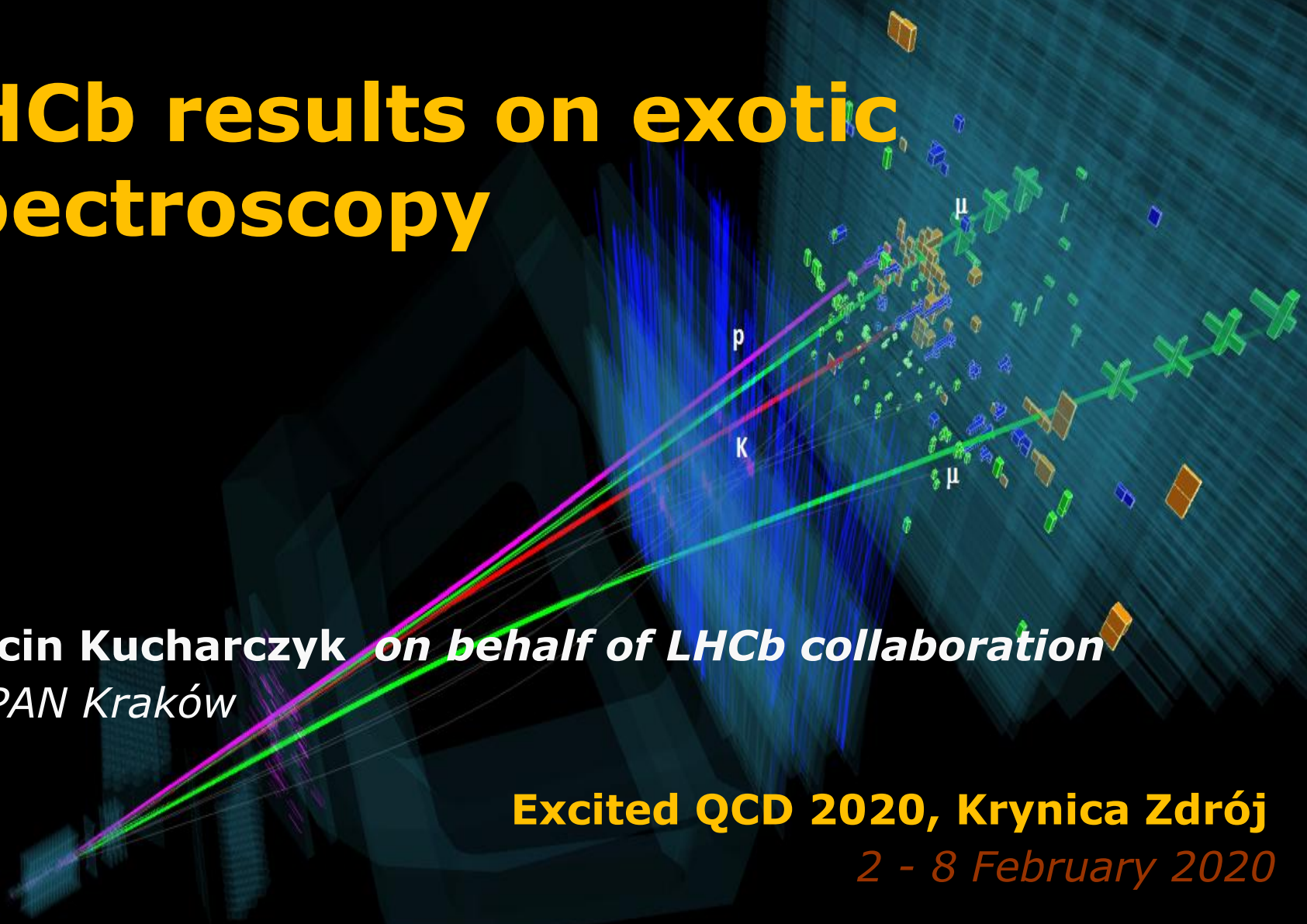
LHCb results on exotic spectroscopy



Marcin Kucharczyk ***on behalf of LHCb collaboration***
IFJ PAN Kraków

Excited QCD 2020, Krynica Zdrój
2 - 8 February 2020

Outline

Exotic baryons

- Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$ [PRL 122 (2019) 222001]

- Observation of $B^0_{(s)} \to J/\psi\, p\bar{p}$ decays and precision measurements of the $B^0_{(s)}$ masses [PRL 122 (2019) 191804]

Exotic mesons

- Evidence of $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ [EPJ C78 (2018) 1019]

- Model-independent observation of exotic contributions to $B^0 \to J/\psi K^+\pi^-$ decays [PRL 122 (2019) 152002]

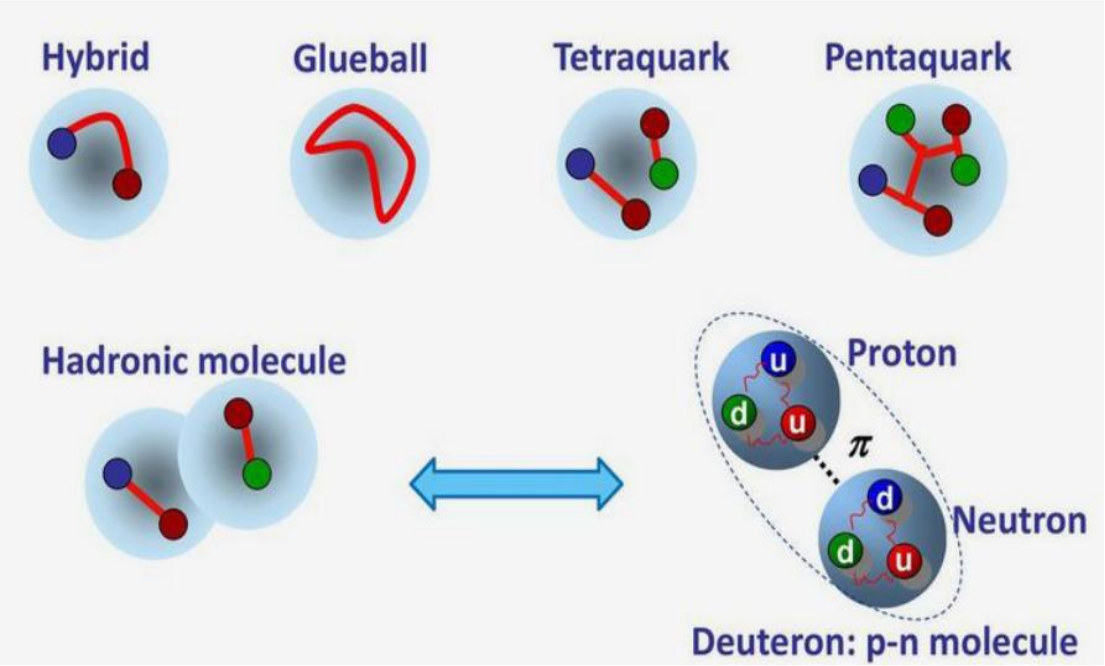
Exotic hadrons

Bound states of quarks were first proposed in 1964 by Gell-Mann and Zweig

- **exotic hadrons:** everything beyond $q\bar{q}$-meson and qqq-baryon scheme
- exotic states can be both neutral *(X, Y)* and charged *(Z^+, P_c^+)*
- exotic hadrons can provide unique probe to QCD

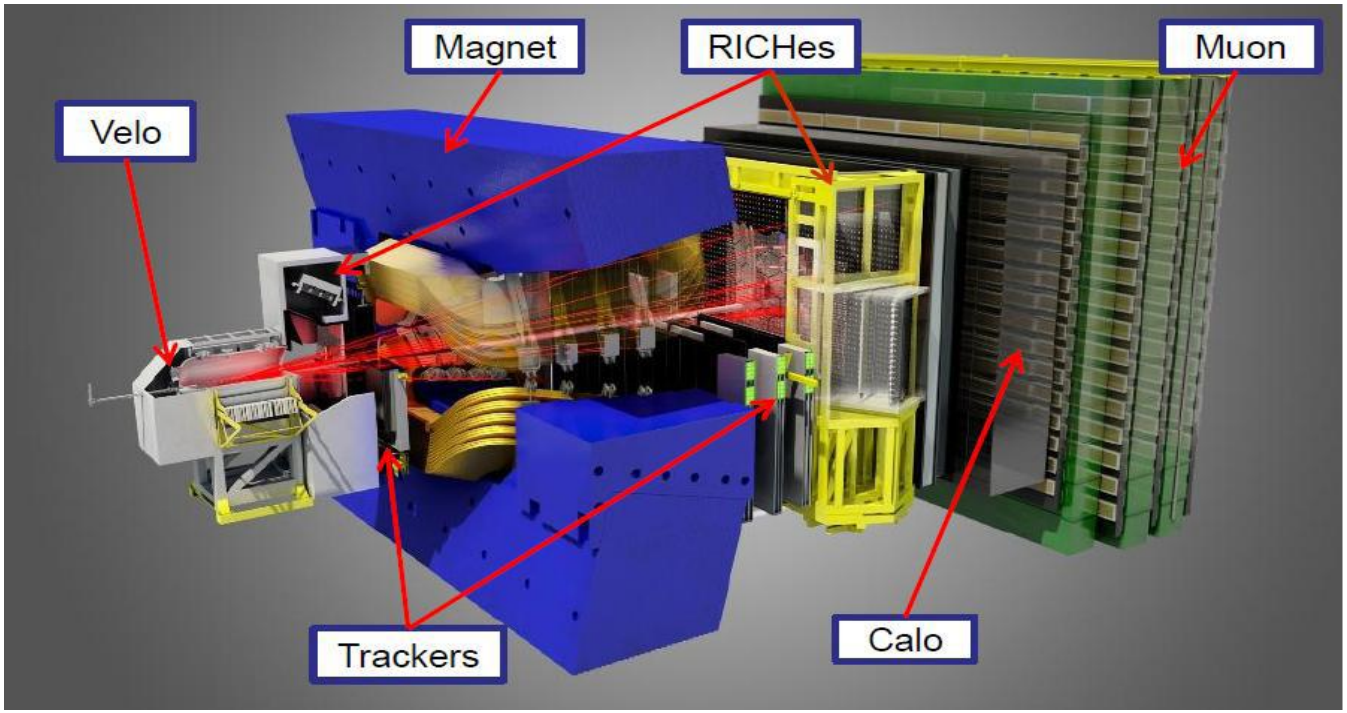
Different properties expected depending on proposed binding mechanism

- tight tetra or pentaquarks
- molecules of meson-meson, meson-baryon
- hybrid-meson
- ...
- or rescattering effects
  → *triangle diagrams*



LHCb detector

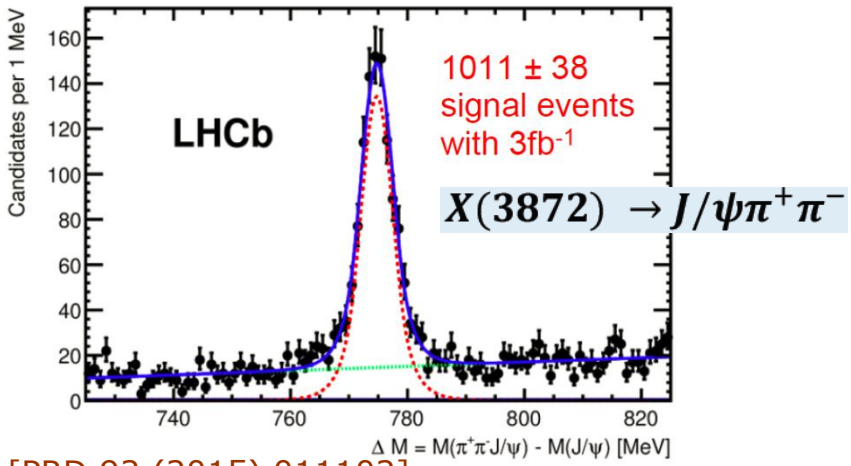
- forward spectrometer at LHC collider [Int. J. Mod. Phys. A30 (2015) 1530022]
- designed for measuring CP violation & rare decays of heavy hadrons



- precision coverage unique for LHCb $2 < \eta < 5$ *(~40% of $b\bar{b}$ in forward region)*
- excellent tracking and vertexing *($\sigma(IP) \sim 20$ μm for high-p_T tracks)*
- good hadron PID separation up to 100 GeV
- efficient trigger with *μ's*

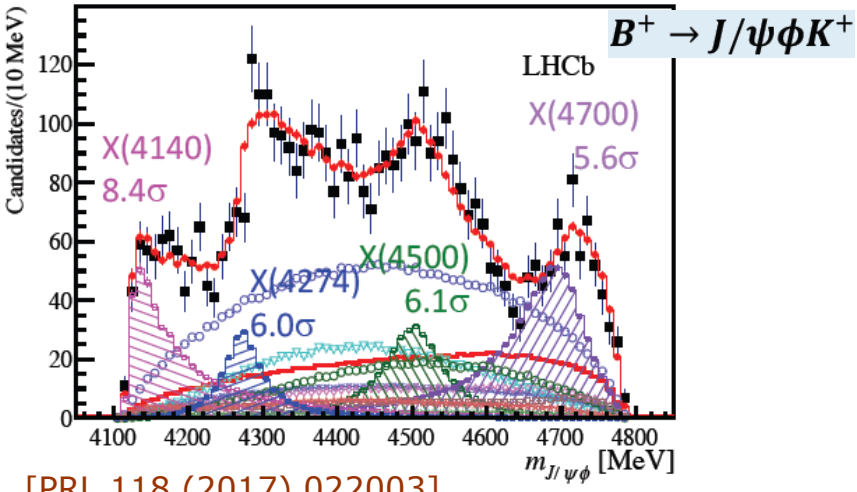
Previous LHCb results

X(3872): Confirmation of $J^{PC} = 1^{++}$



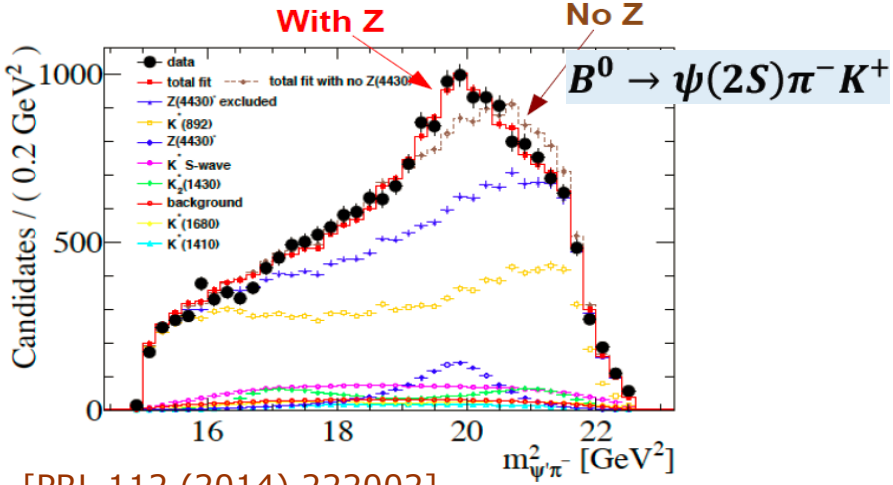
[PRD 92 (2015) 011102]

Observation of four $J/\psi\phi$ structures



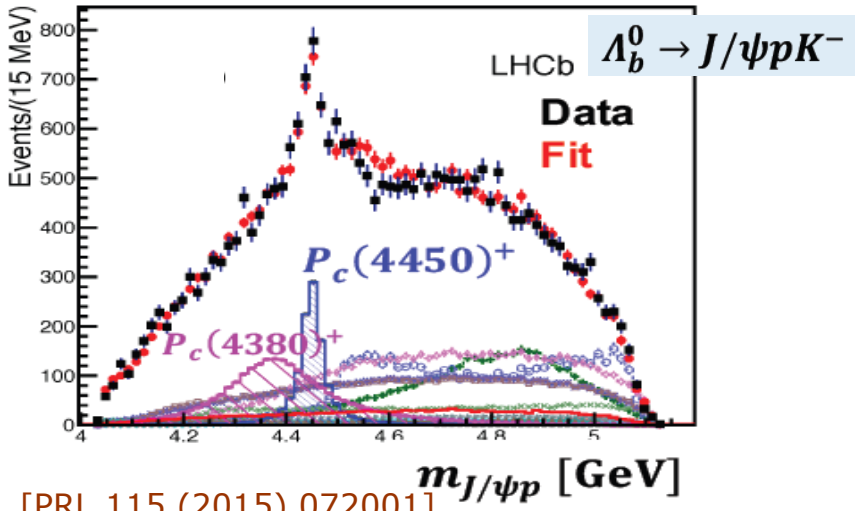
[PRL 118 (2017) 022003]

Z(4430): LHCb confirmation



[PRL 112 (2014) 222002]

Observation of 2 charmonium pentaquarks



[PRL 115 (2015) 072001]

Exotic baryons

$\Lambda_b^0 \to J/\psi p K^-$ with full Run I + II (9 fb^{-1})

[PRL 122 (2019) 222001]

- 2015: LHCb observed exotic contributions decaying to $J/\psi p$ in $\Lambda_b^0 \to J/\psi p$

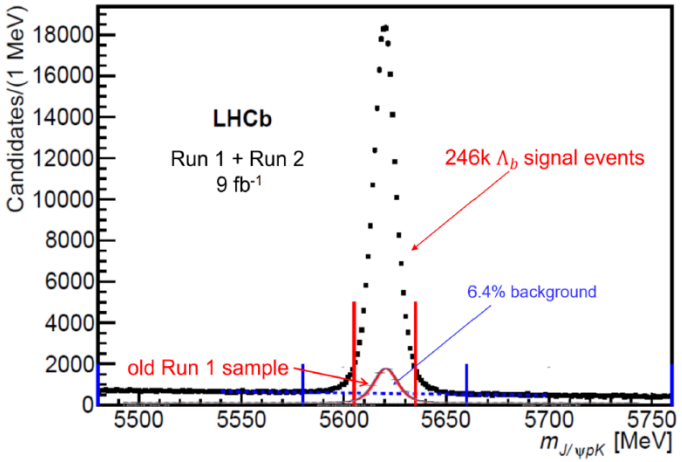
  → exotic contributions near 4450 MeV supported by model independent analysis with more than 9σ [PRL 117 (2016) 082002]

- 2019: dataset 9× larger than used previously

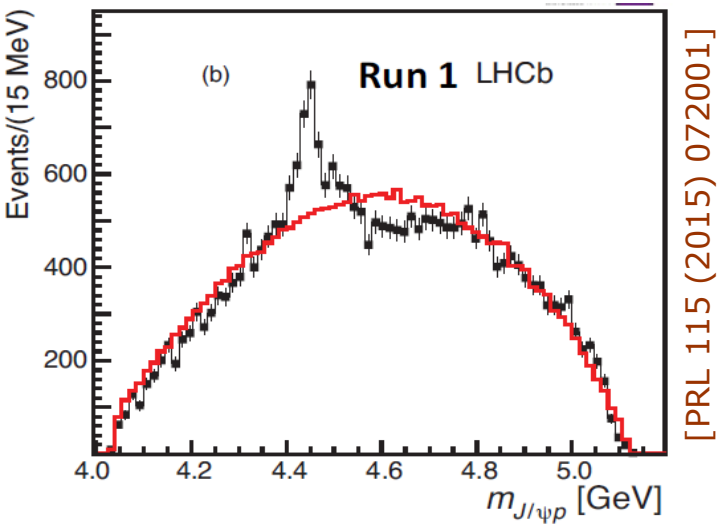
  → *better selection*

  → *higher luminosity*

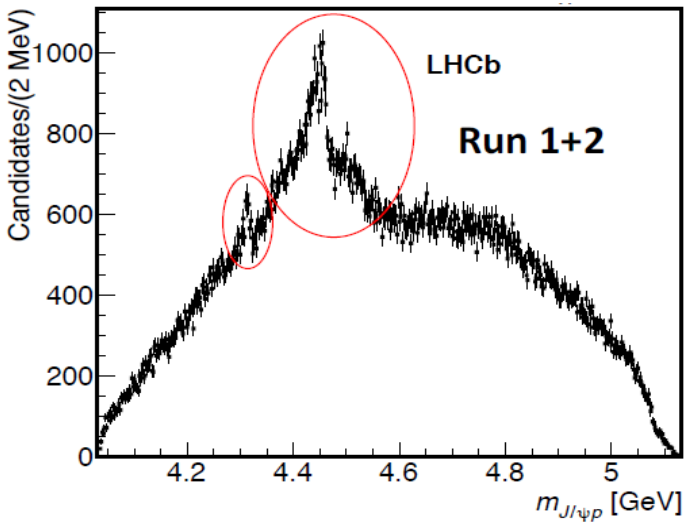
  → *higher cross section at 13 TeV*



Structure at 4312 MeV and $P_c(4450)^+$ resolved into 2 narrower peaks at 4440 and 4457 MeV



[PRL 115 (2015) 072001]

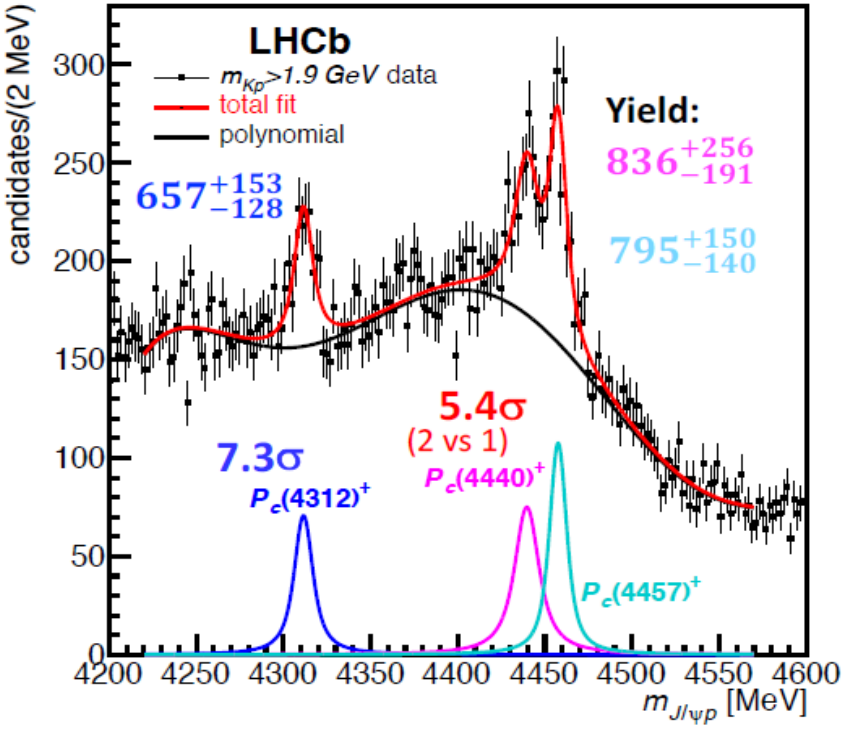


[PRL 122 (2019) 222001]

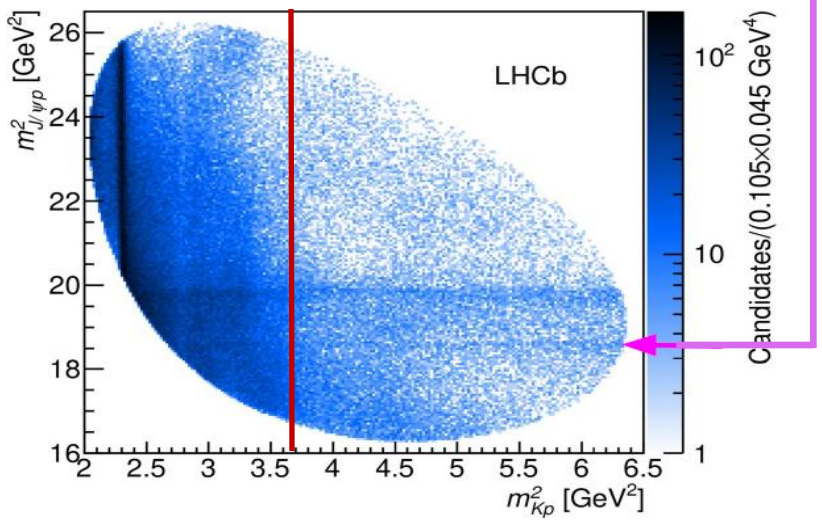
$\Lambda_b^0 \to J/\psi p K^-$ with full Run I + II (9 fb^{-1})

[PRL 122 (2019) 222001]

- new narrow structures
  - → *use 1D mass fit with BW amplitudes*
  - → *not sensitive to broad states*
- fit m_{Kp} > 1.9 GeV events
  - → *~80% Λ^* background removed*
- significances:
  - → $P_c(4312)^+$ **7.3σ**
  - → two-peak structure around 4450 MeV **5.4σ**



Dalitz plot: *evident second horizontal stripe*

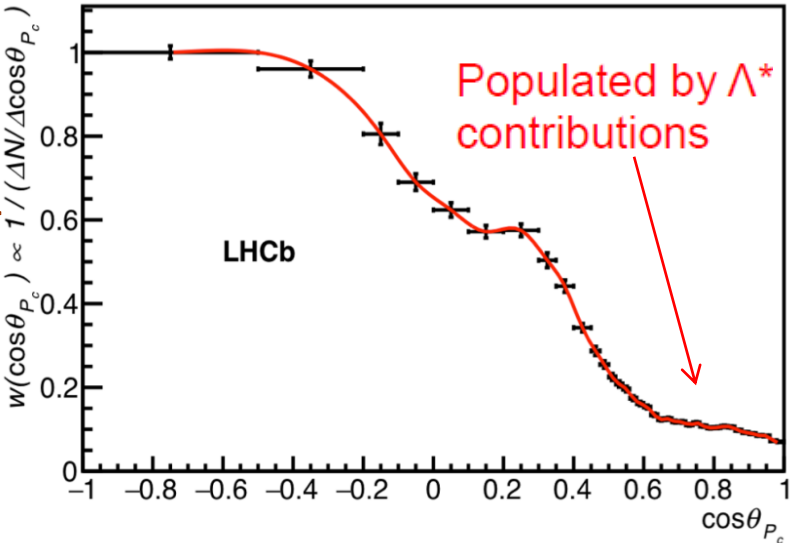


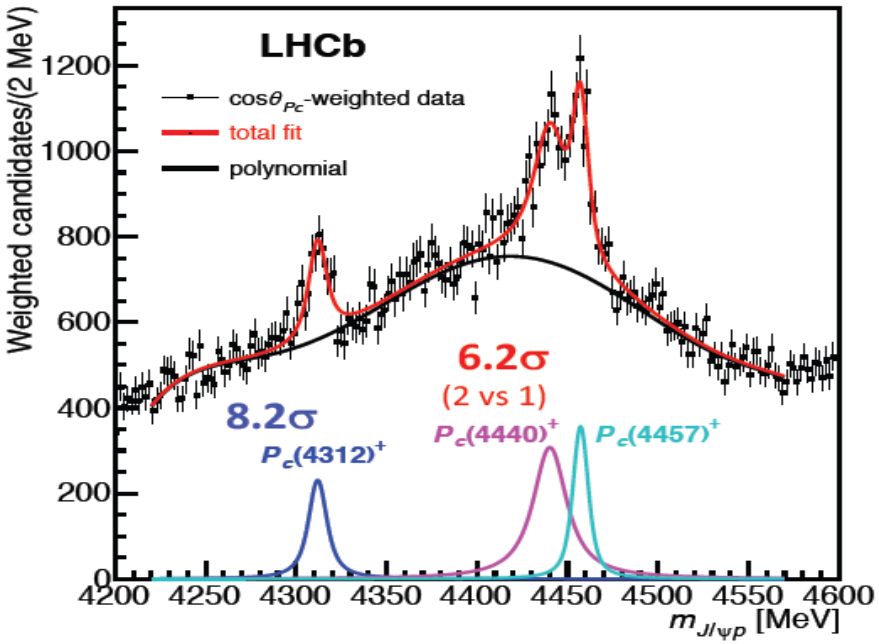
$\Lambda_b^0 \to J/\psi p K^-$ with full Run I + II (9 fb^{-1})

[PRL 122 (2019) 222001]

Novel method to reduce contributions from Λ* states

- reweighting by the angle between K^- and J/ψ in the P_c rest frame
- best statistical significance achieved
- significances:
  - → $P_c(4312)^+$ **8.2σ**
  - → two-peak structure around 4450 MeV **6.2σ**





$\Lambda_b^0 \to J/\psi p K^-$ with full Run I + II (9 fb^{-1})

[PRL 122 (2019) 222001]

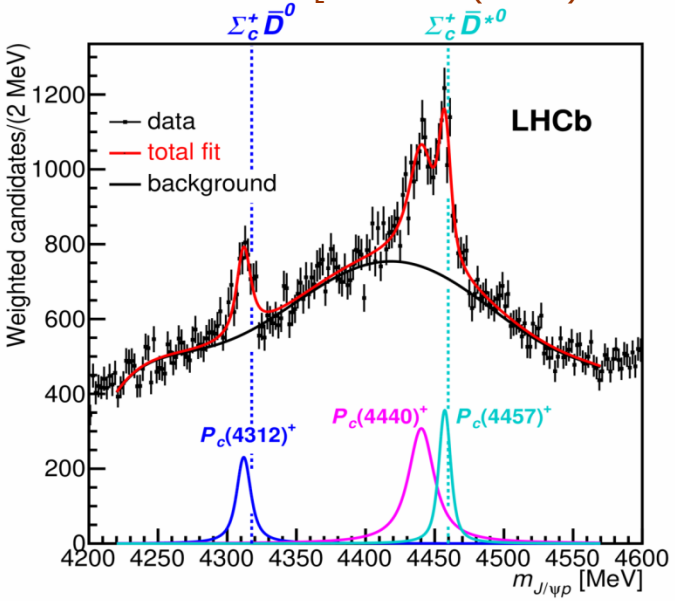
- **best model:** 3 Breit-Wigner's convolved with the resolution function
- masses of $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$ just below mass thresholds of $\Sigma_c^+ \bar{D}^{(*)0}$ favour „molecular" pentaquarks with meson-baryon substructure, but other hypotheses are not ruled out
- 1D fit provides limited information
- amplitude analysis required to:

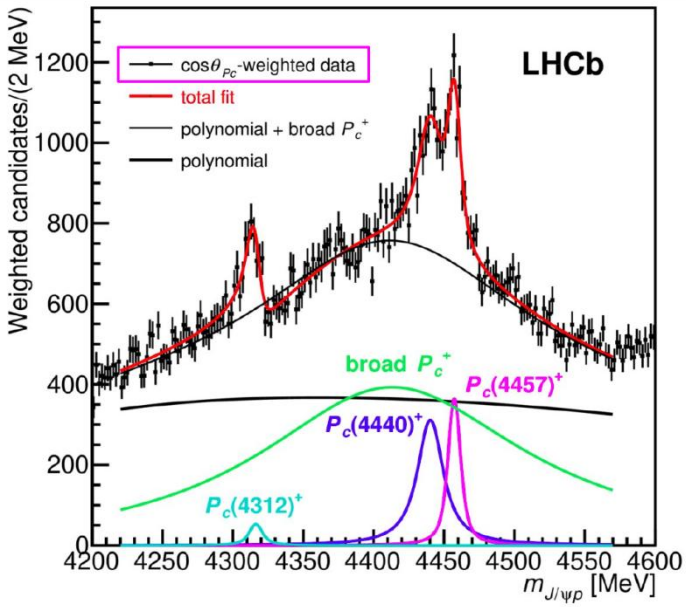
  → *measure J^P and get information of possible $P_c(4380)^+$*

  → *find isospin partners and other decay modes*

Largest systematic uncertainty: unknown interference terms

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)





$\Lambda_b^0 \to J/\psi p K^-$ with full Run I + II (9 fb^{-1})

[PRL 122 (2019) 222001]

Interpretation: molecules

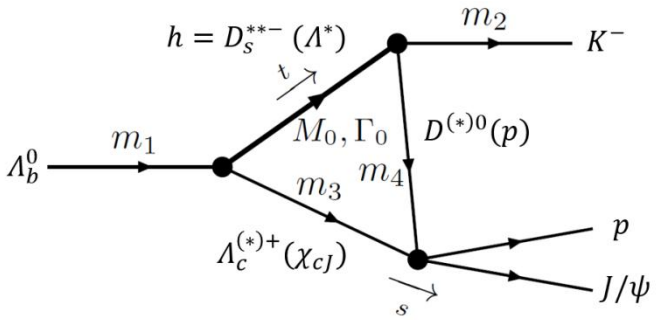
- near-threshold masses and narrow resonances support molecular structure
- J^P assignments, isospin partners, other decays required to confirm

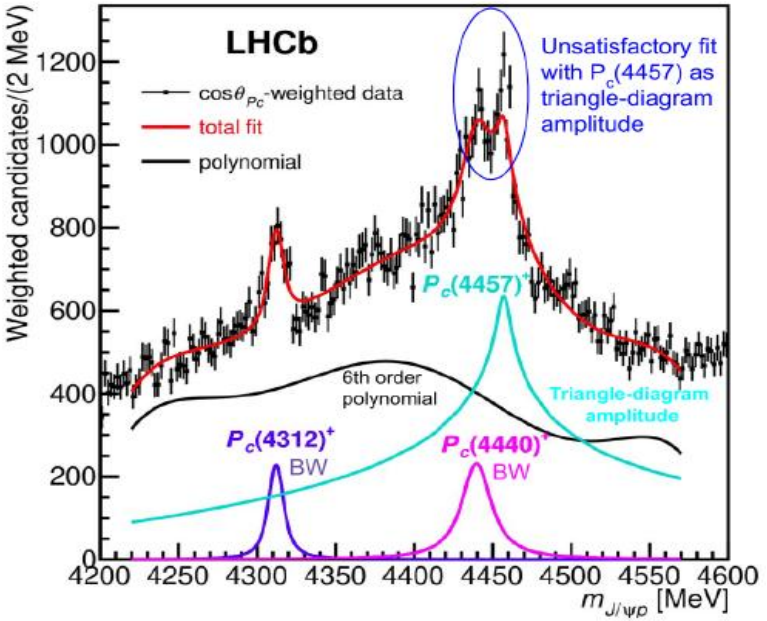
Interpretation: hadronic rescattering

- resonances could also be caused by rescattering of hadrons via a triangle diagram
- can lead to a peaking structure when the rescattered particles are near to on-shell masses
- would correspond to a depletion in the non-rescattered final state due to unitarity
- $P_c(4312)^+$ and $P_c(4440)^+$ are too far from any rescattering thresholds
- $P_c(4457)^+$ peaks at $\Lambda_c(2595)^+\bar{D}^0$ threshold, so possible triangle diagram with $D^*_{s1}(2860)^-$

  → *but using three Breit–Wigner's provides a fit of better quality*

  → *further investigation needed*





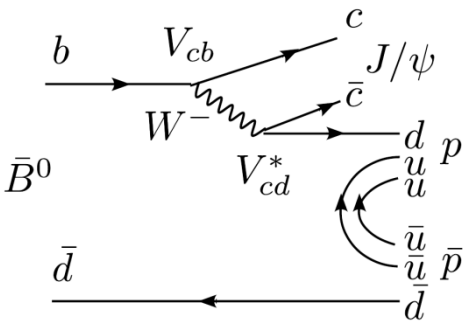
Observation of $B^0_{(s)} \to J/\psi\, p\bar{p}$

[PRL 122 (2019) 191804]

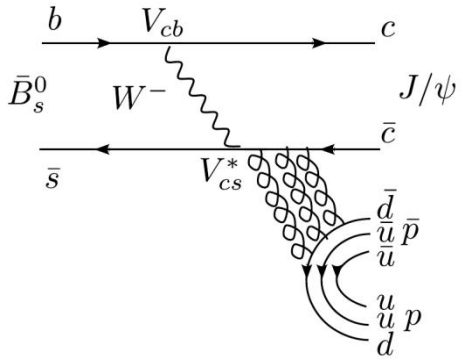
Candidate for pentaquark in $J/\psi p$ and $J/\psi \bar{p}$ and for glueball in $p\bar{p}$ system

- both processes are suppressed due to Cabibbo and OZI suppressions

$B^0_d \to J/\psi p\bar{p}$ - Cabibbo suppressed

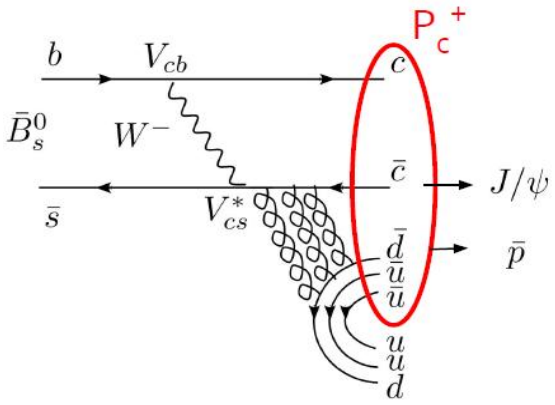


$B^0_s \to J/\psi p\bar{p}$ - OZI-suppressed

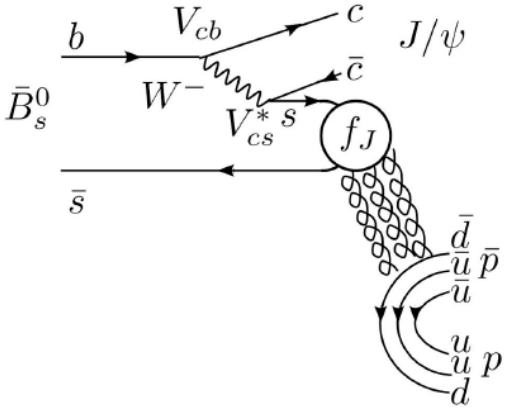


Can be enhanced by contributon from intermediate resonances of exotic nature

exotic states in $J/\psi p$ system



glueballs in $p\bar{p}$ system



Observation of $B^0_{(s)} \to J/\psi\, p\bar{p}$

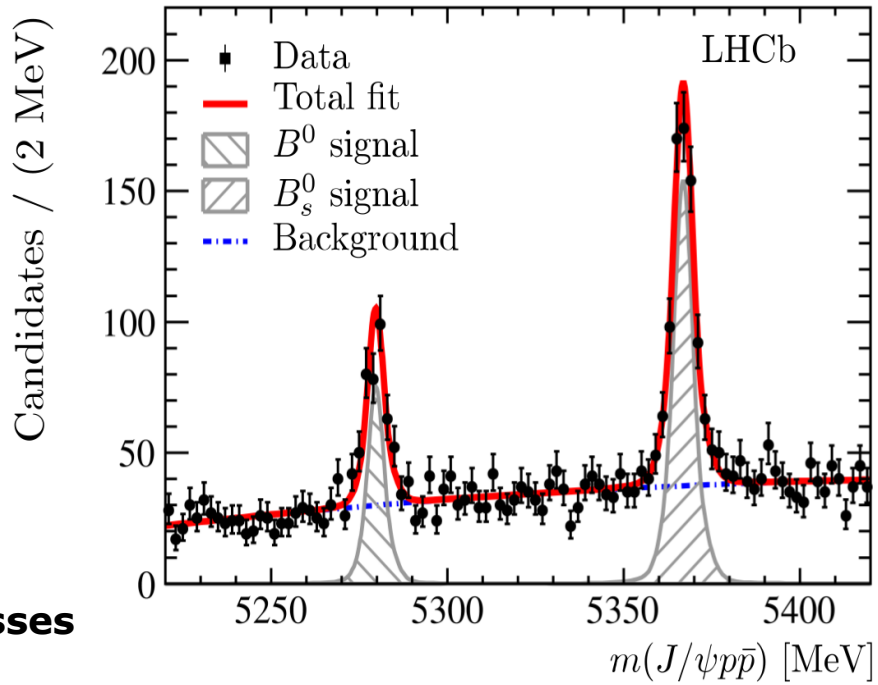
[PRL 122 (2019) 191804]

First observation of $B^0_{(s)} \to J/\psi p\bar{p}$ decays using 2011-2016 data (5.2 fb^{-1})

$$\mathcal{B}(B^0 \to J/\psi\, p\bar{p}) = (4.51 \pm 0.40\ (\text{stat}) \pm 0.44\ (\text{syst})) \times 10^{-7}$$
$$\mathcal{B}(B^0_s \to J/\psi\, p\bar{p}) = (3.58 \pm 0.19\ (\text{stat}) \pm 0.33\ (\text{syst})) \times 10^{-6}$$

11.5σ for B^0 mode
19.5σ for B^0_s mode

- **BR of B_s**
  - → ***2 orders of magnitude higher than expected***
- **BR of B^0**
  - → *good agreement with theoretical expectation*
- need more data for a full Dalitz-analysis for exotic searches



Best single measurement of B_s and B^0 masses

$$m_{B^0} = 5279.74 \pm 0.30\ (\text{stat}) \pm 0.10\ (\text{syst})\ \text{MeV}$$
$$m_{B^0_s} = 5366.85 \pm 0.19\ (\text{stat}) \pm 0.13\ (\text{syst})\ \text{MeV}$$

Mode	Yield
$B^0 \to J/\psi\, p\bar{p}$	256 ± 22
$B^0_s \to J/\psi\, p\bar{p}$	609 ± 31

Exotic mesons

Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$

[EPJ C78 (2018) 1019]

Search for $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

- all Z_c states have at least $c\bar{c}q\bar{q}$ quark content
- measured J^P of observed Z_c states are all 1^+, while $\eta_c(1S)\pi^-$ can access other J^P
- searching for $\eta_c(1S)\pi^-$ resonances is important for understanding nature of exotic hadrons, e.g. for $Z_c(3900)^-$ BESIII [PRL 111 (2013) 242001]

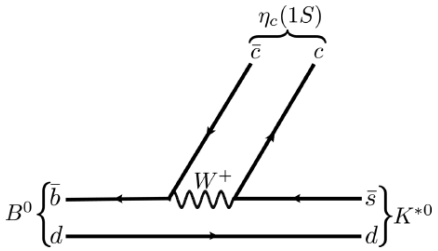
Possible interpretations:

→ hadrocharmonium: a state decaying to $\eta_c(1S)\pi^-$ at mass ~3800 MeV

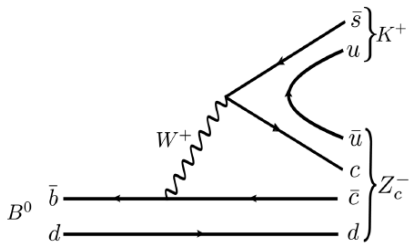
→ quarkonium hybrid model: different multiplets in $\eta_c(1S)\pi^-$ system, their masses and quantum numbers

→ diquark model: predicts $J^P = 0^+$ state in $\eta_c(1S)\pi^-$ below open-charm threshold

LHCb has an evidence of $Z_c(4100)^- \to \eta_c\,\pi^-$ that cannot be 1^+



K^{*0} resonances dominate decay



Exotic resonance predicted in $\eta_c(1S)\pi^-$

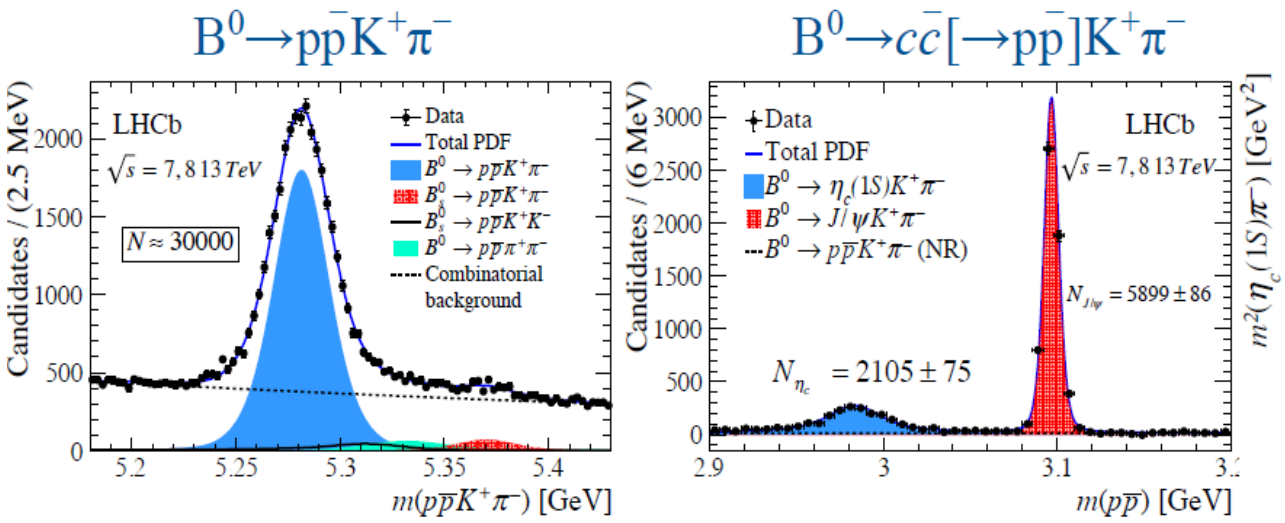
Only pseudoscalar particles in the final state → Dalitz plot analysis is possible

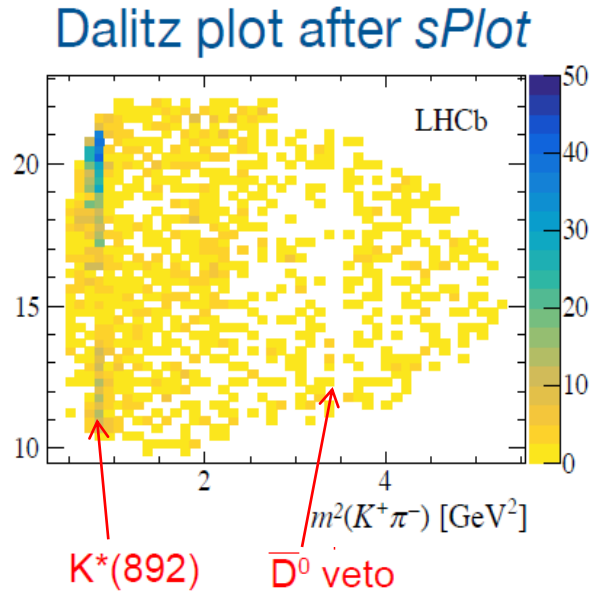
Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$

[EPJ C78 (2018) 1019]

Dalitz plot analysis of $B^0 \to \eta_c K^+ \pi^-$ decays performed where $\eta_c(1S) \to p\bar{p}$

- $\mathcal{L}$ = 4.7 fb^{-1}, 2011-2016 data
- 2D fit to $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$ distribution, N_{sig} = 1870 ± 74
- Dalitz plot dominated by $K^*(892)$ signal



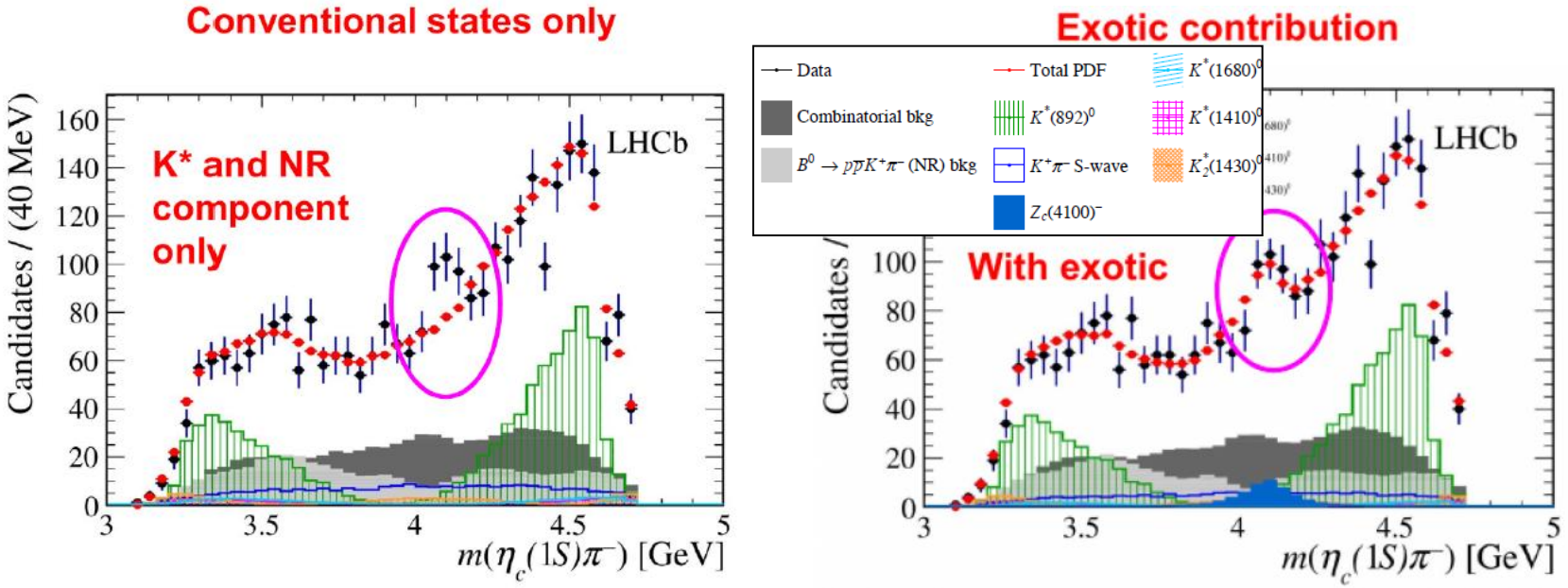


Dalitz plot analysis

- decay amplitude: sum of resonant $K^+\pi^-$ + non-resonant (NR) processes
- six K^{*0} resonances give significant contributions
- exotic $Z_c(4100)^- \to \eta_c \pi^-$ contribution added to improve the fit

Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$

[EPJ C78 (2018) 1019]



- K^{*0} resonances and NR component alone cannot describe the data
- **good description by adding exotic $Z_c(4100)^- \to \eta_c \pi^-$ component**
- evidence for exotic $Z_c(4100)^-$ resonance

  → *3.4σ significance considering systematics*
- both $J^P = 0^+$ and $J^P = 1^-$ are consistent with the data

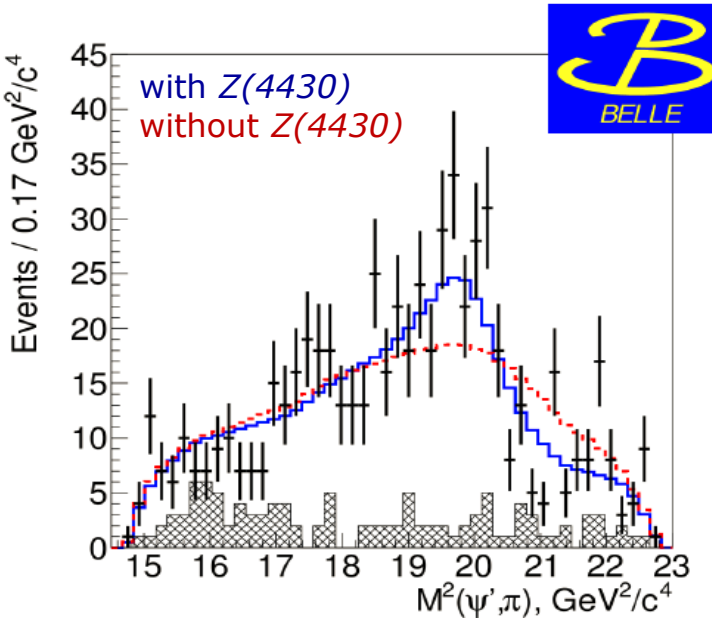
  → *yet 0^+ is not excluded → can't determine its nature with current statistics*

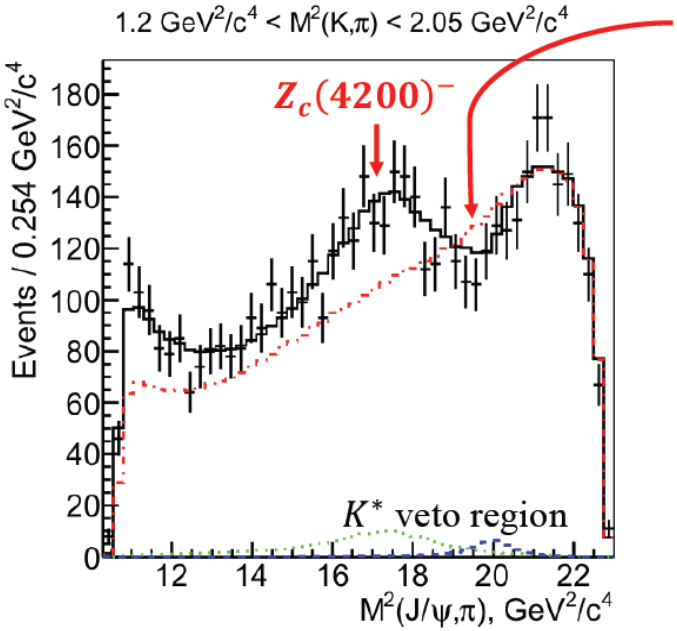
$$Z_c(4100)^-$$
$$M = 4096 \pm 20^{+18}_{-22}\ \text{MeV}$$
$$\Gamma = 152 \pm 58^{+60}_{-35}\ \text{MeV}$$
$$J^P = 0^+/1^-$$

Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

Charged charmonium-like state in $B^0 \to \psi(2S)\pi K$

- originally found by Belle in $B \to (Z(4430)^- \to J/\psi\,\pi^-)\,K$ and $B \to (Z(4430)^- \to \psi(2S)\,\pi^-)\,K$
  [PRL 100(2008) 142001, PR D80(2009) 031104, PR D88(2013) 074026]
  → *not confirmed by BaBar* [PR D79 (2009) 112001]
- exotic $Z(4430)^- \to \psi(2S)\,\pi^-$ confirmed by LHCb in 2014 [PRL 112 (2014) 222002]
- Belle reported another exotic $Z(4200)^-$ in $J/\psi\pi^-$ system [PRD 90 (2014) 112009]





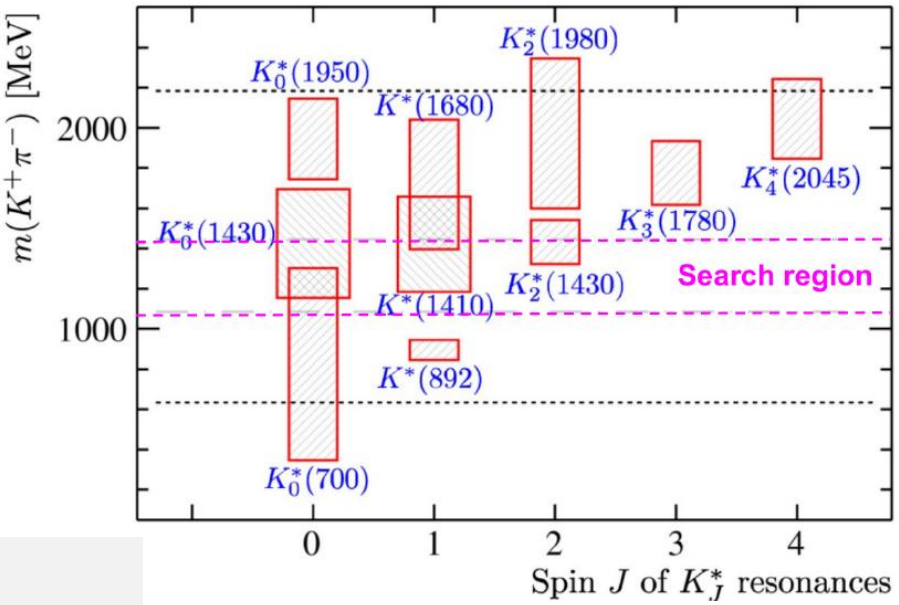
$Z_c(4430)^-$ **presented via destructive interference**

Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

[PRL 122 (2019) 152002]

- $B^0 \to J/\psi K^+\pi^-$ decay dominated by many overlapping K^*_J states
- parameters of K^* spectrum are wide and not very well experimentally measured
- model-independent analysis relying only on highest allowed spin K^*_J for given m($K^+\pi^-$)

  → *no assumption about resonant structures*



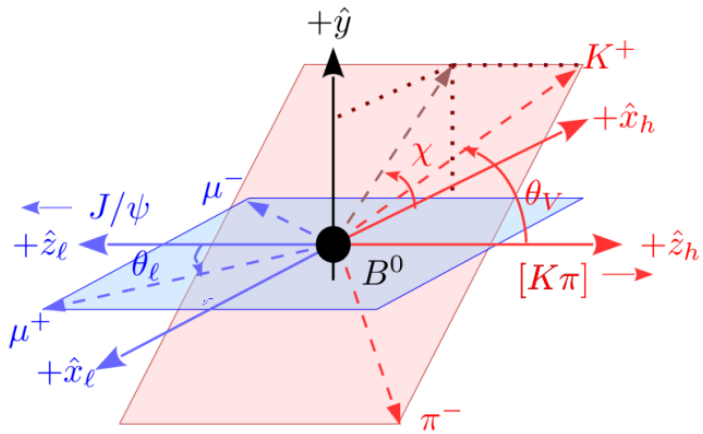
- Run-1 data, x20 Belle

  → signal yield $B^0 \to$ J/ψ π^- K^+ ~5×10^5

- dataset allows for 4D angular analysis in 35 bins of m($K^+\pi^-$)
- novel 3D angular moments to boost sensitivity

  → 2 helicity angles: θ_l, θ_V

  → angle between $(\mu^+\mu^-)$ and ($K^+\pi^-$) decay planes: χ



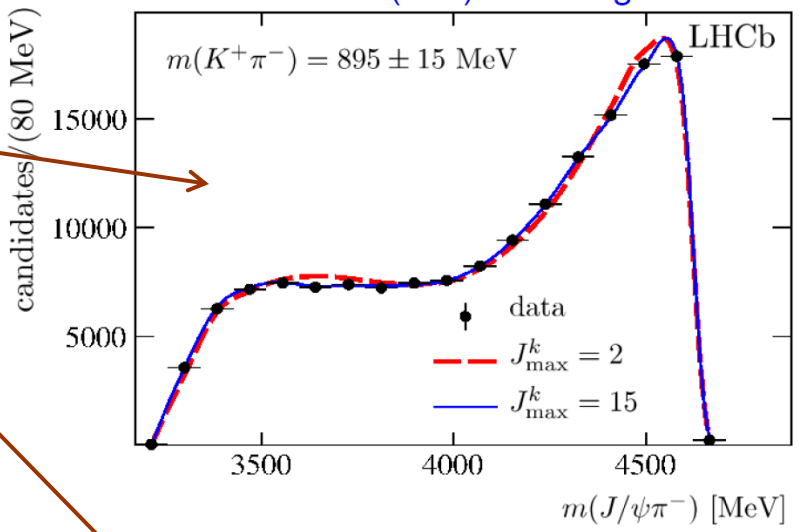
Exotic contributions to $B^0 \to J/\psi K^+\pi^-$

[PRL 122 (2019) 152002]

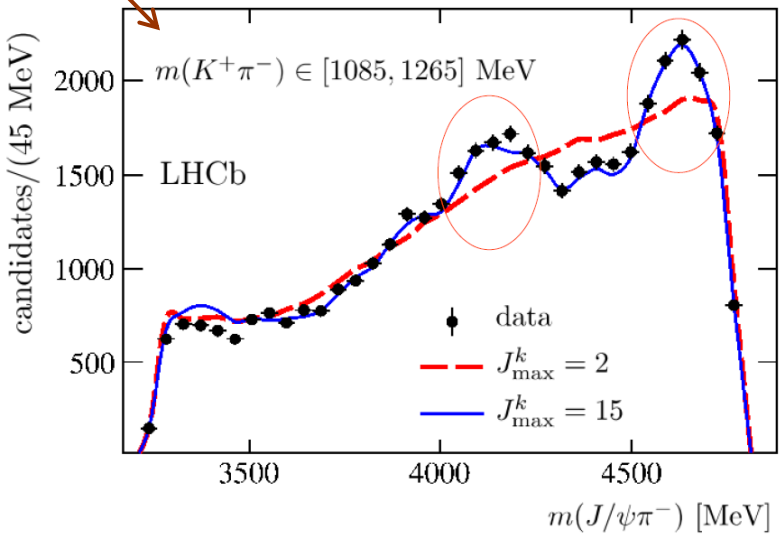
- **data inconsistent with K^*-only contributions by 10σ**
- *$K^*(892)$ region*: well described by contributions with J_{max} = 2 only
- *$K^*(892)$ veto*: unphysical J_{max} = 15 needed to describe the data

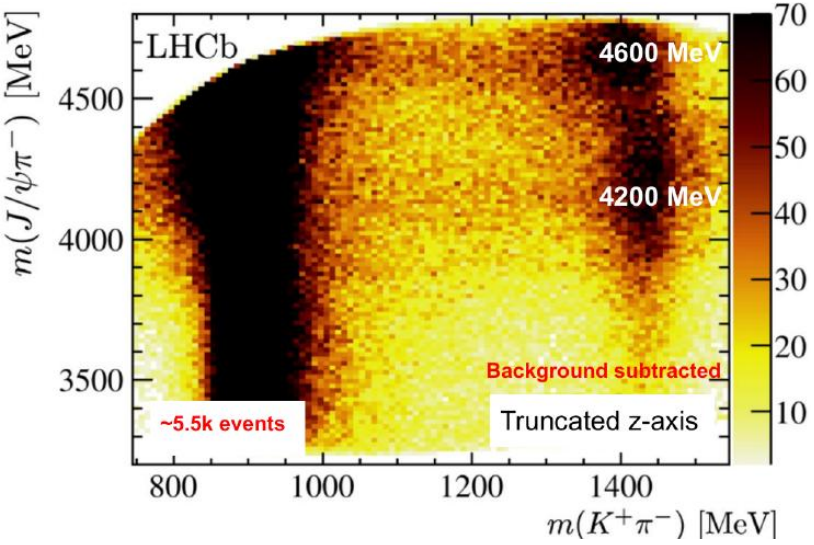
  → *$m(J/\psi\pi)$ ~ 4200 and 4600 MeV regions*
- model dependent amplitude analysis needed to determine properties of these structures

In the K*(892) mass region



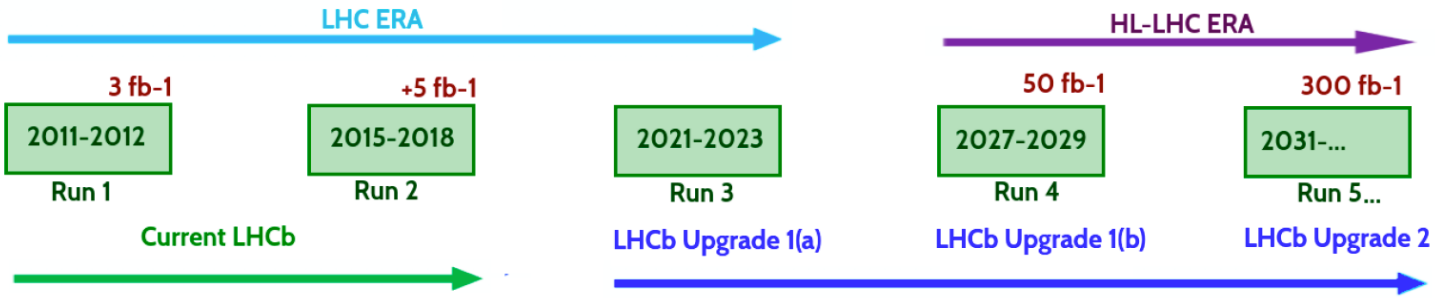
After vetoeing K*(892) mass region





Future prospects

[arXiv:1808.08865]



$L = 4 \times 10^{32}$ cm^{-2}s^{-1}
1.1 visible interact. / xing
8 fb^{-1} collected

$L = 2 \times 10^{33}$ cm^{-2}s^{-1}
5.5 visible interact. / xing
50 fb^{-1} to be collected

$L = 2 \times 10^{34}$ cm^{-2}s^{-1}
55 visible interact. / xing
300 fb^{-1} to be collected

Decay mode	LHCb 23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi p K^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600

[*] updated according to the latest result

LHCb data sample will be boosted

- observation of new states
- precise measurement of observed states

Conclusions

- LHCb has made great progress in exotic spectroscopy
- Many new states discovered since the first observation of *X(3872)*
- LHCb working now on full Run 1 and Run 2 dataset where statistics allow for new amplitude analyses

  → with 10× signal yields 3 narrow pentaquark candidates observed

  → observation of $B^0_{(s)} \to J/\psi\, p\bar{p}$, larger branching fraction wrt theory prediction

  → evidence of $\boldsymbol{Z_c(4100)^- \to \eta_c \pi^-}$, $J^P \neq 1^+$

  → model-independent confirmation of exotic contribution to $B^0 \to J/\psi K\pi$
- Many other LHCb analyses on exotic spectroscopy
- Excellent long term prospects for exotic searches at LHCb

Backup

Some other recent results on baryon spectroscopy

- First observationof excited Ω^-_b states

  [arXiv:2001.00851]

- Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state

  [JHEP 1907 (2019) 035]

- Observation of the $\Lambda^0_b \to \chi_{c1}(3872)\, p\, K^-$ decay

  [JHEP 09 (2019) 028]