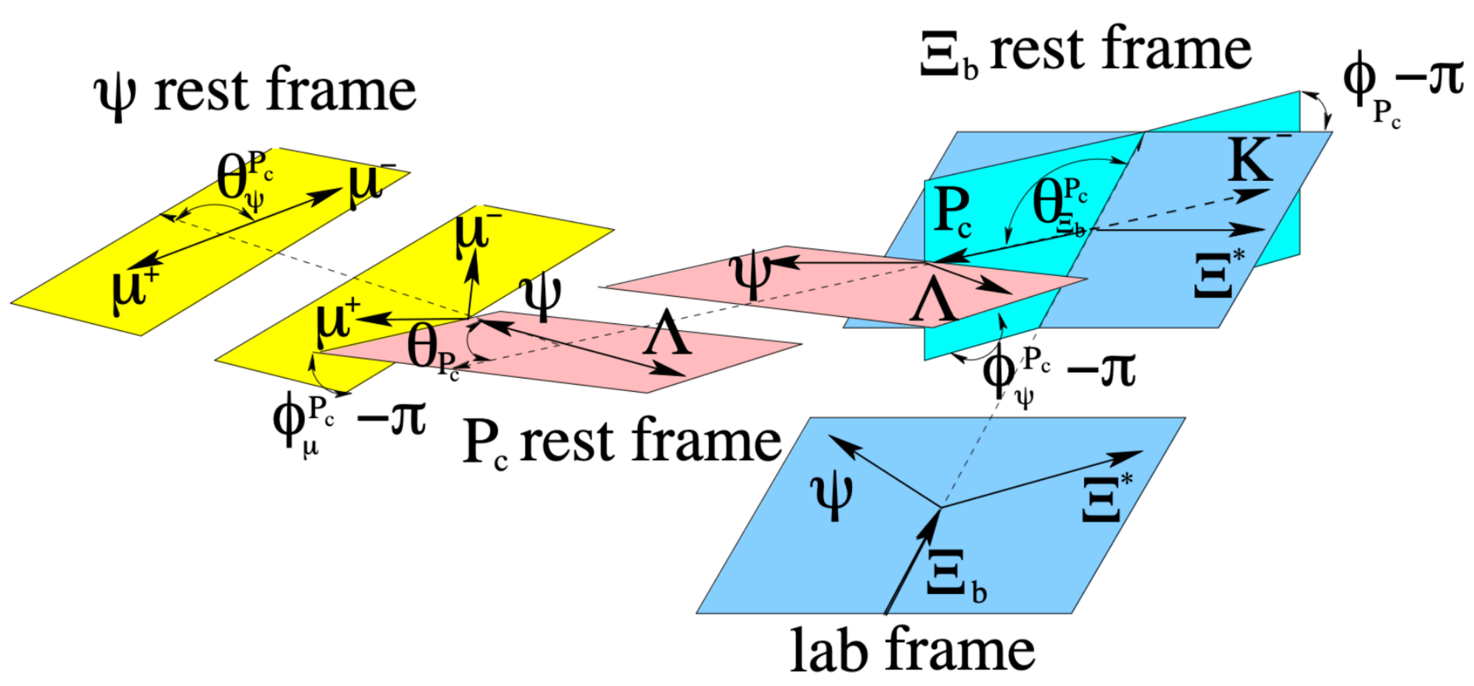


Amplitude analysis of $\Xi_b^- \to J/\psi \Lambda K^-$

[Sci. Bull. 66 (2021) 1278]



$$\mathcal{M}^{\Xi^*}_{\lambda_{\Xi_b},\lambda_\Lambda,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Xi^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Xi_b\to\Xi_n^*\psi}_{\lambda_{\Xi^*},\lambda_\psi} D^{\frac12}_{\lambda_{\Xi_b},\lambda_{\Xi^*}-\lambda_\psi}(0,\theta_{\Xi_b},0)^* \mathcal{H}^{\Xi_n^*\to K\Lambda}_{\lambda_\Lambda,0} D^{J_{\Xi_n^*}}_{\lambda_{\Xi^*},\lambda_\Lambda}(\phi_\Lambda,\theta_{\Xi^*},0)^* R_{\Xi_n^*}(m_{\Lambda K})\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$



$$\mathcal{M}^{P_{cs}}_{\lambda_{\Xi_b},\lambda_\Lambda^{P_{cs}},\Delta\lambda_\mu^{P_{cs}}} \equiv \sum_j\sum_{\lambda_{P_{cs}}}\sum_{\lambda_\psi^{P_{cs}}} \mathcal{H}^{\Xi_b\to P_{cs\,j}K}_{\lambda_{P_{cs}},0} D^{\frac12}_{\lambda_{\Xi_b},\lambda_{P_{cs}}}(\phi_{P_{cs}},\theta^{P_{cs}}_{\Xi_b},0)^* \mathcal{H}^{P_{cs\,j}\to\psi\Lambda}_{\lambda_\psi^{P_{cs}},\lambda_\Lambda^{P_{cs}}} D^{J_{P_{cs\,j}}}_{\lambda_{P_{cs}},\lambda_\psi^{P_{cs}}-\lambda_\Lambda^{P_{cs}}}(\phi_\psi,\theta_{P_{cs}},0)^* R_{P_{cs\,j}}(m_{\psi\Lambda})\; D^1_{\lambda_\psi^{P_{cs}},\Delta\lambda_\mu^{P_{cs}}}(\phi_\mu^{P_{cs}},\theta_\psi^{P_{cs}},0)^*$$

Total amplitude expressed in the basis of helicities in the Ξ^* decay chain:

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Xi_b}}\sum_{\lambda_\Lambda}\sum_{\Delta\lambda_\mu}\left|\mathcal{M}^{\Xi^*}_{\lambda_{\Xi_b},\lambda_\Lambda,\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha_\mu}\sum_{\lambda_\Lambda^{P_{cs}}} d^{\frac12}_{\lambda_\Lambda^{P_{cs}},\lambda_\Lambda}(\theta_\Lambda)\,\mathcal{M}^{P_{cs}}_{\lambda_{\Xi_b},\lambda_\Lambda^{P_{cs}},\Delta\lambda_\mu}\right|^2$$

The number of helicity couplings can be reduced by restricting the L values:

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

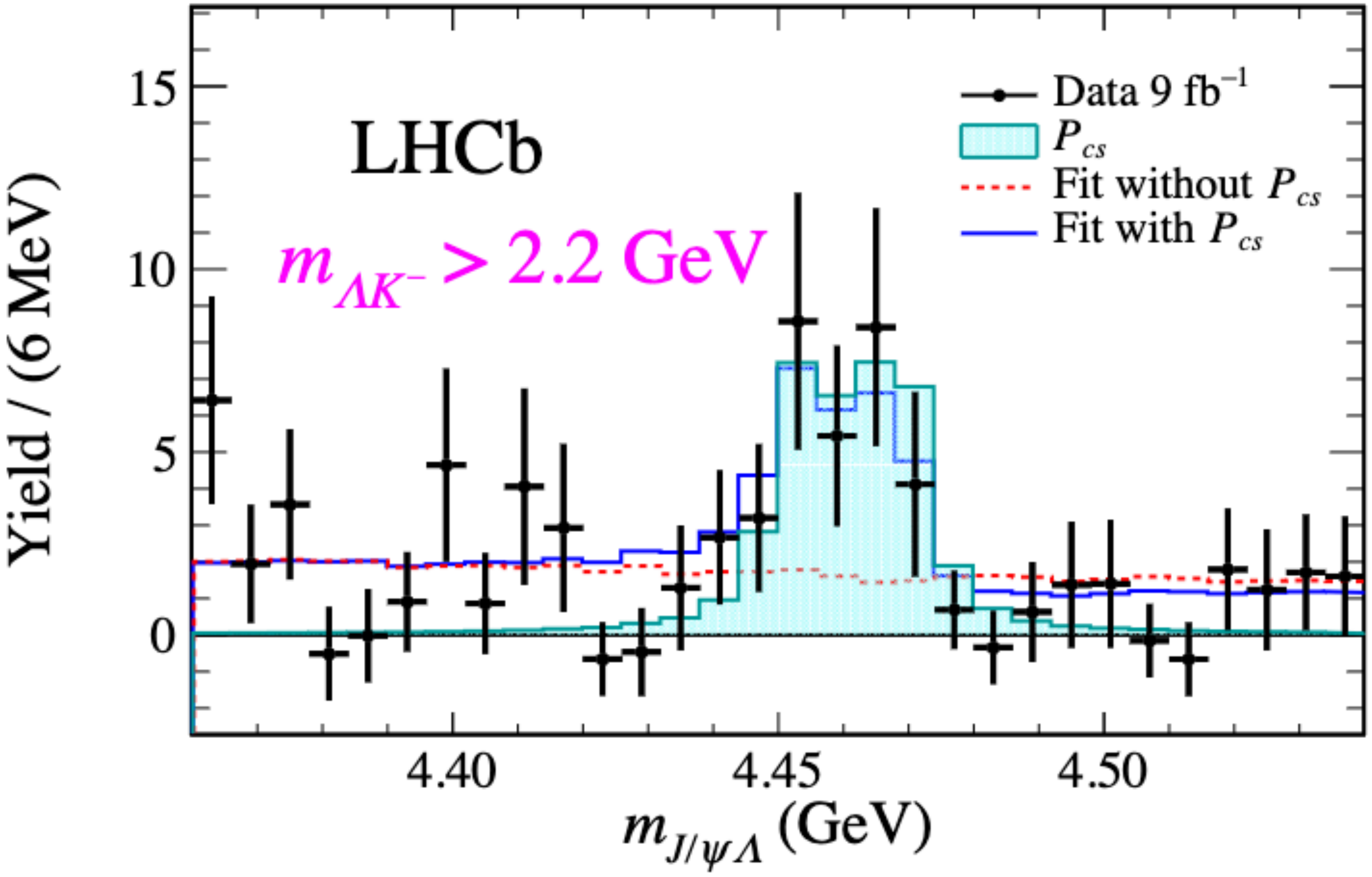
Systematic uncertainties of $P_{\psi s}^{\Lambda}(4459)^0$

[Sci. Bull. 66 (2021) 1278]

Source	$P_{cs}(4459)^0$			$\Xi(1690)^-$			$\Xi(1820)^-$			Ξ^{*-} (1950)	Ξ^{*-} (2030)	NR
	M_0	Γ_0	FF	M_0	Γ_0	FF	M_0	Γ_0	FF	FF	FF	FF
J^P	$^{+4.7}_{-0.3}$	$^{+0.0}_{-5.7}$	$^{+0.1}_{-1.3}$	$^{+1.2}_{-0.1}$	$^{+14.0}_{-0.9}$	$^{+6.7}_{-0.3}$	$^{+0.8}_{-0.2}$	$^{+1.4}_{-0.5}$	$^{+4.2}_{-0.3}$	$^{+0.2}_{-9.4}$	$^{+0.0}_{-4.1}$	$^{+0.9}_{-11.2}$
Model	$^{+0.7}_{-1.1}$	$^{+8.0}_{-2.0}$	$^{+0.7}_{-0.5}$	$^{+0.5}_{-0.4}$	$^{+1.8}_{-13.5}$	$^{+1.9}_{-8.9}$	$^{+1.0}_{-0.6}$	$^{+7.8}_{-8.2}$	$^{+6.9}_{-4.1}$	$^{+49.9}_{-5.4}$	$^{+3.8}_{-1.6}$	$^{+10.3}_{-6.4}$
Λ decay	$^{+0.0}_{-0.7}$	$^{+0.0}_{-4.7}$	$^{+0.0}_{-0.3}$	$^{+0.0}_{-0.4}$	$^{+0.2}_{-0.0}$	$^{+0.0}_{-0.8}$	$^{+0.0}_{-0.5}$	$^{+0.0}_{-7.2}$	$^{+0.0}_{-4.1}$	$^{+2.4}_{-0.0}$	$^{+0.0}_{-1.3}$	$^{+3.9}_{-0.0}$
sWeights	$^{+0.0}_{-0.2}$	$^{+0.3}_{-0.0}$	$^{+0.1}_{-0.0}$	$^{+0.1}_{-0.1}$	$^{+3.1}_{-0.2}$	$^{+1.4}_{-0.0}$	$^{+0.2}_{-0.2}$	$^{+2.2}_{-1.5}$	$^{+1.6}_{-0.5}$	$^{+0.7}_{-1.6}$	$^{+0.0}_{-0.2}$	$^{+0.0}_{-2.7}$
Efficiency	$^{+0.1}_{-0.1}$	$^{+0.0}_{-0.5}$	$^{+0.0}_{-0.1}$	$^{+0.1}_{-0.2}$	$^{+2.1}_{-1.5}$	$^{+0.8}_{-1.3}$	$^{+0.1}_{-0.2}$	$^{+1.1}_{-0.3}$	$^{+0.5}_{-0.7}$	$^{+2.3}_{-1.0}$	$^{+0.3}_{-0.2}$	$^{+1.1}_{-0.9}$
Final	$^{+4.7}_{-1.1}$	$^{+8.0}_{-5.7}$	$^{+0.7}_{-1.3}$	$^{+1.2}_{-0.4}$	$^{+14.0}_{-13.5}$	$^{+6.7}_{-8.9}$	$^{+1.0}_{-0.6}$	$^{+7.8}_{-8.2}$	$^{+6.9}_{-4.1}$	$^{+49.9}_{-9.4}$	$^{+3.8}_{-4.1}$	$^{+10.3}_{-11.2}$

$P_{\psi s}^{\Lambda}(4459)^0$: two-peak hypothesis

[Sci. Bull. 66 (2021) 1278]



$P_{\psi s_1}^{\Lambda}$:

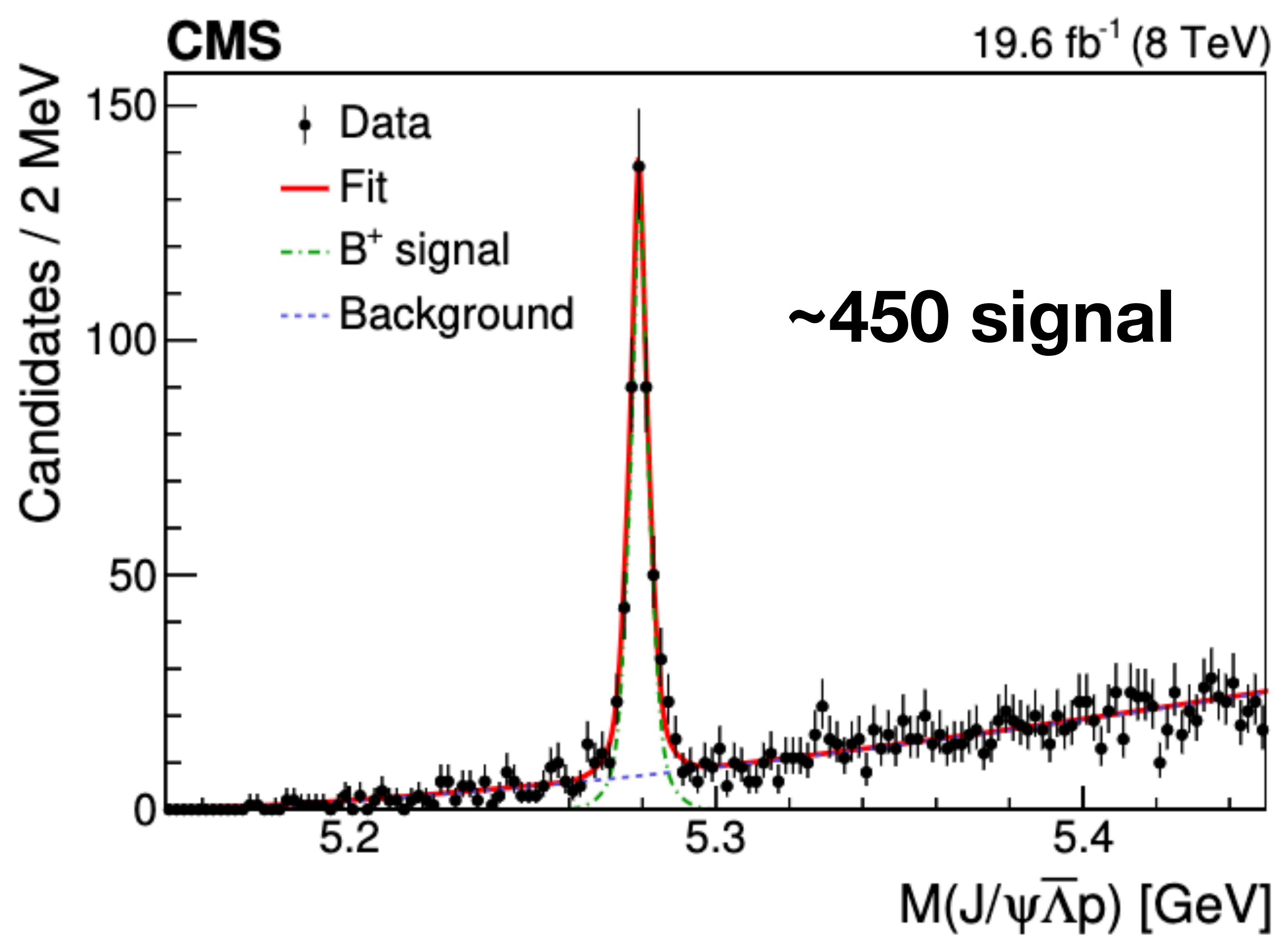
- $m_1 = 4454.9 \pm 2.7$ MeV
- $\Gamma_1 = 7.5 \pm 9.7$ MeV

$P_{\psi s_2}^{\Lambda}$:

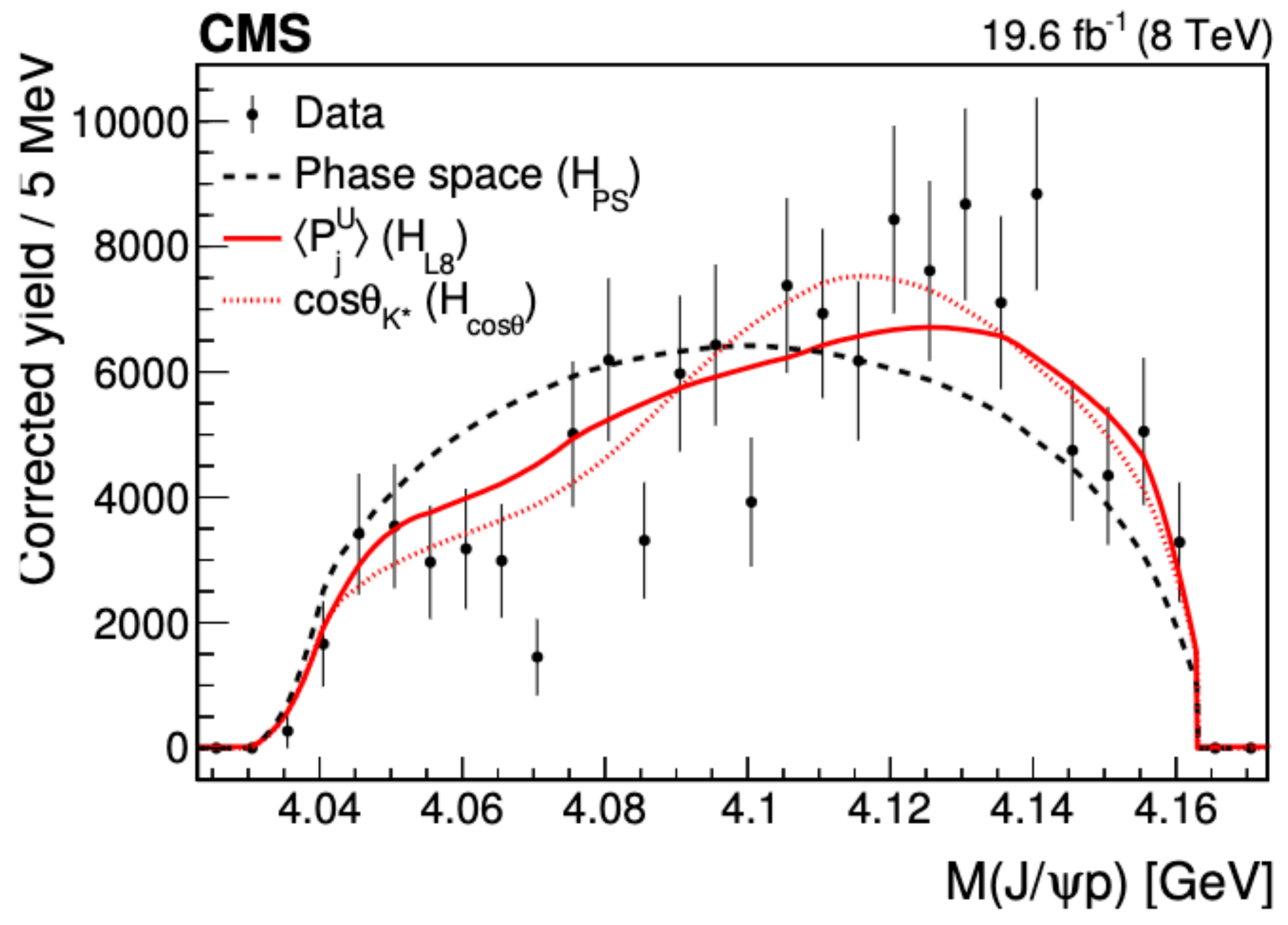
- $m_2 = 4467.8 \pm 3.7$ MeV
- $\Gamma_2 = 5.2 \pm 5.3$ MeV

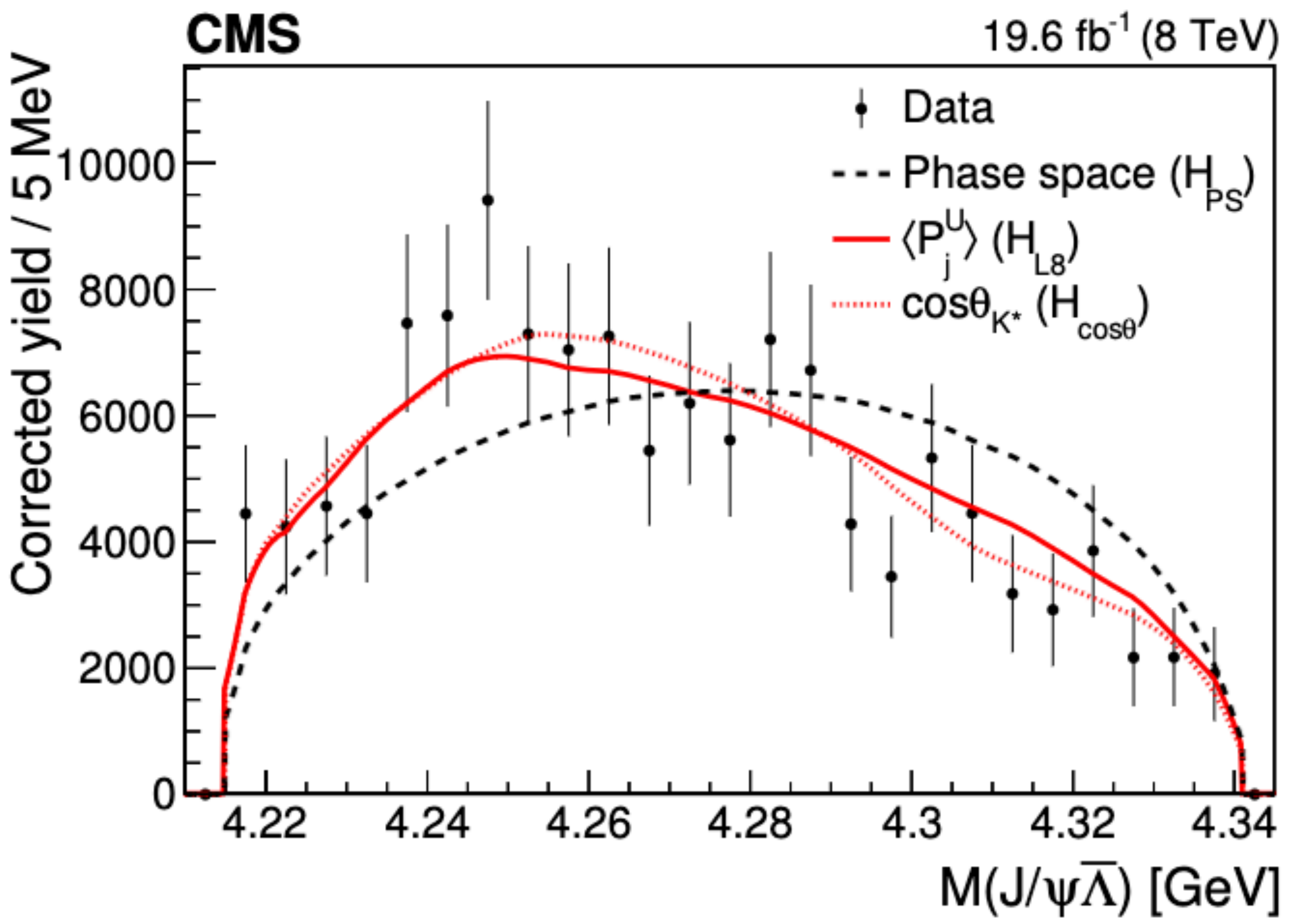
$B^- \rightarrow J/\psi \Lambda \bar{p}$ at CMS: Inconsistent with pure PHSP

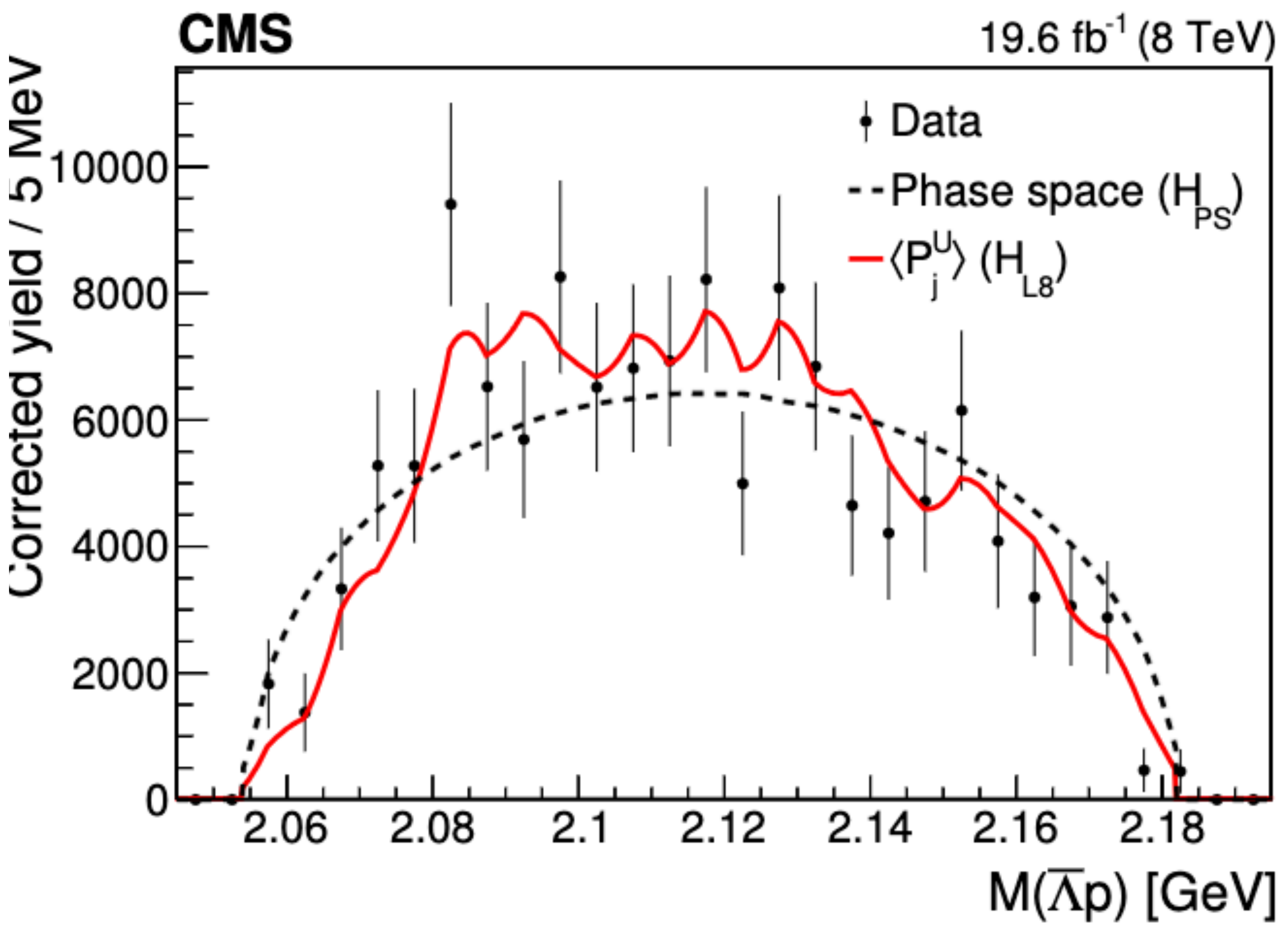
[JHEP 12 (2019) 100]



Inconsistent with pure PHSP,
but can be described by adding $K^*_{2,3,4}$



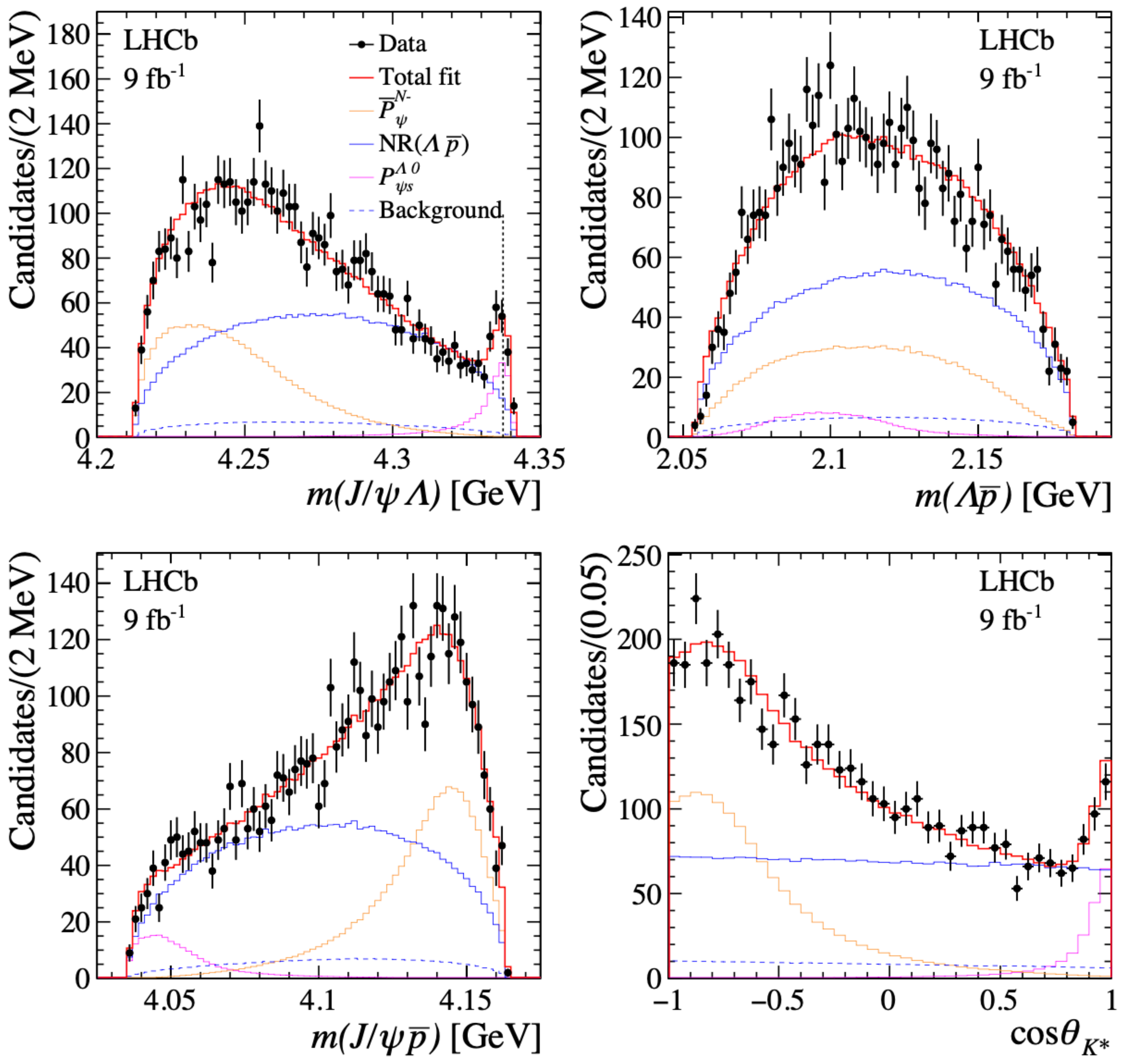




Amplitude fit with an additional $\bar{P}_{\psi}^{N^-}$

[arXiv: 2210.10346]
Accepted by PRL

This model is discarded
due to an increase of 80 in $-2\ln\mathscr{L}$,
compared to the nominal fit.



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

[arXiv: 2210.10346]
Accepted by PRL

$$O^{K^*}_{\lambda_{J/\psi},\lambda_{\bar\Lambda},\lambda_p}(m^2_{J/\psi\bar\Lambda}, m^2_{\bar\Lambda p}) = \sum_{j^{K^*}}\sum_{\{\lambda'\}}\sqrt{\frac{2j^{K^*}+1}{4\pi}}\, H^{B\to K^* J/\psi}_{\lambda'_{J/\psi}}\, R(m^2_{\bar\Lambda p})\, d^{j^{K^*}}_{\lambda'_{J/\psi},\lambda'_{\bar\Lambda}-\lambda'_p}(\theta_{K^*}) H^{K^*\to\bar\Lambda p}_{\lambda'_{\bar\Lambda},\lambda'_p} \tag{5}$$

$$\times\, \delta_{\lambda'_{J/\psi},\lambda_{J/\psi}}\, d^{1/2}_{\lambda'_{\bar\Lambda},\lambda_{\bar\Lambda}}(\zeta^{\bar\Lambda}_{Bp})\, d^{1/2}_{\lambda'_p,\lambda_p}(-\zeta^{p}_{B\bar\Lambda}) \times (-1)^{j^{J/\psi}-\lambda'_{J/\psi}}(-1)^{j^p-\lambda'_p},$$

$$O^{P_c}_{\lambda_{J/\psi},\lambda_{\bar\Lambda},\lambda_p}(m^2_{J/\psi\bar\Lambda}, m^2_{\bar\Lambda p}) = \sum_{j^{P_c}}\sum_{\{\lambda'\}}\sqrt{\frac{2j^{P_c}+1}{4\pi}}\, H^{B\to P_c\bar\Lambda}_{\lambda'_{\bar\Lambda}}\, R(m^2_{pJ/\psi})\, d^{j^{P_c}}_{\lambda'_{\bar\Lambda},\lambda'_p-\lambda'_{J/\psi}}(\theta_{P_c}) H^{P_c\to pJ/\psi}_{\lambda'_p,\lambda'_{J/\psi}} \tag{6}$$

$$\times\, d^{1}_{\lambda'_{J/\psi},\lambda_{J/\psi}}(-\zeta^{J/\psi}_{Bp})\, \delta_{\lambda'_{\bar\Lambda},\lambda_{\bar\Lambda}}\, d^{1/2}_{\lambda'_p,\lambda_p}(\zeta^{p}_{BJ/\psi}) \times (-1)^{j^{\bar\Lambda}-\lambda'_{\bar\Lambda}}(-1)^{j^{J/\psi}-\lambda'_{J/\psi}},$$

$$O^{\bar P_L}_{\lambda_{J/\psi},\lambda_{\bar\Lambda},\lambda_p}(m^2_{J/\psi\bar\Lambda}, m^2_{\bar\Lambda p}) = \sum_{j^{\bar P_L}}\sum_{\{\lambda'\}}\sqrt{\frac{2j^{\bar P_L}+1}{4\pi}}\, H^{B\to \bar P_L p}_{\lambda'_p}\, R(m^2_{J/\psi\bar\Lambda})\, d^{J^{\bar P_L}}_{\lambda_p,\lambda'_{J/\psi}-\lambda'_{\bar\Lambda}}(\theta_{\bar P_L}) H^{\bar P_L\to J/\psi\bar\Lambda}_{\lambda'_{J/\psi},\lambda'_{\bar\Lambda}} \tag{7}$$

$$\times\, d^{1}_{\lambda'_{J/\psi},\lambda_{J/\psi}}(\zeta^{J/\psi}_{B\bar\Lambda})\, d^{1/2}_{\lambda'_{\bar\Lambda},\lambda_{\bar\Lambda}}(-\zeta^{\bar\Lambda}_{BJ/\psi})\, \delta_{\lambda'_p,\lambda_p} \times (-1)^{j^p-\lambda'_p}(-1)^{j^{\bar\Lambda}-\lambda'_{\bar\Lambda}},$$

Final amplitude:

$$A_{\lambda_p,\lambda_{\bar p},\Delta\mu}(6D) = \sum_{\lambda_{\bar\Lambda},\lambda_{J/\psi}}\left(O^{K^*}+O^{P_c}+O^{\bar P_L}\right)_{\lambda_{J/\psi},\lambda_{\bar\Lambda},\lambda_p}(m^2_{J/\psi\bar\Lambda}, m^2_{\bar\Lambda p})$$

$$\times\, D^{1*}_{\lambda_{J/\psi},\Delta_\mu}(\phi_\mu,\theta_{J/\psi},0)\, H^{\bar\Lambda\to\bar p\pi}_{\lambda_{\bar p}}\, D^{1/2*}_{\lambda_{\bar\Lambda},\lambda_{\bar p}}(\phi_{\bar p},\theta_{\bar\Lambda},0)$$

Systematic uncertainties of $P_{\psi s}^{\Lambda}(4338)^0$

[arXiv: 2210.10346]
Accepted by PRL

Source	$M_{P_{\psi s}^{\Lambda}}$	$\Gamma_{P_{\psi s}^{\Lambda}}$	$f_{P_{\psi s}^{\Lambda}}$	$f_{\mathrm{NR}(J/\psi\overline{p})}$	$f_{\mathrm{NR}(\Lambda\overline{p})}$
Hadron radius	0.1	0.4	0.3	0.2	0.2
LS values	0.3	0.1	0.8	0.7	0.6
Breit–Wigner $\overline{P}_{\psi}^{N-}$	0.1	0.9	0.8	...	...
$J^P(P_{\psi s}^{\Lambda}{}^0)$ assignment	0.1	0.9	1.2	0.4	0.9
Fitting procedure	0.1	0.2	0.1	1.0	1.1
Efficiency	0.02	0.19	0.02	0.3	0.2
Λ decay parameters	0.02	0.04	0.01	0.3	0.2
Background	0.01	0.05	0.96	0.4	0.7
Mass resolution	0.01	0.03	0.01	0.1	0.1
Total	0.4	1.3	1.9	1.4	1.7