

XYZ States at LHCb



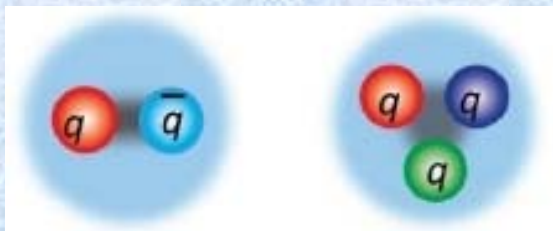
Tadeusz Lesiak

on behalf of the LHCb collaboration

Institute of Nuclear Physics Polish Academy of Sciences, Kraków

1. (Very brief) introduction to the spectroscopy of hadron states
2. LHCb spectrometer - an excellent tool for heavy hadron spectroscopy
3. Exotic hadrons at LHCb (pentaquarks excluded)
 - ✓ $X(3872)$ and $X(3842)$
 - ✓ The X states decaying to $J/\psi \phi$
 - ✓ Tetraquark $X(5568)$?
 - ✓ $Z_c(4430)$, $Z_c(4200)$ and $Z_c(4100)$
 - ✓ Search for beautiful tetraquarks
 - ✓ Search for dibaryons
 - ✓ Open charm exotic states in Λ_c^+ excitations

➤ Standard states:



A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

California Institute of Technology, Pasadena, California

Phys. Lett. 8
(1964) 214-215

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

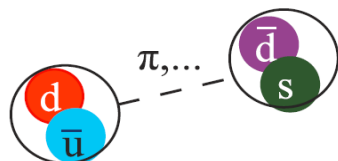
➤ Exotic states:

Pentaquark



diquark-diquark-
antiquark

Molecule

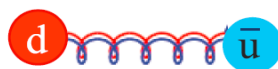


H-dibaryon



diquark-diquark-
diquark

Hybrid



Tetraquark



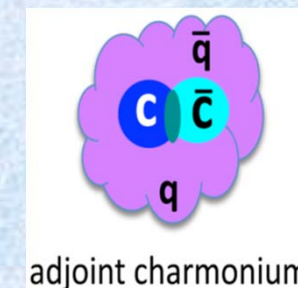
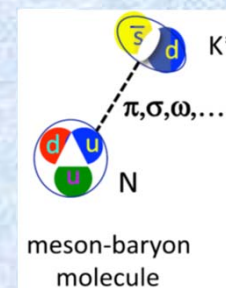
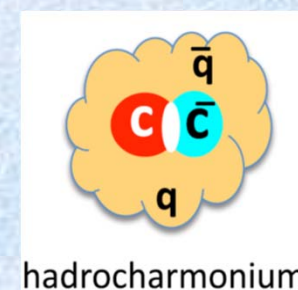
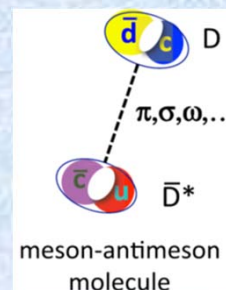
diquark-diantiquark

Glueball



Front. Phys. 10 101401

but also:



Rev. Mod. Phys. 90 (2018) 015003

And near threshold kinematical effects: cusps, anomalous triangular singularities (ATS)

- **~30 heavy, potentially exotic states observed (since 2003) - most of them are $(c\bar{c})$ or $(b\bar{b})$ like**

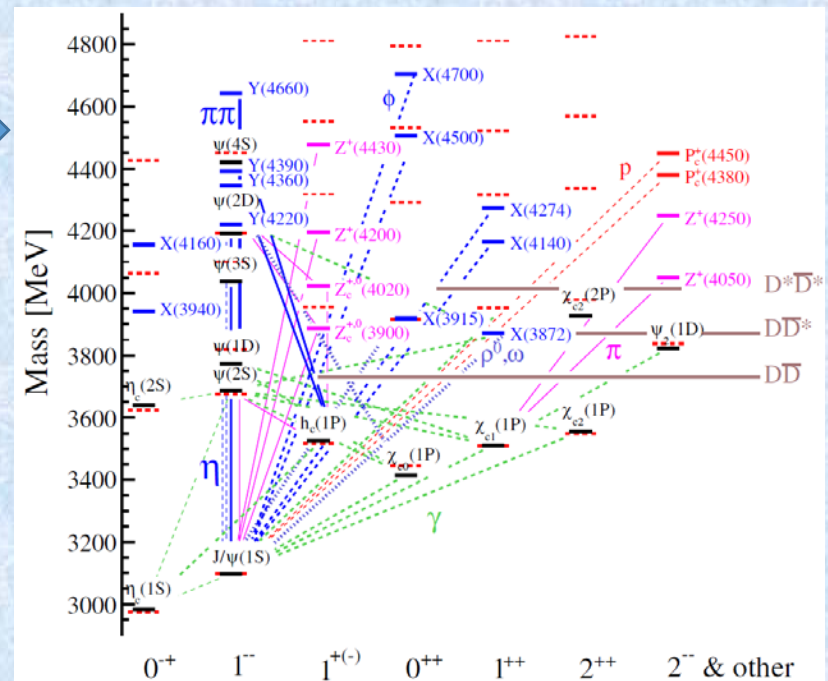
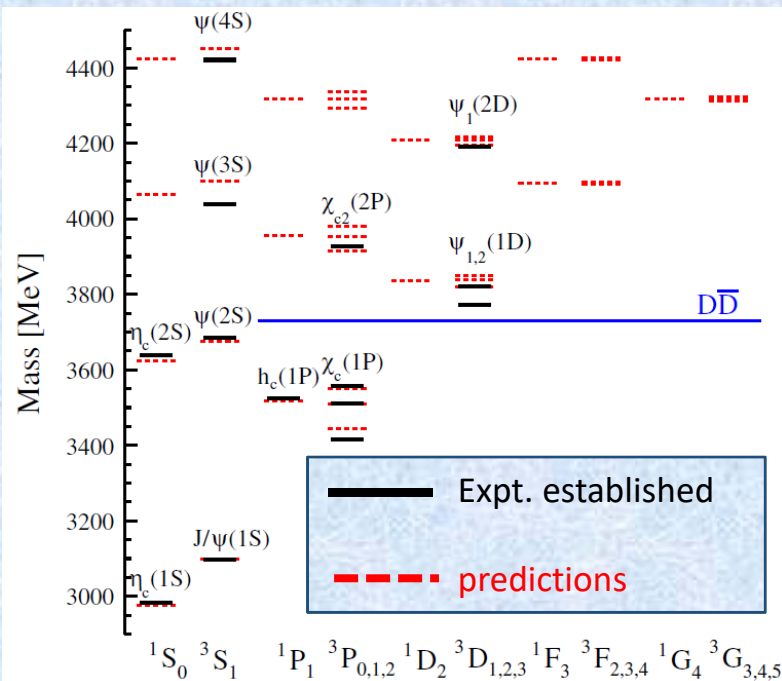
- **The properties of new states to be determined**

- Mass and width
- Spin, parity, C-parity....
- Production rates
- Decay channels, branching fractions....

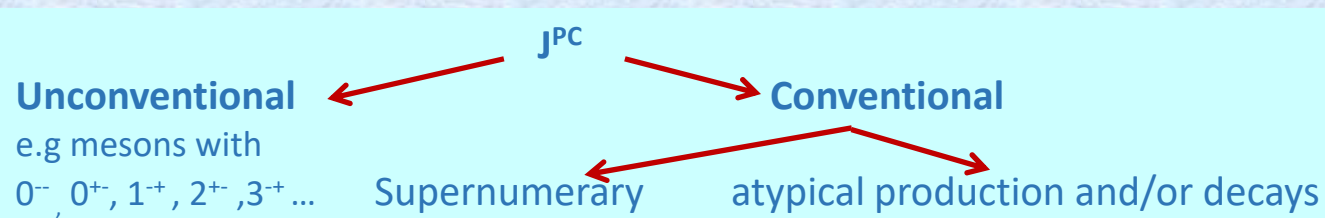
- **Notation of quarkonium states**

$$n^{2S+1}L_J$$

- n** – QQ radial quantum number
- S** – combined spin of the QQ pair
- L** – the relative angular momentum of the pair (S: $L=0$, P: $L=1$, D: $L=2$)
- J** – the total angular momentum



➤ Quantum numbers:



- Unconventional charges may occur (e.g. baryon with $S=1$ or meson with electric charge $+2$)

➤ Tools:

angular distributions, amplitude analysis, model independent approach, Dalitz and Argand plots, ...

➤ Taxonomy (general, not universally accepted, guidelines):

P	pentaquarks
X	Neutral-charge resonances (most of them observed in B decays), positive parity
Y	States produced in the Initial State Radiation (ISR) processes, negative parity
Z	Charmonium-like, charged states (and its isospin partners)

➤ The first hadron-collider experiment that is dedicated to heavy flavour (HF) physics

➤ The geometry of forward spectrometer

RICH:

Separation of K, p from π :

$$\varepsilon(K \rightarrow \pi) \approx 95 \% \quad \varepsilon(\pi \rightarrow K) \approx 5 \%$$

$$\varepsilon(p \rightarrow \pi) \approx 95 \% \quad \varepsilon(\pi \rightarrow p) \approx 5 \%$$

Vertex Detector:

Impact parameter resolution:

$$\sigma_{IP} = 20 \mu\text{m}$$

Decay time resolution:

heavy hadrons: ≈ 50 fs

Dipole magnet:

Bending power: 4 Tm

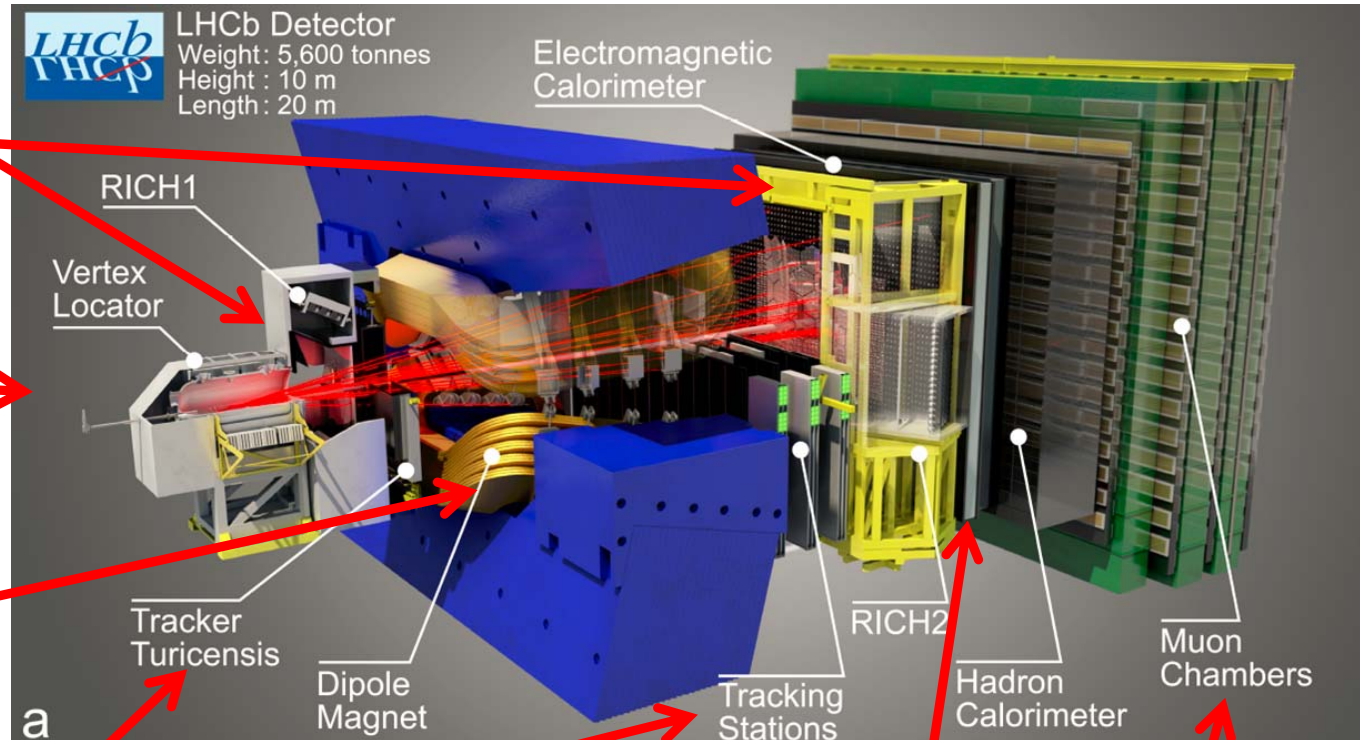
Precise tracking system:

$$\varepsilon(\text{trk}) \approx 96 \%$$

Momentum resolution:

$$\frac{\Delta p}{p} = 0.5 \% \quad p = 20 \text{ GeV}$$

$$0.8 \% \quad p = 100 \text{ GeV}$$



a

JINST 3 (2008) S08005;
JMPA 30 (2015) 1530022

Electromagnetic and hadronic calorimeters

$$\text{ECAL: } \frac{\sigma_E}{E} = 1 \% \oplus \frac{10 \%}{\sqrt{E[\text{GeV}]}}$$

Muon system:

$$\varepsilon(\mu \rightarrow \mu) \approx 97 \%$$

$$\varepsilon(\pi \rightarrow \mu) \approx (1-3) \%$$

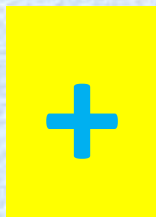
Spectrometer:

very good mass resolution $\sigma(m_{B \rightarrow hh}) \approx 22 \text{ MeV}$

Trigger:

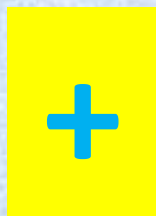
Highly flexible, currently have "offline quality"

➤ **General advantages (pp interaction):**



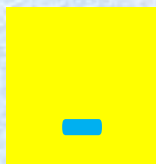
- **High production cross-sections for HF** (2×10^4 bbar pairs/s i.e. 10^3 larger than at the e^+e^- B factories)
- **Simultaneous accumulation of huge B_d , B_s and b-baryons data samples** (composition 4:1:2)
- **The decay vertices are well separated from the production point** (high boost of heavy hadrons)

➤ **LHCb specific advantages** (single arm forward spectrometer: $0.8^\circ < \Theta < 15.4^\circ$) :



- **LHCb captures a HF production cross-section, comparable to that of ATLAS and CMS** (high- p_T range) **MUCH SMALLER SOLID ANGLE** → smaller number of electronic channels → smaller event size → larger trigger bandwidth to store (dominated by b and c physics)
- **LHCb – forward detector ($p \gg p_T$): efficient muon identification for lower P_T values**
- **Space to accommodate excellent RICH detectors** (flavour tagging, background suppression)

➤ **General drawbacks:**



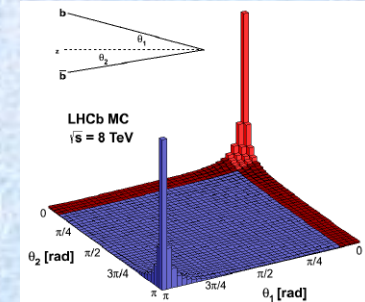
- **The instantaneous luminosity is limited by the detector readout capabilities** ($4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$)
- **The efficiencies of γ , π^0 and η reconstruction are much lower, compared with the e^+e^-**

Run	Years	Lum. [fb ⁻¹]	$\sqrt{s}$ [TeV]	$\sigma_{b\bar{b}}$ [μb]	$\sigma_{c\bar{c}}$ [μb]
1	2011-12	3.0	7,8	70	1400
2	2015-17	3.3	13	150	2400
2	2018	2.7	13		

Goal for Run3 and Run4: 50 fb⁻¹

$$2 < \eta < 4.5$$

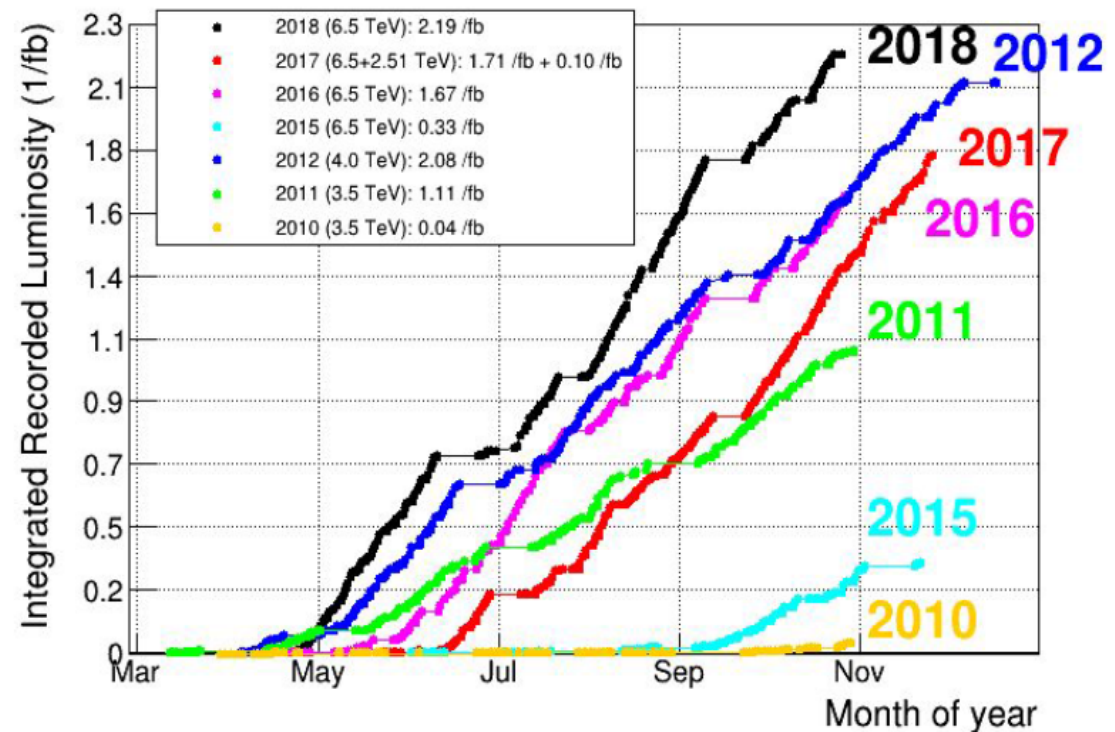
Nucl. Phys. B871 (2013) 1
JHEP 03 (2016) 159
JHEP 09 (2016) 013
JHEP 03 (2017) 074
PRL 118 (2017) 052002



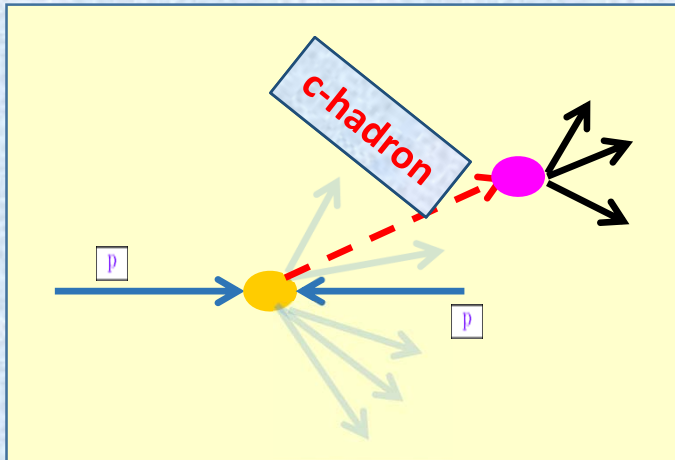
- All results presented here correspond to Run 1 data:
3 fb⁻¹
4 x 10¹² b-hadrons produced

➤ Run 2 vs Run 1:

- more abundant production of b-hadrons
- improvements in trigger and selection efficiencies

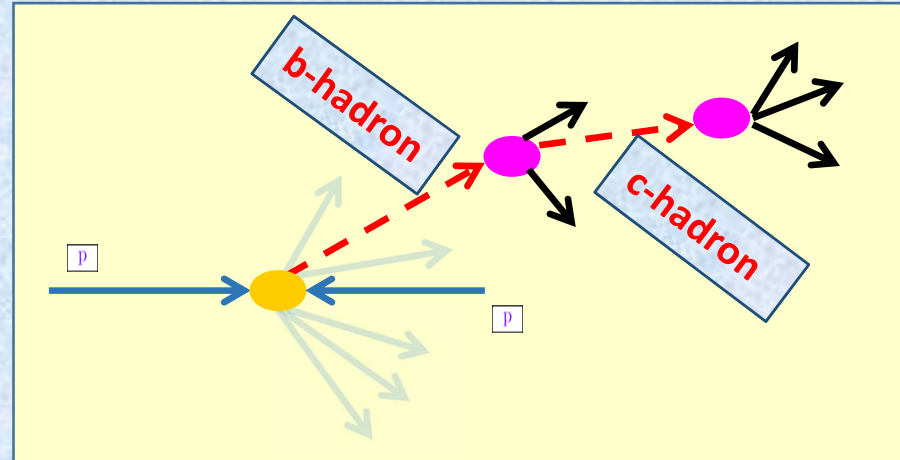


➤ Direct (prompt) production



- high cross-section (high statistics)
- Substantial combinatorial background
- All states can show up

➤ Production in weak decays of beauty hadrons

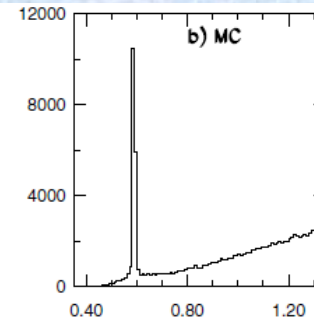
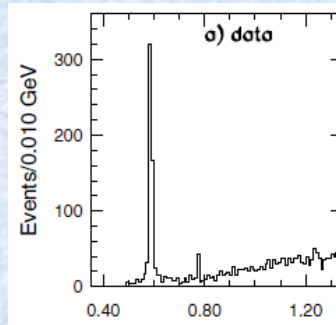


- Smaller yields, but much reduced background
- More tools e.g. kinematical constraints, detached vertices...
- Knowledge about the initial state → determination of quantum numbers of the observed states
- Only states, with specific spin-parities can be observed
- The c-hadron can show up in high(-er) multiplicity final states

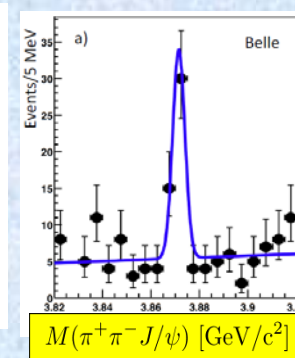
➤ X(3872) - the trigger of exotic revolution

- Belle (2003): PRL 91 (2003) 262001
- observation of narrow state X in $B \rightarrow [\pi^+\pi^- J/\psi] K$ decay

➤ The current nomenclature of the PDG: $X(3872) \equiv \chi_{c1}(3872)$



$$M(\pi^+\pi^-l^+l^-) - M(l^+l^-) [\text{GeV}/c^2]$$



$$M(\pi^+\pi^-J/\psi) [\text{GeV}/c^2]$$



➤ Follow-up observations by BaBar, CDF, D0, BESIII, CMS, LHCb...

➤ The (striking) properties of X(3872):

1. Mass close to the $D^0\bar{D}^{0*}$ threshold

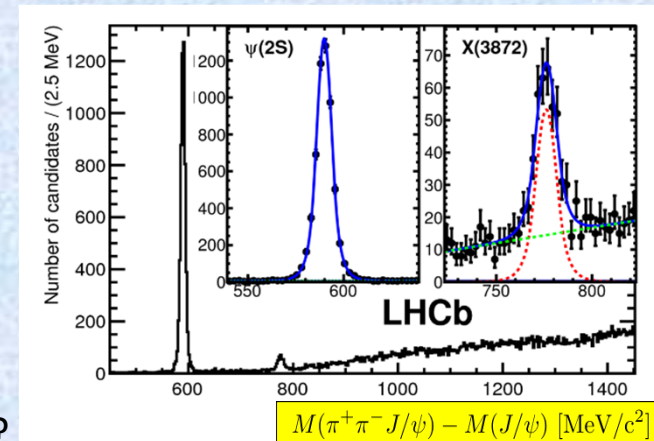
LHCb (2012; data: 35 pb^{-1}) EPJC 72 (2012) 1972 585±74 events
the first observation of the inclusive production of the X(3872)
in the process: $pp \rightarrow X(3872) + \text{anything}$, $X(3872) \rightarrow \pi^+\pi^- J/\psi$
 $M(X(3872)) = 3871.95 \pm 0.48 \pm 0.12 \text{ MeV}/c^2$

PDG:

$$M(X(3872)) = 3871.69 \pm 0.17 \text{ MeV}/c^2$$

$$M(D^0 + \bar{D}^{0*}) = 3871.68 \pm 0.10 \text{ MeV}/c^2$$

$$M(D^0 + \bar{D}^{0*}) - M(X(3872)) = 0.01 \pm 0.20 \text{ MeV}/c^2 \rightarrow \text{a } D^0\bar{D}^{0*} \text{ molecule?}$$



2. Narrow width in decays to charmonia:

$$\Gamma < 1.2 \text{ MeV}/c^2$$

(Belle PR D84 (2011) 052004)

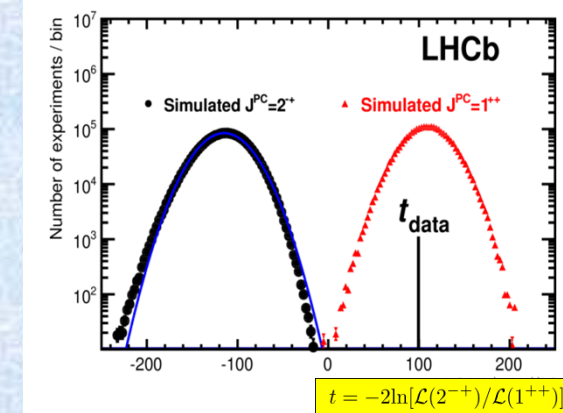
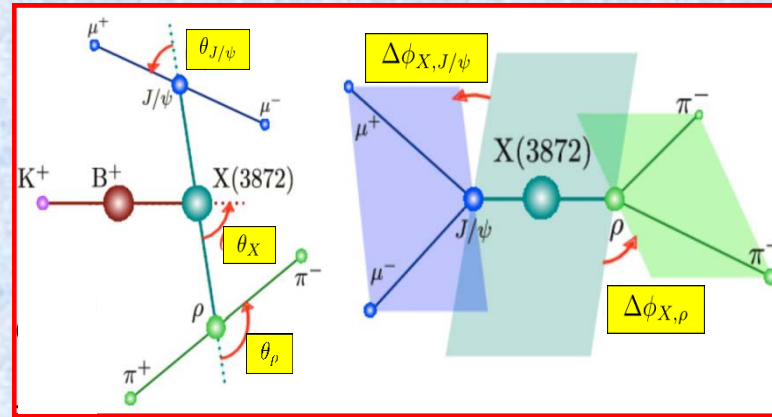
3. Spin-parity: $J^{PC} = 1^{++}$ - unequivocally determined by the LHCb (2013): data: 1 fb^{-1} , 313 ± 26 ev.

PRL 110 (2013) 222001

The amplitude analysis of 5D angular correlations of the decay
 $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \rho^0 J/\psi$, $\rho^0 \rightarrow \pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$
 (helicity formalism)

The variables:

$$\theta_X, \theta_{J/\psi}, \theta_\rho, \\ \Delta\phi_{X,J/\psi}, \Delta\phi_{X,\rho}$$



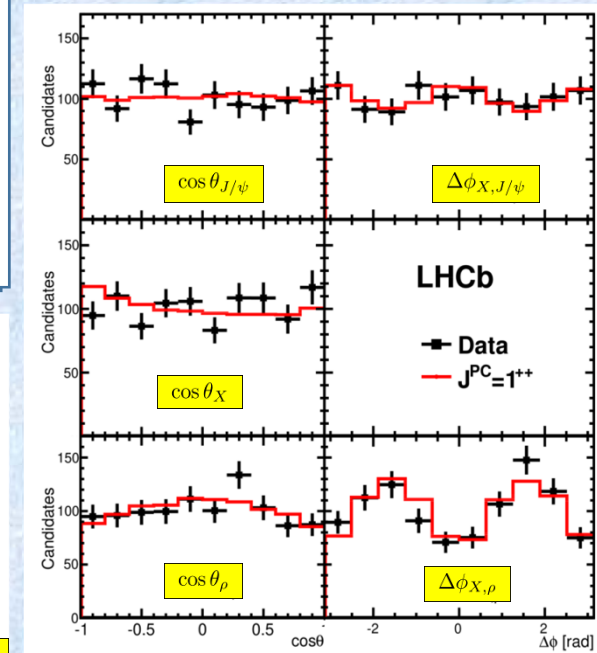
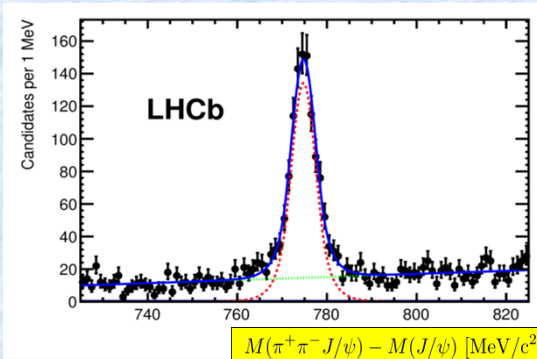
The last remaining controversy (2^-+ vs 1^{++}) solved:
The 2^-+ hypothesis excluded with a significance $> 8\sigma$

LHCb (2015): PRD 92 (2015) 011102

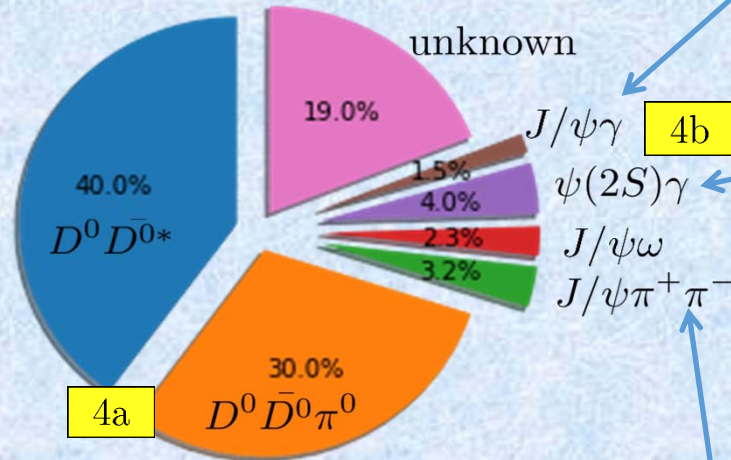
data 3 fb^{-1} , 1011 ± 38 events

**For the first time, no assumption
 about the orbital angular momentum
 in the X(3872) decay**

$J^{PC}=1^{++}$ confirmed



4. Decay modes



BaBar (2009):

$$\mathcal{B}(X(3872) \rightarrow J/\psi \gamma) > 4\%$$

PRL 102 (2009) 132001

LHCb (2014):

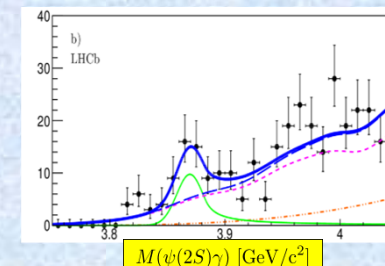
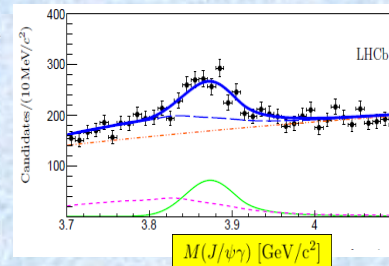
NuclPhys B886 (2014) 665

$$R_{J/\psi \gamma} = \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S) \gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi \gamma)} = 2.46 \pm 0.64 \pm 0.29$$

$$C = 1$$

PLB 588 (2004) 189

Set constraints on molecular interpretation ($R_{J/\psi \gamma} \ll 1$)



But BESIII:

$$R_{J/\psi \gamma} < 0.59 \quad (90\% \text{ C.L.})$$

arXiv:2001.01156

5. In the decay $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ the $M(\pi\pi)$ is concentrated around the ρ mass

The X decays to $J/\psi \rho$ and $J/\psi \omega$ with comparable branching fractions $\rightarrow$ **isospin violation**

EPJC 72 (2012) 1972

PRD 92 (2015) 011102

6. In the decay $X(3872) \rightarrow \rho^0 J/\psi$, no significant D-wave fraction ($< 4\%$ at 95% CL) was found by LHCb:

The decay in S-wave dominates

PRD 92 (2015) 011102

7. **I = 0** No charged partner, no C = -1 partner found (Belle & BaBar; searches for $X(3872)^+ \rightarrow J/\psi \pi^+ \pi^0$, $J/\psi \rho^+$)

8. Negative results of the searches for $X(3872) \rightarrow p \bar{p}$ and $X(3872) \rightarrow \phi \phi$ (**LHCb (2017)** 3fb^{-1})

$$R_{X(3872)} = \frac{\mathcal{B}(B^+ \rightarrow X(3872) K^+) \times \mathcal{B}(X(3872) \rightarrow p \bar{p})}{\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow p \bar{p})} < 0.25 \times 10^{-2} \quad (95\% \text{ C.L.})$$

PLB 769 (2017) 305

$$\mathcal{B}(b \rightarrow X(3872) + \text{anything}) \times \mathcal{B}(X(3872) \rightarrow \phi \phi) < 4.5 \times 10^{-7} \quad (95\% \text{ C.L.})$$

EPJ C77 (2017) 609

9. The first observation of $\chi_{c1}(3872)$ in a baryon decay

➤ **LHCb (2019):**

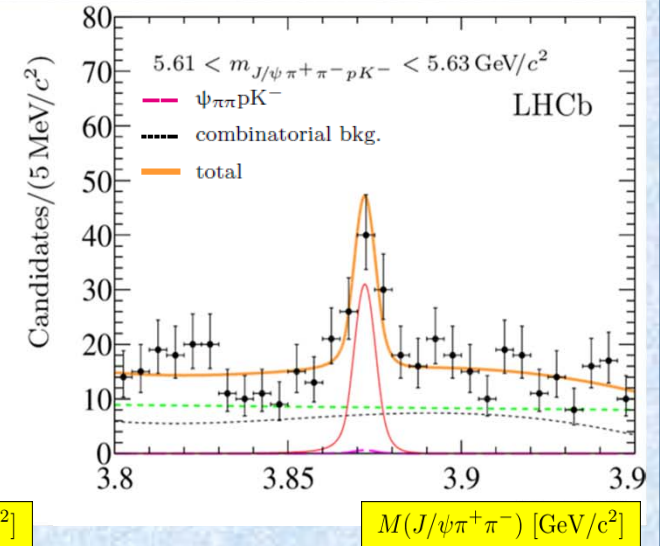
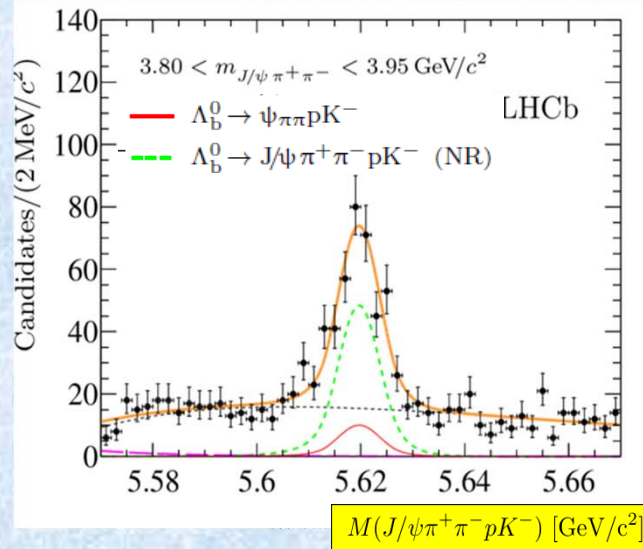
search for the decay

$$\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-$$

$$\chi_{c1} \rightarrow J/\psi \pi^+ \pi^-$$

(2011-12, 2016 data 4.9 fb⁻¹)

JHEP 09 (2019) 028



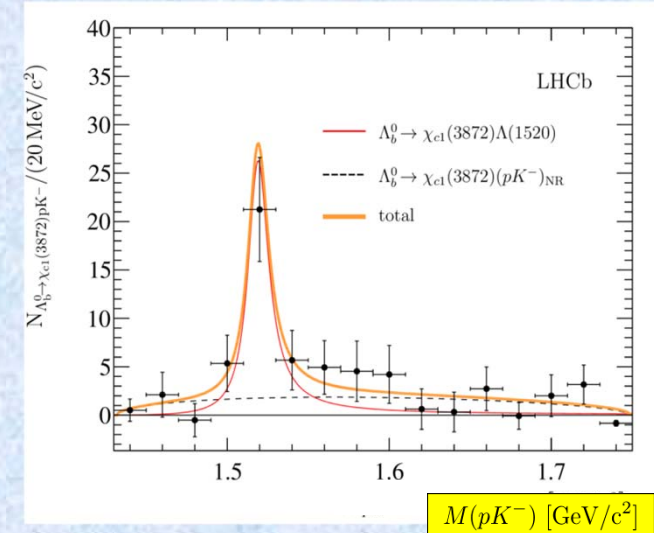
Fit to $J/\psi \pi^+ \pi^- p K^-$ and $J/\psi \pi^+ \pi^-$ mass spectra:
the signal of 55 ± 11 events; 7.2σ

$$R_{X(3872)} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)pK^-)} \times \frac{\mathcal{B}(\chi_{c1} \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1}(3872)pK^-) \times \mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-) = (1.24 \pm 0.25^{+0.23}_{-0.19}) \times 10^{-6}$$

(58±15)% of signal decays proceed through 2-body decay

$$\Lambda_b^0 \rightarrow \chi_{c1}(3872)\Lambda^0(1520)(\rightarrow pK^-)$$



10. The relative production of $\chi_{c1}(3872)$ and $\psi(2S)$ vs particle multiplicity

➤ **LHCb (2019)** 2fb^{-1} : LHCb-CONF-2019-005

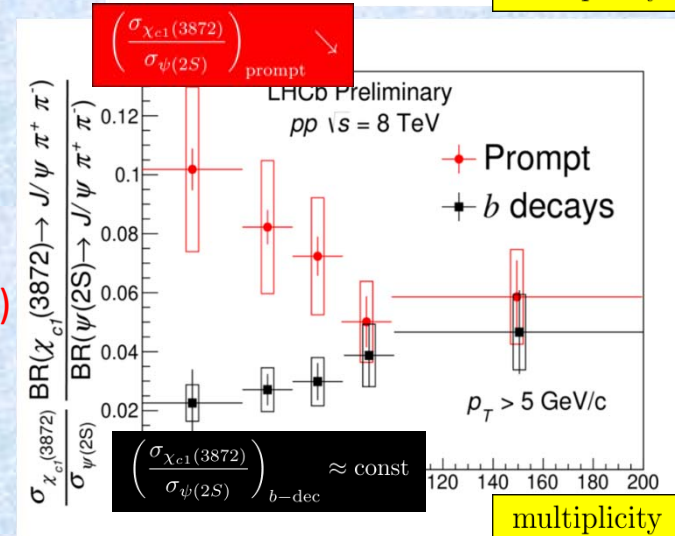
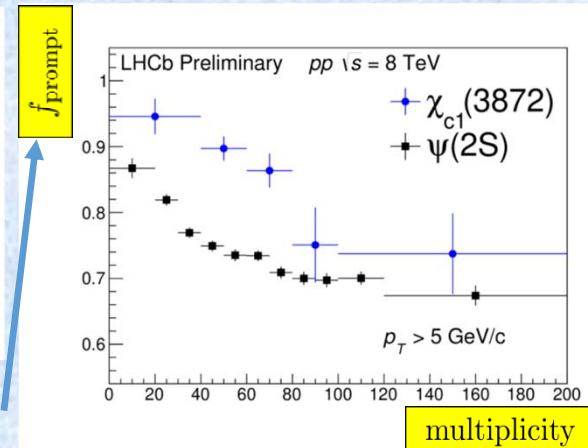
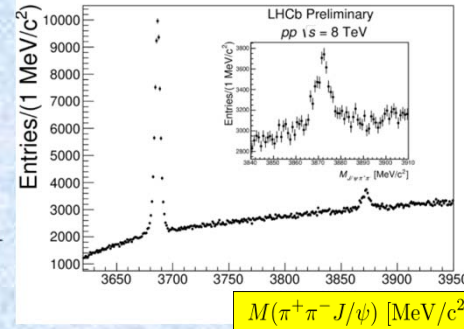
studies of the decays $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$
and $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$

$$f_{\text{prompt}} = \frac{N(\chi_{c1}(3872))}{N(\psi(2S))} \text{ that are produced promptly}$$

□ With the increasing multiplicity:

- for the production via b-decays: the rates for $\chi_{c1}(3872)$ and $\psi(2S)$ decrease in the similar way (decays in vacuum)
- **the prompt production of $\chi_{c1}(3872)$ is suppressed relative to prompt $\psi(2S)$ production** (final state interactions with hadrons from the underlying event and with co-moving ones)

➔ consistent with the interpretation of the $\chi_{c1}(3872)$ as a weakly bound state e.g. a $D^0 \bar{D}^{0*}$ hadronic molecule which should dissociate strongly in prompt production



Interpretation: **X(3872)** is likely a mixture of a $\chi_{c1}(2^3P_{1++})$ charmonium and of $D^0 \bar{D}^{0*}$ molecule
Molecule: properties 1, 2, 3, 4a, 5 (→ only a small admixture of $D^+ \bar{D}^{+*}$, compare with $D^0 \bar{D}^{0*}$), 6 and 10
Charmonium: radiative decays ($4b^*$), 7 and observation of prompt production rates (ALICE and ATLAS)

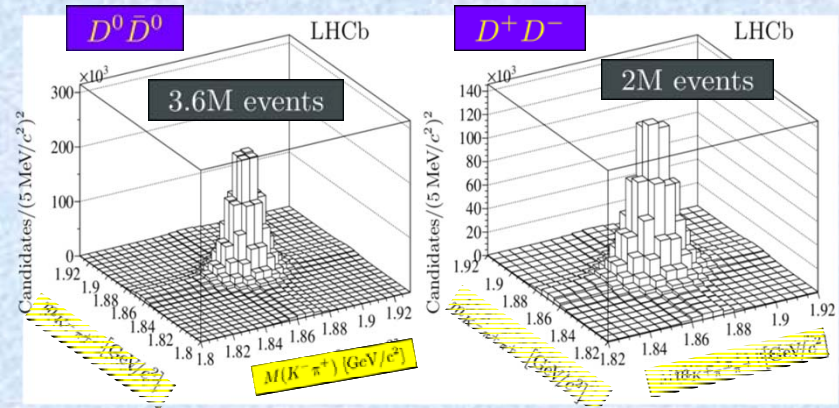
➤ LHCb (2019):

JHEP 07 (2019) 035

▪ Study of near $D\bar{D}$ threshold spectroscopy:

Prompt $D^0\bar{D}^0$ and D^+D^- pairs combined;
two displaced vertices coming from
the same primary vertex

The first LHCb analysis using Run1 & Run2 data: 9fb^{-1}



➤ Four peaking structures observed:

1. A narrow peak just above the threshold:

$X(3872) \equiv \chi_{c1} \rightarrow D^{*0}\bar{D}^0$, $D^{*0} \rightarrow D^0\pi^0$ or $D^{*0} \rightarrow D^0\gamma$

2. A broad maximum: $\psi(3770) \rightarrow D\bar{D}$ - the 1st observation of hadroproduction of $\psi(3770)$

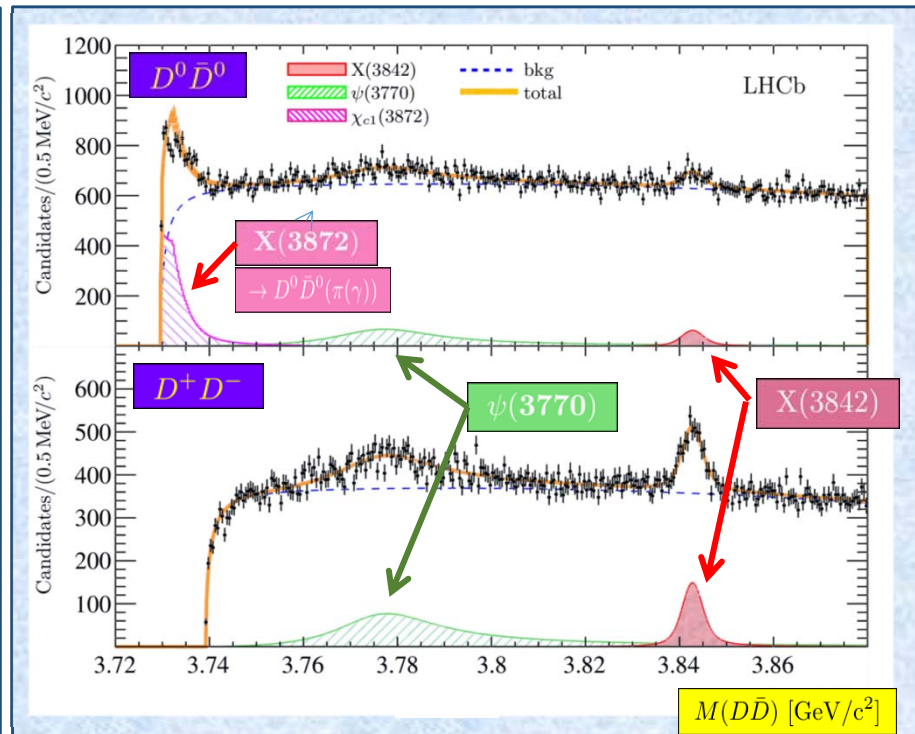
$$M_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6 \text{ MeV}/c^2$$

3. A narrow peak corresponding to the NEW STATE:

$$M_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}/c^2$$

$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35 \text{ MeV}/c^2$$

The properties consistent with the $\psi_3(1^3D_3)$ charmonium state with $J^P = 3^-$



4. A wide structure, mostly in the $D^+\bar{D}^-$ mass spectrum at $\approx 3920 \text{ MeV}/c^2$, interpreted as:

$$\chi_{c2}(3930) \rightarrow D\bar{D}$$

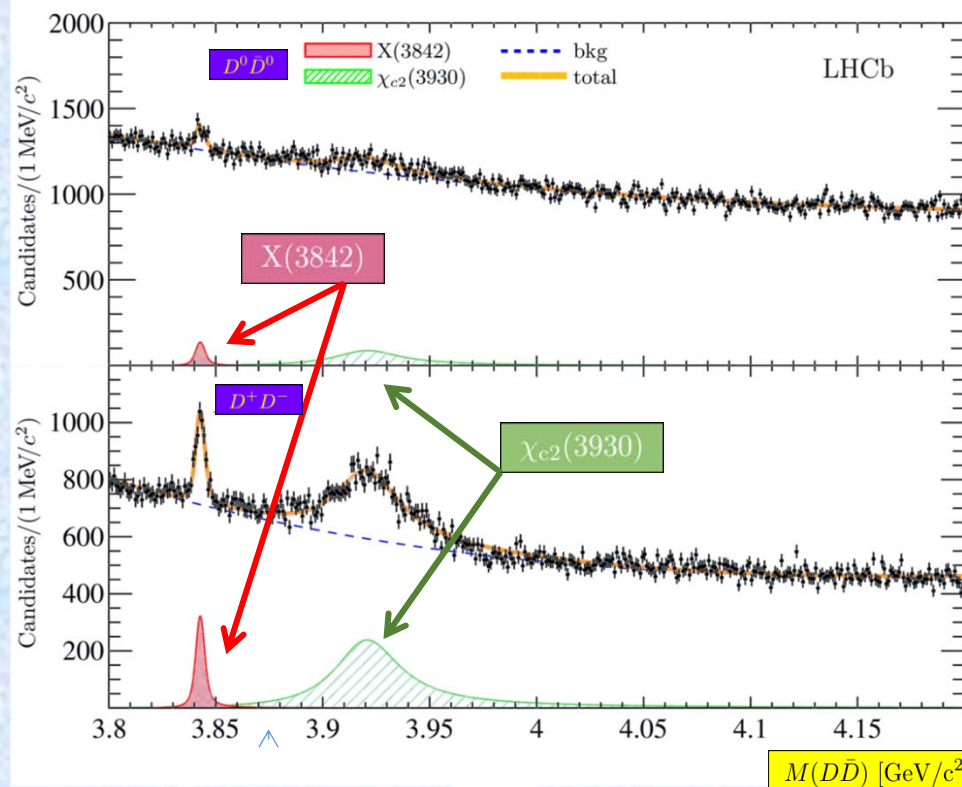
$$M_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \pm 0.2 \text{ MeV}/c^2$$

$$\Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \pm 0.9 \text{ MeV}/c^2$$

However:

- The measured mass of the $\chi_{c2}(3930)$ is about 2σ below the current world average
- The width of the $\chi_{c2}(3930)$ is about 2σ above the current world average
- The measured mass of the $\chi_{c2}(3930)$ is midway between the PDG mass of this state and the mass of the X(3915) hadron, which is only known to decay to the $J/\psi\omega$ final state

The open question: are the $\chi_{c2}(3930)$ and X(3915) two distinct hadrons or there is just one charmonium state in this mass region?



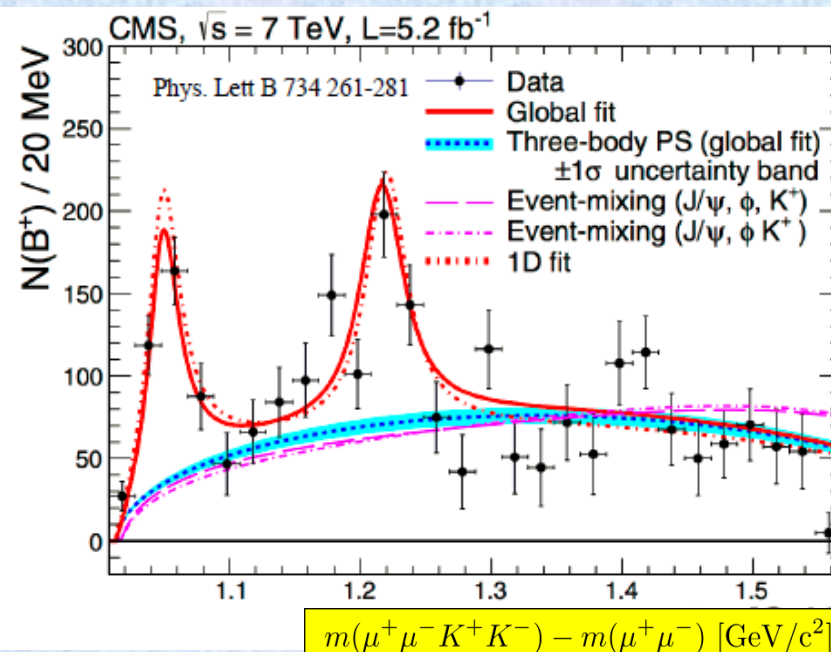
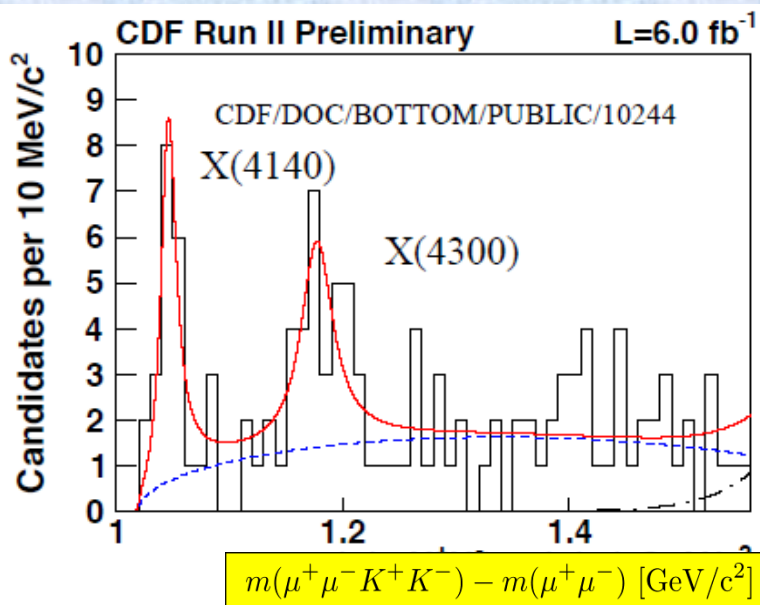
PRL 115 (2015) 022001

- **X(4140)** - evidence for a narrow near threshold structure in $B^+ \rightarrow (J/\psi \phi) K^+$ decays: CDF, D0, CMS
- **X(4274)** – the second relatively narrow $[J/\psi \phi]$ state – evidence from CDF and CMS

CDF:
PRL 102 (2009) 242002
arXiv: 1101.6058 [hep-ex]

D0:
PR D89 (2014) 012004
PRL115 (2015) 232001

CMS:
PL 734 (2014) 261



- Negative results from B-factories

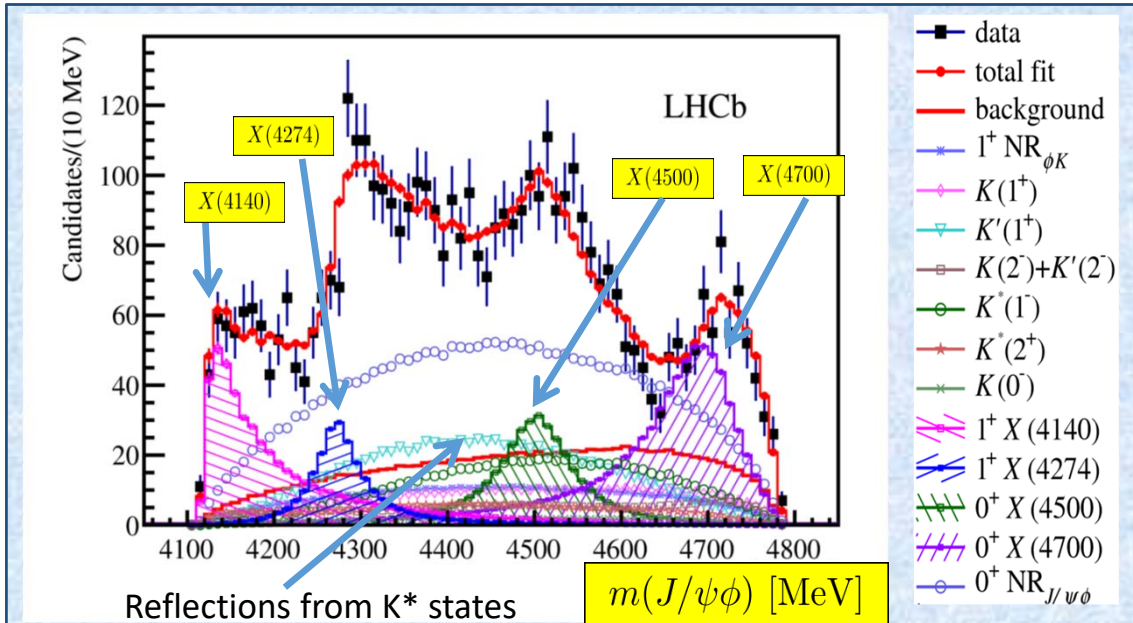
➤ **LHCb (2017): the first amplitude analysis of $B^+ \rightarrow [J/\psi \phi] K^+$ decays**

PRL 118 (2017) 02203, PR D95 (2017) 012002

- 4289 $\pm$ 151 candidates; nearly background free
- 6D phase space composed of $m(\phi K)$, helicity angles and $\Delta\phi$ angles
- The amplitude analysis aimed to resolve $K^* \rightarrow K \phi$ from the potential $X \rightarrow J/\psi \phi$ resonances
- The model with excited K^* s ($\rightarrow K\phi$) does not describe the data
- **Good description upon inclusion of four broad exotic resonances**
- The X(4140) width is substantially larger than previously determined (average of other meas. (1D fits): 15.7 ± 6.3 MeV/c²)

- X(4140) and X(4274) – the leading interpretation as tetraquarks (no light valence quarks) or $\chi_{c1}(3P)$

- X(4140) - $D_s^{*+} D_s^{*-}$ molecules 0^{++} and 2^{++} ruled out; possible cusp $D_s^{\pm} D_s^{*\mp}$
- X(4274) - incompatible with cusps and molecular bound states



State	Sign. [σ]	Mass [MeV]	Width [MeV]	J^{PC}	
X(4140)	8.4	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}	5.7σ
X(4274)	6.0	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++}	5.8σ
X(4500)	6.1	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}	4.0σ
X(4700)	5.6	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}	4.5σ

- X(4500) and X(4700) – $D_s^{*+} D_s^{*-}$ (0^{++}) molecule or $\chi_{c0}(4P)$, $\chi_{c0}(5P)$

- **D0 (2016):** reports a narrow structure X(5568) in the $B_s^0 \pi^\pm$ spectrum $X^\pm(5568) \rightarrow B_s^0 \pi^\pm$

PRL 117 (2016) 022003

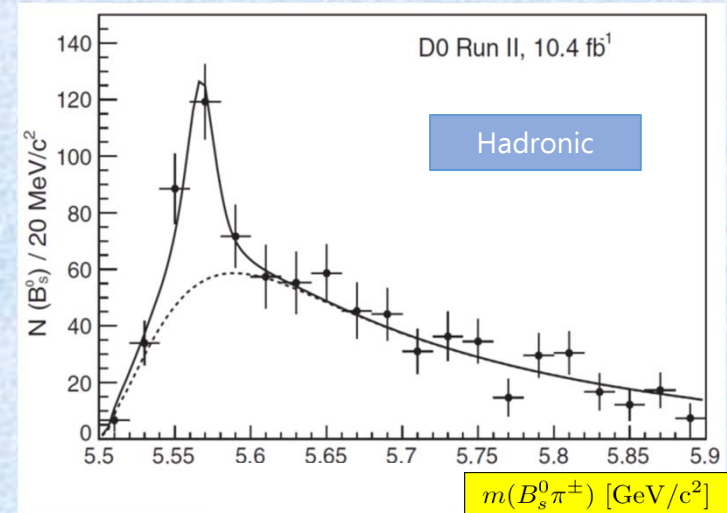
$$B_s^0 \rightarrow J/\psi \phi$$

$$m = 5567.8 \pm 2.9 \text{ (stat)} {}^{+0.9}_{-1.9} \text{ (syst)} \text{ MeV}/c^2 \quad (5.1 \sigma)$$

- The ratio of yields: $\rho_X = \frac{\sigma(pp \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_s^0 \pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \text{anything})}$

$$\rho_X = (8.6 \pm 1.9 \pm 1.4) \%$$

- Possible interpretation:** a system containing valence (anti)quarks with four different flavours b,s,d,u e.g. $[bd] - [\bar{s}\bar{u}]$, $[bu] - [\bar{d}\bar{s}]$ - just one heavy quark (tightly bound tetraquark or a loosely bound B_d -K molecule) ?



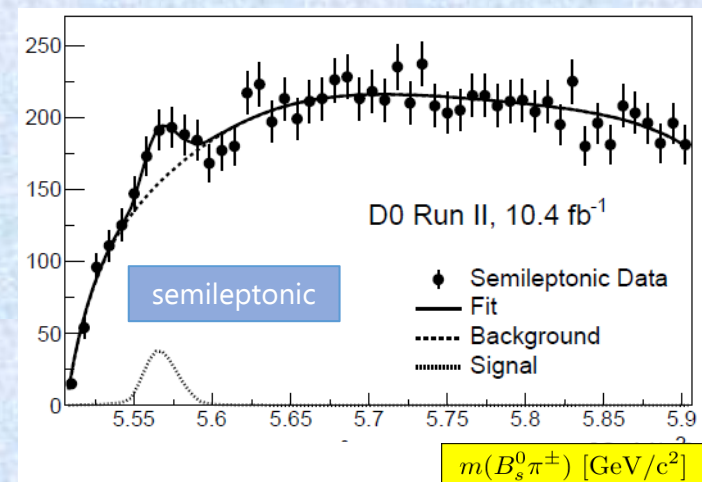
- **D0 (2017):** the second evidence for the state X(5568) in the decay $X^\pm(5568) \rightarrow B_s^0 \pi^\pm$

$$B_s^0 \rightarrow \mu^\mp D_s^\pm X, D_s^\pm \rightarrow \psi \pi^\pm$$

- **Combining hadronic and semileptonic data:**

$$m = 5566.9 {}^{+3.2}_{-3.1} \text{ (stat)} {}^{+0.6}_{-1.2} \text{ (syst)} \text{ MeV}/c^2$$

$$\Gamma = 18.6 {}^{+7.9}_{-6.1} \text{ (stat)} {}^{+3.5}_{-3.8} \text{ (syst)} \text{ MeV}/c^2 \quad (6.7 \sigma)$$



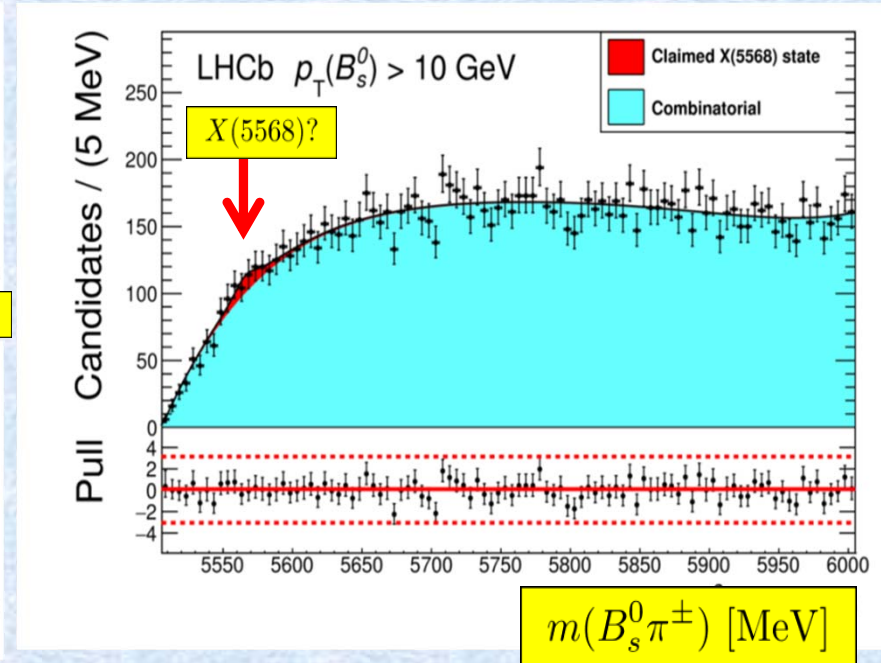
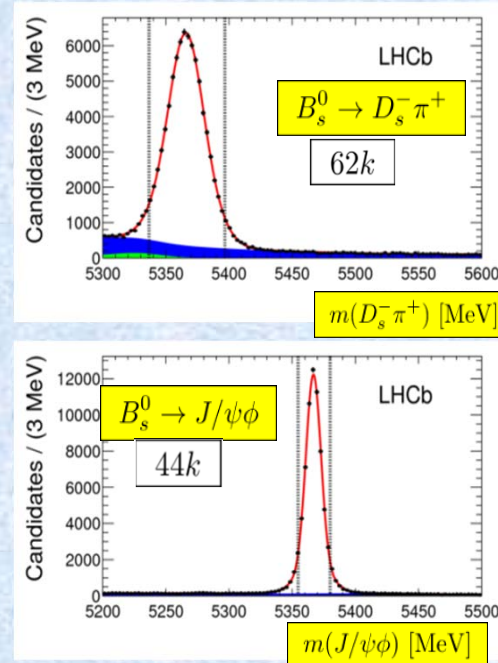
- **LHCb (2016):** 20x more D_s than D0 collab. - lack of observation of any X(5568)-like signal

PRL 117 (2016) 152003

3fb^{-1}

$$\rho_X < 2 \%$$

(95 % C.L.)



- **Negative results also from:**

CDF (2018)

$$\rho_X < 6.7 \%$$

PRL 120 (2018) 202006

ATLAS (2018)

$$\rho_X < 1.5 \%$$

PRL 120 (2018) 202007

CMS (2018)

$$\rho_X < 1.1 \%$$

PRL 120 (2018) 202005

(95 % C.L.)

- **Belle (2008):** the 1st evidence for $Z_c(4430)^-$ in $\psi'\pi$ mass distribution ($B^0 \rightarrow \psi(2S)\pi^- K^+$ decay)

$$M_{Z_c(4430)^-} = 4485_{-22-11}^{+22+28} \text{ MeV}/c^2$$

PRL 100 (2008) 142001

PR D80 (2009) 031104

PR D88 (2013) 074026

$$\Gamma_{Z_c(4430)^-} = 200_{-46-35}^{+41+26} \text{ MeV}/c^2$$

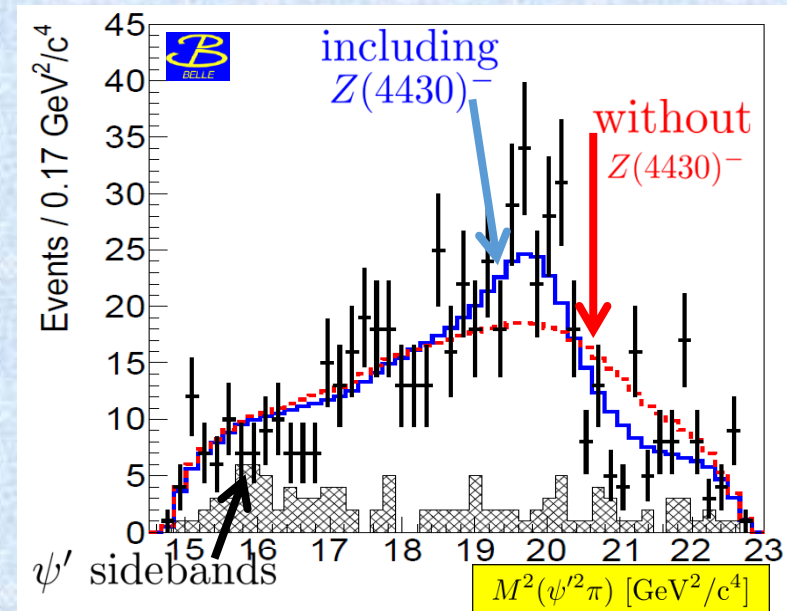
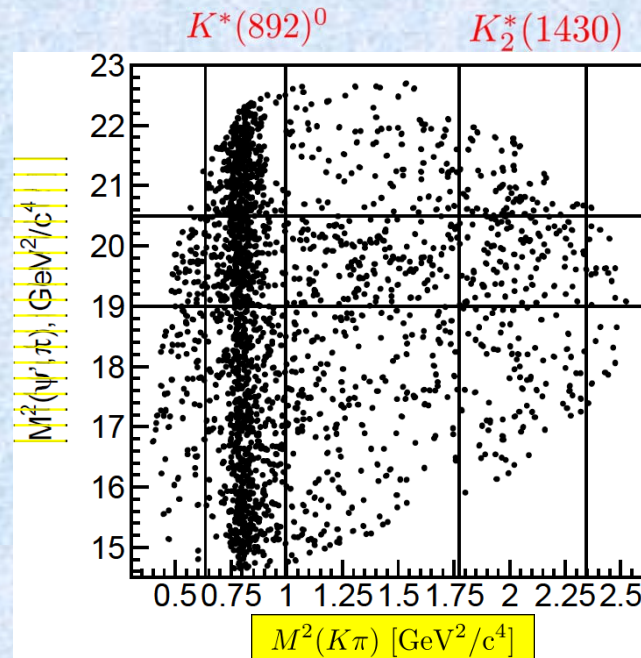
$$\mathcal{B}(B^0 \rightarrow Z_c(4430)^- (\rightarrow \psi'\pi^-) K^+) = (6.0_{-2.0-1.4}^{+1.7+2.5}) \times 10^{-5}$$

- **4D amplitude analysis** with the set of variables: $m^2(K^+\pi^-)$, $m^2(\psi'\pi^-)$, $\cos\theta_{\psi'}$, ϕ

- The preferred spin parity assignment $J^P = 1^+$

$\Theta_{\psi'}$ - The ψ' helicity angle

ϕ - the angle between the K^* and ψ' decay planes



- **BaBar (2009):** null result

PR D79 (2009) 112001

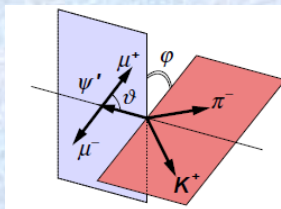
➤ **LHCb (2014-15):** tenfold increase in the signal yield (25 000 decays; Run1 3fb^{-1}); **two approaches:**

4D amplitude analysis

PRL 112 (2014) 222002

- The variables:

$$m(K^+\pi^-), m^2(\psi'\pi^-), \cos\theta_{\psi'}, \phi$$

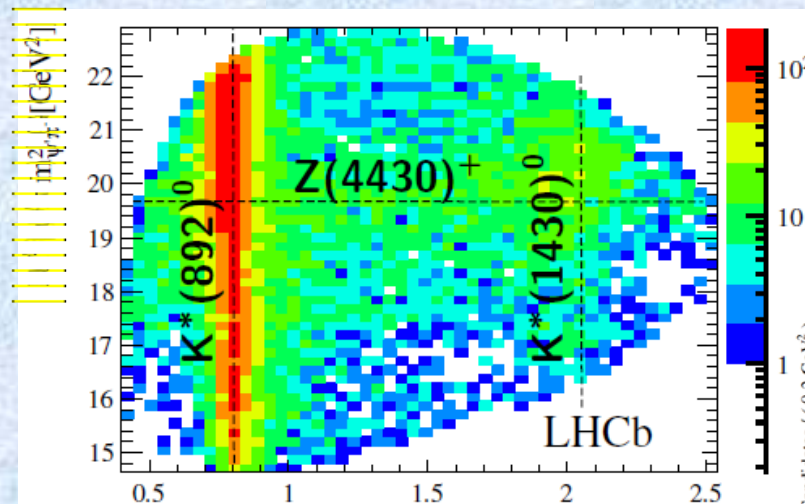


Model independent approach:

PRD 92 (2015) 112009

- The $K\pi$ ang. distributions are extracted from data with Legendre polynomial moments and projected as reflection of the $m(\psi'\pi)$ spectrum

4D amplitude analysis cont

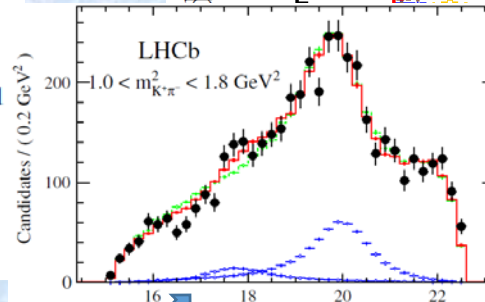
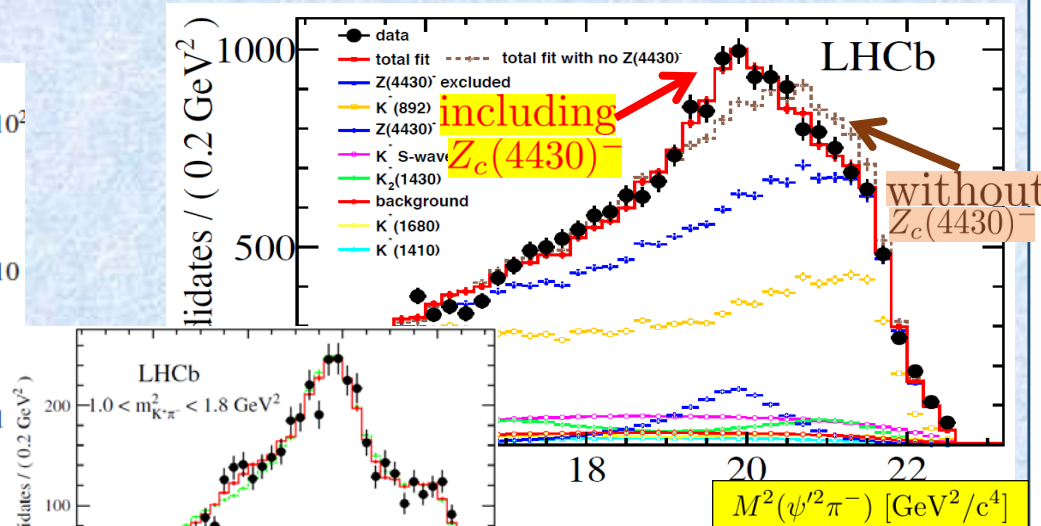


$$J^P = 1^+$$

Assignment fully established

relative to:	J^P	0^-	1^-	2^+	2^-
sign. $[\sigma]$		9.7	15.8	16.1	14.6

$$M^2(K^+\pi^-) [\text{GeV}^2/c^4]$$



The second state (Z_0^-)?

$$J^P = 0^-$$

$$M(Z_0^-) = 4239 \pm 18^{+45}_{-10} \text{ MeV}/c^2$$

$$\Gamma(Z_0^-) = 220 \pm 47^{+108}_{-74} \text{ MeV}/c^2$$

6σ

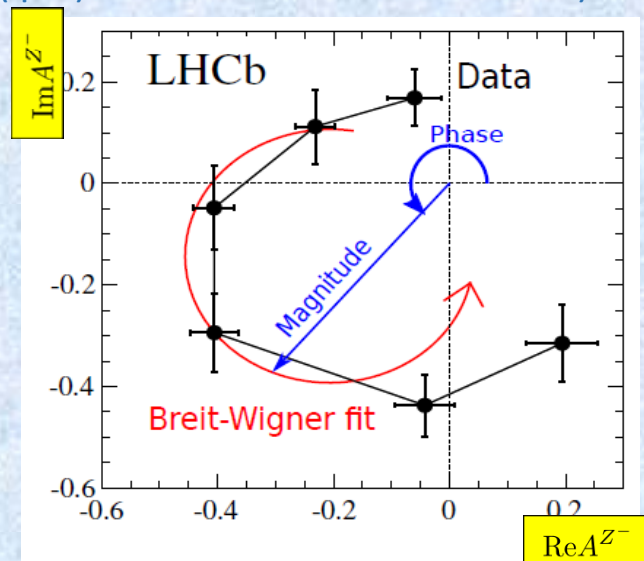
$$M(Z_c(4430)^-) = 4475 \pm 7^{+15}_{-25} \text{ MeV}/c^2$$

$$\Gamma(Z_c(4430)^-) = 172 \pm 13^{+37}_{-34} \text{ MeV}/c^2$$

4D amplitude analysis cont

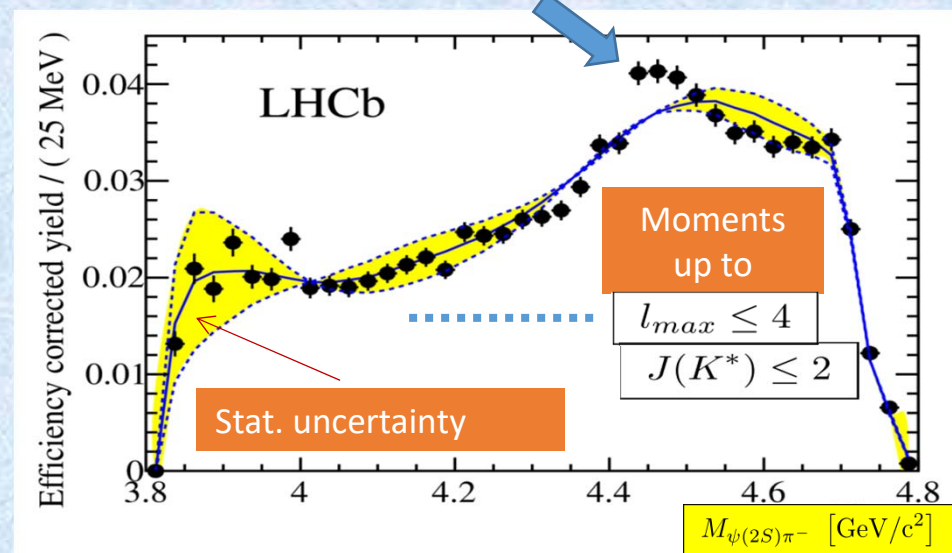
Argand plot: clear resonant behavior

Additional fit to the $Z_c(4430)^-$ Breit-Wigner amplitude in 6 $M^2(\psi'\pi)$ bins ($M_Z = 4475 \text{ MeV}/c^2$, $\Gamma_Z = 172 \text{ MeV}/c^2$; $M^2(\psi'\pi)$ increases counterclockwise)



Model independent approach:

- The $K\pi$ angular distributions are extracted from data with Legendre polynomial moments and projected as reflection of the $m(\psi'\pi)$ spectrum
- The hypothesis that $K\pi$ reflections with $J(K^*) \leq 2$ can explain the $m(\psi'\pi)$ spectrum excluded ($>8\sigma$)
- The discrepancy concentrates around $4430 \text{ MeV}/c^2$



- Positive parity $\rightarrow$ hypotheses of threshold effect $\bar{D}^*(2007)D_1(2420)$ and $\bar{D}^*(2007)D_2^*(2460)$ ruled out
- The most plausible interpretation of $Z_c(4430)$: a tetraquark; the minimal quark content $c\bar{c}d\bar{u}$

- **Belle (2014):** the 1st evidence for $Z_c(4200)^-$ in $J/\psi \pi$ mass distribution ($\sim 3 \times 10^4 B^0 \rightarrow J/\psi \pi^- K^+$ decays)

In addition, the first evidence for $Z_c(4430)^- \rightarrow J/\psi \pi^-$

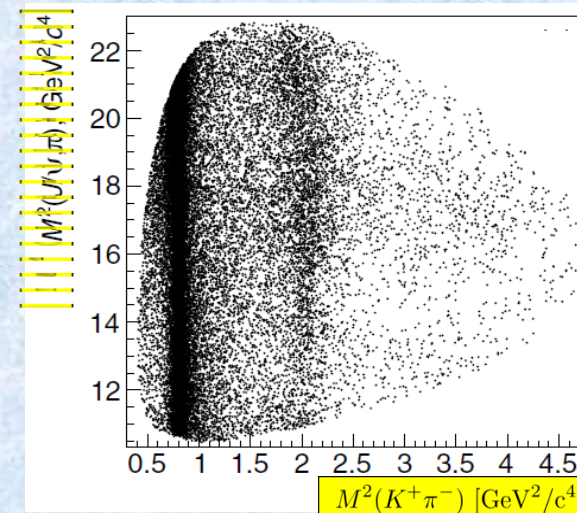
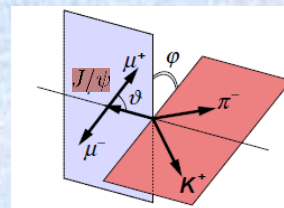
- $M_{Z_c(4200)^-} = 4196^{+31+17}_{-29-13} \text{ MeV}/c^2$

PR D90 (2014) 112009

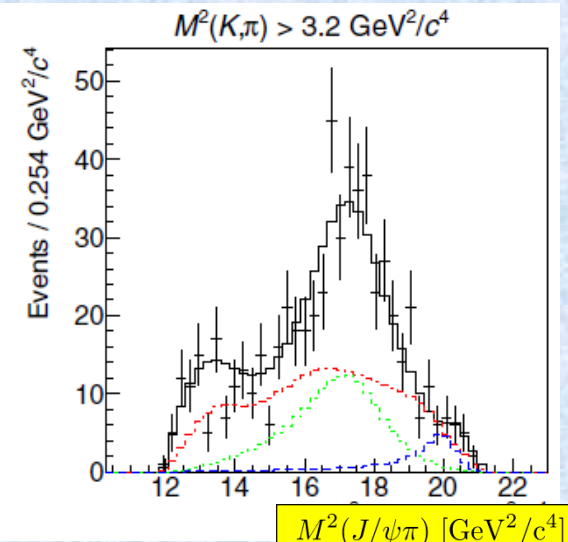
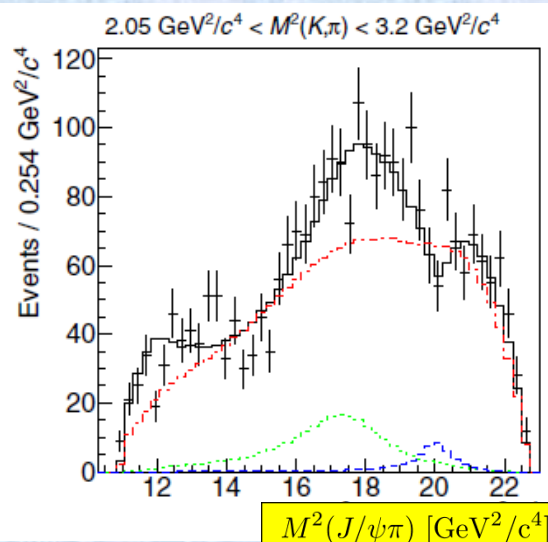
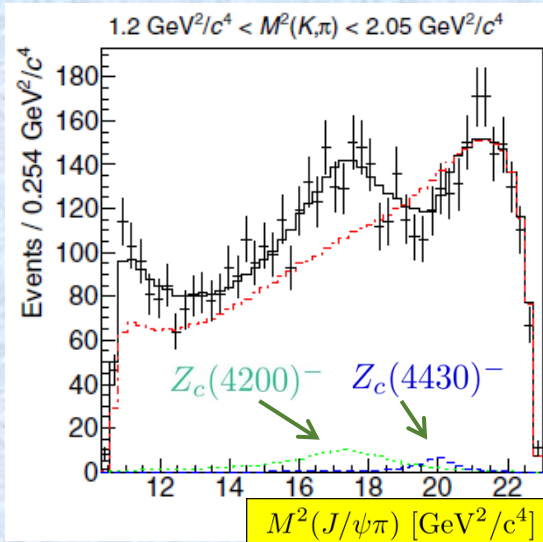
- $\Gamma_{Z_c(4200)^-} = 370^{+70+70}_{-70-132} \text{ MeV}/c^2$

- **4D amplitude analysis** with the set of variables:

$$m^2(K^+ \pi^-), m^2(J/\psi \pi^-), \cos \theta_{J/\psi}, \phi$$



- The preferred spin-parity assignment $J^P = 1^+$



➤ **LHCb (2019):** twentyfold increase in the signal yield ($\sim 5.5 \times 10^5$ $B^0 \rightarrow J/\psi \pi^- K^+$ decays, Run1 3fb $^{-1}$)

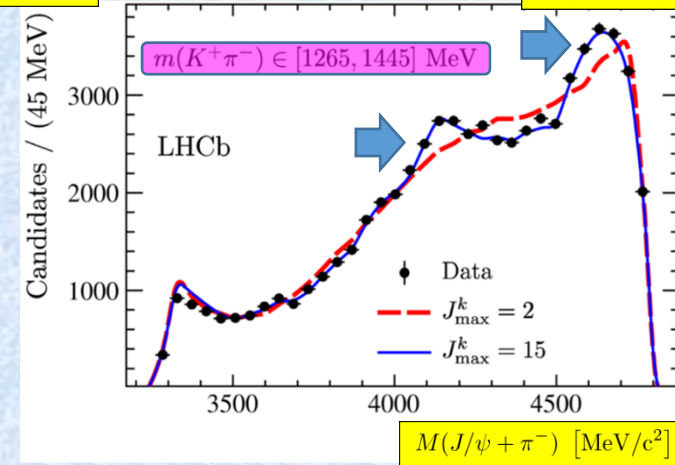
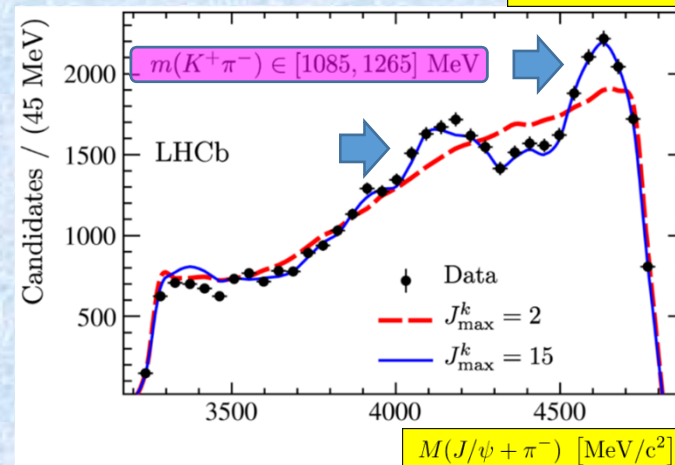
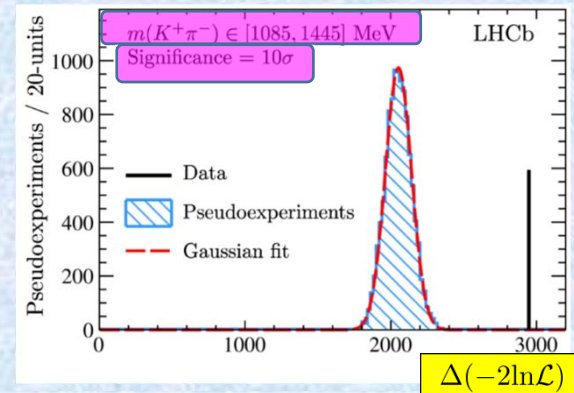
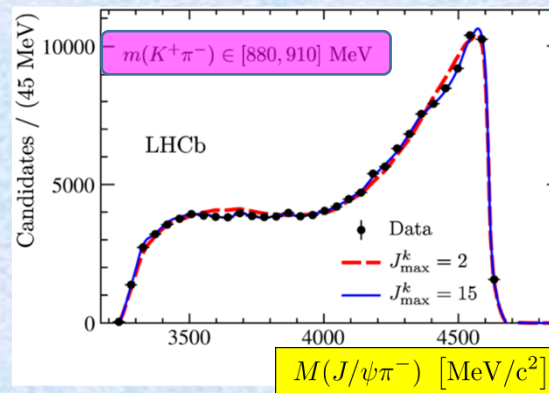
- The decay $B^0 \rightarrow J/\psi \pi^- K^+$ is known to be dominated by K^* resonances: exotic fraction 2.4 % (to compare with 10.3 % contribution from $Z_c(4430)^-$ for $B^0 \rightarrow \psi' \pi^- K^+$) PRL 122 (2019) 152002
- **Model independent approach** – no information about the exact content of the K^* states is needed

➤ 4D study ($M(K^+ \pi^-)$, $\cos \theta_{K^*}$, $\cos \theta_l$, ϕ)

➤ **Data inconsistent with K^* reflections only at 10 σ level**

➤ Unphysical $J_{max}^k = 15$ states are needed to describe the data

Confirmation of the presence of exotic contribution



LHCb:

model-dependent amplitude analysis data is necessary to identify the origin of non- K^* contributions

➤ **LHCb (2018):** Dalitz plot analysis of $B^0 \rightarrow \eta_c(1S)(\rightarrow p\bar{p})K^+\pi^-$ decays (2011, 2012 and 2016 data 4.7 fb^{-1})

EPJC 78 (2018) 1019

➤ **Motivation:**

- $Z_c(3900)^-$ state - discovered in $J/\psi\pi^-$ final state by BESIII, confirmed by Belle and CLEO (all in 2013)
- Possible interpretations of the $Z_c(3900)^-$

✓ **Hadrocharmonium**

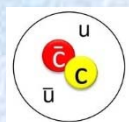
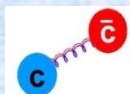


Image from Godfrey & Olsen,
Ann. Rev. Nucl. Part. Sci. 58 (2008) 51

➔ expectation of a new charmonium-like state with a mass of $\sim 3800 \text{ MeV}/c^2$, decaying into $\eta_c\pi^-$

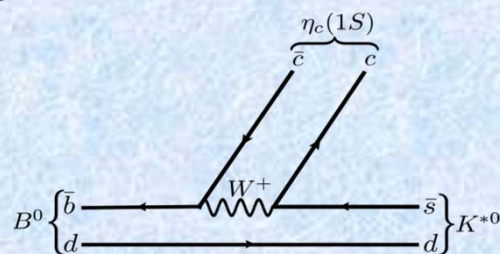
✓ **Quarkonium hybrid**



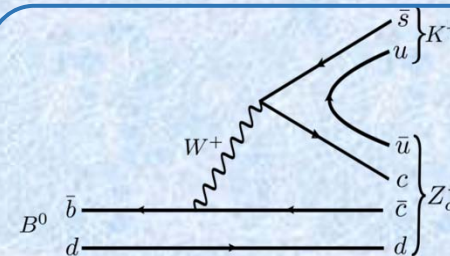
(with the valence gluon replaced by $l=1$ excitation of the gluon and light quarks)
➔ expectation of several charmonium tetraquarks in the mass range $(3800, 4500) \text{ MeV}/c^2$, decaying into $\eta_c\pi^-$

✓ **The diquark model** (diquarks are as important as quarks in the hadron spectrum)

➔ expectation of a $J^P = 0^+$ state below the open-charm threshold, decaying into $\eta_c\pi^-$

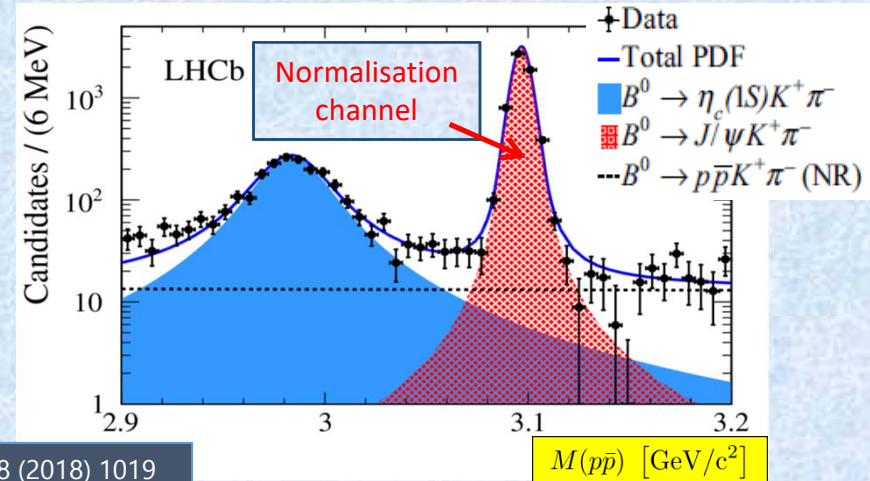
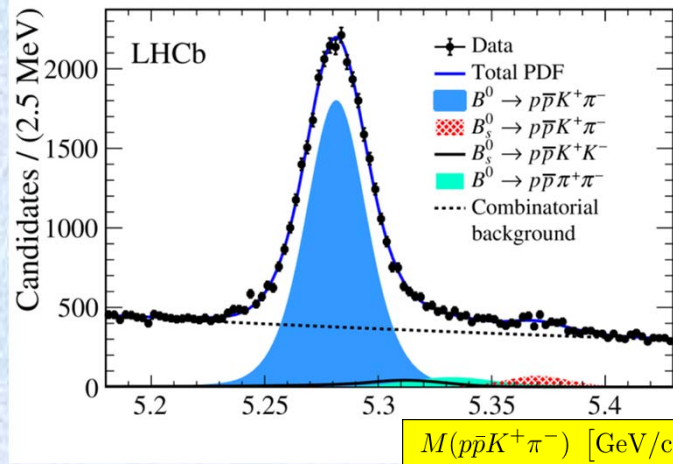


„Standard” K^*_J resonances
dominate the decay
 $B^0 \rightarrow \eta_c(1S) K^+ \pi^-$



With the exotic contribution(s) Z_c ,
decaying into $\eta_c\pi^-$

$Z_c(4100)^-$ in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ Decays

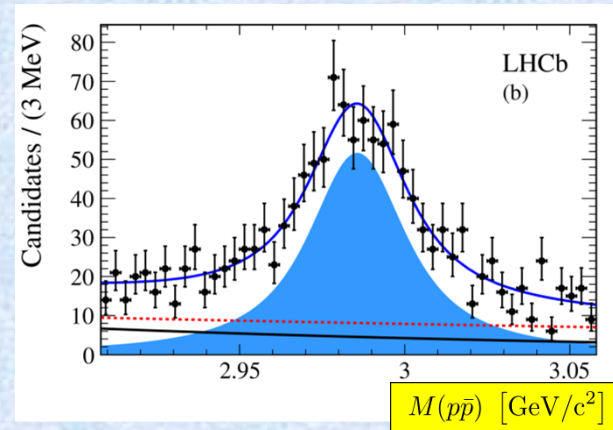
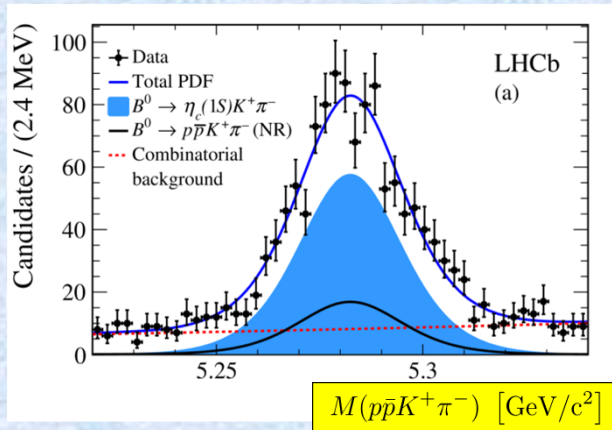


EPJC 78 (2018) 1019

$$\mathcal{B}(B^0 \rightarrow \eta_c(1S)K^+\pi^-) = (5.73 \pm 0.24(\text{stat}) \pm 0.13(\text{syst}) \pm 0.66(\mathcal{B})) \times 10^{-4}$$

- the first measurement

➤ 2D unbinned fit to $M(p\bar{p}K^+\pi^-)$ and $M(p\bar{p})$ distributions:

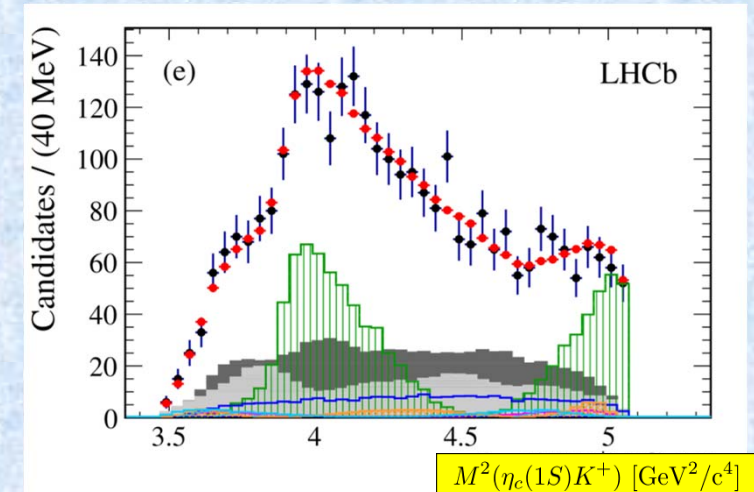
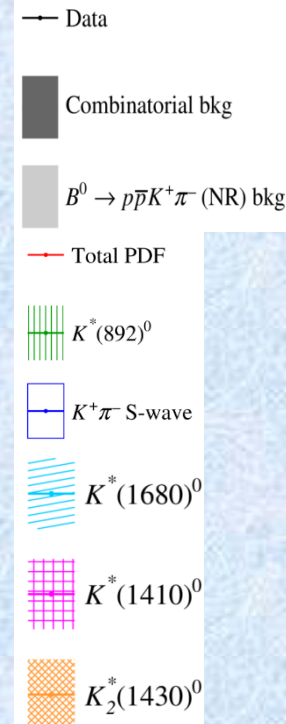
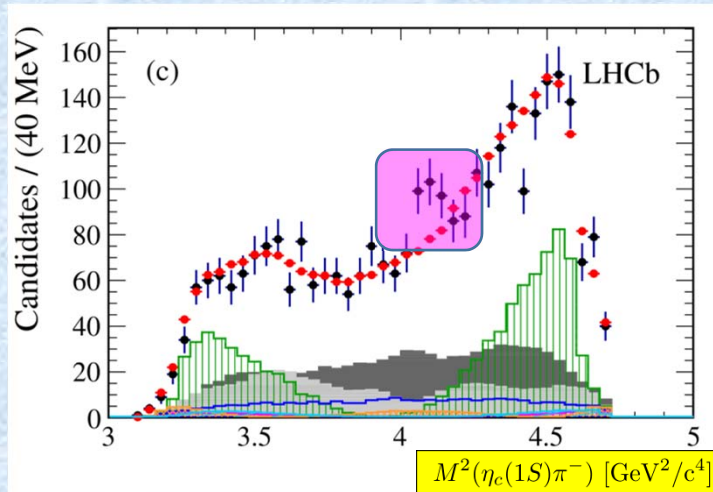
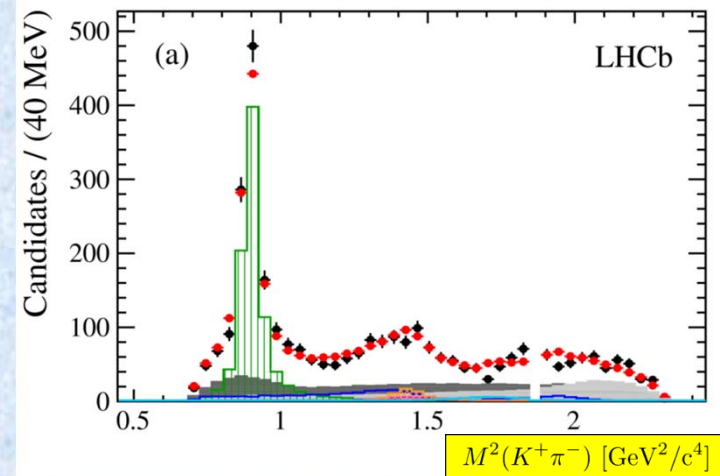
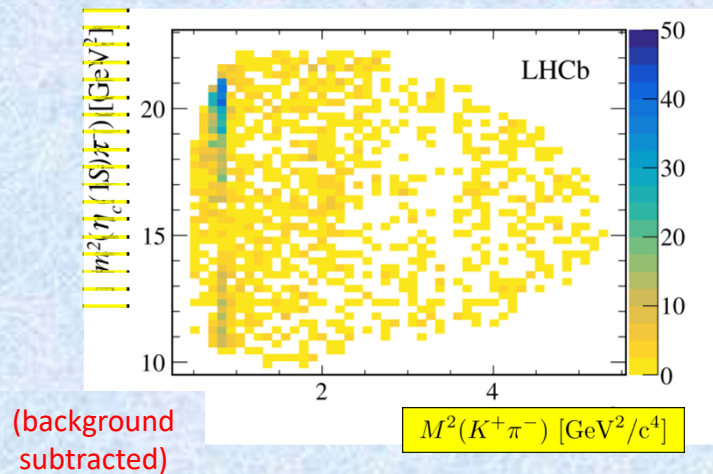


(plots for Run1 data)

$$N(B^0 \rightarrow \eta_c K^+\pi^-) = 1870 \pm 74$$

➤ Dalitz plot analysis: baseline fit – only K^* contributions

EPJC 78 (2018) 1019



➤ Dalitz plot analysis: the fit including an exotic contribution

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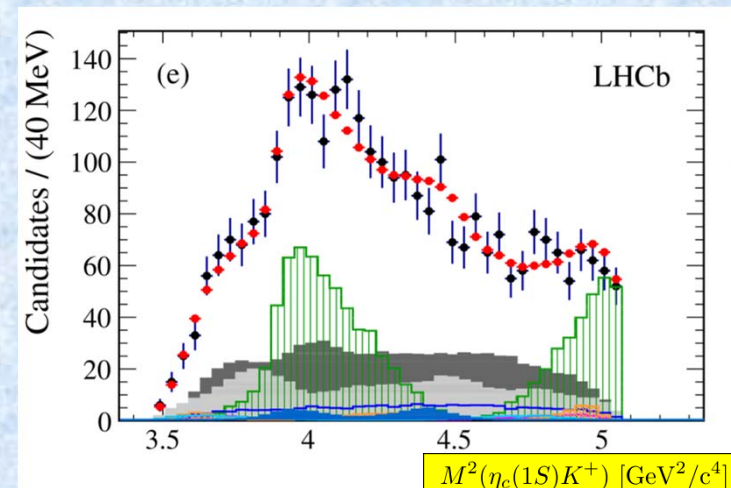
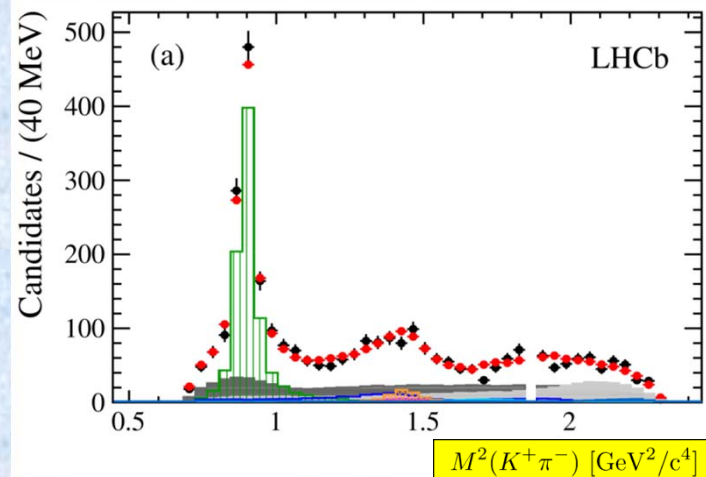
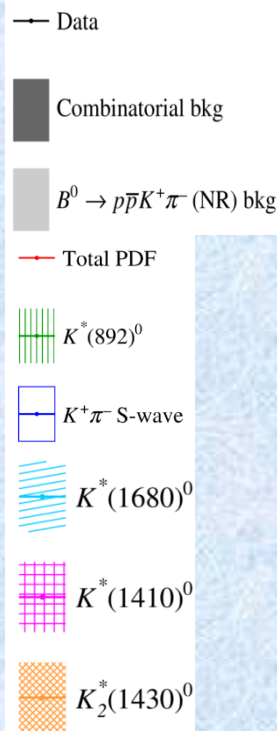
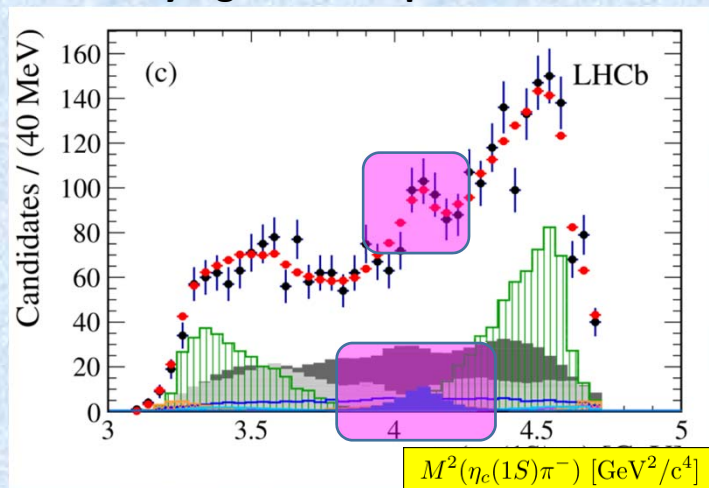
- The addition of a $J^P=1^-$ resonance in $\eta_c\pi^-$ improves the fit by $\Delta(-2\ln\mathcal{L}) = 41.4$ (4.8σ)

$$M_{Z_c(4100)^-} = 4096 \pm 20^{+18}_{-22} \text{ MeV}/c^2$$

Significance 3.4σ
(4.8σ – stat. only)

$$\Gamma_{Z_c(4100)^-} = 152 \pm 58^{+60}_{-35} \text{ MeV}/c^2$$

- The mass above open charm threshold $J^P=1^-$ favoured; $J^P=0^+$ not excluded
- The first evidence for an exotic state decaying into two pseudoscalars



➤ More data needed for unequivocal quantum number determination

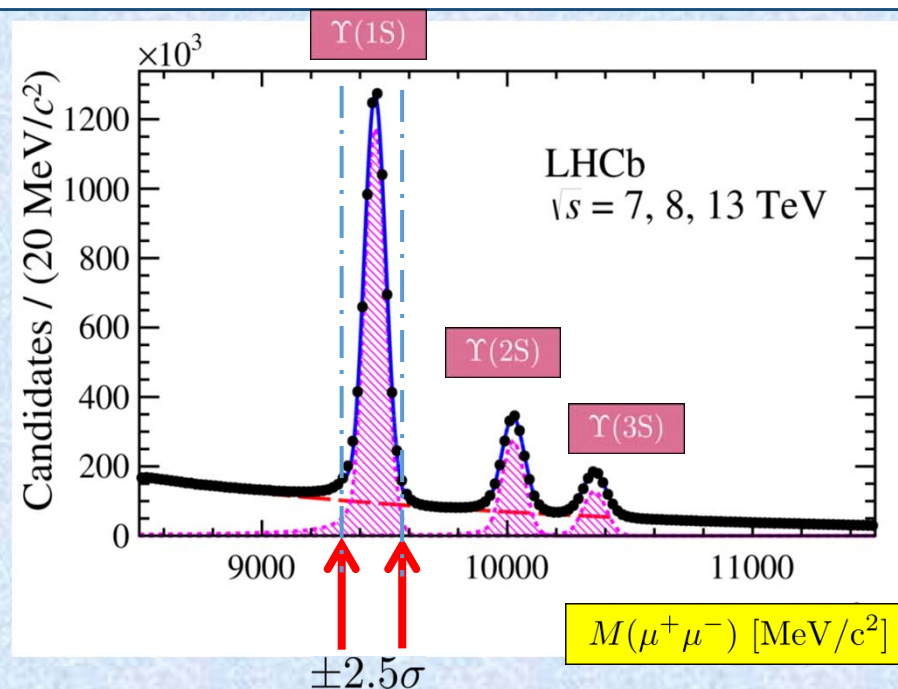
- No exotic hadron, composed of more than two heavy quarks has been observed so far
- Several theoretical predictions for the existence of an exotic state $X_{b\bar{b}b\bar{b}}$
 - Mass in the range $[18.4, 18.8] \text{ GeV}/c^2$, close but below the $\eta_b\eta_b$ threshold $(18.798 \pm 0.005) \text{ GeV}/c^2$
 - ➔ The expected, experimentally favorable, decay mode: $X_{b\bar{b}b\bar{b}} \rightarrow \Upsilon(1S)l^+l^-$, ($l = e, \mu$)
 - Lattice QCD calculations: no indication for the X state in the hadron spectrum

➤ LHCb(2018):

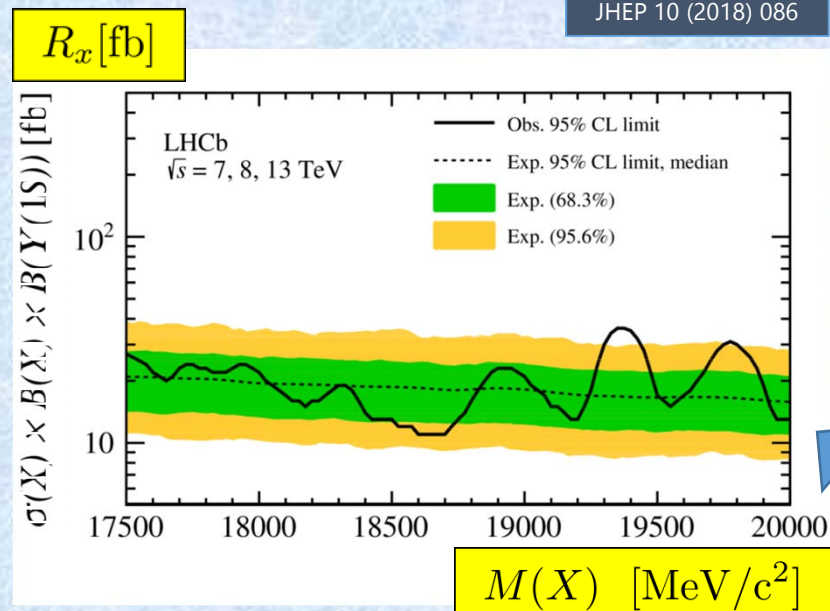
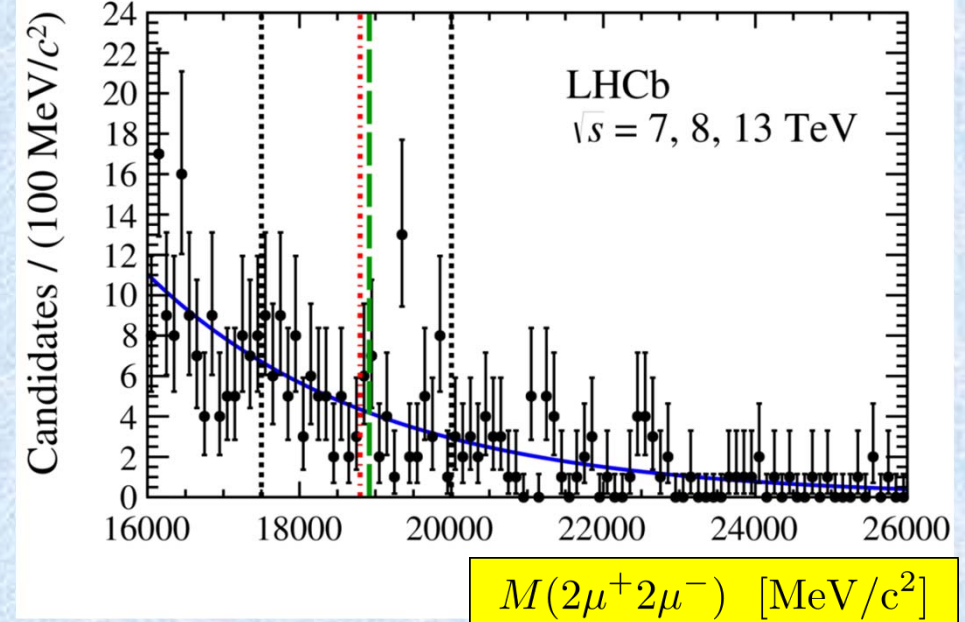
JHEP 10 (2018) 086

- 6.3 fb^{-1} of data recorded between 2011 and 2017
- the search for the X state decaying to $\Upsilon(1S)(\rightarrow \mu^+\mu^-)\mu^+\mu^-$
- the normalization decay channel: $\Upsilon(1S) \rightarrow \mu^+\mu^-$

$$N(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (6.37 \pm 0.12) \times 10^6$$



- The search for an excess in the $M(2\mu^+2\mu^-)$ in the mass range [17.5, 20] GeV/c^2
- Cut based selection
- J/ψ mass veto applied:
 $M(\mu^+\mu^-) \notin [3050, 3150] \text{ MeV}/c^2$



- No significant excess is observed in data in the mass range [17.5, 20] GeV/c^2

- An upper limit is set for

$$R_X = \sigma(pp \rightarrow X) \times \mathcal{B}(X \rightarrow \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)$$

- **LHCb (2018):** search for the dibaryon states in $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^- (\Lambda_c^+ \rightarrow p K^- \pi^+)$

PL B784 (2018) 101

- Motivated by the paper by L.Maiani, A.D.Polosa and V.Riquer

PL B750 (2015) 37

Run1 3 fb⁻¹

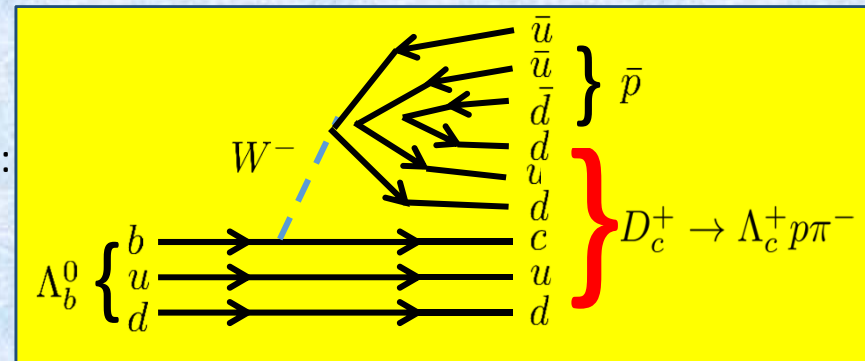
- **The lightest charmed dibaryon D_c^+** (quark content [cd][ud][ud]) with the mass below 4682 MeV/c² is expected to participate in the decay $\Lambda_b^0 \rightarrow D_c^+ \bar{p}$:

- Two options for the subsequent decays of the D_c :

$$D_c^+ \rightarrow p \Sigma_c^0, \quad \Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$$

$$D_c^+ \rightarrow p P_c^0, \quad P_c^0 \rightarrow \Lambda_c^+ \pi^-$$

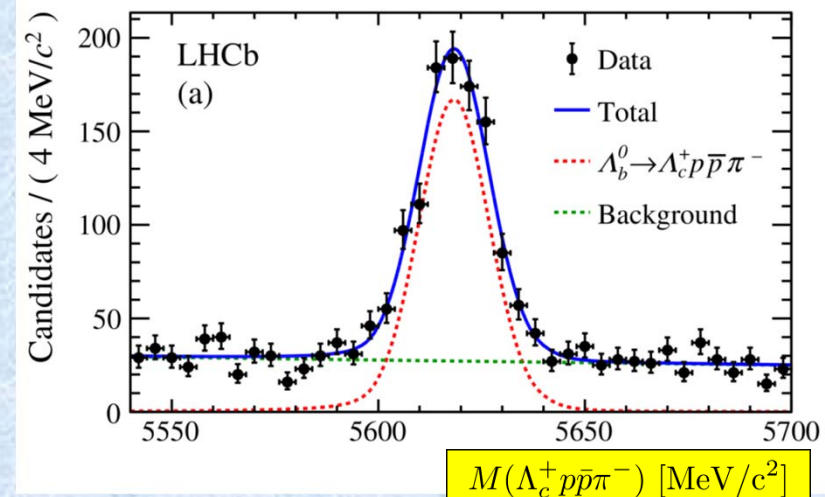
P_c – lighter, yet undiscovered pentaquark [cddu $\bar{u}$]



- **The first observation of the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$**

$$N(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-) = 926 \pm 43$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

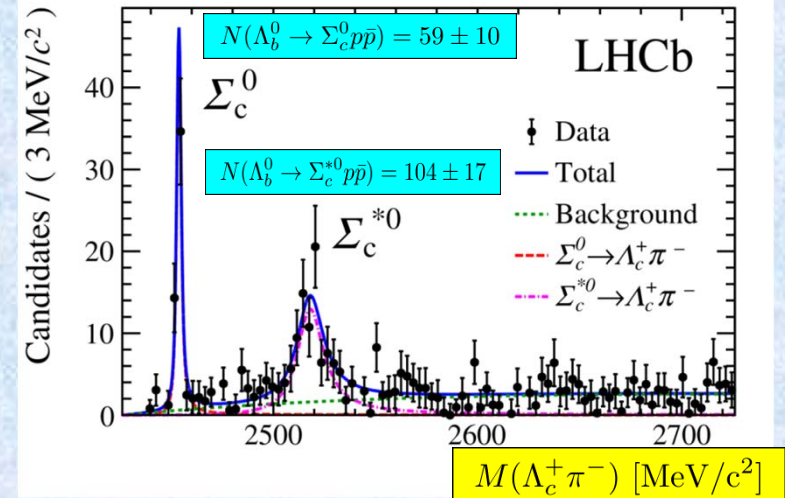


➤ **Studies of the resonance structures in the $\Lambda_c^+ \pi^-$ mass spectrum**

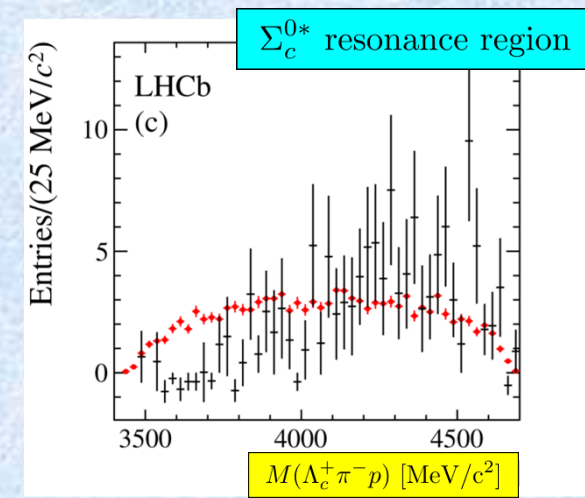
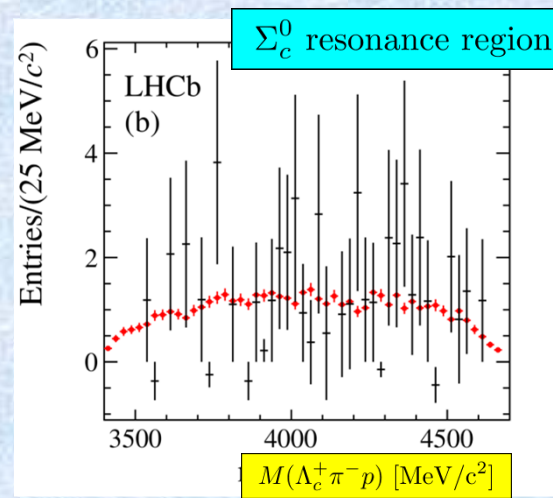
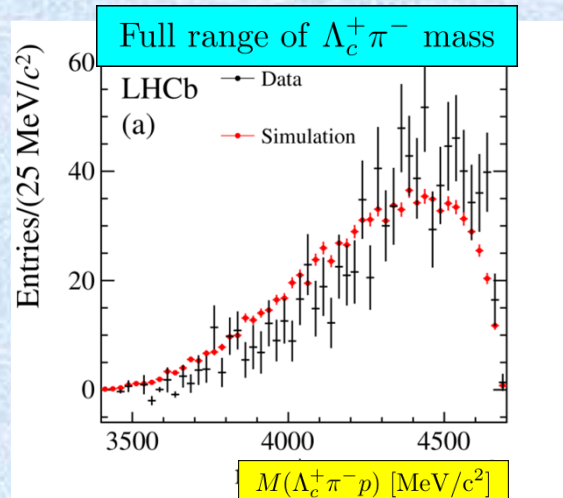
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^0 (\rightarrow \Lambda_c^+ \pi^-) p \bar{p})}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)} = 0.089 \pm 0.015 \pm 0.006$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*0} (\rightarrow \Lambda_c^+ \pi^-) p \bar{p})}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)} = 0.119 \pm 0.020 \pm 0.014$$

PL B784 (2018) 101



➤ **Background subtracted (with sPlot technique) spectra of the $(\Lambda_c^+ \pi^- p)$ system**



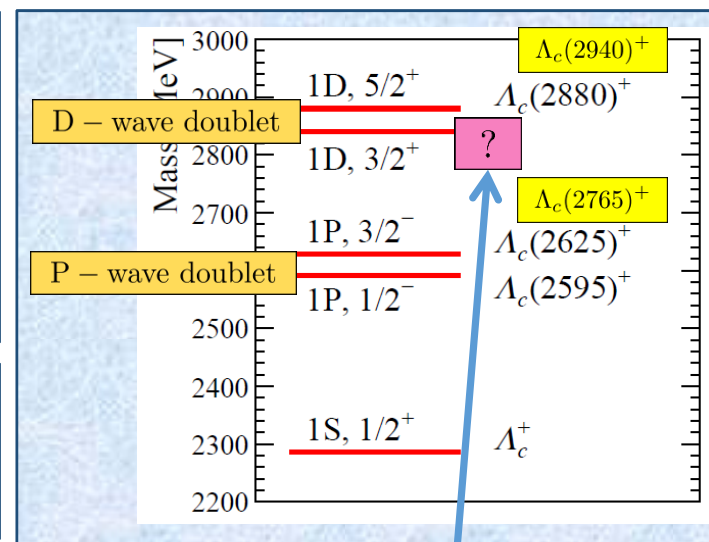
➤ **No evidence of peaking structures found**

NR heavy quark – light diquark model expectations:

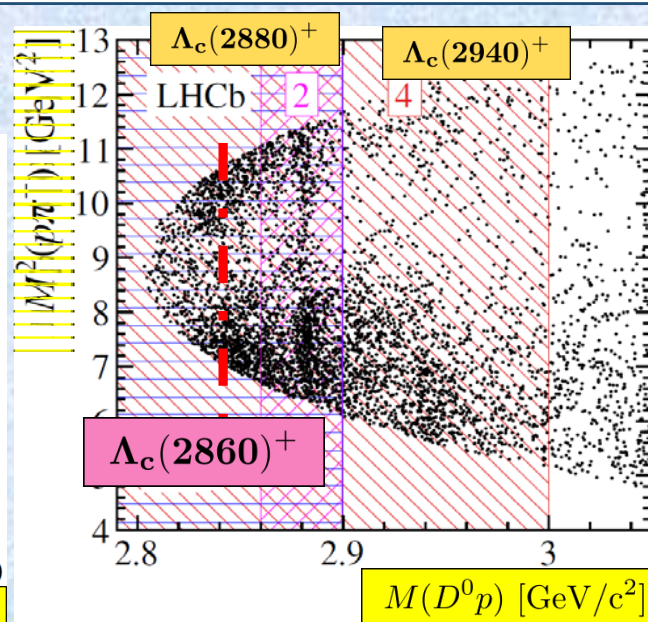
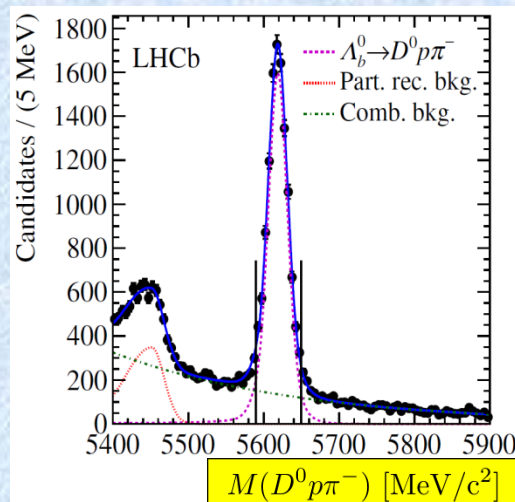
- Missing: $J^P = 3/2^+$ state (2nd member of the D-wave doublet)
- Two experimentally observed states lacking a clear assignment: $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$ (CLEO & BaBar)

LHCb (2017) JHEP 1705 (2017) 030

The first study of excited Λ_c^+ states in exclusive Λ_b decays
 $\Lambda_b^0 \rightarrow D^0 p \pi^-$, $D^0 \rightarrow K^- \pi^+$ (5D amplitude analysis)



11212 $\pm$ 126 signal events
 (16% of background)



Near threshold enhancement in the $D^0 p$ mass $\rightarrow$ a new resonance $\Lambda_c(2860)^+$ and with $J^P=3/2^+$

The first, most likely assignment for the $\Lambda_c(2940)^+$: $J^P = 3/2^- \rightarrow$ consistent with the interpretation of $\Lambda_c(2940)^+$ as a $D^* N$ molecule

PLB 718 (2013) 1381

Int J. Mod. Phys. Conf. (2014) 1460220 7

or as a radial 2P excitation

Eur. Phys. J A (2015) 51

- The renaissance of heavy flavour spectroscopy in recent 15 years:
 - Observation of numerous new states: many of them exotic-like
 - A vivid field of research with strong liaisons between theory and experiment
- LHCb has been one of crucial players in heavy flavour spectroscopy of exotic states – the discussed states shown in black fields
- More precise spectroscopic measurements from the LHCb experiment and, hopefully, some discoveries should follow with the analysis of Run 2 data
- LHC and LHCb upgrade: 50 fb⁻¹ of integrated luminosity expected by 2030....

