Trieste, Italy, May 27 – 31, 2019

Interpreting the LHC Run 2 Data and Beyond

Exotic hadron states at LHCb

Daria Savrina (ITEP & SINP MSU)
on behalf of the LHCb collaboration

Outline

- Why exotic hadrons?
- The LHCb experiment
- Exotic mesons
  - Study of the $B^0 \to J/\psi K^+\pi^-$ decay
  - Study of the $B^0 \to \eta_c(1S)K^+\pi^-$ decay
  - Search for the fully beautiful tetraquarks
- Exotic baryons
  - Updated $\Lambda_b \to J/\psi pK^-$ analysis
  - Search for weakly decaying b-flavoured pentaquarks
- Future prospects
  - Observation of the $\Lambda_b \to \chi_{c1,2}pK$ decays
  - Observation of the $\Lambda_b \to \psi(2S)p\pi$ decay
  - Observation of the $\Xi_b \to J/\psi pK$ decay
  - Observation of the $B^0_{(s)} \to J/\psi p\bar{p}$ decays
  - Studies after LS2

Exotic hadrons

Exotic hadrons – everything beyond $q\bar{q}$-meson and qqq-baryon scheme

Could be various multiquark states, hadron molecules, glueballs, hybrids...

First predicted in 1964 the original papers by M.Gell-Mann and G.Zweig
[CERN-TH-412, Phys.Lett. 8 (1964) 214]

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

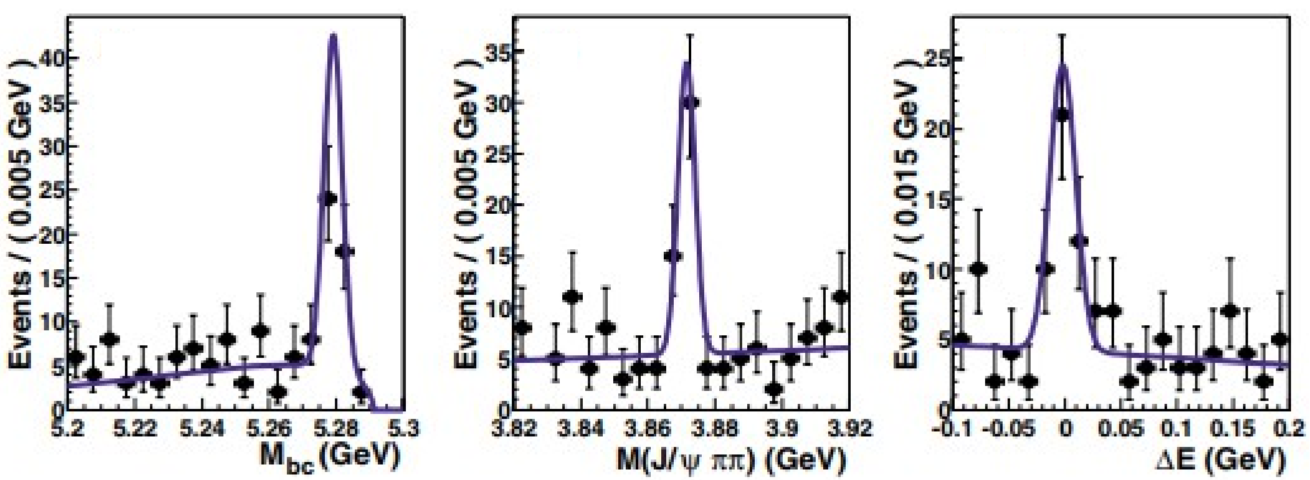
Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes

First seen by Belle in 2003
[Phys. Rev. Lett. 91, 262001 (2003)]

VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays



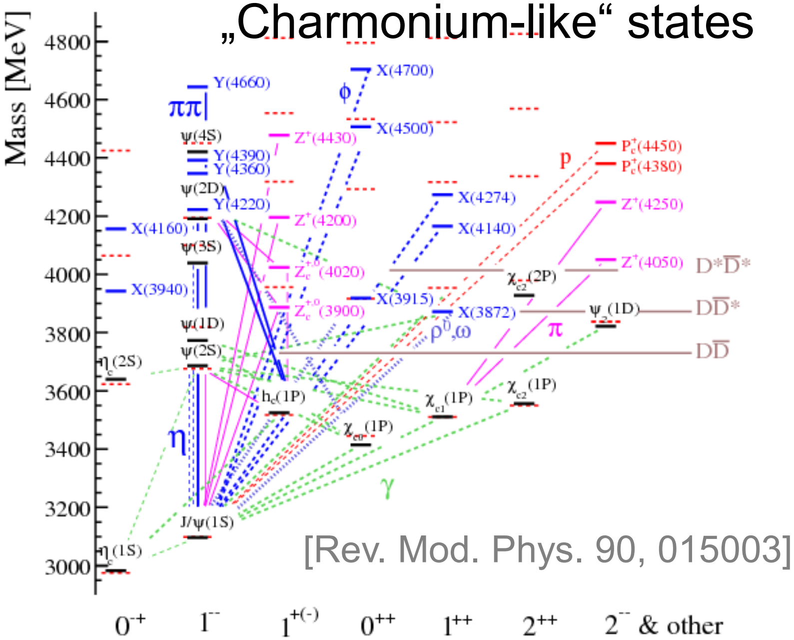
$B^+ \to X(3872)K^+$
$X(3872) \to J/\psi\pi^+\pi^-$

Extremely close to $\bar{D}^{*0}D^0$ mass threshold
Branching fraction ~40%

Comparable rates for $J/\psi\rho$ and $J/\psi\omega$ decays
Isospin violation?

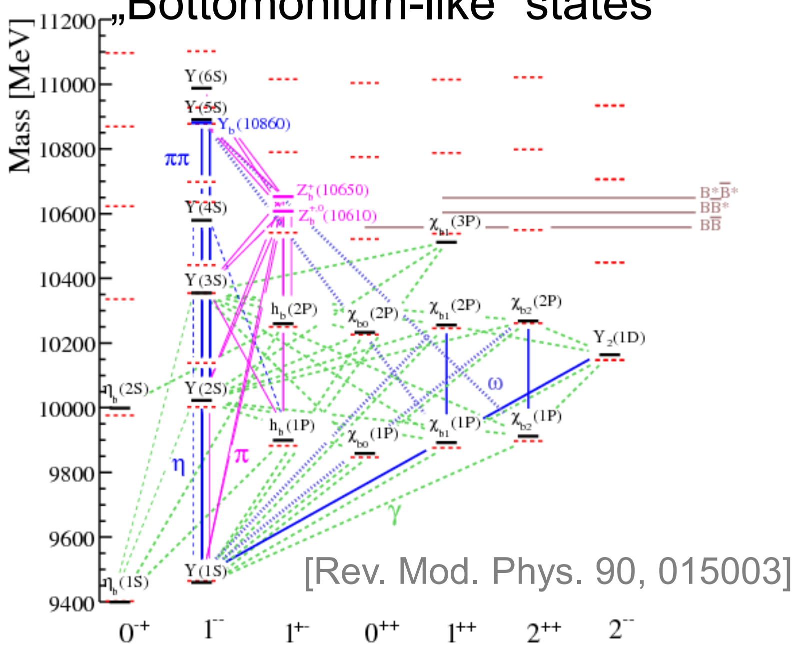
Exotic „zoo“

„Charmonium-like“ states



[Rev. Mod. Phys. 90, 015003]

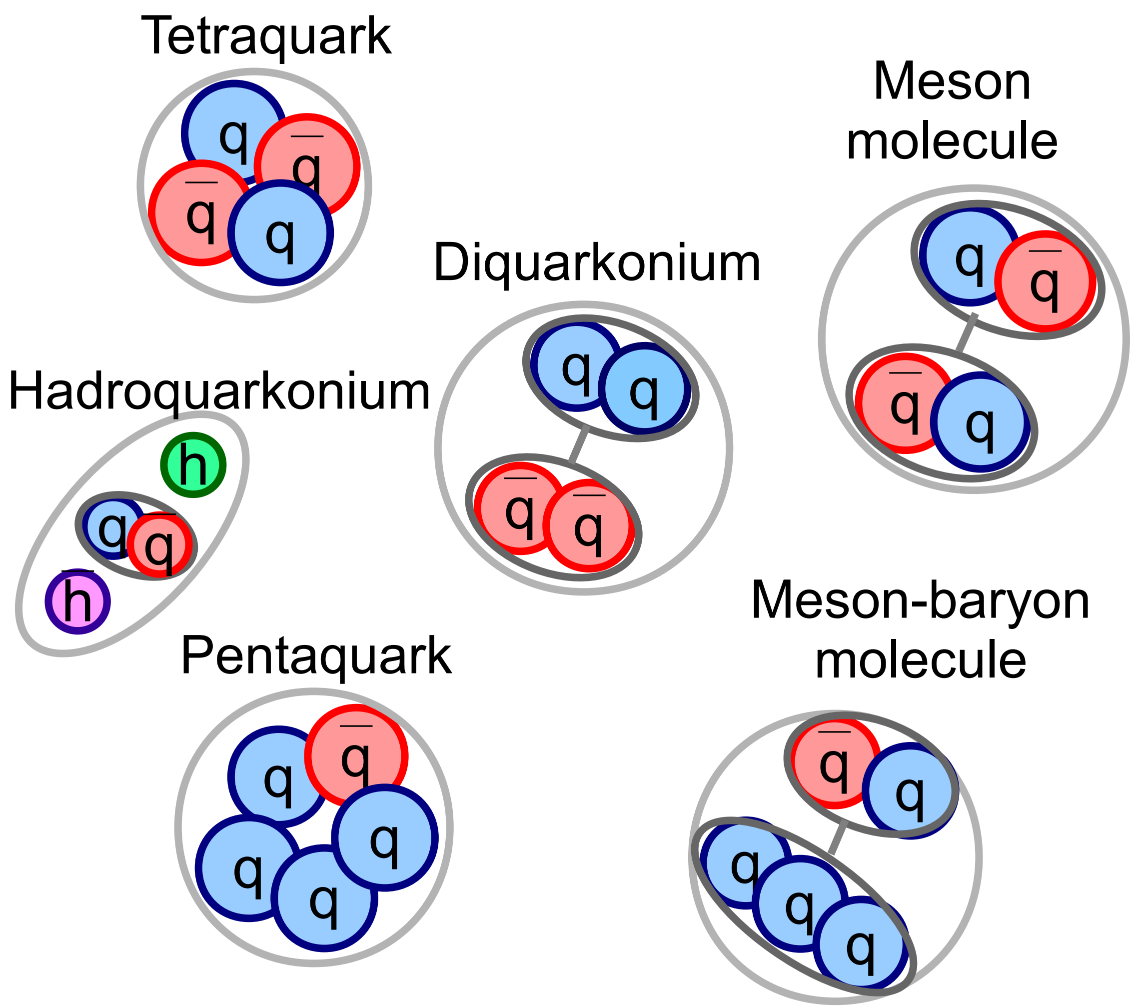
„Bottomonium-like“ states



[Rev. Mod. Phys. 90, 015003]

No clear pattern seen yet

Different properties are expected depending on the proposed binding mechanism



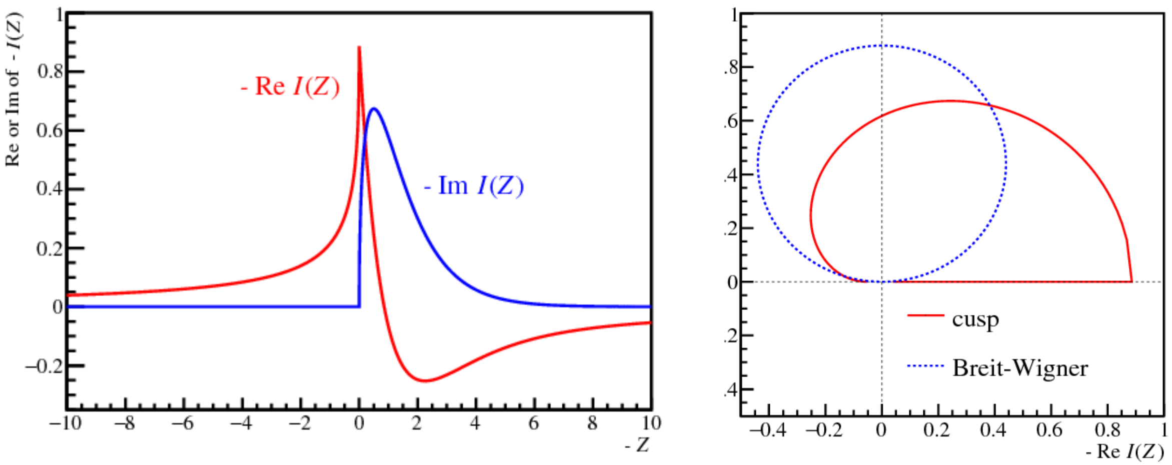
Would like not only to find new exotic hadrons, but also determine their properties: production rates, quantum numbers, lineshapes etc.

Searches for exotics

Most of them are not narrow

Need amplitude analysis

Use Argand diagram to prove their resonance nature



Decay quite fast

Pentaquark lifetime ~10^{-23}s

Direct production

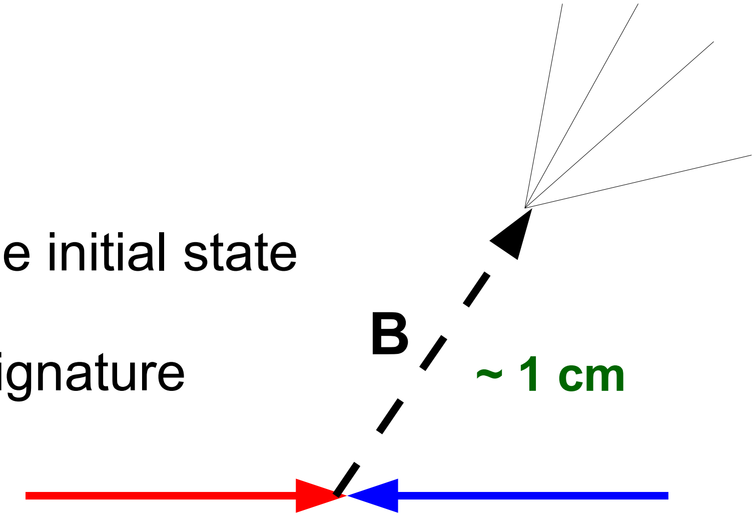
Access to high mass region

Decays of b-hadrons

Inclusive decays: good understanding of the initial state

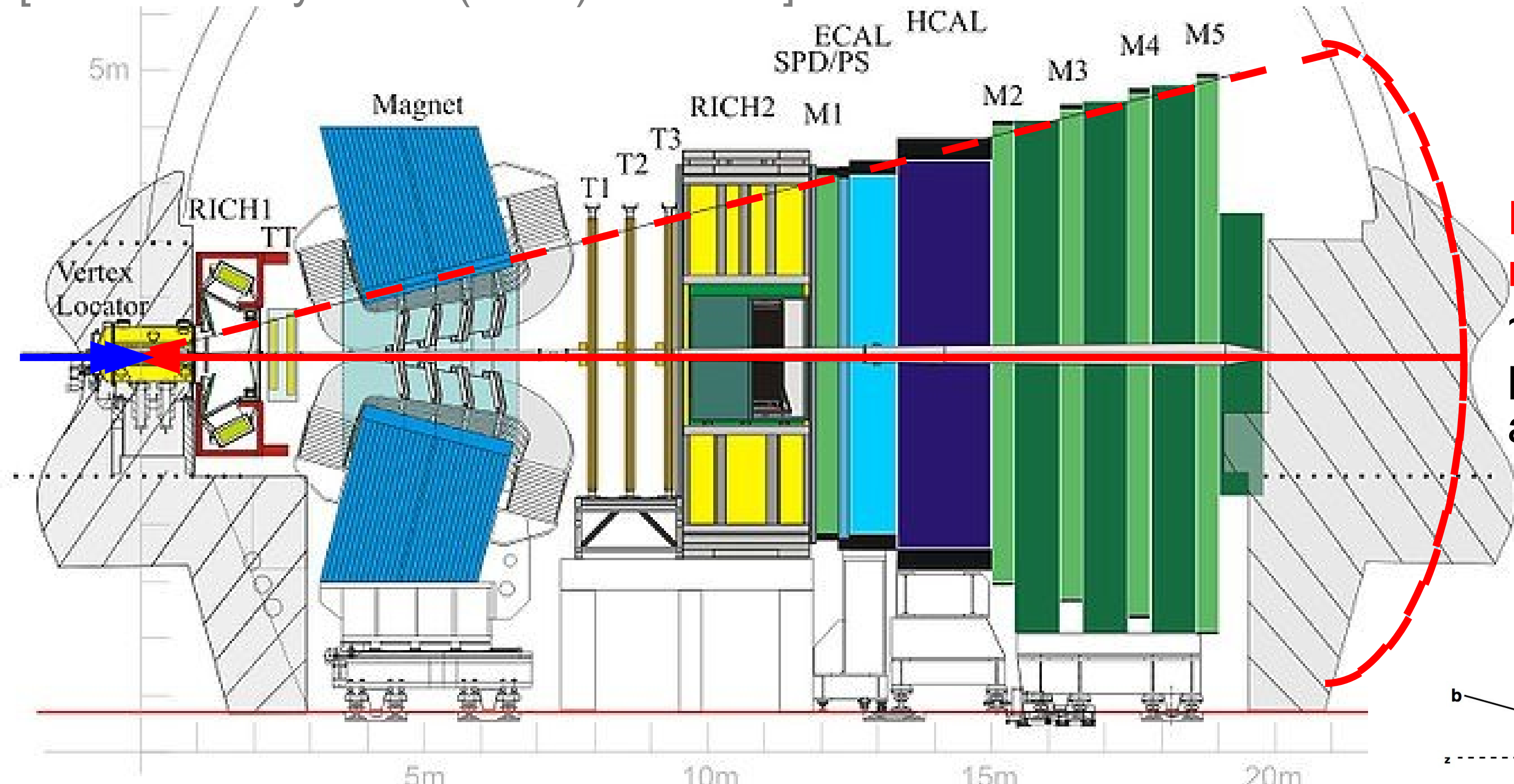
Relatively long lifetime

Decays with charmonium provide a clear signature



The LHCb experiment

[JINST 3 (2008) S08005]
[Int.J.Mod.Phys. A30 (2015) 1530022]



Fully instrumented rapidity range $2 < \eta < 5$:
~25% of b-quarks produced in the detector acceptance

Working with pp collisions at the LHC:

Production cross-section in the LHCb acceptance:

$\sigma_{pp\to b\bar{b}} = 72.0 \pm 0.3 \pm 6.8\ \mu b\ @\sqrt{s} = 7\ TeV$

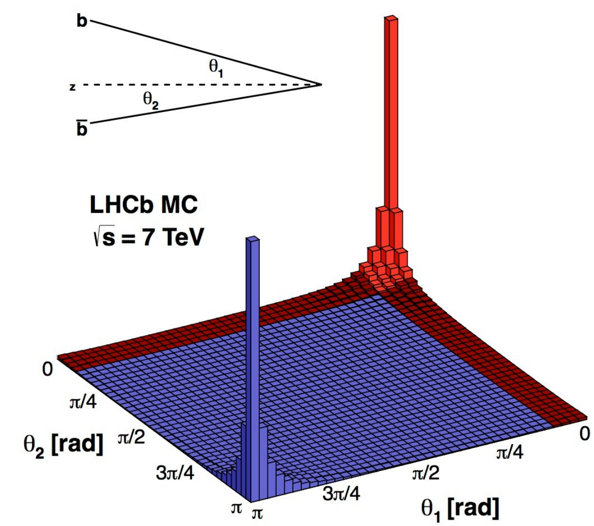
$\sigma_{pp\to b\bar{b}} = 144 \pm 1 \pm 21\ \mu b\ @\sqrt{s} = 13\ TeV$

[Phys. Rev. Lett. 118, 052002 (2017)]

Hadronization in all possible b-species

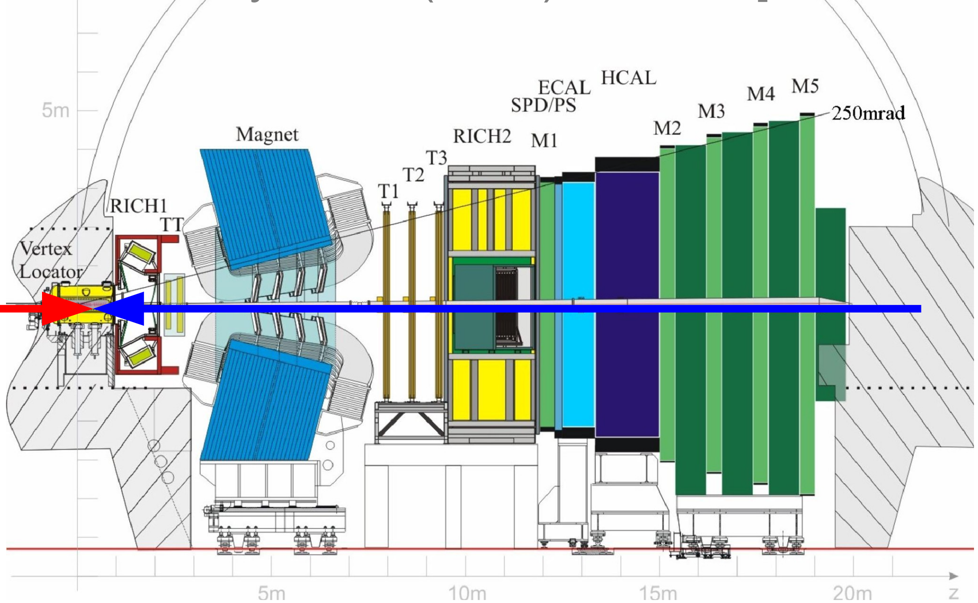
$B^0:\Lambda^0_b:B^0_s \sim 4:2:1$

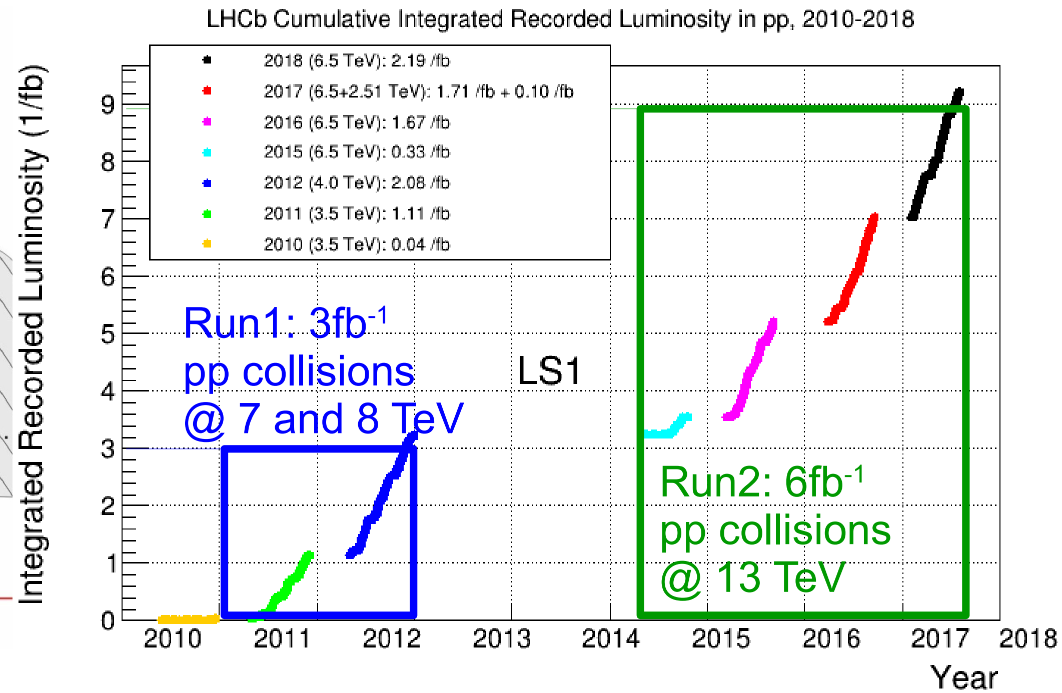
[JHEP08 (2014) 143]



The LHCb experiment

[JINST 3 (2008) S08005]
[Int.J.Mod.Phys. A30 (2015) 1530022]





VELO: Decay time resolution ~45 fs
Impact parameter resolution: (15 +29/pT[GeV]) μm

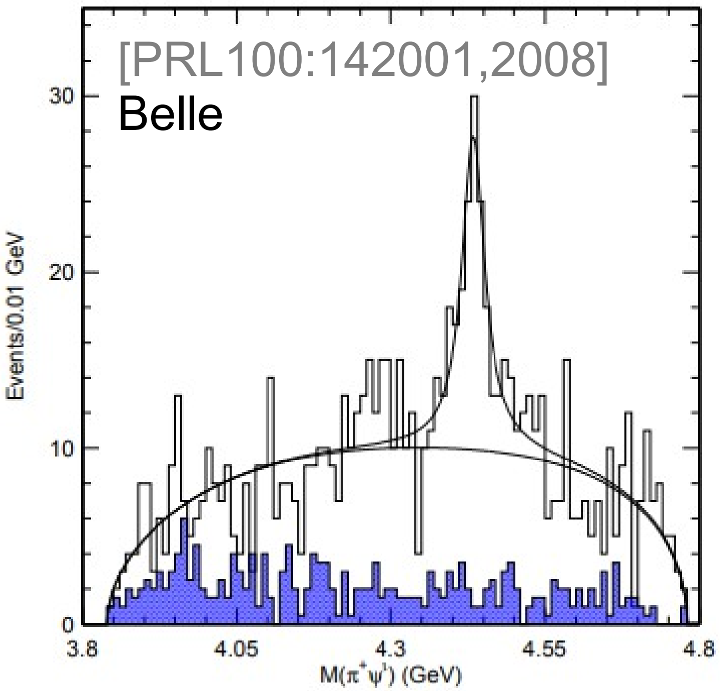
Relative track momentum resolution: 0.5% at low momentum, 1.0% at 200 GeV/c

Particle identification:
Kaon ID ~95 % for ~ 5 % $\pi \rightarrow K$ mis-id probability
Muon ID ~97 % for 1-3 % $\pi \rightarrow \mu$ mis-id probability

Muon system: ~90% trigger efficiency for dimuon channels

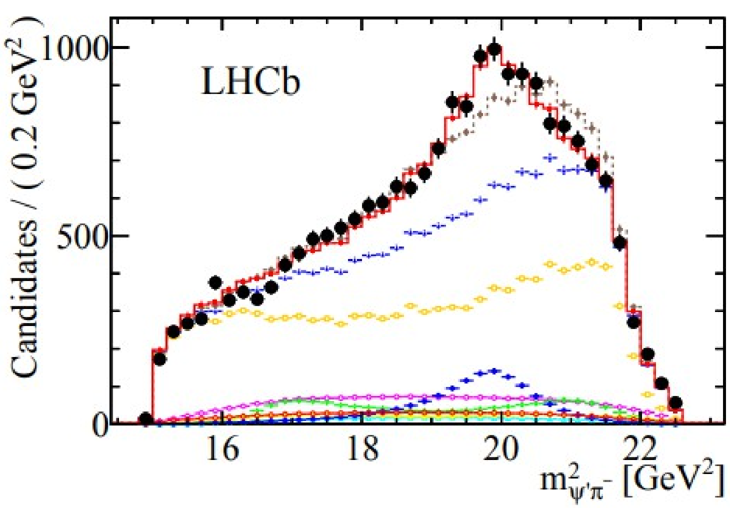
Exotic mesons

Study of the $B^0 \to J/\psi K^+\pi^-$ decay



$Z(4430)^-$ is one of the most well-known exotic states

- Discovered by Belle experiment
  - $B^0 \to Z(4430)^- K^+$
  - $Z(4430)^- \to \psi(2S)\pi^-$
- Not confirmed by the BaBar collaboration [Phys.Rev.D79:112001,2009]
- Confirmed by the LHCb collaboration [PRL 112, 222002 (2014)]
- Minimal quark content [$c\bar{c}u\bar{d}$]



[PRL 112, 222002 (2014)]

Evidence for $Z(4430)^-$ is found the $B^0 \to J/\psi\pi^- K^+$ decays by Belle

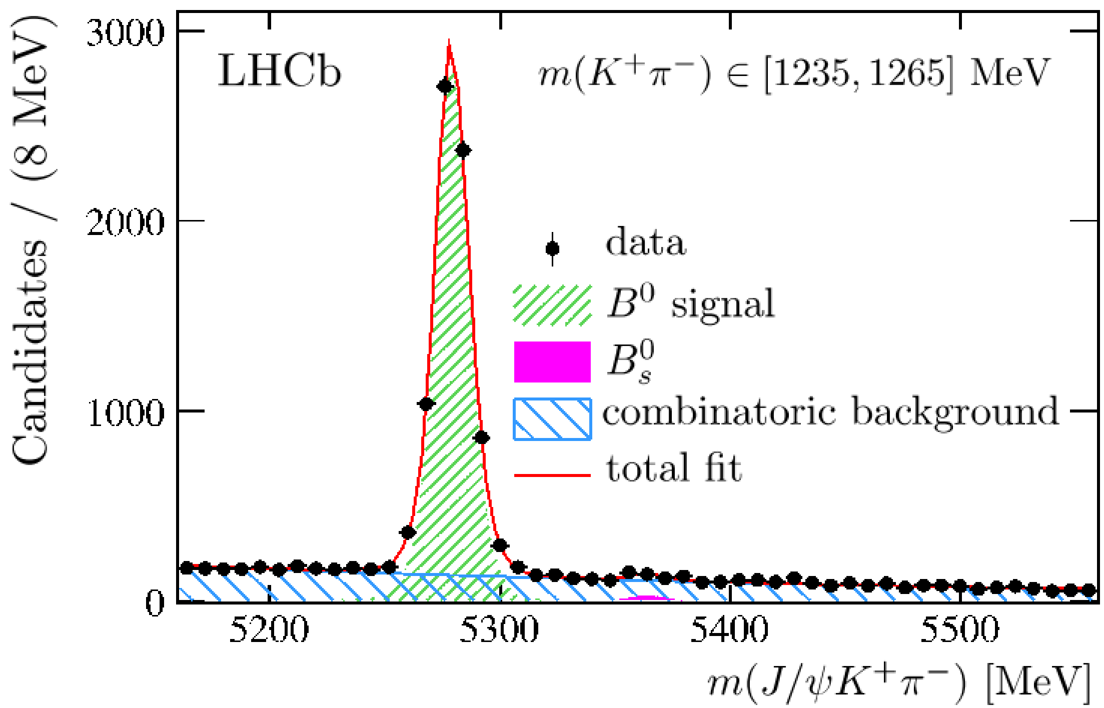
- $Z(4430)^- \to J/\psi\pi^-$ decay is supressed by at least a factor of 10
- A new exotic hadron is observed:
  - $B^0 \to Z(4200)^- K^+$
  - $Z(4200)^- \to J/\psi\pi^-$

[Phys. Rev. D90 (2014) 112009]

Study of the $B^0 \to J/\psi K^+\pi^-$ decay

[Phys. Rev. Lett. 122, 152002 (2019)]

3 fb^{-1} (Run 1)



Signal yield $B^0 \to J/\psi\pi^-K^+$ ~5×10^5

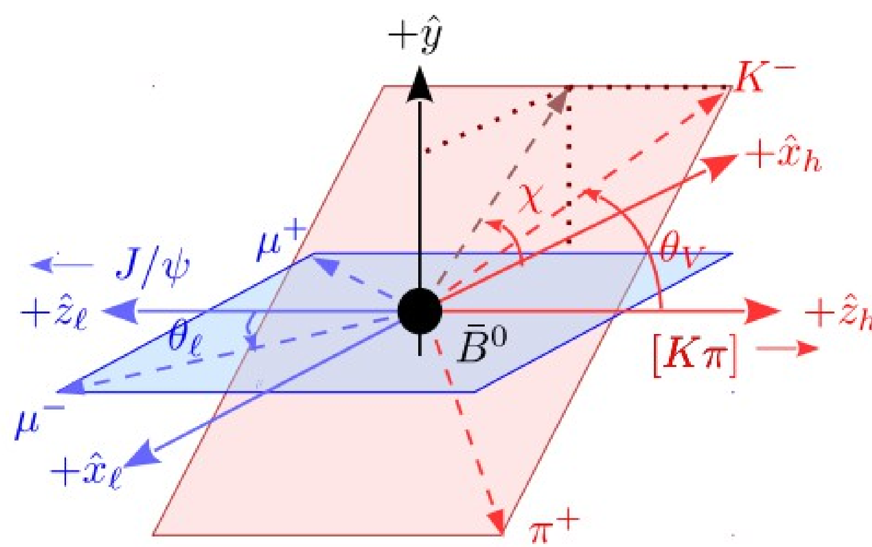
40 times larger than in BaBar study

20 times larger than in Belle study

Angular analysis in 35 $K^+\pi^-$ mass bins

Signal purity above 90% in every bin

3D angular fit in each bin



2 helicity angles: θ_l, θ_V

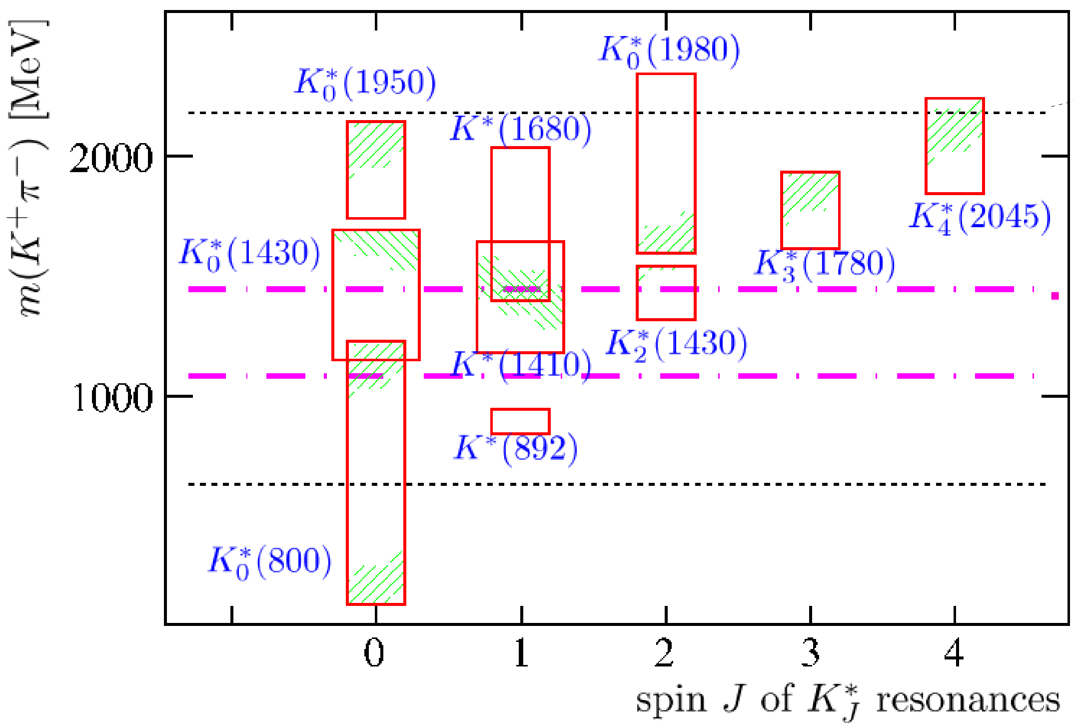
Angle between ($\mu^+\mu^-$) and ($K^+\pi^-$) decay planes: χ

Study of the $B^0 \to J/\psi K^+\pi^-$ decay

[Phys. Rev. Lett. 122, 152002 (2019)]

Parameters of K* spectrum are not very well experimentally measured

Model-independent analysis – relying only on highest allowed spin, J_{max}



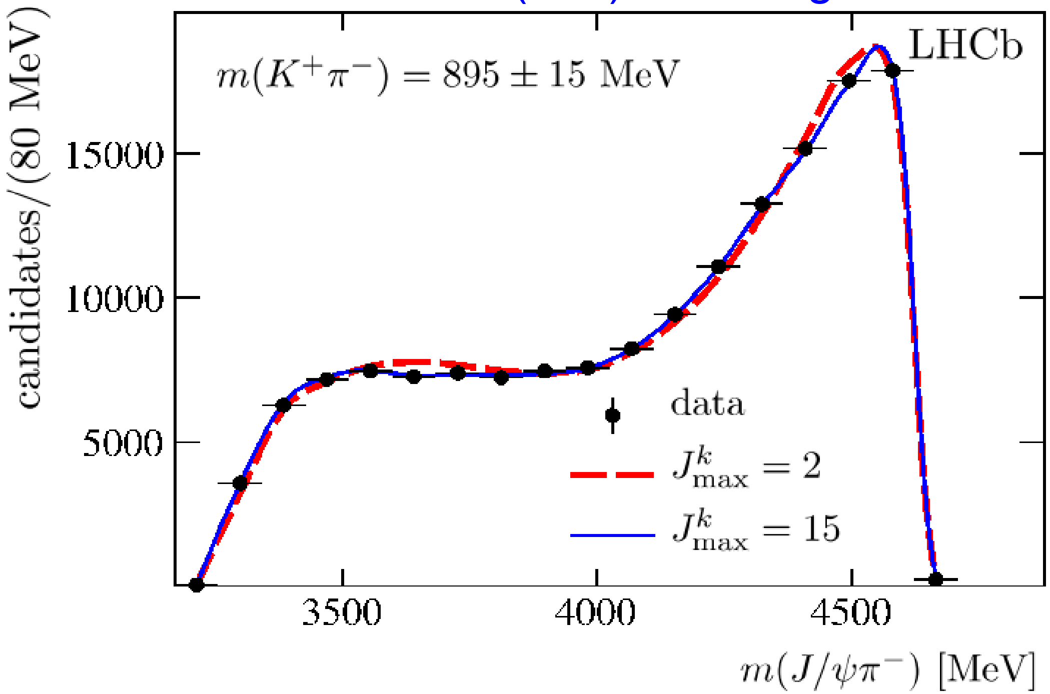
K*-only model

$$J^k_{\rm max} = \begin{cases} 2 & \text{if} \quad 1085 \le m(K^+\pi^-) < 1265 \text{ MeV} \\ 3 & \text{if} \quad 1265 \le m(K^+\pi^-) < 1445 \text{ MeV}. \end{cases}$$

Study of the $B^0 \rightarrow J/\psi K^+\pi^-$ decay

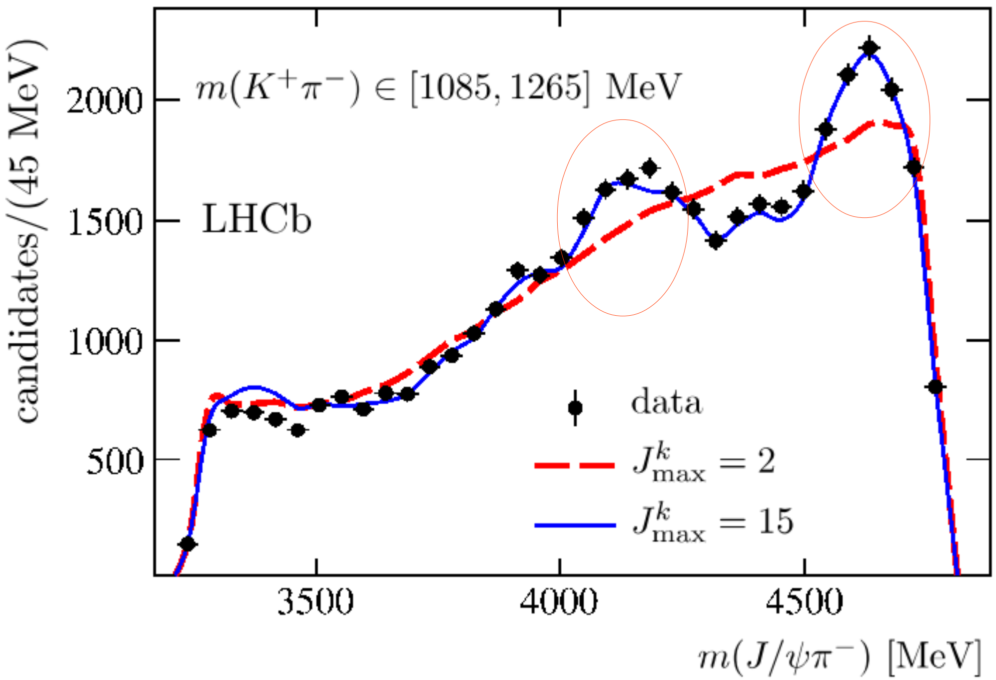
[Phys. Rev. Lett. 122, 152002 (2019)]

In the K*(892) mass region



Well described by contributions with J_{max} = 2 only

After vetoeing K*(892) mass region



Unphysical J_{max} = 15 is needed to describe the data

m(J/ψπ) ~ 4200 and 4600 MeV regions

Significance well exceeds 5σ

Model-dependent amplitude analysis is needed to determine the nature of these states

Study of the $B^0 \to \eta_c(1S)K^+\pi^-$ decay

[Eur.Phys.J. C78 (2018) 1019]

3 fb^{-1} (Run 1)
1.7 fb^{-1} (Run 2)

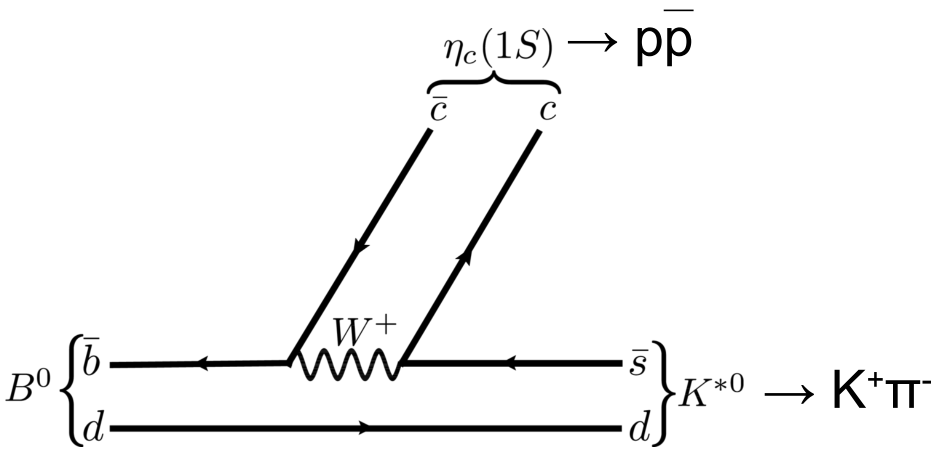
Z(3900)$^-$ discovered by BESIII collaboration $B^0 \to Z(3900)^- K^+$
$Z(3900)^- \to J/\psi\pi^-$

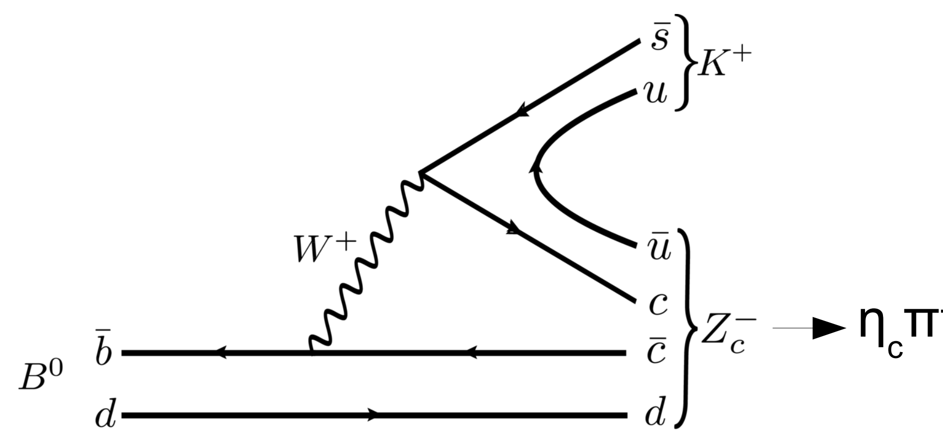
Confirmed by Belle and CLEO collaborations

Possible interpretations:

- Hadrocharmonium: predictes a state decaying to $\eta_c(1S)\pi^-$ at mass ~3800 MeV/c^2
- Lattice QCD for hybrid-like state: predicts 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 the open-charm threshold

Current analysis

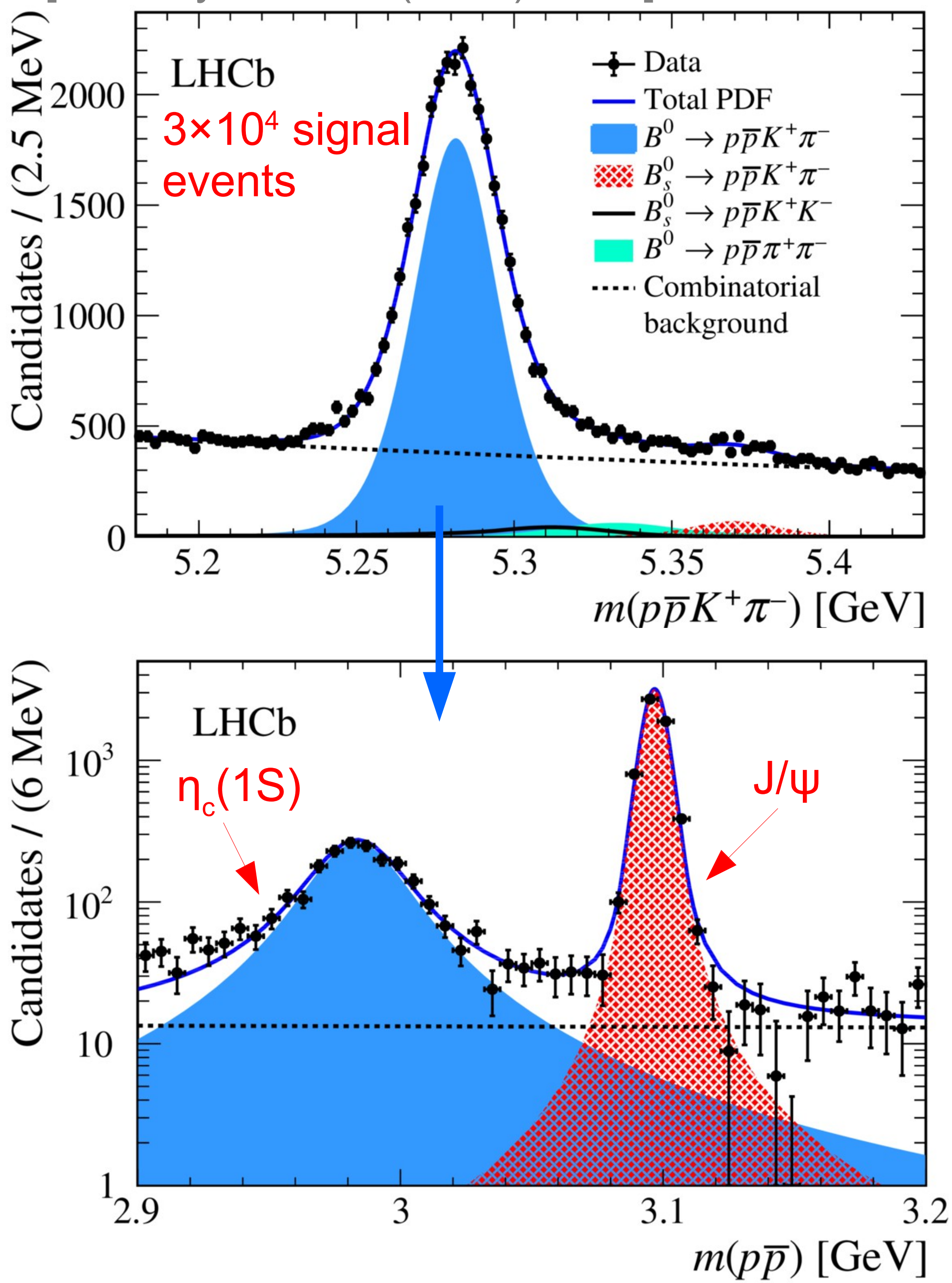




Only pseudoscalar particles in the final state → Dalitz plot analysis is possible

Study of the $B^0 \to \eta_c(1S)K^+\pi^-$ decay

[Eur.Phys.J. C78 (2018) 1019]



Event selection: loose cut-based preselection
+multivariate analysis

Branching fraction of the $B^0 \to \eta_c(1S)K^+\pi^-$ decay is determined as the following:

$$\mathcal{B}(B^0 \to \eta_c K^+\pi^-) = R \times \mathcal{B}(B^0 \to J/\psi\, K^+\pi^-) \times \frac{\mathcal{B}(J/\psi \to p\overline{p})}{\mathcal{B}(\eta_c \to p\overline{p})}$$

$$R = \frac{N_{\eta_c}}{N_{J/\psi}} \times \frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}}$$

Event yields from data

$N_{\eta c} = 2105 \pm 75$

$N_{J/\psi} = 5899 \pm 86$

Efficiencies from simulation

$\frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}} = 1.000 \pm 0.013$

First measurement!

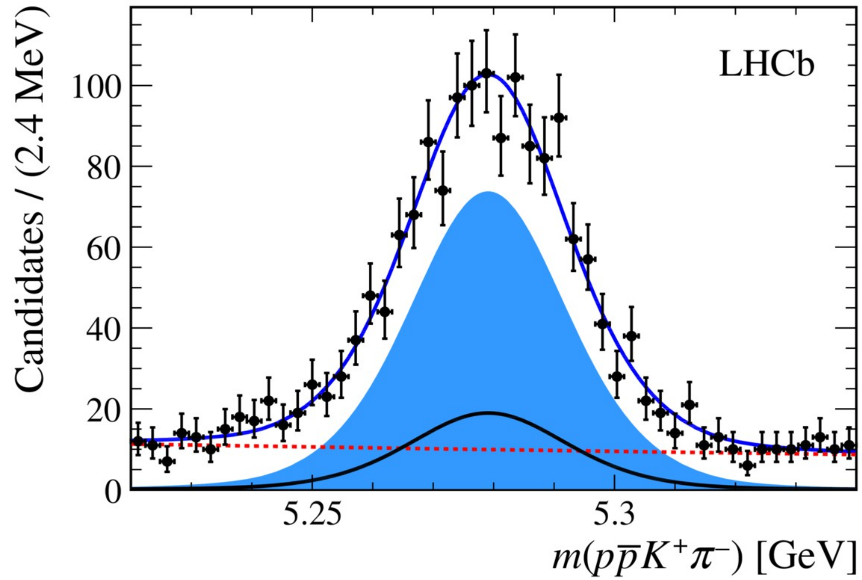
$$\mathcal{B}(B^0 \to \eta_c K^+\pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$$

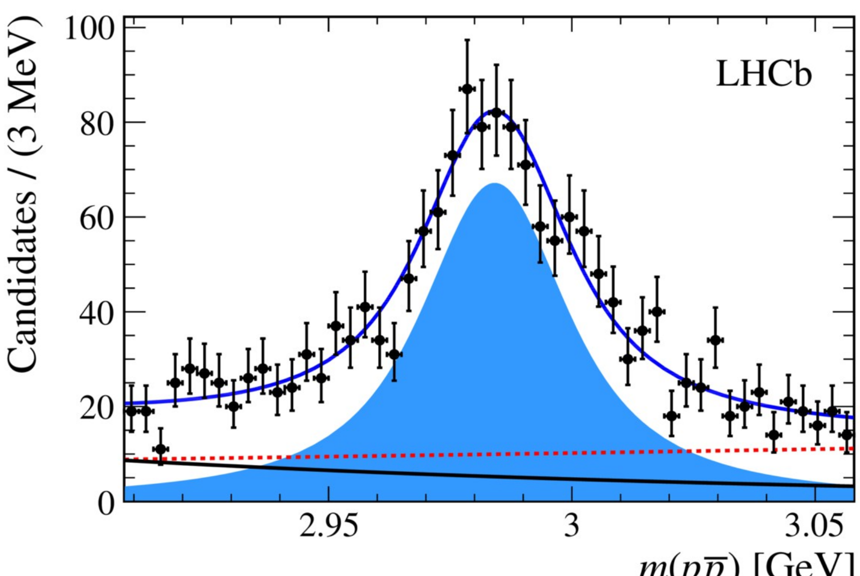
Dominated by knowledge of the external branching fractions

Study of the $B^0 \to \eta_c(1S)K^+\pi^-$ decay

[Eur.Phys.J. C78 (2018) 1019]

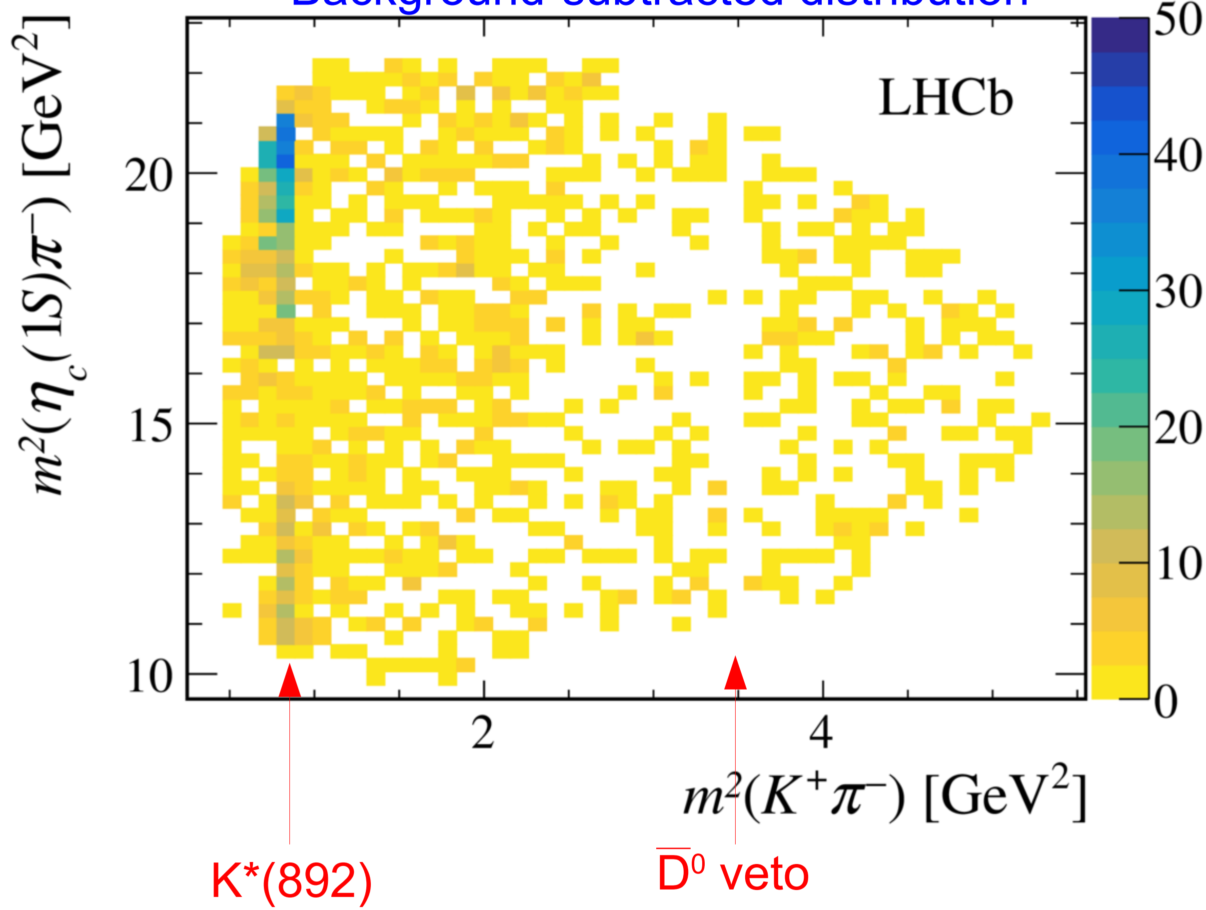
2D fit to $p\bar{p}K\pi$ and $p\bar{p}$ mass in the $\eta_c(1S)$ mass region





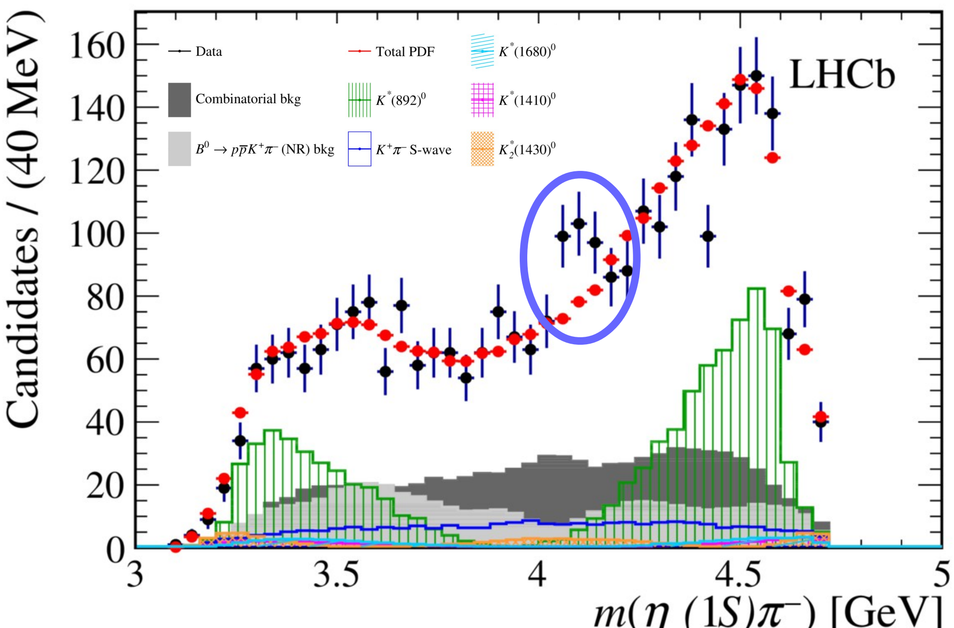
Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	805 ± 48	1065 ± 56
$B^0 \to p\bar{p}K^+\pi^-$ (NR)	234 ± 48	273 ± 56
Combinatorial background	409 ± 36	498 ± 41

Background-subtracted distribution

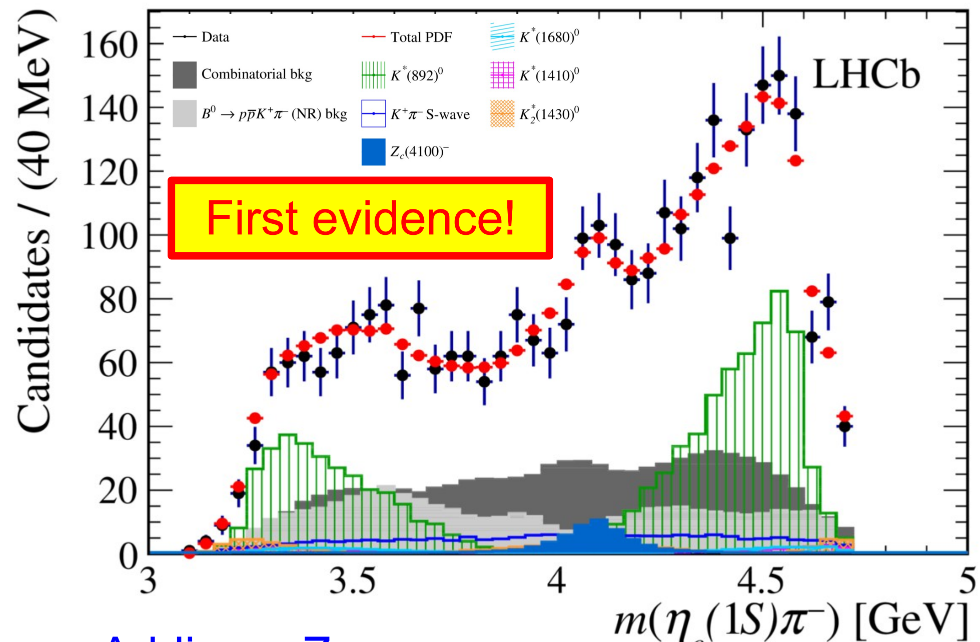


Study of the $B^0 \to \eta_c(1S)K^+\pi^-$ decay

[Eur.Phys.J. C78 (2018) 1019]



Baseline model



Adding a Z_c^- resonance

Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

+LASS for non-resonant contribution

Adding higher K* resonances does not improve the fit result

Signal significance lower limit after inclusion of all systematic uncertainties is 3.2σ

Several possible J^P considered: 0^+, 1^-, 2^+
Yet 0^+ is not excluded → can't determine its nature with current statistics

Nominal fit gives

$$m_{Z_c^-} = 4096 \pm 20 \ ^{+18}_{-22} \text{ MeV}$$
$$\Gamma_{Z_c^-} = 152 \pm 58 \ ^{+60}_{-35} \text{ MeV}$$

Search for beauty-full tetraquarks

[JHEP 10 (2018) 086]

No hadron containing more than 2 heavy quarks has been observed so far

3 fb^{-1} (Run 1)
3.3 fb^{-1} (Run 2)

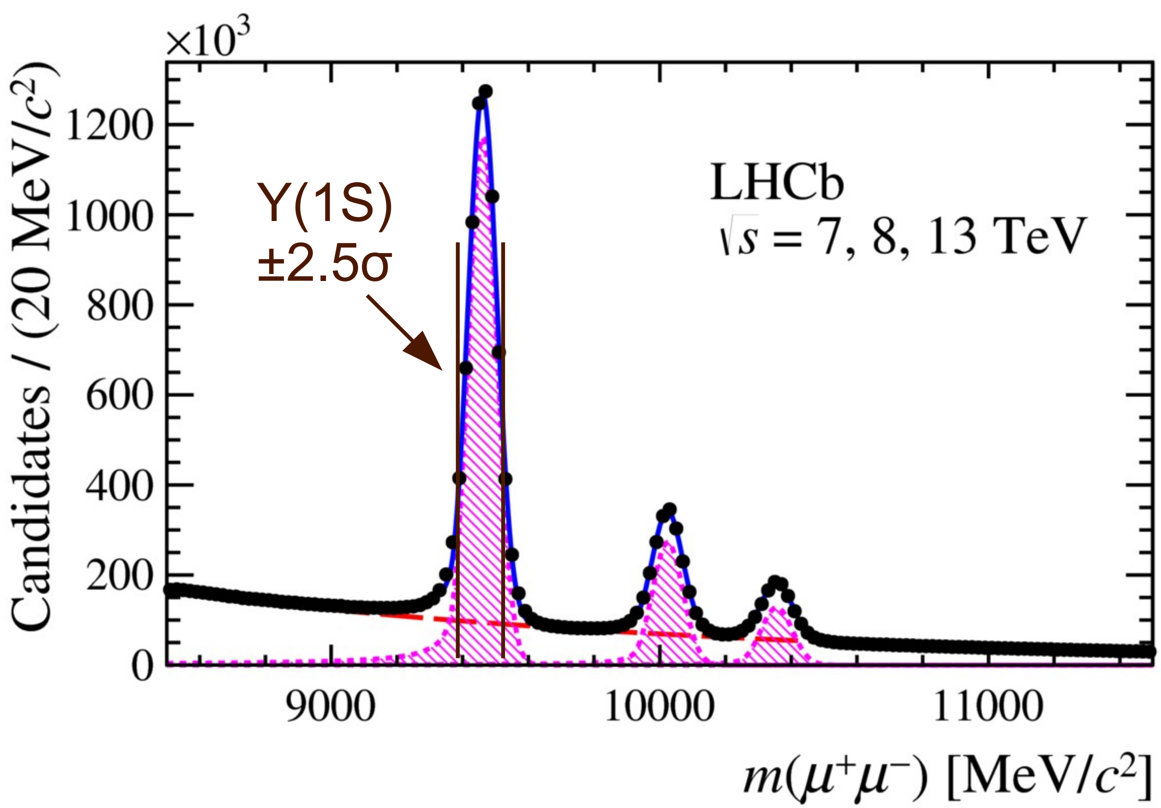
$X_{b\bar{b}b\bar{b}}$ theoretical predictions

Mass within [18.4; 18.8] GeV/c^2

Typically below $\eta_b\eta_b$ threshold → could decay to Υl^+l^- (l = e, μ) [see backup]

Expected σ×Br($l^+l^-l^+l^-$) ~1fb at the LHC energies [FERMILAB-PUB-17-395-T]

Lattice QCD calculations do not find any evidence of this state



Search for $X_{b\bar{b}b\bar{b}}$ → Υ(1S)$\mu^+\mu^-$
with Υ(1S) → $\mu^+\mu^-$

In normalization to Υ(1S) → $\mu^+\mu^-$

Wide 4μ invariant mass range
[17.5; 20.0] GeV/c^2

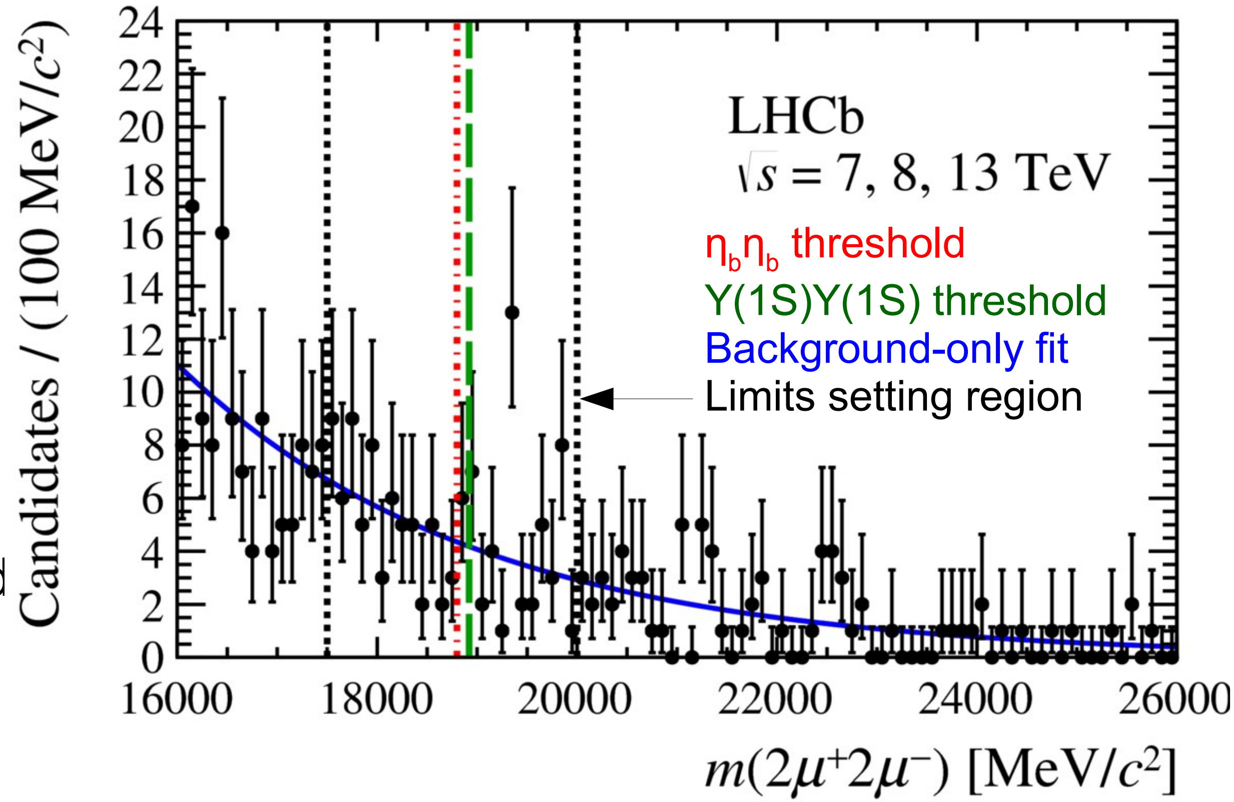
Use Run I and Run II data
1.0 fb^{-1} @ 7 TeV pp collisions
2.0 fb^{-1} @ 8 TeV pp collisions
3.3 fb^{-1} @ 13 TeV pp collisions
and combined sample

Search for beauty-full tetraquarks

[JHEP 10 (2018) 086]

Events selected with cut-based selection
J/ψ veto for muons in m(μμ) in [3050;3150] MeV/c^2

Υ(1S) yields after the selection (±2.5σ region):
~ 6×10^6 signal events for combined sample



No significant excess is seen in data. Upper limits are set for

$$S \equiv \sigma(pp \to X) \times \mathcal{B}(X \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$$

In normalization to known value of $\sigma(pp \to \Upsilon(1S)) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$

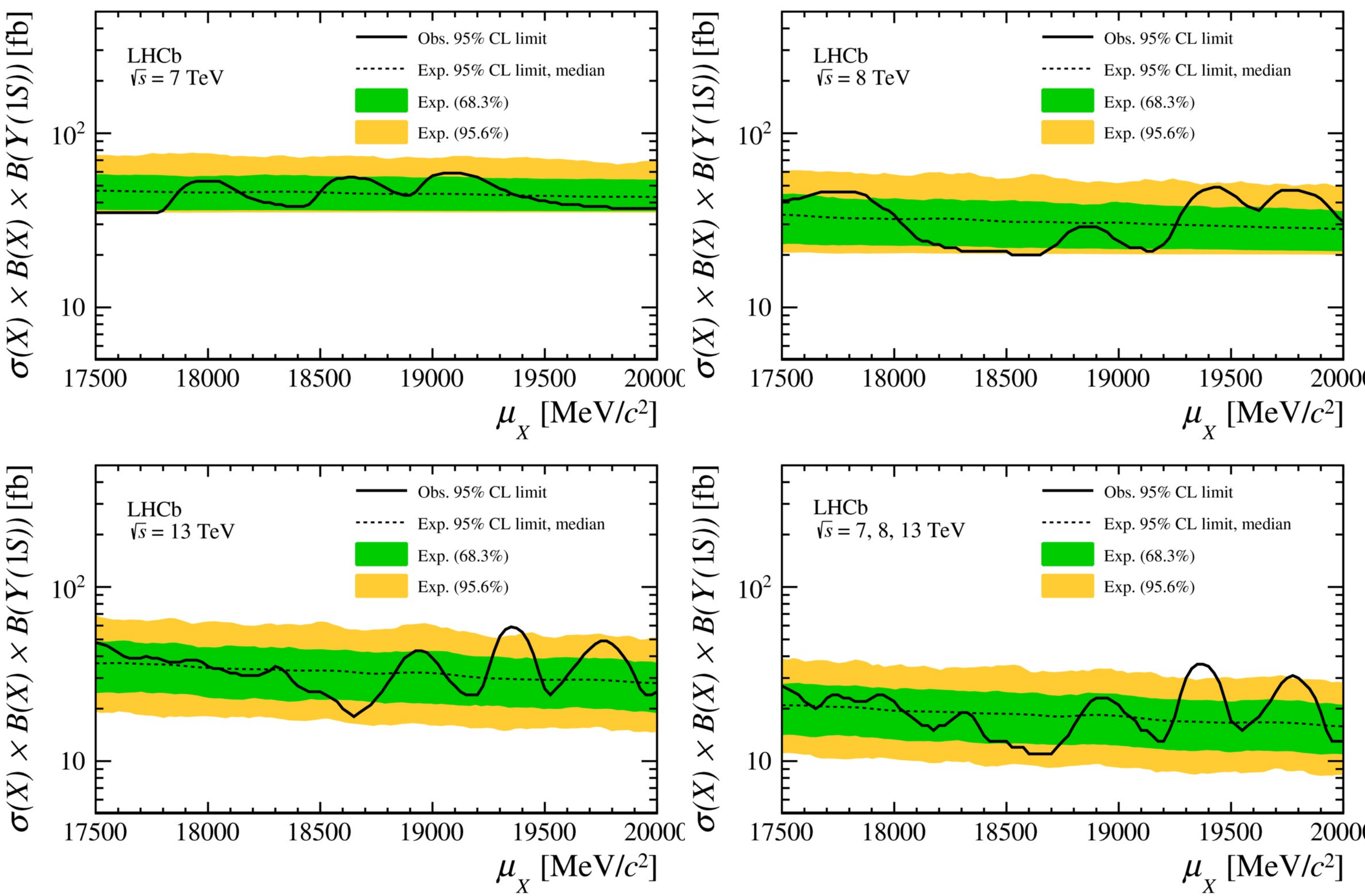
[JHEP 11 (2015) 103]
[arXiv:1804.09214]

Search for beauty-full tetraquarks

[JHEP 10 (2018) 086]

Likelihood profile as a function of S is integrated to determine upper limits

Scan over 101 values of $X_{b\bar{b}b\bar{b}}$ mass



Fiducial region

p_T < 30 GeV/c

2.0 < y < 4.5

Theoretical expectation of σ×Br($l^+l^-l^+l^-$) is ~1fb

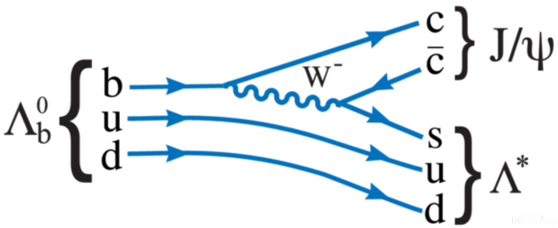
[FERMILAB-PUB-17-395-T]

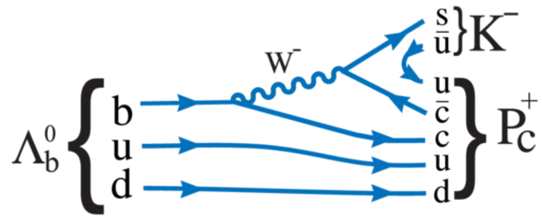
Exotic baryons

Pentaquarks

2015 – first observation of resonances consistent with pentaquark states

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

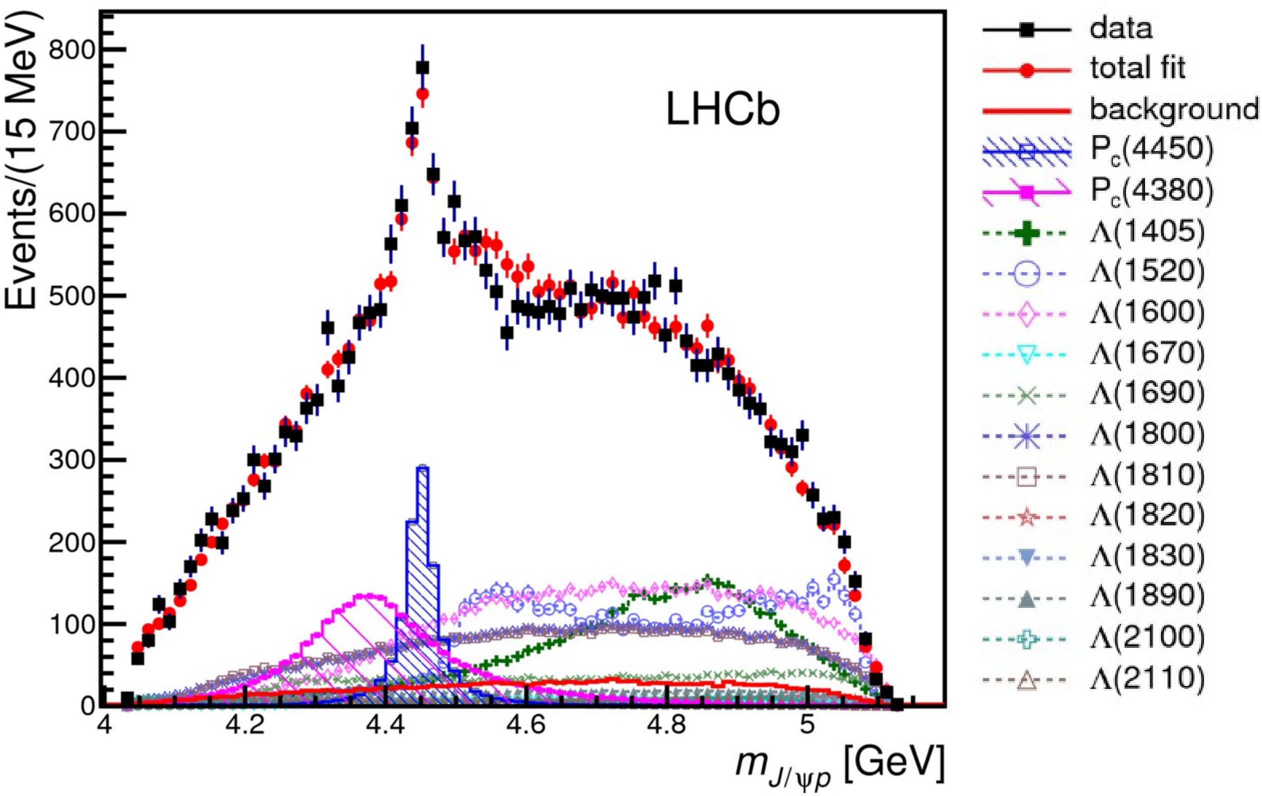




$P_c(4380)^+$ @ 9σ significance

M = 4380 ± 8 ± 29 MeV/c²

Γ = 205 ± 18 ± 86 MeV/c²



$P_c(4450)^+$ @ 12σ significance

M = 4450 ± 2 ± 3 MeV/c²

Γ = 39 ± 5 ± 19 MeV/c²

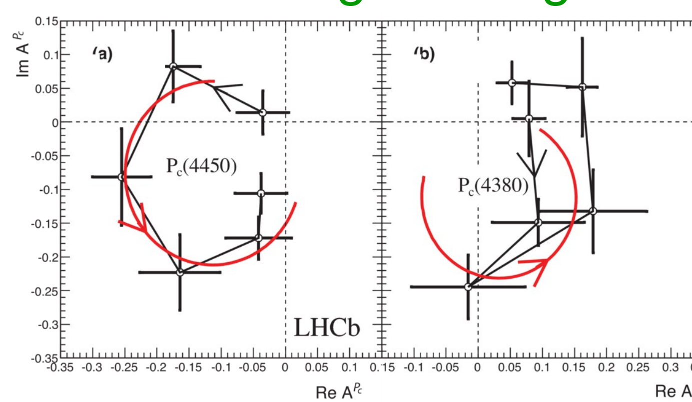
Possible J^P combinations:

Best fit ($3/2^-$, $5/2^+$)

Satisfactory fits

($3/2^+$, $5/2^+$) or ($5/2^+$, $3/2^+$)

Check their resonance nature with Argand diagram

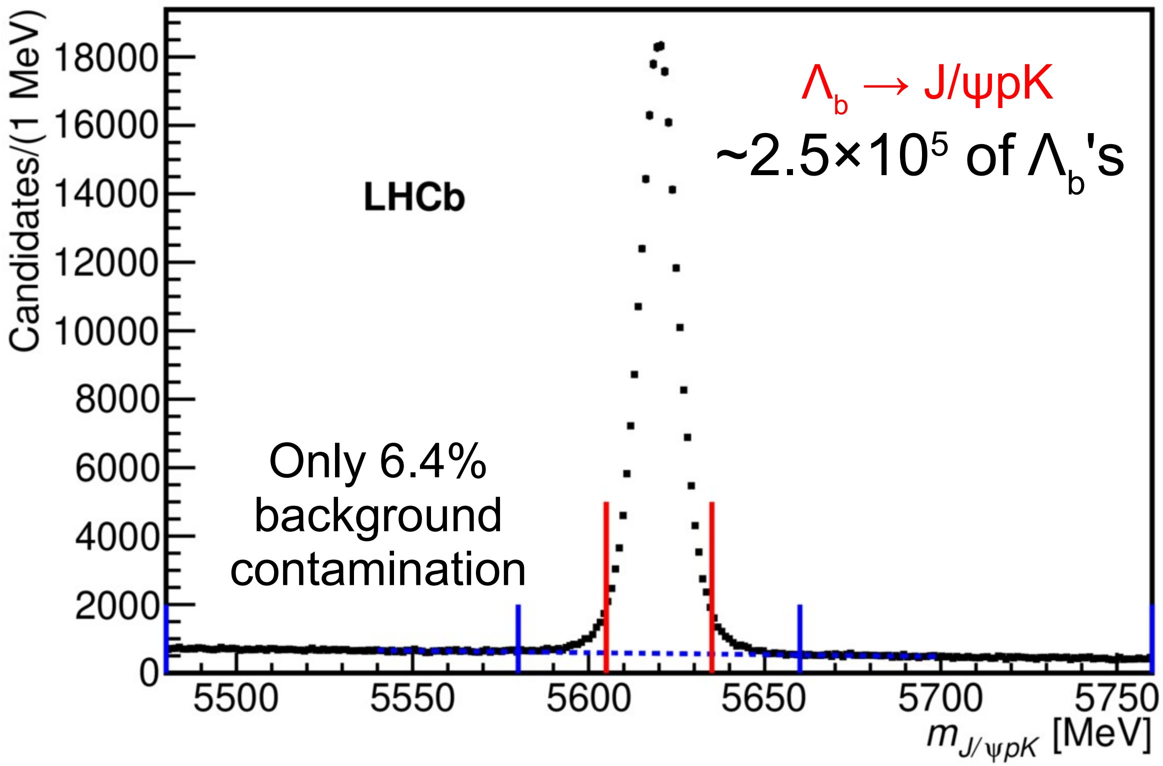


Cross-check with the help of model-independent analysis – supports the observation

[Phys. Rev. Lett. 117, 082002 (2016)]

P_c^+ states with Run1+Run2 data

[arXiv:1904.03947 (submitted to PRL)]

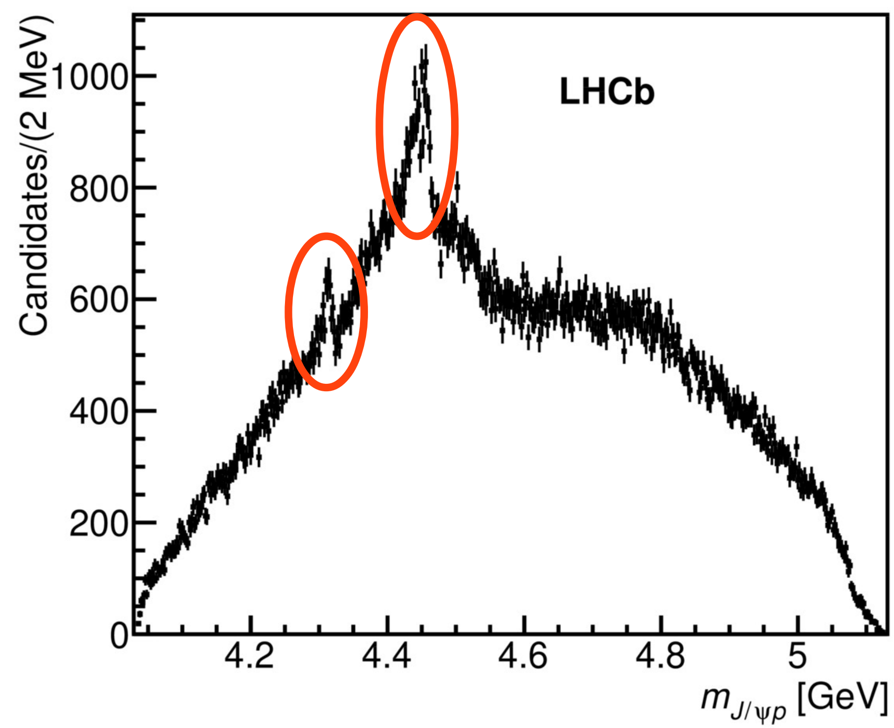


3 fb^{-1} (Run 1)
6 fb^{-1} (Run 2)

Updates of the analysis:

- Larger datasample
- Better selection with BDT

x9 larger sample of Λ_b's



Narrow state in a region around 4312 MeV

2 narrow peaks at 4440 and 4457 MeV

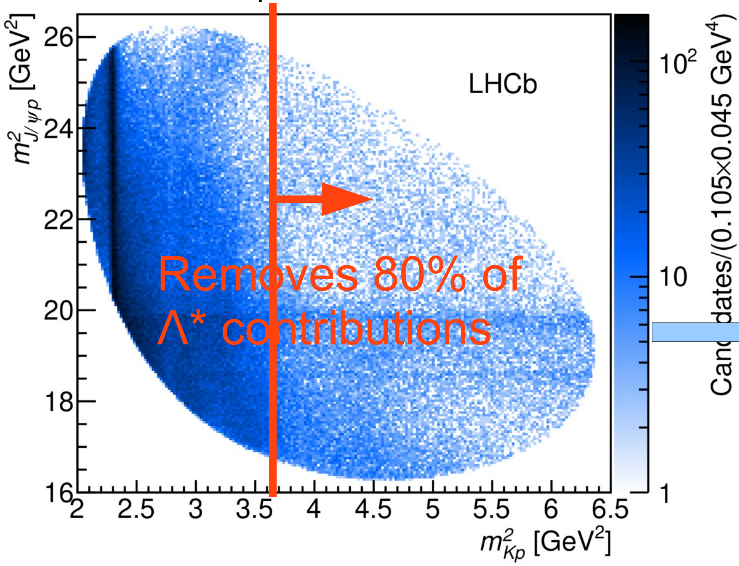
- Narrow peaks can be studied without amplitude analysis
- Binned 1D fit to the data
- 1D fit is not enough to confirm/update the wide $P_c(4380)^+$

P_c^+ states with Run1+Run2 data

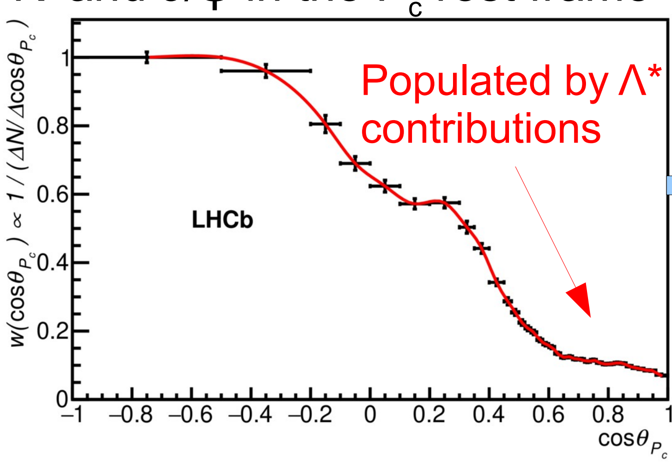
[arXiv:1904.03947 (submitted to PRL)]

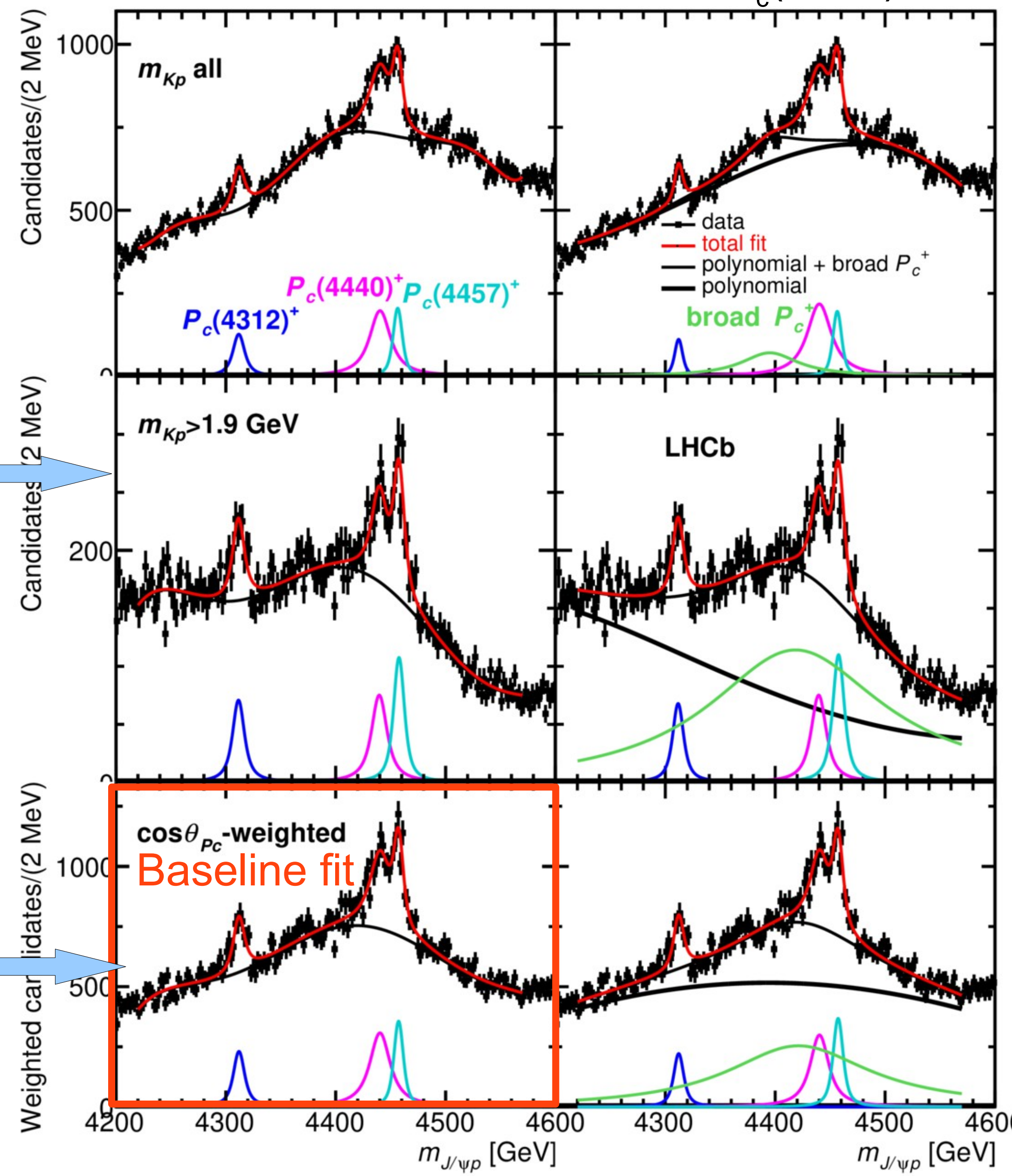
Two ways to reduce contributions from Λ* states:

Use m_{Kp} > 1.9 GeV/c² cut



Reweighting by the angle between K^- and J/ψ in the P_c rest frame





P_c^+ states with Run1+Run2 data

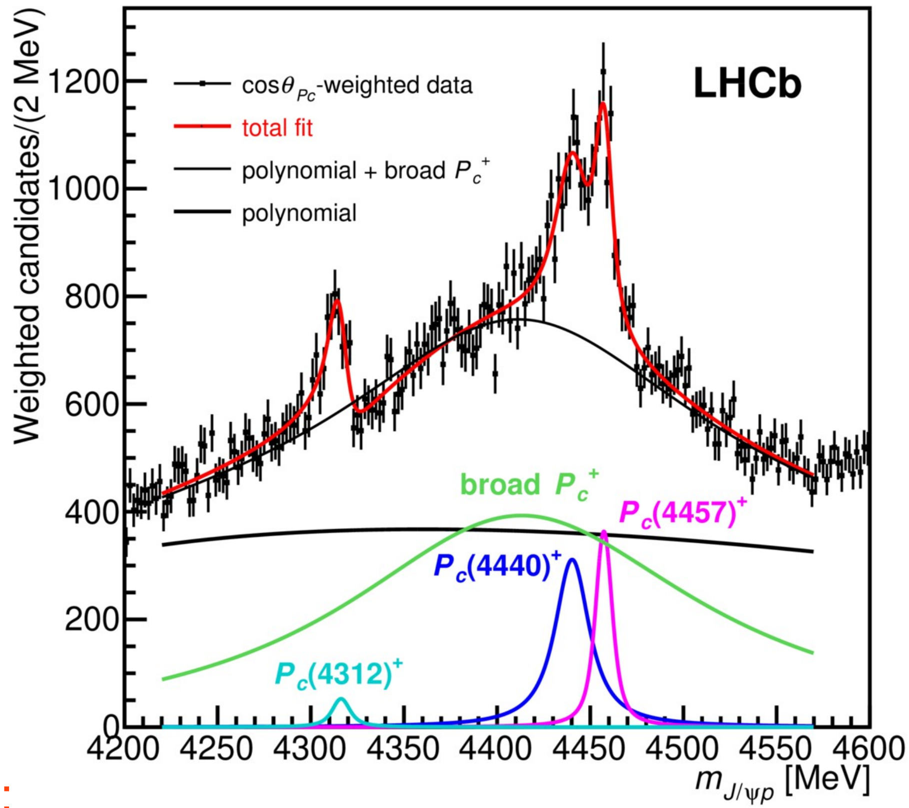
[arXiv:1904.03947 (submitted to PRL)]

Baseline model uses incoherent sum of Breit-Wigner amplitudes

- Fits with various possible interference
- No big interference observed
- Largest source of systematic uncertainty for masses and widths

Further cross-checks:

- Various polynomial orders for background description
- Local fit in the $P_c(4312)^+$ region
- Alternative data selection



Signal significances for m > 1.9 GeV (cosθ-weighted):

- 7.3σ (8.2σ) for $P_c(4312)^+$ (includes look-elsewhere effect)
- 5.4σ (6.2σ) for two-peak against one-peak structure around 4450 MeV

Fit fractions determined from efficiency-weighted distribution. Efficiencies are parametrised in 6D Λb phase-space → J^P-independent.

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)}$$

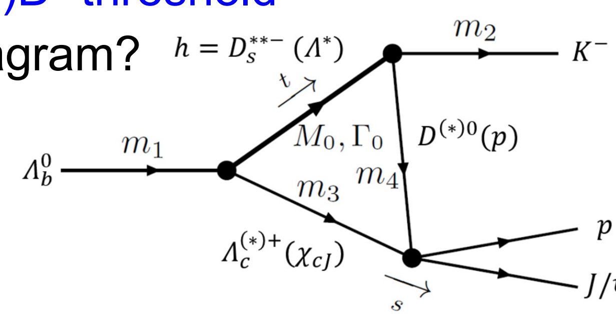
P_c^+ states with Run1+Run2 data

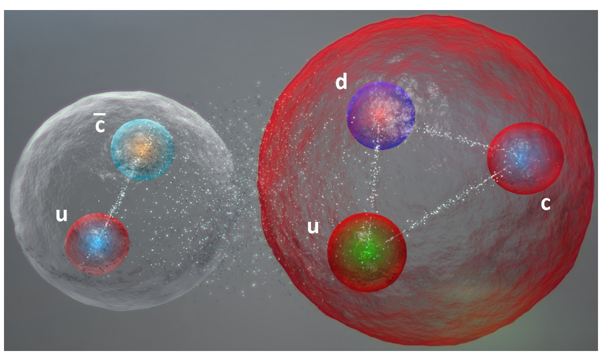
[arXiv:1904.03947 (submitted to PRL)]

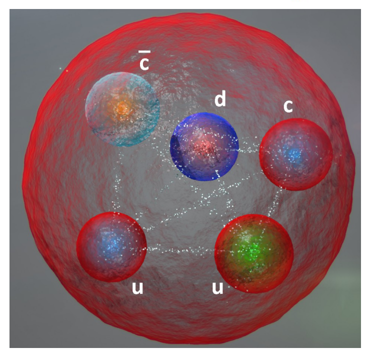
Interpretations?

$P_c(4457)^+$ close to $\Lambda_c^+(2595)D^0$ threshold

Could be a triangle diagram?







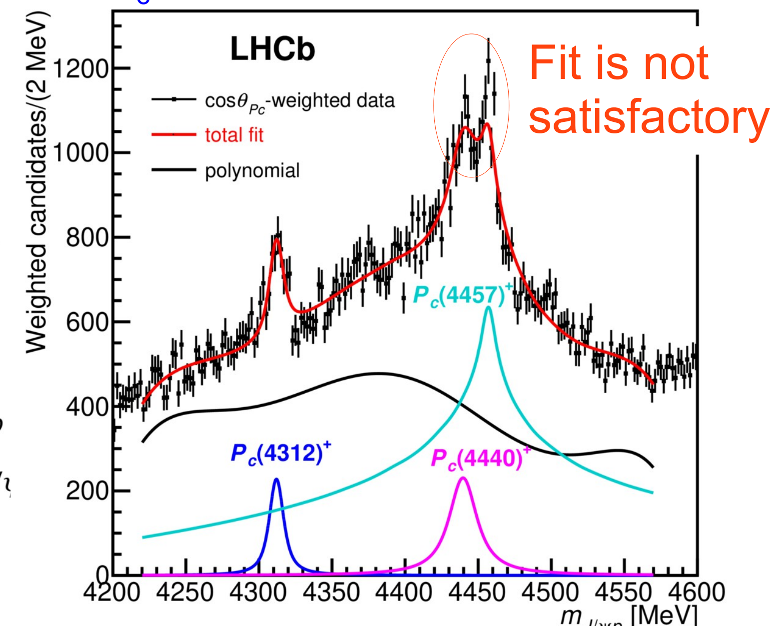
$P_c(4312)^+$ and $P_c(4457)^+$ close to $\Sigma^+_c\overline{D}^0$ and $\Sigma^+_c\overline{D}^{*0}$ thresholds

Could be excellent candidates for meson-baryon molecules

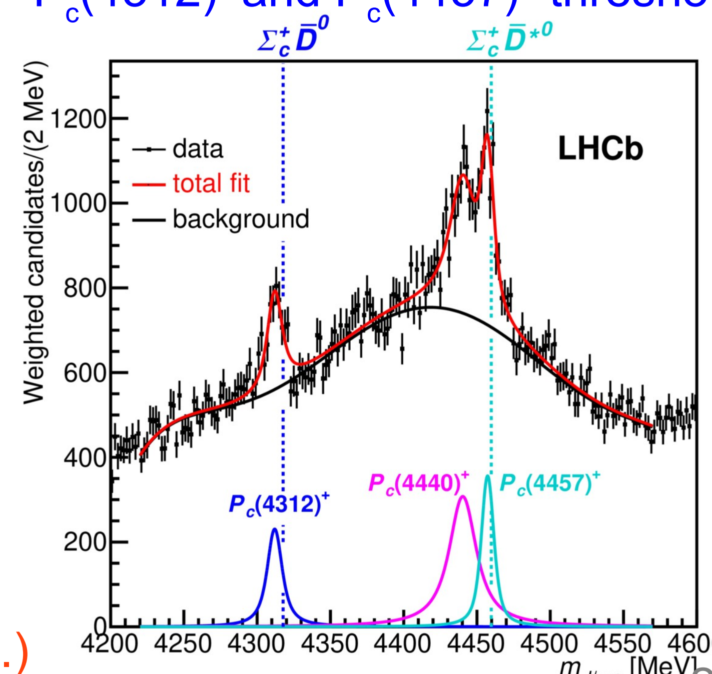
$P_c(4440)^+$ could be the second $\Sigma_c\overline{D}^*$ state

Need angular analysis to determine quantum numbers (work in progress...)

Fit $P_c(4457)^+$ as a triangle diagram



$P_c(4312)^+$ and $P_c(4457)^+$ thresholds



Search for weakly decaying b-flavoured pentaquarks

[Phys. Rev. D97 (2018) 032010]

The heavier the constituent quarks, the more tightly bound the pentaquark states

[Proc. Roy. Soc. Lond. A260 (1961) 127], [Phys. Lett. B590 (2004) 185]
[Phys. Lett. B586 (2004) 337], [Phys. Lett. B331(1994) 362]

No experimental searches have been published before

3 fb^{-1} (Run 1)

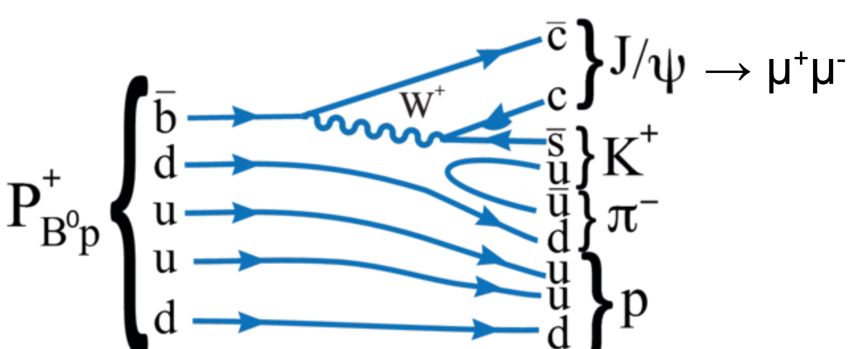
Simultaneous search for four different states:

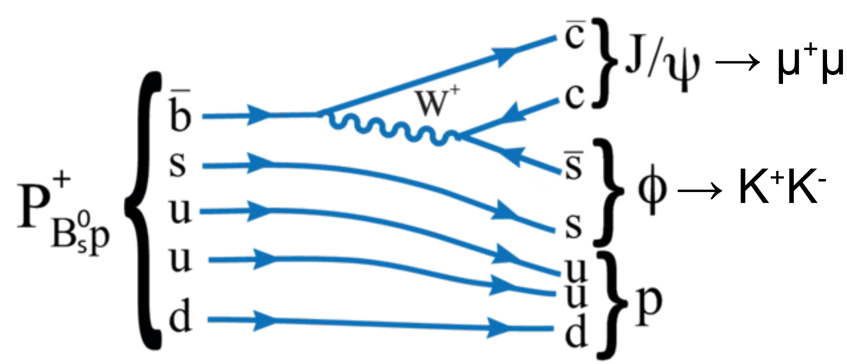
Case IV implicitly includes corresponding $P^{+}_{\bar{B}^0_s p}$ decay

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^{+}_{B^0 p} \to J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^{-}_{\Lambda_b^0\pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^{+}_{\Lambda_b^0\pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^{+}_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

Subscript: dominant strong decay modes for the state, if its mass above the threshold

Search mass windows: below the strong decay threshold

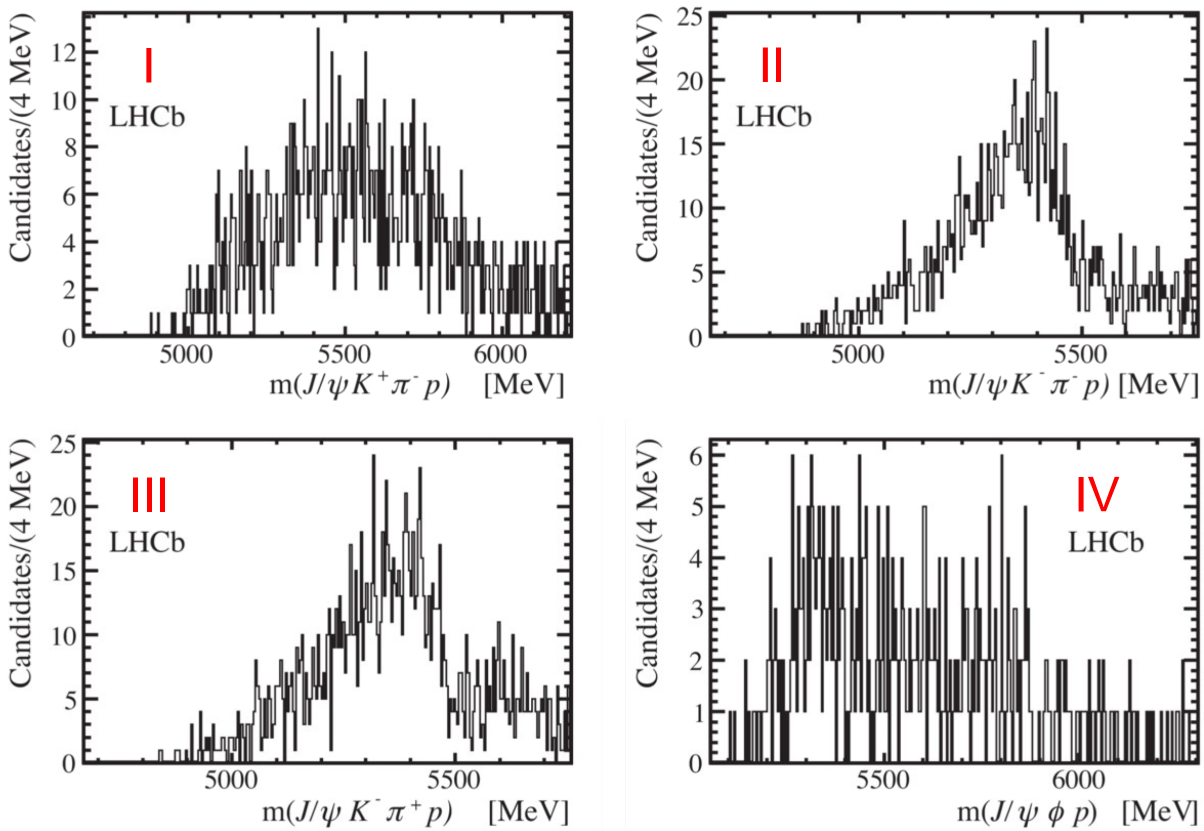




Search for weakly decaying b-flavoured pentaquarks

[Phys. Rev. D97 (2018) 032010]

Invariant mass distributions after the selection



Blinded analysis

Event selection:
- Loose cut-based preselection
- Boosted-decision tree (BDT)

Simulation used for BDT training and efficiencies calculations
- 4 different masses for each P^+
- P^+ lifetime set to 1.5 ps
- Phase-space assumption for P^+ decays

Total efficiencies 0.45-1.4% depending on the mode

A narrow signal is expected with resolution of 5.2 – 6.0 MeV/c^2

No significant narrow structures are observed. Upper limits are set.

Search for weakly decaying b-flavoured pentaquarks

[Phys. Rev. D97 (2018) 032010]

90% upper limits are set for the ratio

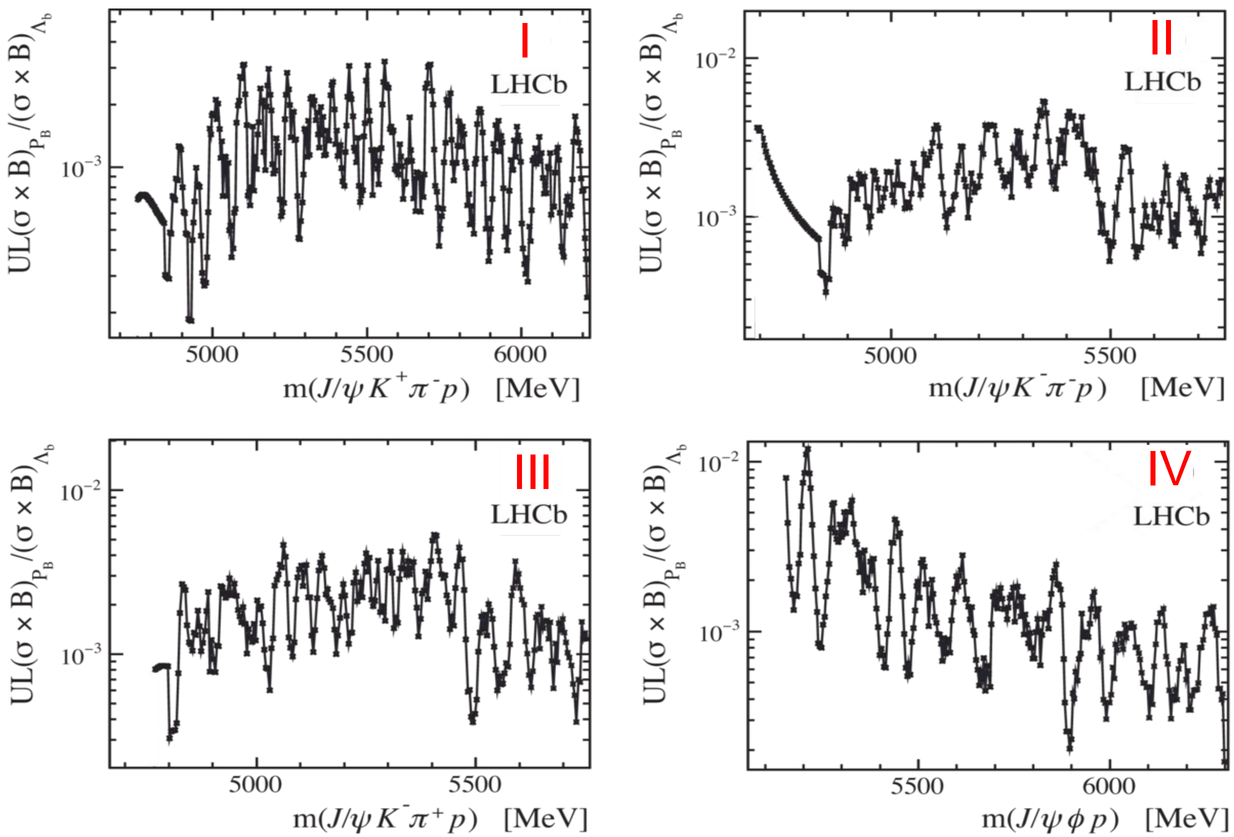
$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p)}$$

where

$$\sigma(\Lambda_b^0, \sqrt{s} = 7\,\text{TeV}) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p) = 6.12 \pm 0.10 \pm 0.25\,\text{nb},$$

$$\sigma(\Lambda_b^0, \sqrt{s} = 8\,\text{TeV}) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p) = 7.51 \pm 0.08 \pm 0.31\,\text{nb},$$

[Chin. Phys. C40 (2016) 011001]



Fiducial region

$p_T < 20$ GeV/c

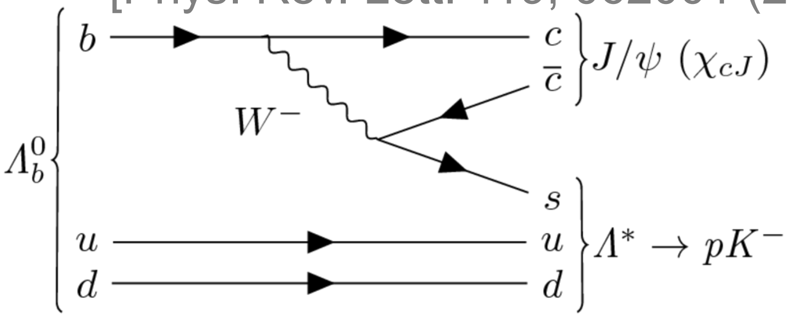
$2.0 < y < 4.5$

Averaged between 7 and 8 TeV samples

Future prospects

$\Lambda_b \to \chi_{c1,2} pK$ decays

[Phys. Rev. Lett. 119, 062001 (2017)]



3 fb^{-1} (Run 1)

Search for 2 decays together: $\Lambda^0_b \to \chi_{c1,2}pK$

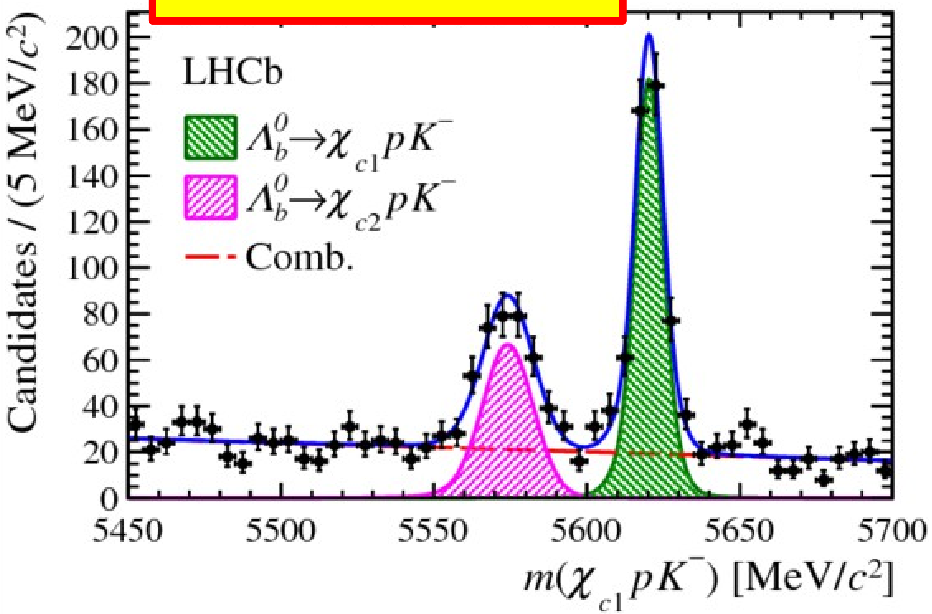
Normalize by $\Lambda^0_b \to J/\psi pK$

$\chi_{c1,2} \to J//\psi\gamma$ decays reconstructed

Mass constrained to χ_{c1} mode

χ_{c2} mode shifted to lower mass values

2 first observations!



$\Lambda^0_b \to \chi_{c1}pK$:

453 ± 25 signal events

29σ significance

$\Lambda^0_b \to \chi_{c2}pK$:

285 ± 23 signal events

17σ significance

Too few for the amplitude analysis yet

Can measure the branching fractions:

$$\mathcal{B}\left(\Lambda_b^0 \to \chi_{c1} pK^-\right) = \left(7.3 \pm 0.4 \pm 0.4 \pm 0.6\,^{+1.0}_{-0.6}\right) \times 10^{-5}$$

$$\mathcal{B}\left(\Lambda_b^0 \to \chi_{c2} pK^-\right) = \left(7.5 \pm 0.6 \pm 0.4 \pm 0.6\,^{+1.1}_{-0.6}\right) \times 10^{-5}$$

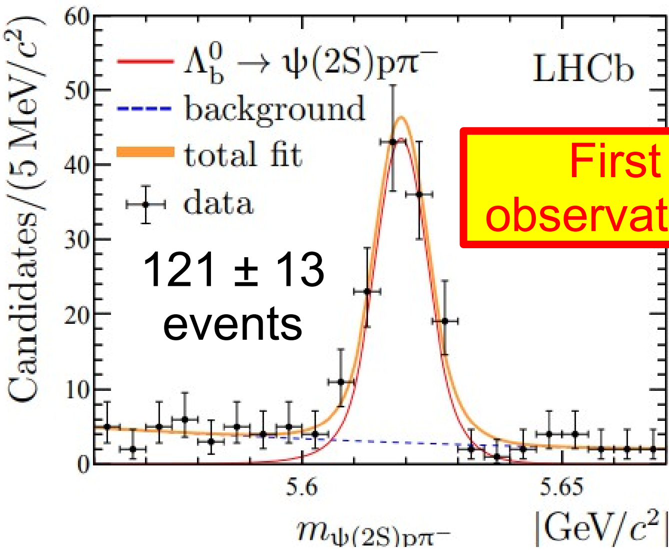
$\Lambda_b \to \psi(2S)p\pi$ decay

3 fb^{-1} (Run 1)
1.9 fb^{-1} (Run 2)

Study of the the Cabibbo-suppressed $\Lambda_b \to J/\psi p\pi$ decay has been performed not long ago

Yet not very conclusive [Phys. Rev. Lett. 117, 082003 (2016)]

Other decay modes may be of interest



First observation!

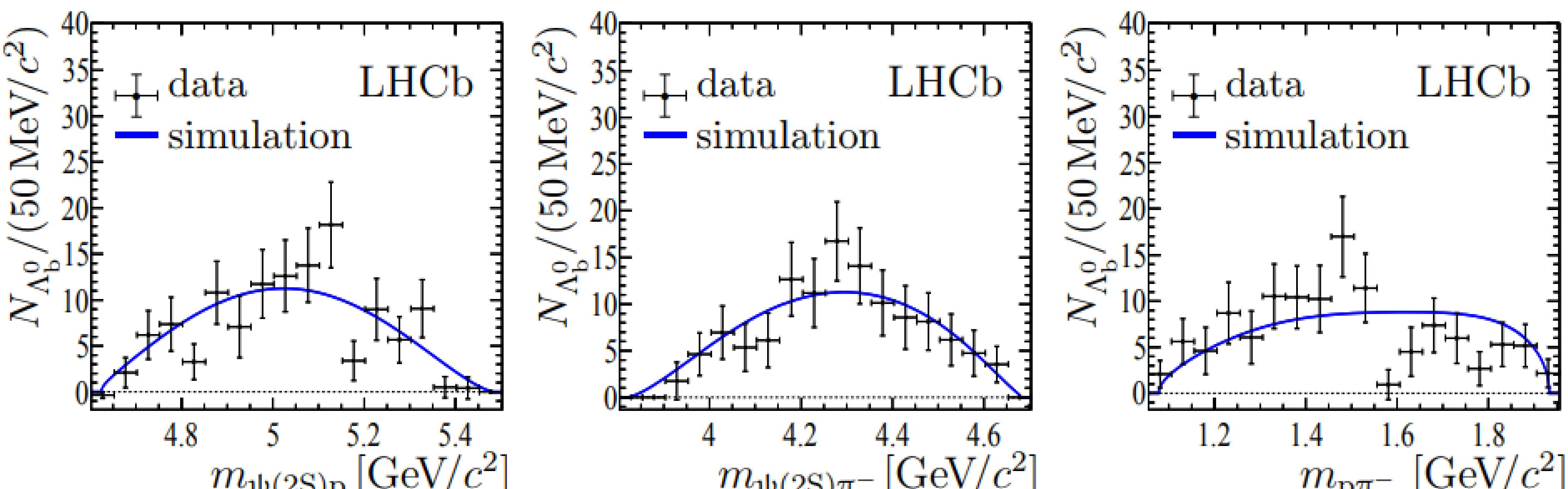
Branching fraction measured in normalization to $\Lambda_b \to \psi(2S)pK^-$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)pK^-\right)} = (11.4 \pm 1.3 \pm 0.2)\%$$

$$\mathcal{B}\left(\Lambda_b^0 \to \psi(2S)p\pi^-\right) = \left(7.17 \pm 0.82 \pm 0.33^{+1.30}_{-1.03}\right) \times 10^{-6}$$

First look at the final state particles combinations was made

No peaking structures so far



$\Xi_b \to J/\psi pK$ decay

Need to see other pentaquarks

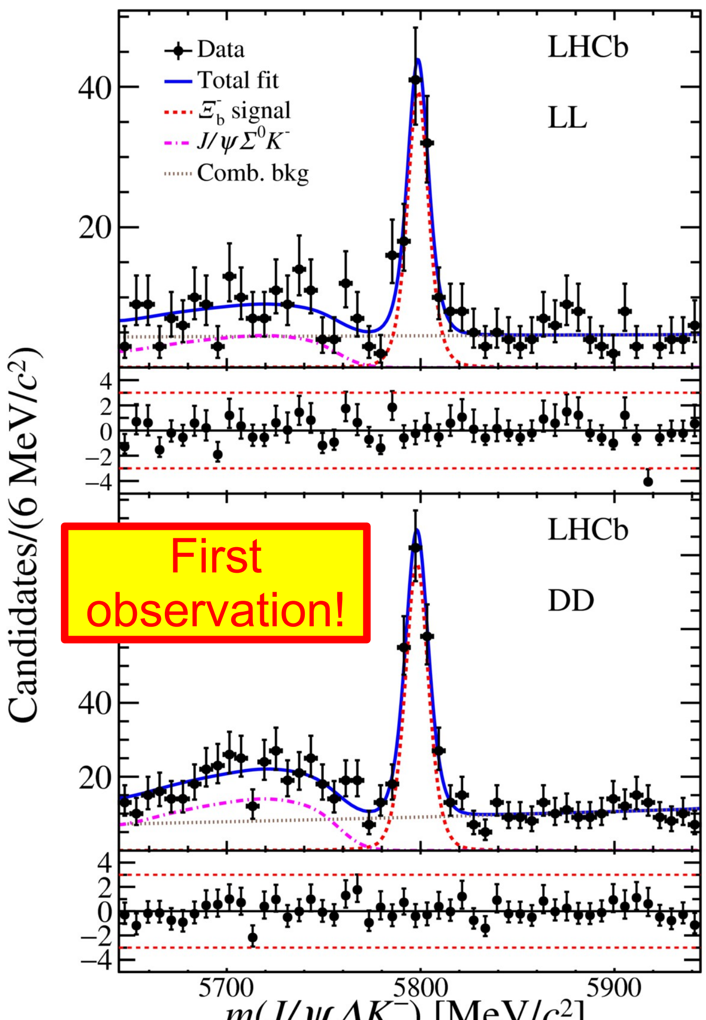
[Phys. Lett. B 772 (2017) 265-273]

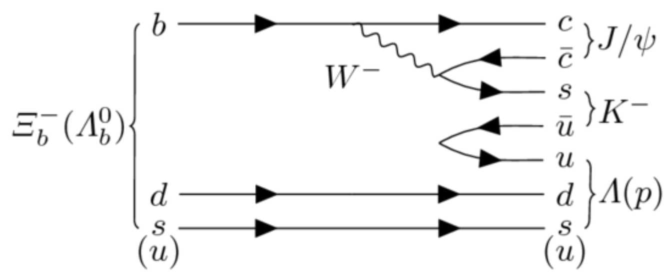
3 fb^{-1} (Run 1)

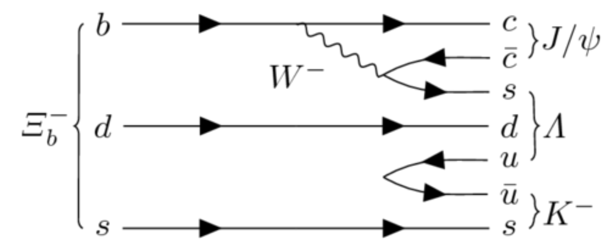
Decay similar to $\Lambda_b \to J/\psi pK$

Just replace u-quark with s-quark

One may expect appearence of a hidden-charm pentaquark with open strangeness: [$sc\bar{c}ud$]







Total signal yield ~300 events

Signal significance 21σ

Branching fraction is measured through normalization by $\Lambda_b \to J/\psi\Lambda$ channel

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

By now there should be enough data for an amplitude analysis

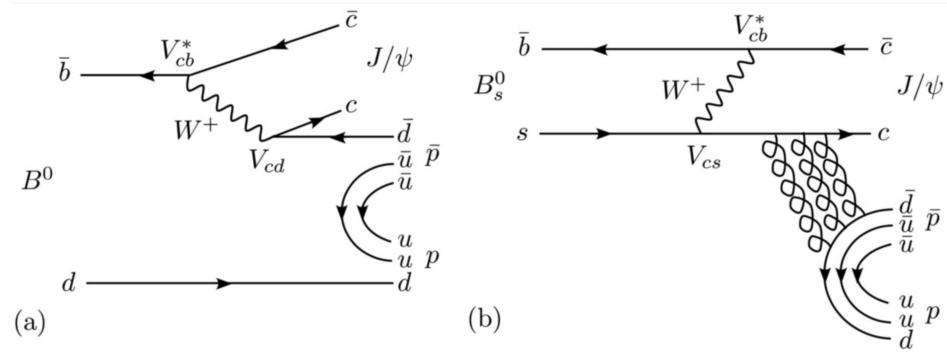
$B^0_{(s)} \to J/\psi p\bar{p}$ decay

[Phys. Rev. Lett. 122 (2019) 191804]

3 fb^{-1} (Run 1)
2.2 fb^{-1} (Run 2)

B^0 decay: Cabibbo supressed, BF ~10^{-7}
B^0_s decay: OZI supressed , BF ~10^{-9}

[Prog. Theor. Phys.Suppl. 37 (1966) 21]

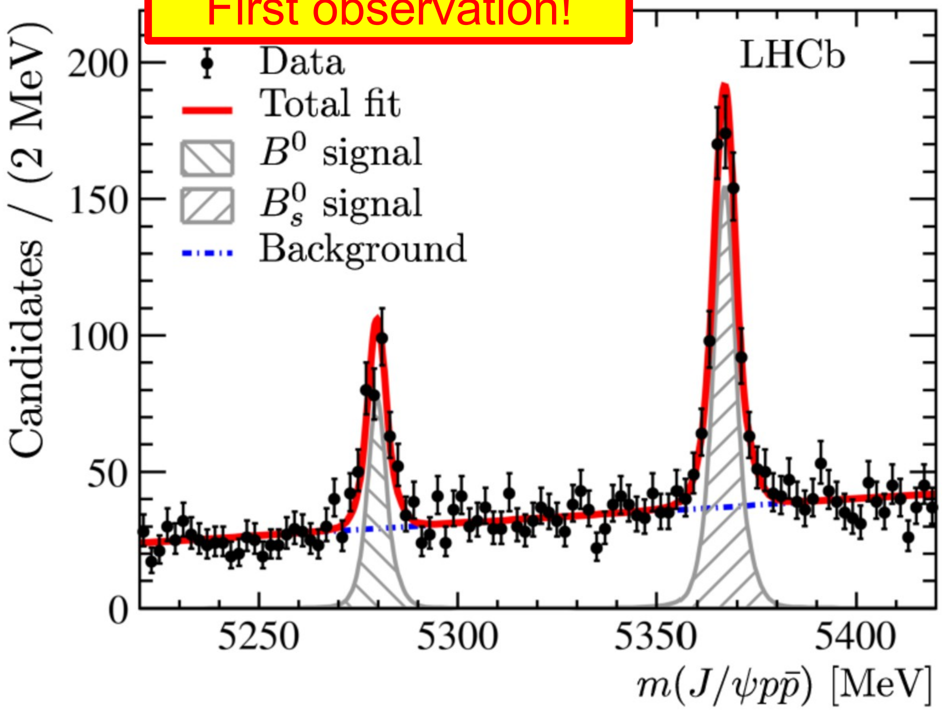


Can be enhanced by contributon from intermediate resonances of exotic nature

One of the possibilities: $f_J(2220)$

[Eur. Phys. J. C75, 101 (2015)]

First observation!



Mode	Yield	$B^0_{(s)}$ mass [MeV]
$B^0 \to J/\psi p\bar{p}$	256 ± 22	5279.74 ± 0.30
$B^0_s \to J/\psi p\bar{p}$	609 ± 31	5366.85 ± 0.19

Measured branching fractions through normalization to $B^0_s \to J/\psi(\varphi \to K^+K^-)$

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

► Two orders higher than expected

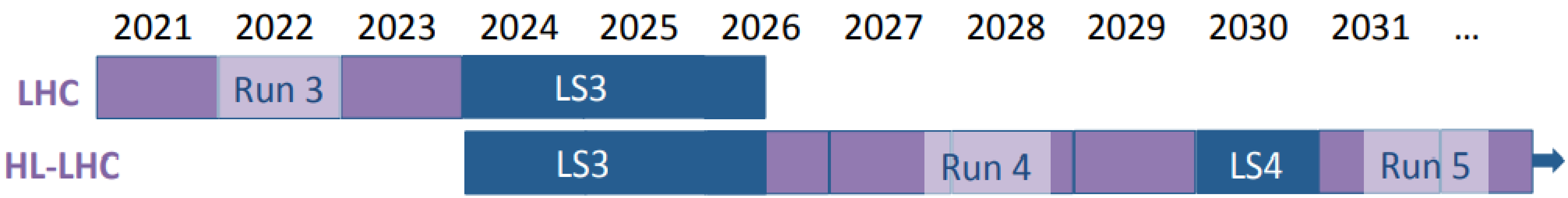
► In good agreement with theoretical expectation

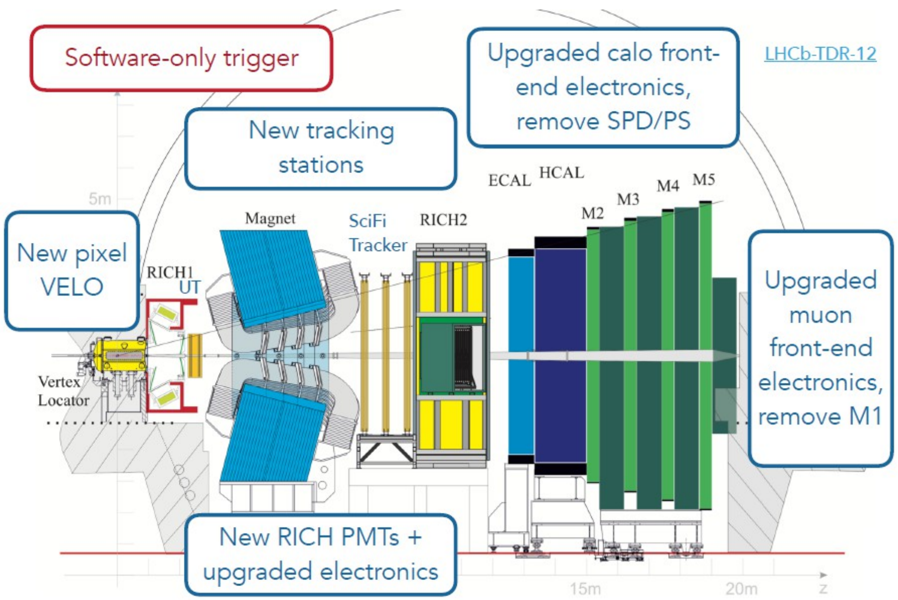
Need more data for a full Dalitz-analysis

Most precise single mass measurement of B^0 and B^0_s together

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

Future interest

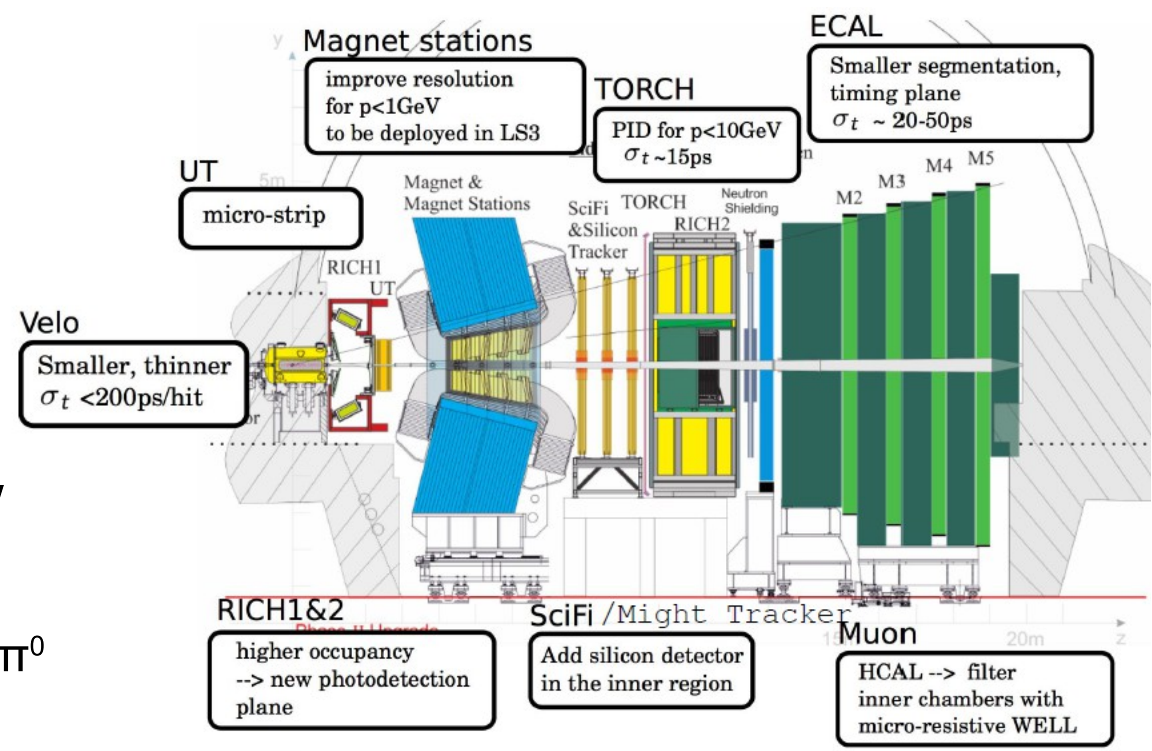




Upgrade I

Higher luminosities

- Faster readout
- Better lifetime resoluton



Upgrade II

Faster readout

- Better resolution and PID (for low momentum particles also)
- Faster readout
- Better resoluton for photons and π^0

Future interest

[arXiv:1812.07638]

Detailed studies of the properties
- Determining the mass and width of the X(3872) state
- Searches for C-odd and charged partners of X(3872)

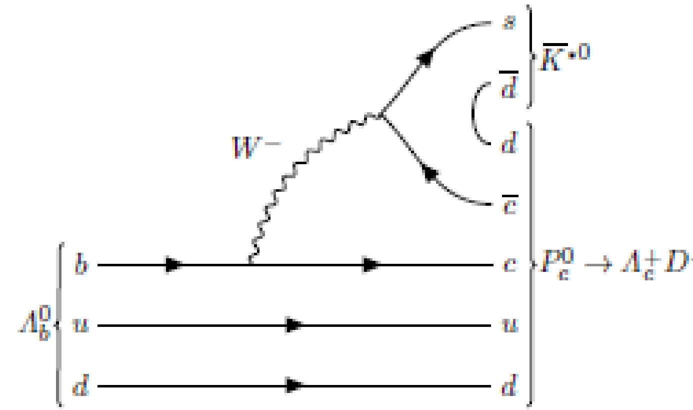
Prompt production of exotic hadrons
- A sign of compact component

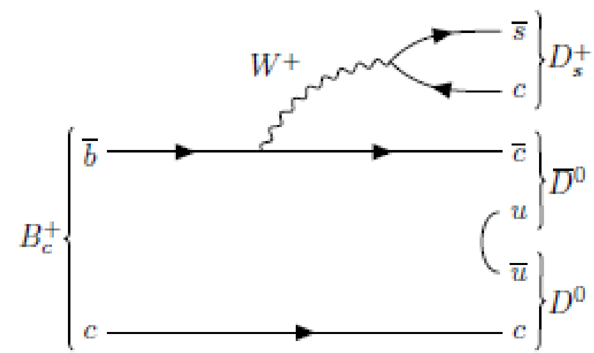
Search for pentaquark multiplets
- Neutral pentaquark candidate?
- Doubly charged pentaquark?

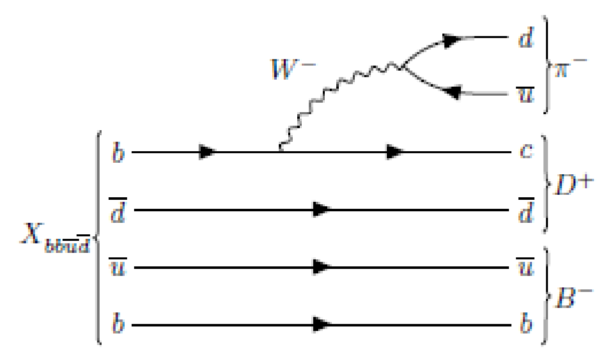
Exotic hadrons with more heavy quarks
- Search for the doubly charmed tetraquark

Search for beauty exotic hadrons

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 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
$\Lambda_b^0 \to J/\psi\, pK^-$	340k	700k	4M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600







Conclusions

The exotic studies sector is rapidly developing

- Many new states confirmed/unconfirmed/waiting for confirmation
- Still a large area for studies
  - both from experimental and theoretical sides

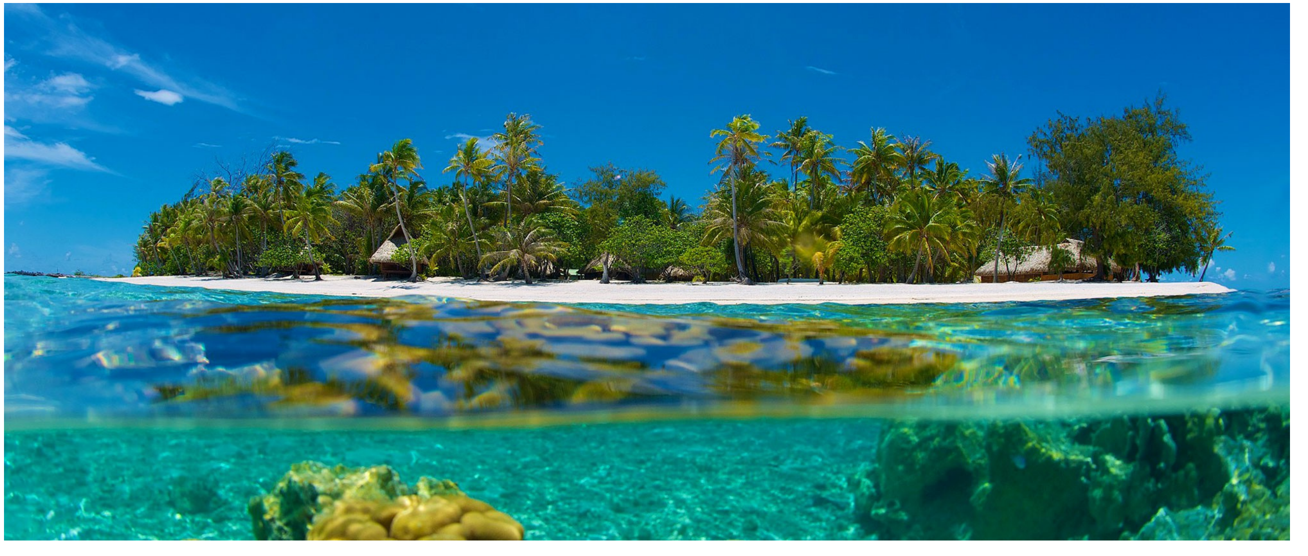
The LHCb Run 2 data is actively included in many analyses

- The whole sample is now available
- More updates are coming!

LHC and LHCb are heading towards higher energies and luminosities

- Many prospects and ideas

Looking forward to new exciting exotic results!



Backup

Predictons for $X_{b\bar{b}b\bar{b}}$

L. Heller and J. A. Tjon, On bound states of heavy $Q^2\overline{Q}^2$ systems, Phys. Rev. D32 (1985) 755.

A. V. Berezhnoy, A. V. Luchinsky, and A. A. Novoselov, Heavy tetraquarks production at the LHC, Phys. Rev. D86 (2012) 034004, arXiv:1111.1867.

J. Wu et al., Heavy-flavored tetraquark states with the $QQ\overline{QQ}$ configuration, Phys. Rev. D97 (2018) 094015, arXiv:1605.01134.

W. Chen et al., Hunting for exotic doubly hidden-charm/bottom tetraquark states, Phys. Lett. B773 (2017) 247, arXiv:1605.01647.

M. Karliner, S. Nussinov, and J. L. Rosner, $QQ\overline{QQ}$ states: Masses, production, and decays, Phys. Rev. D95 (2017) 034011, arXiv:1611.00348.

Y. Bai, S. Lu, and J. Osborne, Beauty-full tetraquarks, arXiv:1612.00012.

Z.-G. Wang, Analysis of the $QQ\overline{QQ}$ tetraquark states with QCD sum rules, Eur. Phys. J. C77 (2017) 432, arXiv:1701.04285.

J.-M. Richard, A. Valcarce, and J. Vijande, String dynamics and metastability of all-heavy tetraquarks, Phys. Rev. D95 (2017) 054019, arXiv:1703.00783.

M. N. Anwar et al., Spectroscopy and decays of the fully-heavy tetraquarks, arXiv:1710.02540.