Hadron spectroscopy at LHCb (recent results)

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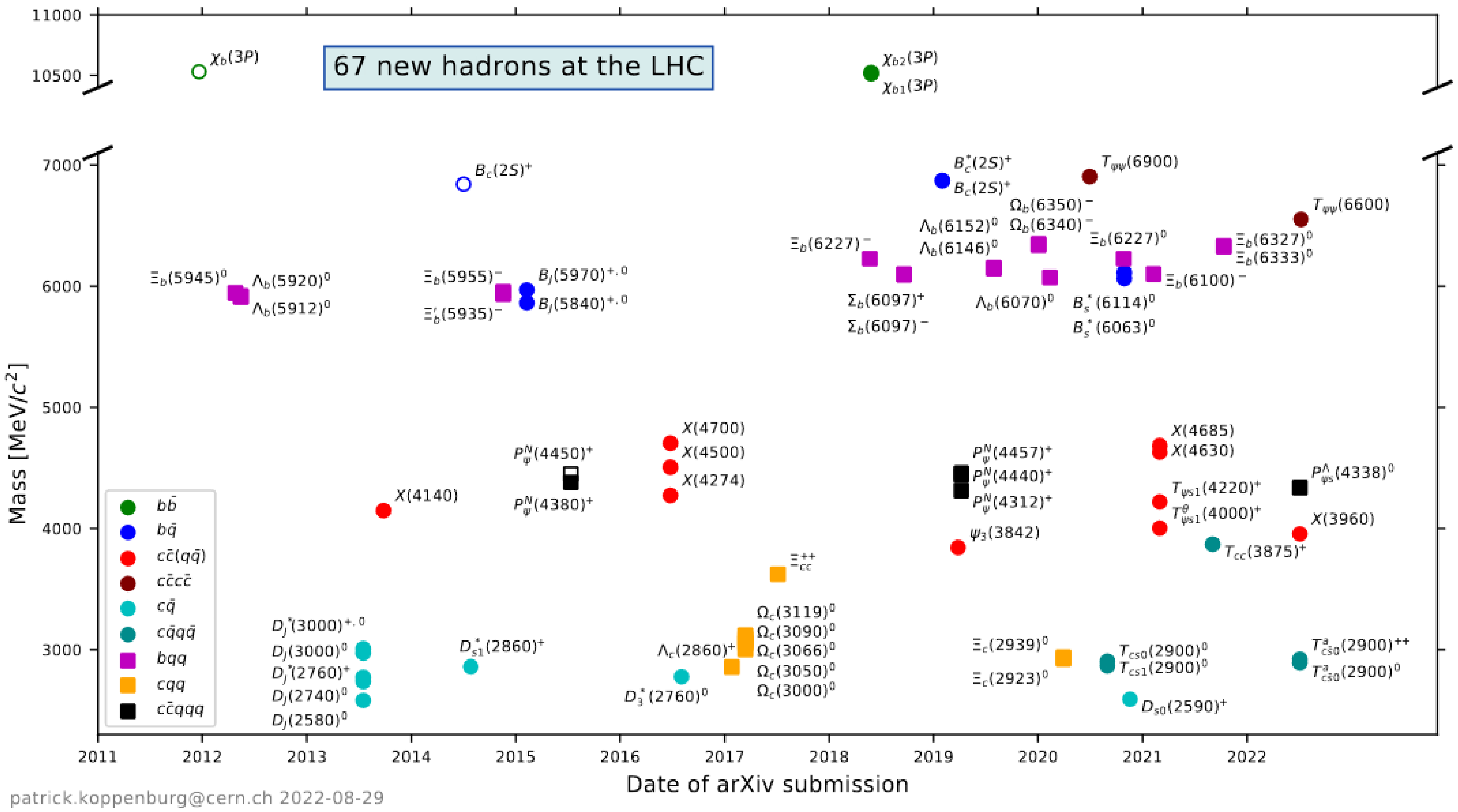
8th of September 2022, QNP-2022 – virtual

New particles discovered at the LHC

https://www.nikhef.nl/~pkoppenb/particles.html



- Higgs boson + **67 new hadronic states** so far (most from LHCb)

New exotic hadrons discovered at the LHC

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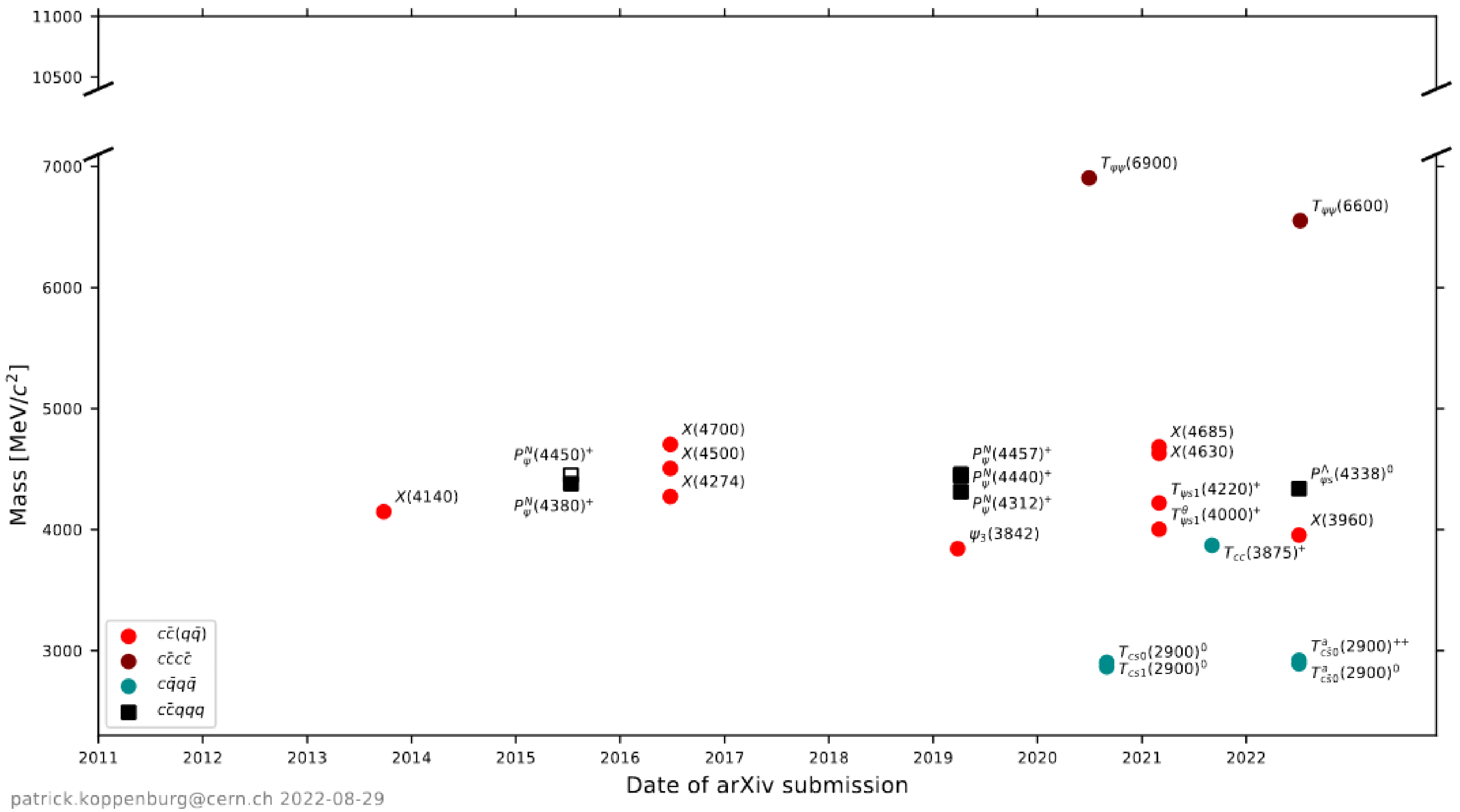
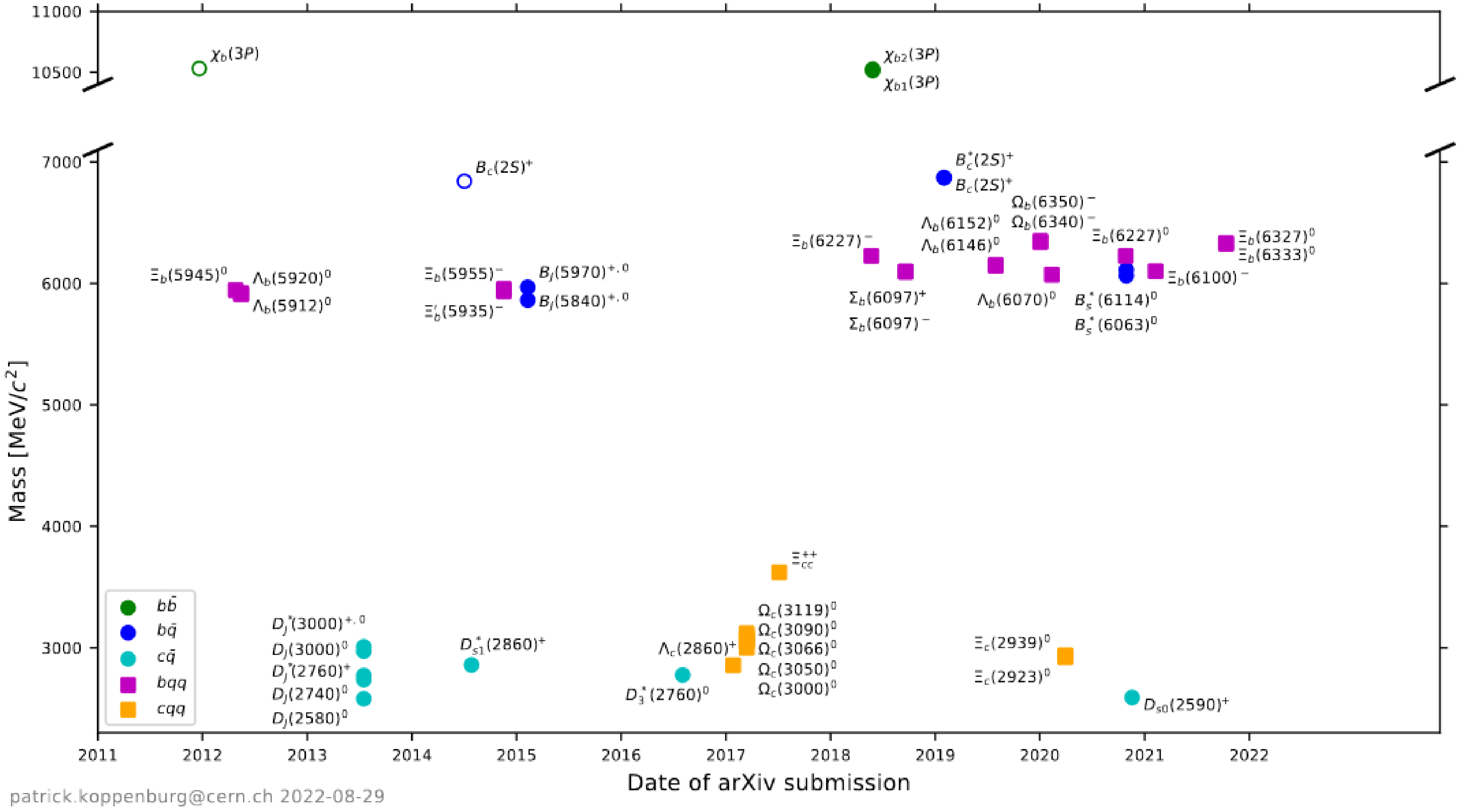


- Higgs boson + **67 new hadronic states** so far (most from LHCb)
- Exciting discoveries in the exotic sector (**see a contribution done by Mikhail Mikhasenko**)
- What about conventional hadrons?

New conventional hadrons discovered at the LHC

https://www.nikhef.nl/~pkoppenb/particles.html



- Higgs boson + **67 new hadronic states** so far (most from LHCb)
- Exciting discoveries in the exotic sector (**see a contribution done by Mikhail Mikhasenko**)
- What about conventional hadrons?
- No new conventional states observed in 2022
- **Many results on properties:**
  - ❑ **new decay channels,**
  - ❑ **branching ratios,**
  - ❑ **lifetimes**

LHCb: Find \ Identify \ Measure

Excellent vertexing allows efficient heavy quark hadrons selection / gives access to decay time distribution / prompt-secondary separation for charm

Protons collision point

$\sigma(IP) \approx 20\mu m$
$\delta p/p = 0.4 - 0.6~\%$
$\epsilon_{track} > 96~\%$

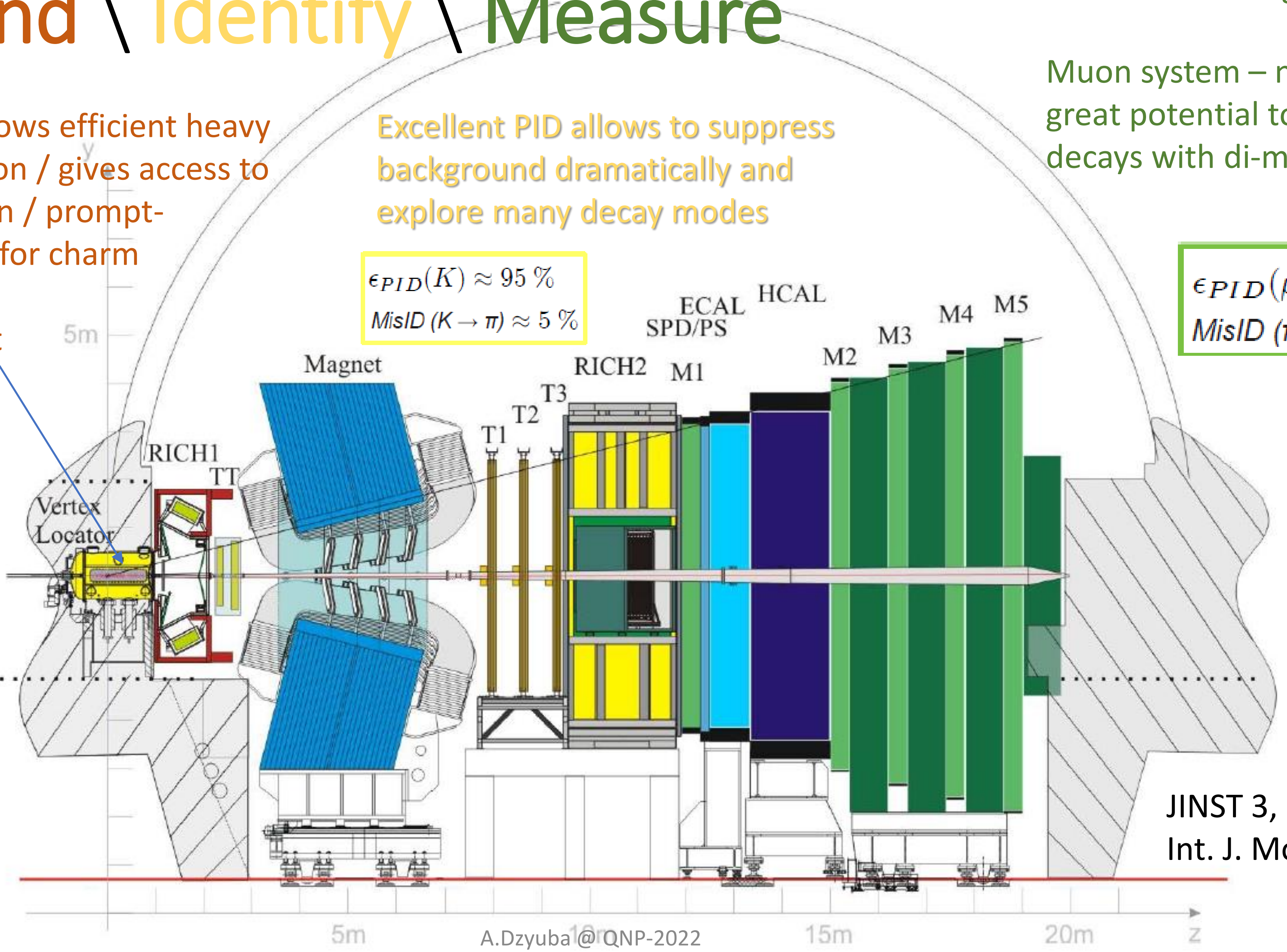
Excellent PID allows to suppress background dramatically and explore many decay modes

$\epsilon_{PID}(K) \approx 95~\%$
MisID $(K \to \pi) \approx 5~\%$

Excellent tracking

Muon system – nice tagging & great potential to search for rare decays with di-muons

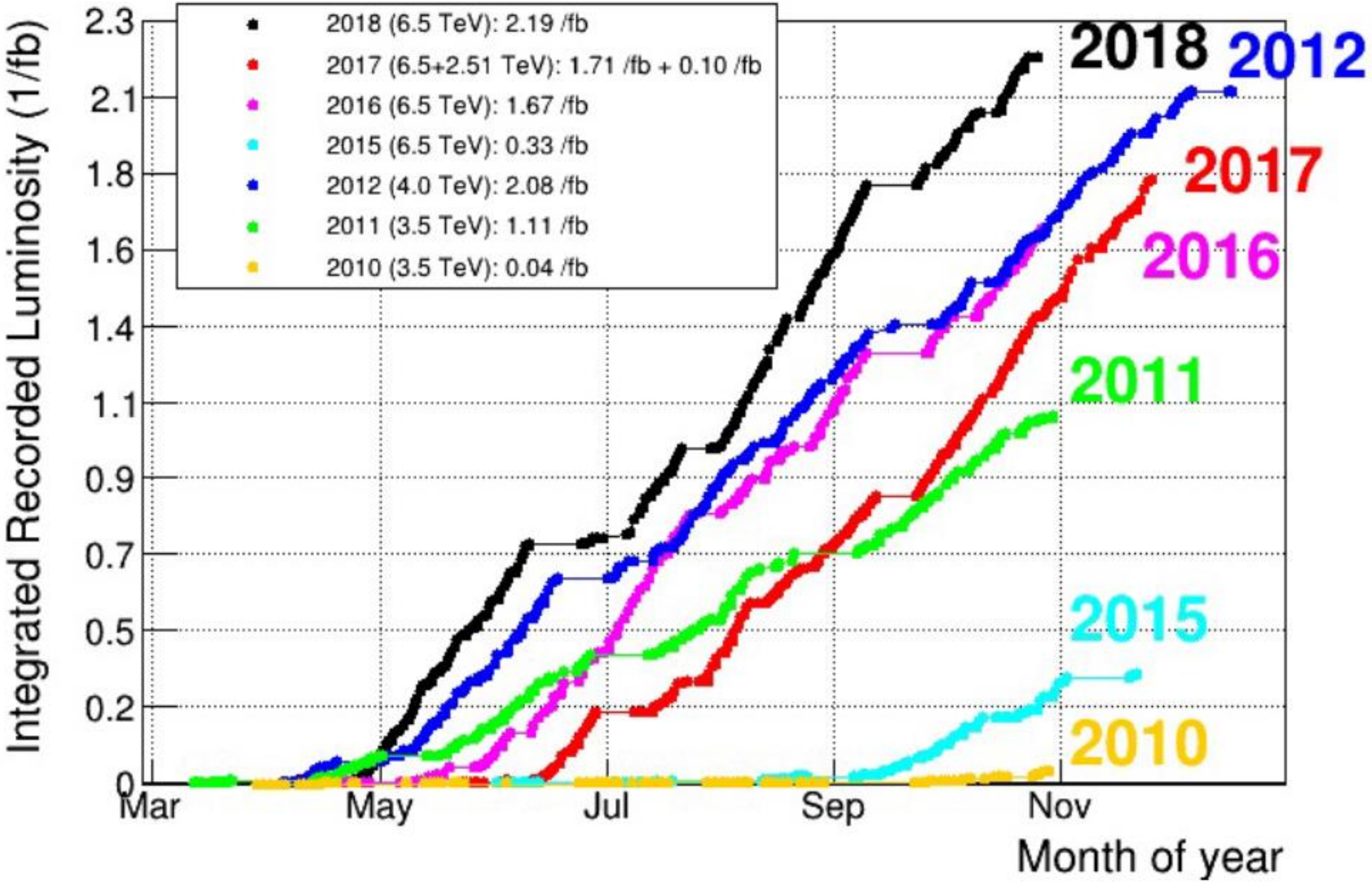
$\epsilon_{PID}(\mu) \approx 97~\%$
MisID $(\pi \to \mu) \approx 3~\%$



JINST 3, (2008) S08005;
Int. J. Mod. Phys. A 30, (2015) 153022

LHCb data taking

- ✓ Run-I (2010-12):
  - 1 fb^{-1} at 7 TeV
  - 2 fb^{-1} at 8 TeV
- ✓ Run-II (2015-18):
  - 6 fb^{-1} at 13 TeV
- ➢ Run-III
  - emerging now



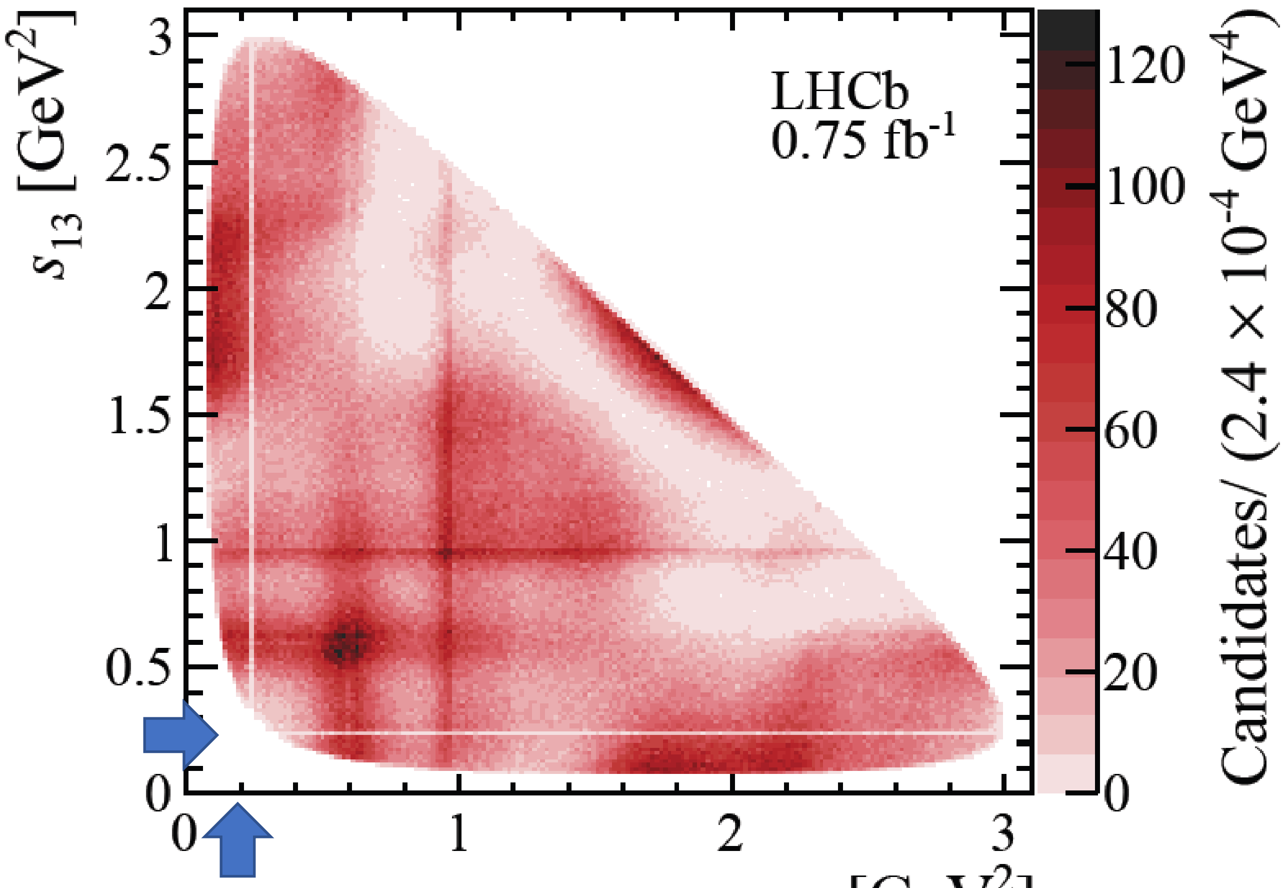
Recent spectroscopy results for conventional hadrons

Will be discussed today

- **I) Amplitude analyses for charm hadron decays**
  - ✓ Amplitude analysis of $D^+ \to \pi^-\pi^+\pi^+$ — arXiv:2208.03300
  - ✓ Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ — arXiv:2208.03262
- **II) Decays of B mesons into charmonia and light hadrons**
  - ❑ B_c^+ into charmonia and many hadrons — arXiv:2208.08660
  - ❑ Intermediate charmonia contributions in $B^+ \to J/\psi\eta K^+$ — arXiv:2202.04045
  - ❑ Measurement of τ_L using the $B_s^0 \to J/\psi\eta$ — arXiv:2206.03088
- **III) Baryonic decays of B mesons**
  - ❖ Search for the rare baryonic decay $B_s^0 \to p\bar{p}$ — arXiv:2206.06673
  - ❖ Study of $B^+ \to \Lambda_c^+\bar{\Lambda}_c^- K^-$ — LHCb-PAPER-2022-028 (in preparation)
- Baryons which contain two heavy quarks
  - ➢ Search for $\Xi_{bc}^+ \to J/\psi\Xi_c^+$ — arXiv:2204.09541
  - ➢ Observation of $\Xi_{cc}^{++} \to \Xi_c'^+\pi^+$ — JHEP 05 (2022) 038

Amplitude analysis of the $D^{+} \to \pi^{-}\pi^{+}\pi^{+}$ decay

- 8 TeV sample collected in 2012 during Run-I data taking
- The sample contains ~600k candidates with a signal purity of 95%.
- Resonant structure from the Dalitz plot analysis (s_{1i}: 1= π^{-}, i={2,3} randomly assigned π^{+})
- S-wave amplitude is extracted as a function of $\pi^{-}\pi^{+}$ mass, and spin-1 and spin-2 resonances coherently included (isobar model)
- Quasi model dependent partial wave analysis



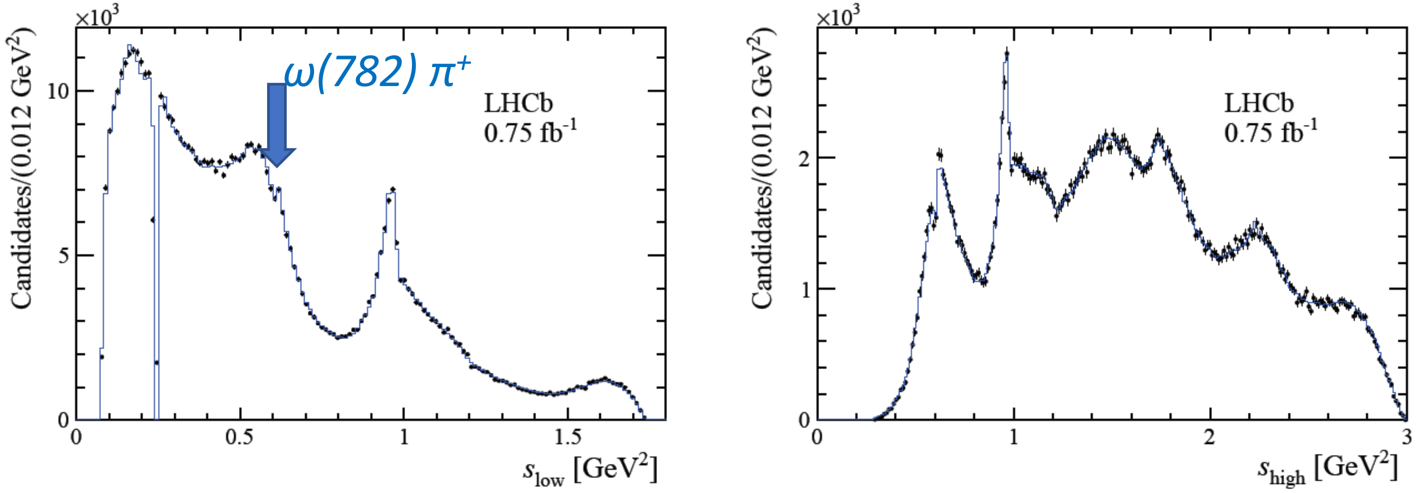
Veto on K_S^0

arXiv:2208.03300

Amplitude analysis of the $D^+ \to \pi^- \pi^+ \pi^+$ decay

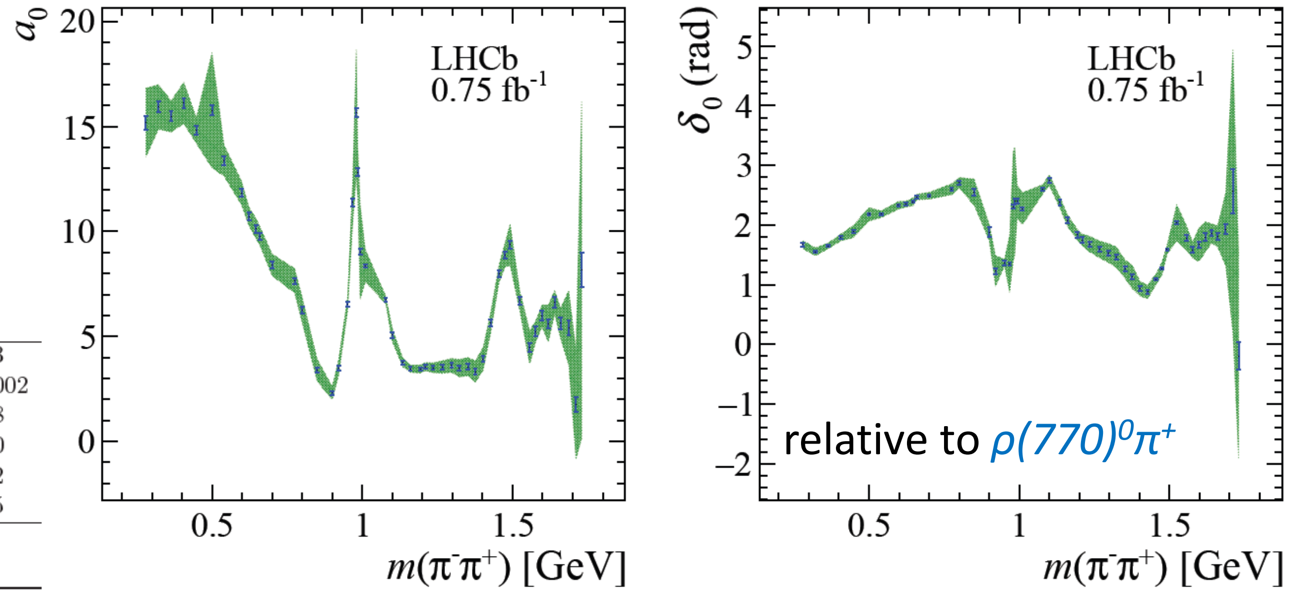
$$\mathcal{A}(s_{12}, s_{13}) = \left[\mathcal{A}_{\text{S-wave}}(s_{12}) + \sum_i a_i e^{i\delta_i} \mathcal{A}_i(s_{12}, s_{13})\right] + (s_{12} \leftrightarrow s_{13}),$$

$$\mathcal{A}_{\text{S-wave}}(s_{12}) = a_0(s_{12}) e^{i\delta_0(s_{12})},$$



- The S-wave component is found to be dominant
- Significant contribution from followed by the $\rho(770)^0\pi^+$ and $f_2(1270)\pi^+$ components.
- A small contribution from the $\omega(782)$ decay **is seen for the 1st time** in the $D^+ \to \pi^- \pi^+ \pi^+$ decay

Component	Magnitude	Phase [°]	Fit fraction [%]
$\rho(770)^0\pi^+$	1 [fixed]	0 [fixed]	$26.0 \pm 0.3 \pm 1.6 \pm 0.3$
$\omega(782)\pi^+$	$(1.68 \pm 0.06 \pm 0.15 \pm 0.02) \times 10^{-2}$	$-103.3 \pm 2.1 \pm 2.6 \pm 0.4$	$0.103 \pm 0.008 \pm 0.014 \pm 0.002$
$\rho(1450)^0\pi^+$	$2.66 \pm 0.07 \pm 0.24 \pm 0.22$	$47.0 \pm 1.5 \pm 5.5 \pm 4.1$	$5.4 \pm 0.4 \pm 1.3 \pm 0.8$
$\rho(1700)^0\pi^+$	$7.41 \pm 0.18 \pm 0.47 \pm 0.71$	$-65.7 \pm 1.5 \pm 3.8 \pm 4.6$	$5.7 \pm 0.5 \pm 1.0 \pm 1.0$
$f_2(1270)\pi^+$	$2.16 \pm 0.02 \pm 0.10 \pm 0.02$	$-100.9 \pm 0.7 \pm 2.0 \pm 0.4$	$13.8 \pm 0.2 \pm 0.4 \pm 0.2$
S-wave			$61.8 \pm 0.5 \pm 0.6 \pm 0.5$
$\sum_i \text{FF}_i$			112.8
χ^2/ndof (range)	[1.47 - 1.78]		$-2\log\mathcal{L} = 805622$



arXiv:2208.03300

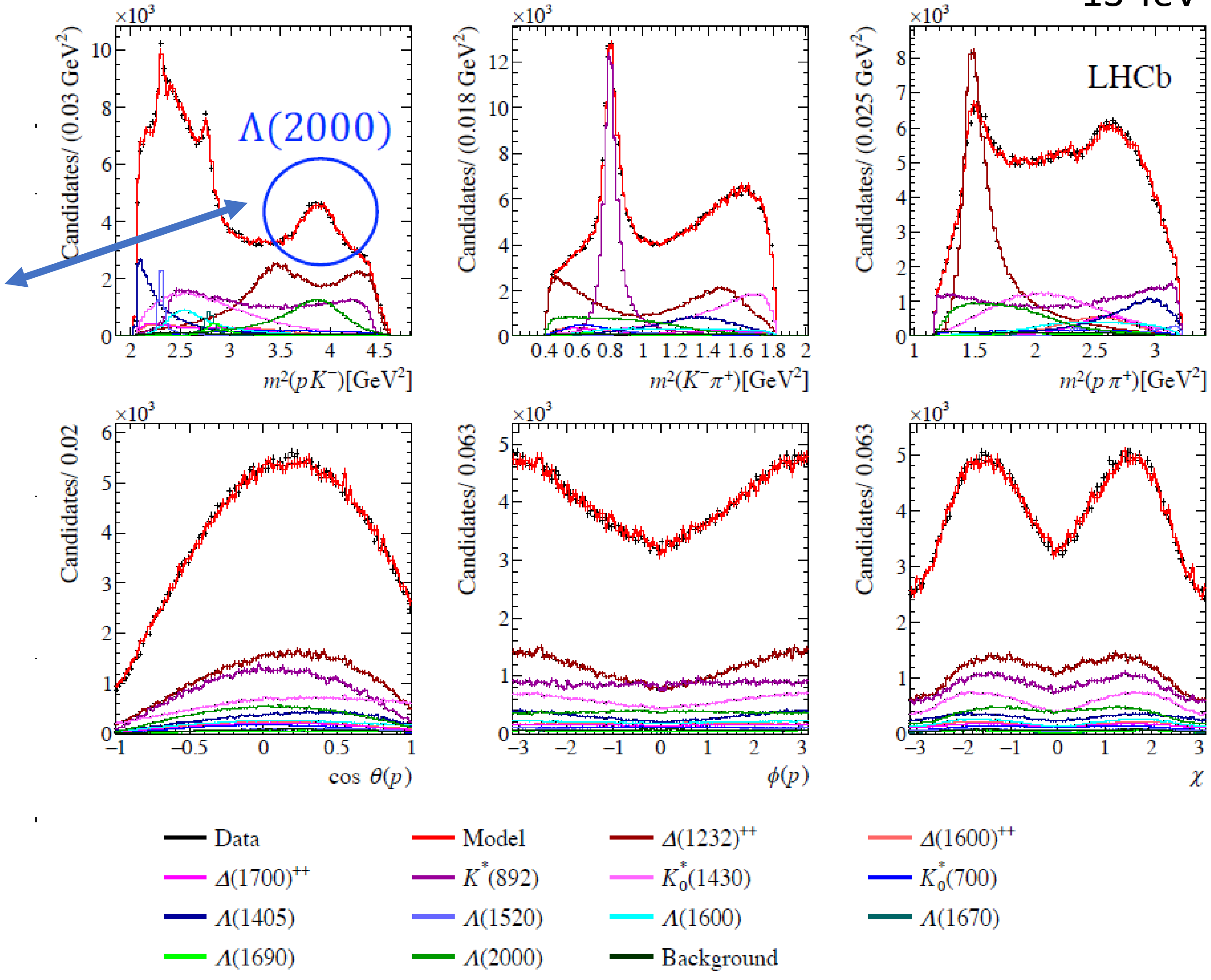
Amplitude analysis of the $\Lambda_c^+ \to pK^-\pi^+$ decay

- 400k candidates from semileptonic b-decays
- Purity of the sample: 98.3%
- All parameters of the amplitude model reported
- **M = 1988±2±21MeV, Γ = 179±4±16 MeV, J^P=1/2⁻**

Resonance	J^P	Mass (MeV)	Width (MeV)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5
$\Lambda(1520)$	$3/2^-$	1515 – 1523	10 – 20
$\Lambda(1600)$	$1/2^+$	1630	250
$\Lambda(1670)$	$1/2^-$	1670	30
$\Lambda(1690)$	$3/2^-$	1690	70
$\Lambda(2000)$	$1/2^-$	1900 – 2100	20 – 400
$\Delta(1232)^{++}$	$3/2^+$	1232	117
$\Delta(1600)^{++}$	$3/2^+$	1640	300
$\Delta(1700)^{++}$	$3/2^-$	1690	380
$K_0^*(700)$	0^+	824	478
$K^*(892)$	1^-	895.5	47.3
$K_0^*(1430)$	0^+	1375	190

Largest contributions

13 TeV



arXiv:2208.03262

II) *b*-physics with charmonia

- Muons are easy to identify online, therefore they provides a fruitful trigger options widely used in LHCb
- Decay of ***B*** mesons into charmonum states + light hadrons are used:
  - As a tool for CPV studies in *b*-sector.
  - As calibration channels for searches of new physics
- But they can also provide:
  - Playground to test different QCD approaches
  - An excellent opportunity for studies of charmonium and charmonium-like exotic states
  - Tool to measure various properties of ***B*** mesons

B_c^+ decays into *charmonia + hadrons*

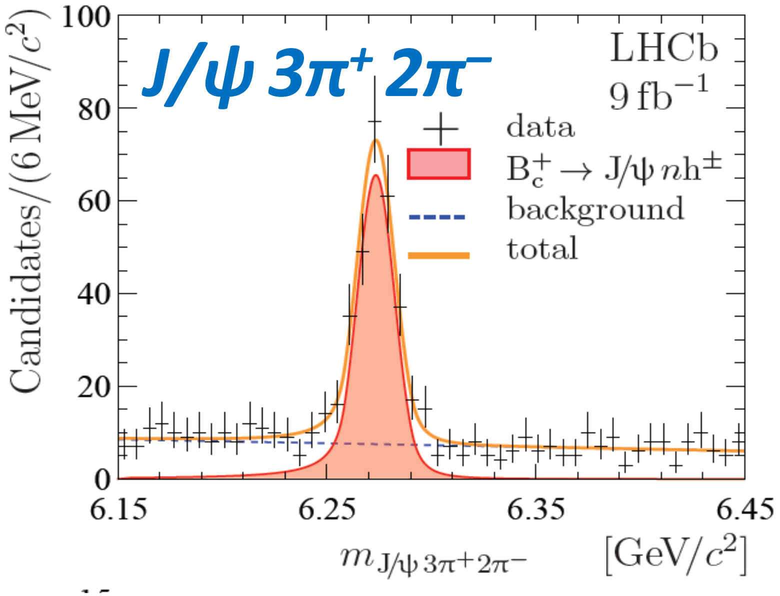
- Run-I and II datasets
- Three decay channels

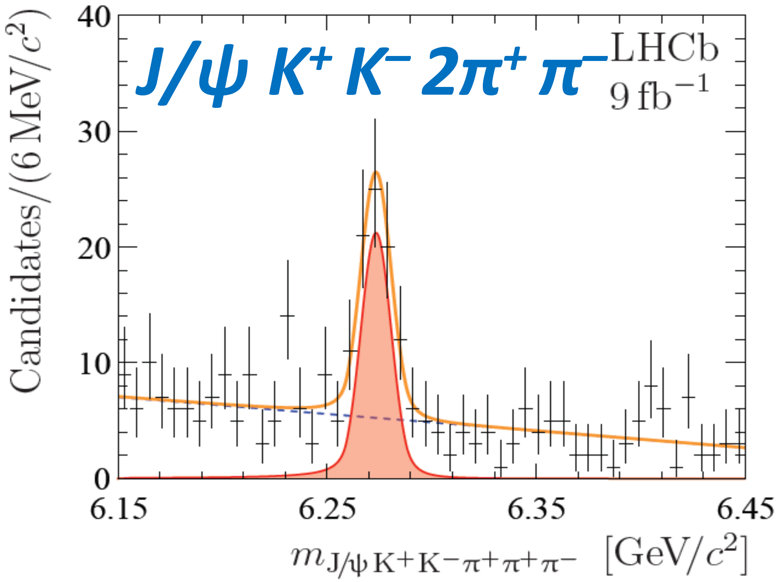
- Large number of light hadrons and large energy release
- Test a possibility to apply statistical, or quasi-classical, approaches to describe the multibody system of the light hadrons

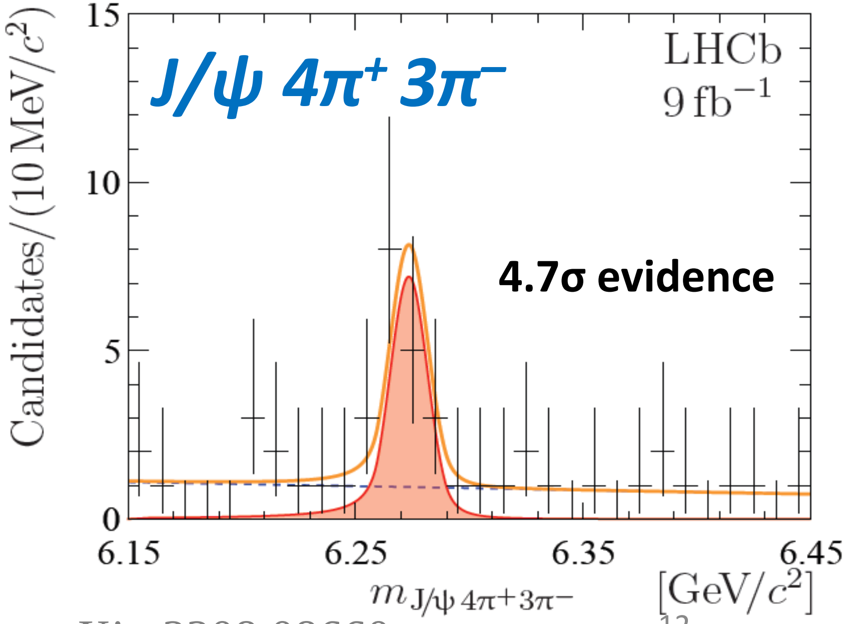
$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+2\pi^-)},$$

$$\mathcal{R}^{J/\psi 4\pi^+3\pi^-}_{J/\psi 3\pi^+2\pi^-} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi 4\pi^+3\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+2\pi^-)},$$

$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} \equiv \frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+2\pi^-)}.$$



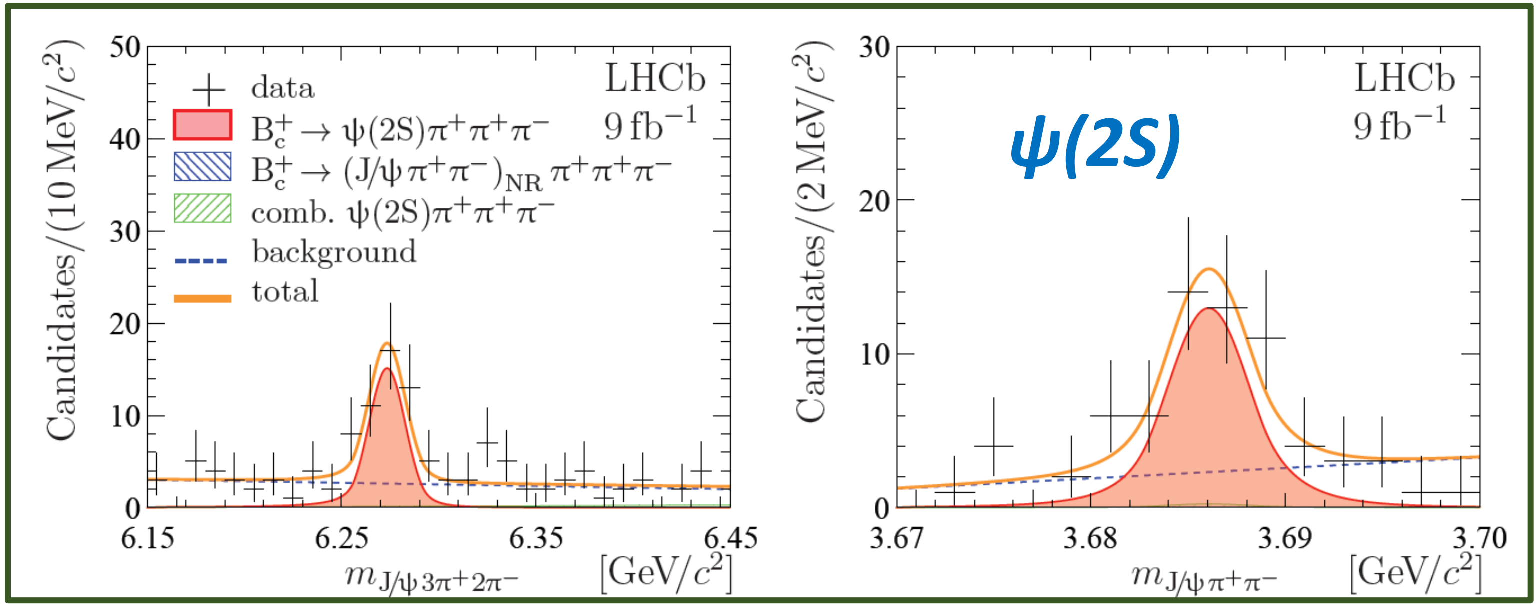




arXiv:2208.08660

B_c^+ into *charmonia + hadrons*

- For *$J/\psi 3\pi^+ 2\pi^-$* channel a contribution from *$\psi(2s)$* is observed
- Distributions of events in the ***ψ(2S)*** *region* →



- Ratios of branching fractions are reported
- The mass spectra for the light-hadron system, as well as the mass spectra for the intermediate combinations of light hadrons agree with the phenomenological model based on QCD factorization approach

$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (33.7 \pm 5.7 \pm 1.6) \times 10^{-2}$$

$$\mathcal{R}^{J/\psi 4\pi^+3\pi^-}_{J/\psi 3\pi^+2\pi^-} = (28.5 \pm 8.7 \pm 2.0) \times 10^{-2}$$

$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} = (17.6 \pm 3.6 \pm 0.8) \times 10^{-2}$$

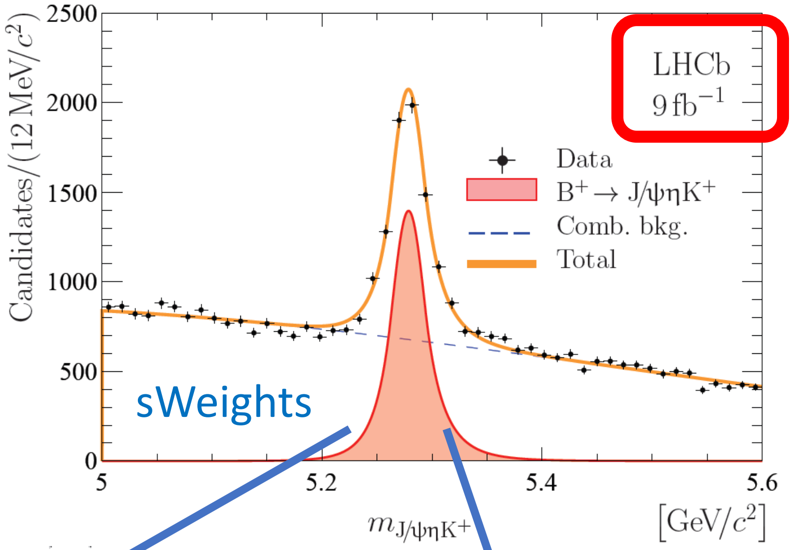
arXiv:2208.08660

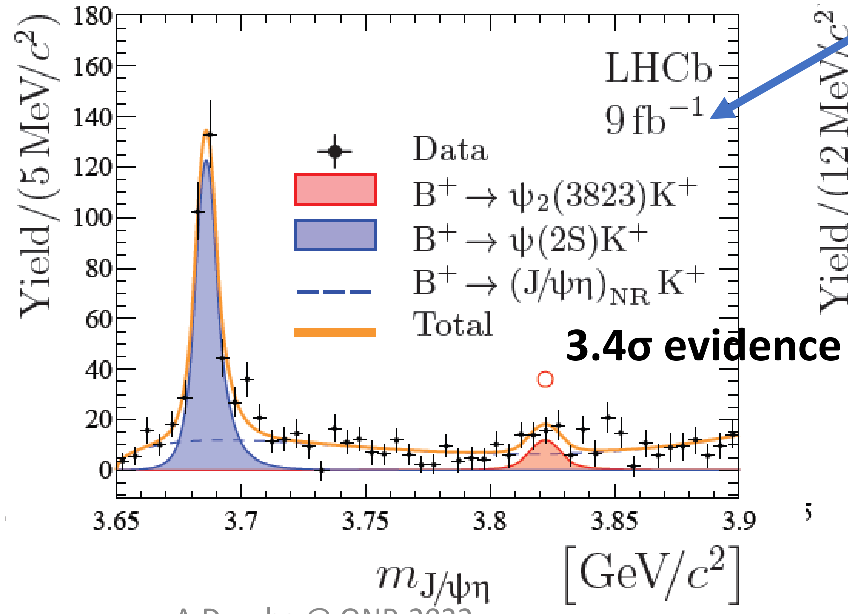
Intermediate charmonia contributions in $B^+ \to J/\psi \eta K^+$

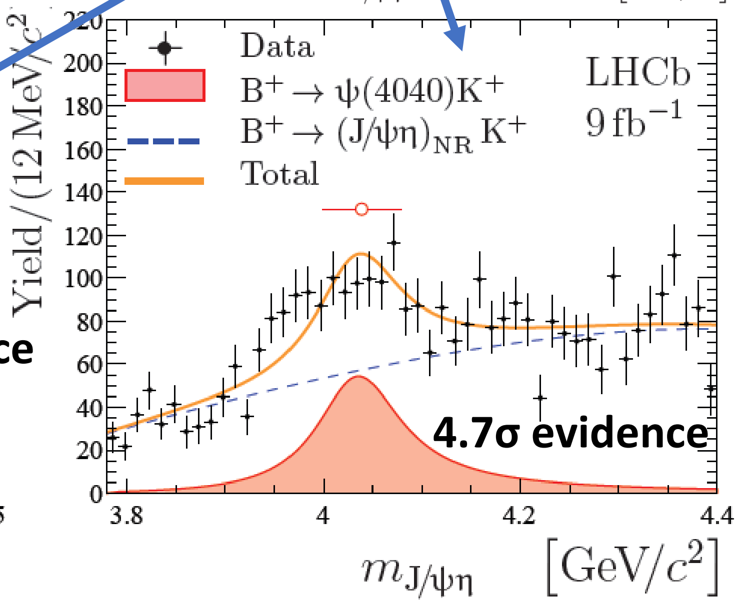
- Exclusive *B*-decays provides an excellent opportunity for studies of charmonium and charmonium-like exotic states
- Some models predict the existence of $\chi_{c1}(3872)$ partner ($X_c' \to J/\psi\eta$) →
- Same ratios for other states
- $J/\psi \to \mu^+\mu^-$, $\eta \to \gamma\gamma$

$$F_X \equiv \frac{\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)}{\mathcal{B}(B^+ \to \psi(2S)K^+) \times \mathcal{B}(\psi(2S) \to J/\psi\eta)},$$

$$B_X \equiv \mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)$$







	Upper limit at 90% CL	
	F_X [10^{-2}]	B_X [10^{-7}]
ψ(3770)	2.2	4.6
ψ_3(3842)	2.9	6.1
ψ(4160)	4.2	8.7
ψ(4415)	4.6	9.6
R(3760)	2.0	4.1
R(3790)	3.2	6.7
$Z_c(3900)^0$	2.1	4.3
ψ(4230)	1.9	3.9
ψ(4360)	6.0	12.4
ψ(4390)	11.6	24.1
$Z_c(4430)^0$	6.1	12.7
X_C'	1.9	3.9

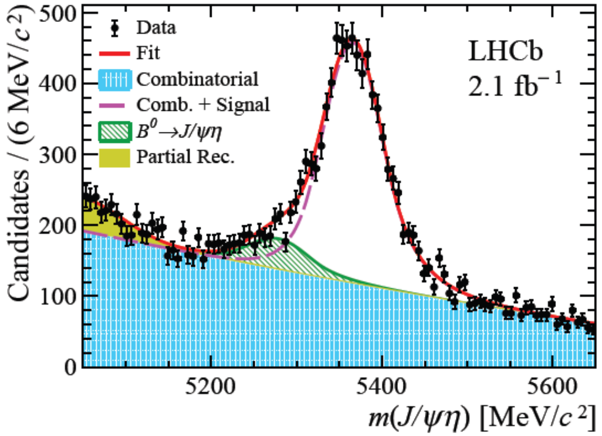
arXiv:2202.04045

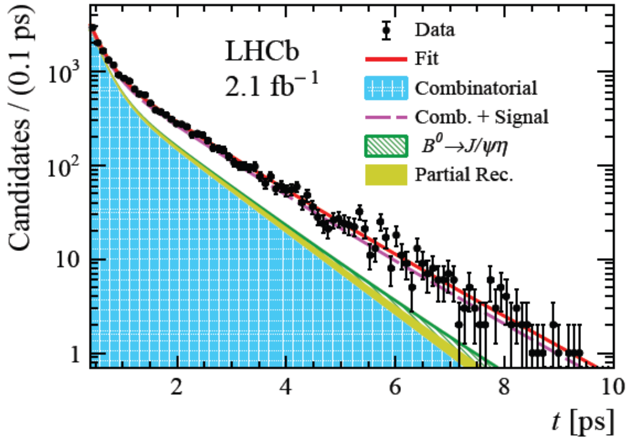
Measurement of τ_L using the $B_s^0 \to J/\psi\eta$

- Neutral mesons can be considered in deafferent basses: flavor, mass and CP eigenstates
- Sizable difference is predicted between decay widths of heavy (H) and light (L) eigenstates of B_s^0
- Small CPV in mixing → mass eigenstates are also CP eigenstates
- Use CP even modes to determine $\tau_L = 1/\Gamma_L$
- Update for $B_s^0 \to J/\psi\eta$ with full Run-II data (6 fb^{-1})

- Reconstruction: $J/\psi \to \mu^+\mu^-$, $\eta \to \gamma\gamma$
- 2D maximum likelihood fit of mass and time spectra

Example of fit (2018 dataset)

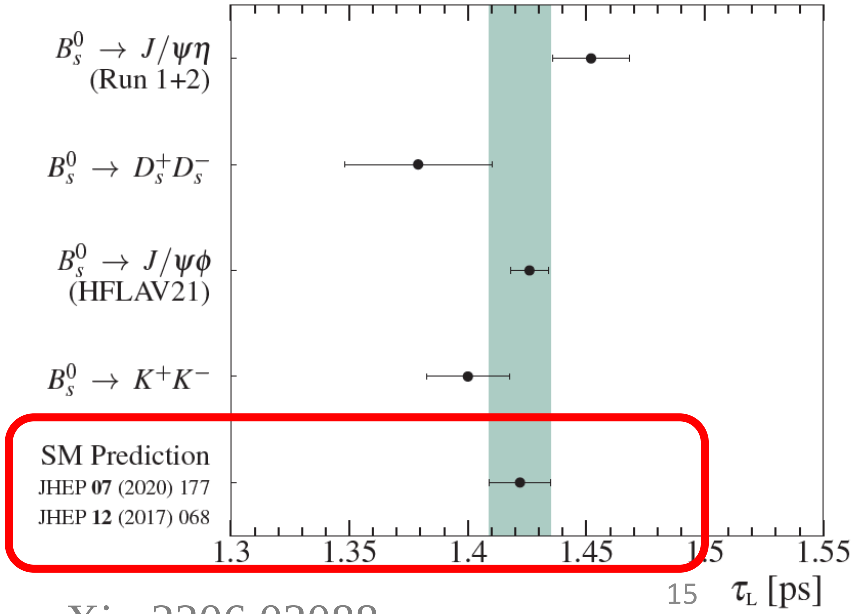




Run-II:
$$\tau_L = 1.445 \pm 0.016(\text{stat}) \pm 0.008(\text{syst})\ \text{ps}.$$

Combination with Run-I:
$$\tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002\ \text{ps}$$

correlated syst.



arXiv:2206.03088

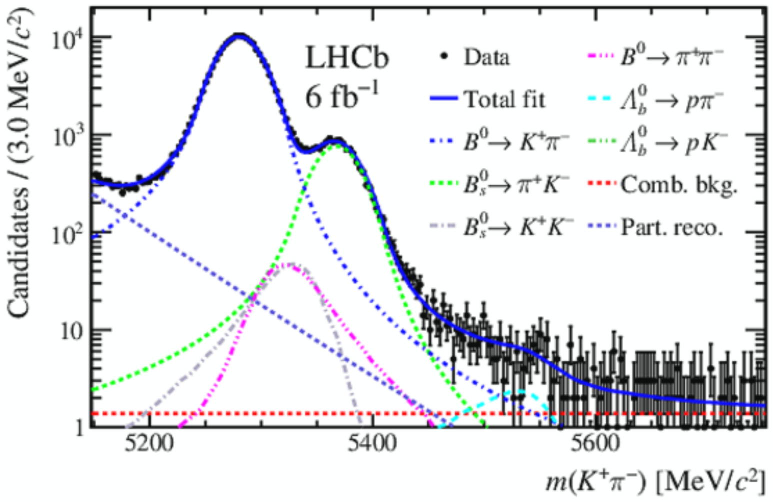
III) Search for the rare hadronic decay $B_s^0 \to \bar{p}p$

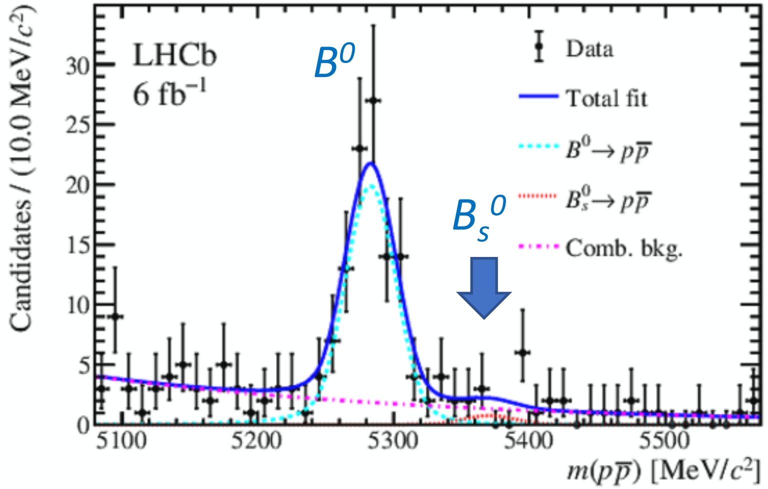
- Study role of exchange and annihilation diagrams in baryonic *B* decays
- Run-2 sample of 6 fb^{-1} at 13 TeV
- Analysis relays on excellent LHCb PID capabilities
- *Kπ* as a normalization mode
- No B_s^0 signal observed → upper limit on the branching fraction

$$\mathcal{B}(B_s^0 \to p\bar{p}) < 4.4\ (5.1) \times 10^{-9} \text{ at } 90\%\ (95\%) \text{ CL.}$$

- B^0 decay mode observation is confirmed with very large significance.
- The combination with Run-I

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$$

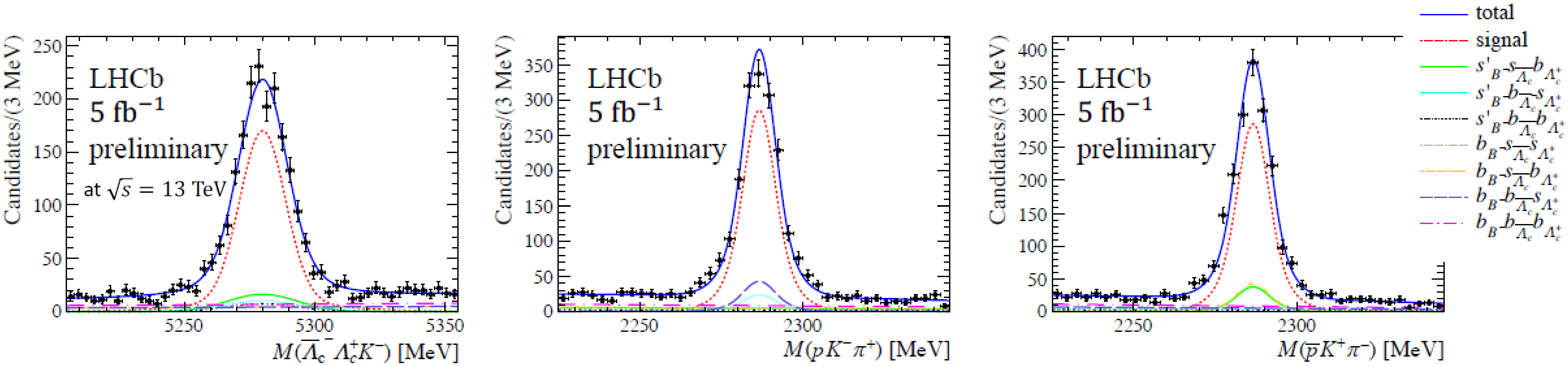




arXiv:2206.06673

Study of $B^+ \to \Lambda_c^+ \Lambda_c^- K^-$

- Low background channel to search for ***exotics***, as well as for ***excited Ξ_c states***
- Run-II data, 5 fb^{-1} at 13 TeV
- Signal is extracted with a 3D-fit of mass spectra



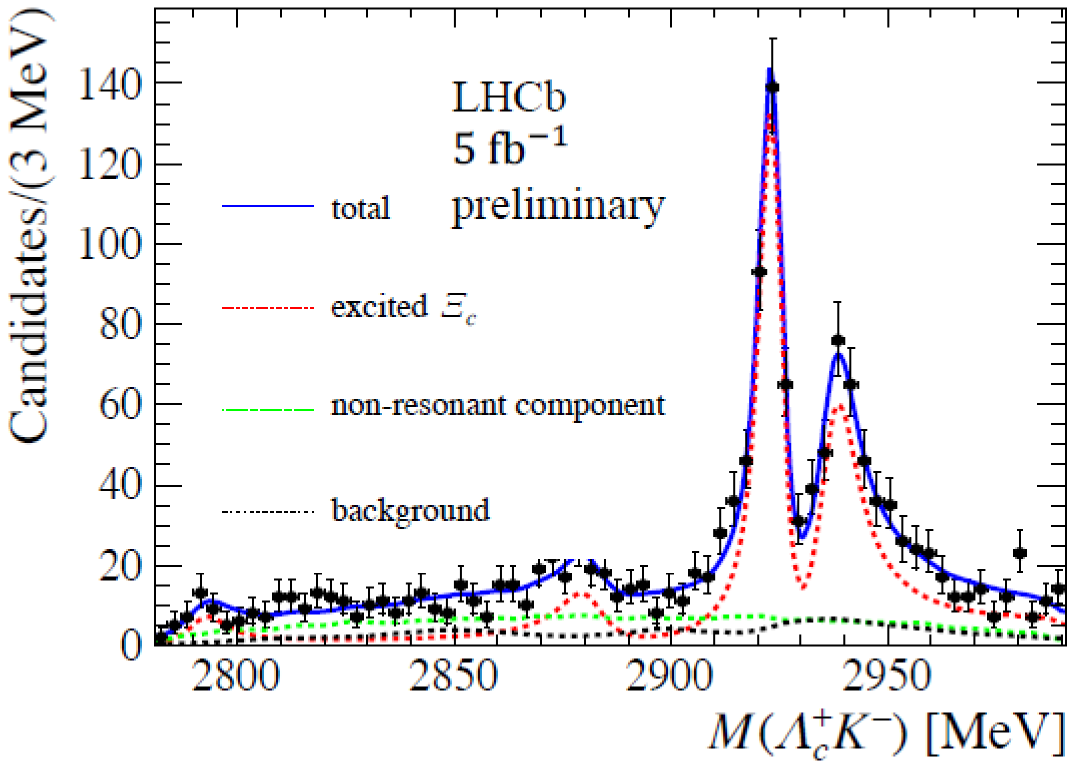
$$N_{\rm sig} = 1365 \pm 42$$

$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-)}{\mathcal{B}(B^- \to D^+ D^- K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25$$

[LHCb-PAPER-2022-028] In preparation

Study of $B^+ \to \Lambda_c^+ \Lambda_c^- K^-$

- $\Xi_c(2790)^0, \Xi_c(2880)^0, \Xi_c(2923)^0, \Xi_c(2939)^0$ included in the nominal fit
  - ✓ $J^P = 1/2^-$ (known), $1/2^-, 3/2^-, 3/2^-$ (1P $J^P_{[qq]} = 1^+$ multiplets; alternatives studied in systematics); interference considered



3.8σ ⇒ evidence of a new state

$$M(\Xi_c(2880)^0) = 2881.8 \pm 3.1 \pm 8.5 \text{ MeV}$$
$$\Gamma(\Xi_c(2880)^0) = 12.4 \pm 5.3 \pm 5.8 \text{ MeV}$$

$$M(\Xi_c(2923)^0) = 2924.5 \pm 0.4 \pm 1.1 \text{ MeV}$$
$$\Gamma(\Xi_c(2923)^0) = 4.8 \pm 0.9 \pm 1.5 \text{ MeV}$$

Confirm prompt observation

$$M(\Xi_c(2939)^0) = 2938.5 \pm 0.9 \pm 2.3 \text{ MeV}$$
$$\Gamma(\Xi_c(2939)^0) = 11.0 \pm 1.9 \pm 7.5 \text{ MeV}$$

Also, $\Xi_c(2790)^0$: 3.7σ ⇒ evidence of new decay mode

[LHCb-PAPER-2022-028] In preparation

Summary

- LHCb is the ultimate factory for spectroscopy of conventional mesons
  - Huge statistics / perfect vertexing and PID
- Many new analyses released in 2022:
  - Amplitude analyses
  - Decays to charmonia and light hadrons
  - Baryonic *b*-decays
  - Study of baryons, which contain two heavy quarks
- LHCb results on other topics can be found *via*
  - https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html
- Looking forward for Run-III data
- **Thank you for your attention!**