XYZ States at LHCb

Clusters & Hierarchies

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1. (Very brief) introduction to the spectroscopy of hadron states

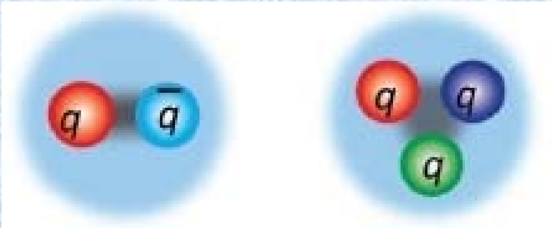
2. LHCb spectrometer - an excellent tool for heavy hadron spectroscopy

3. Exotic hadrons at LHCb (pentaquarks excluded)

   - ✓ X(3872) and X(3842)
   - ✓ The X states decaying to J/ψ ϕ
   - ✓ 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 vs Exotic States

➢ Standard states:



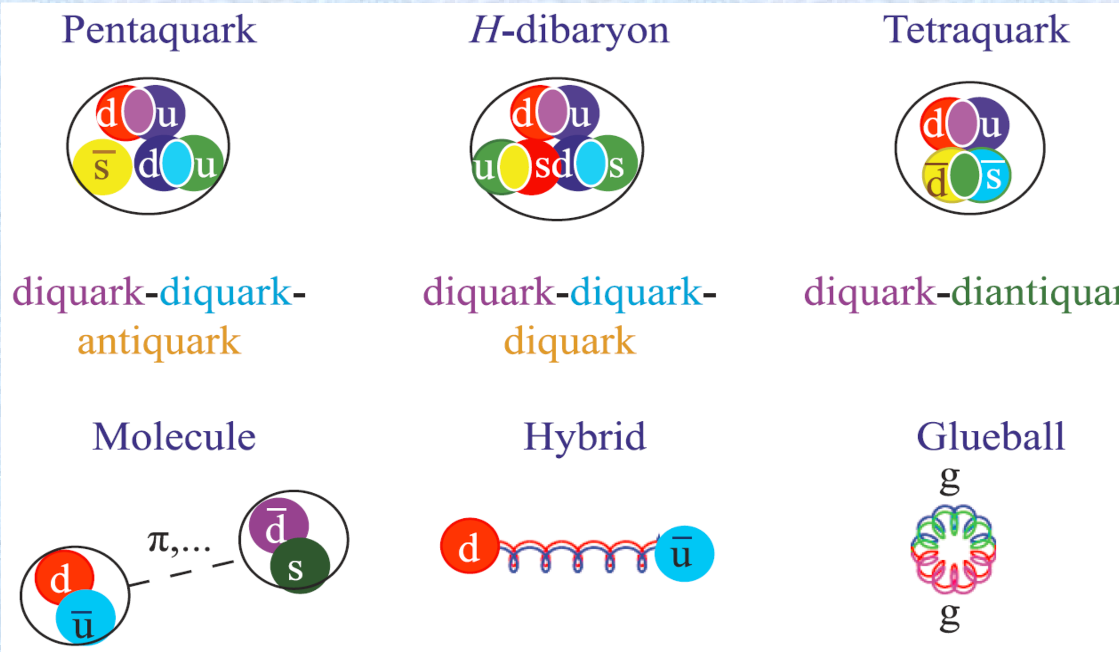
A SCHEMATIC MODEL OF BARYONS AND MESONS

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

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

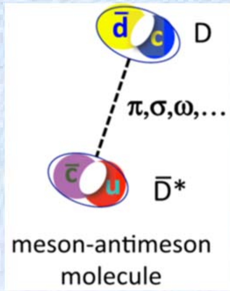
Phys. Lett. 8 (1964) 214-215

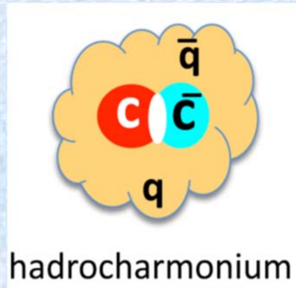
➢ Exotic states:

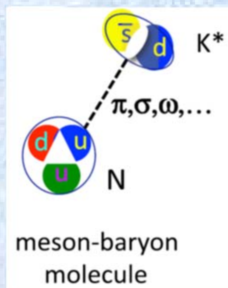


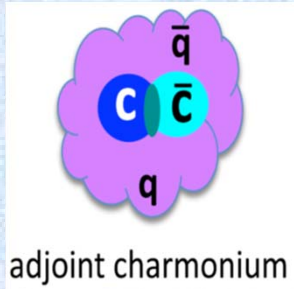
Front. Phys. 10 101401

but also:









Rev. Mod. Phys. 90 (2018) 015003

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

Charmonium ($c\bar{c}$) Mass Spectrum

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

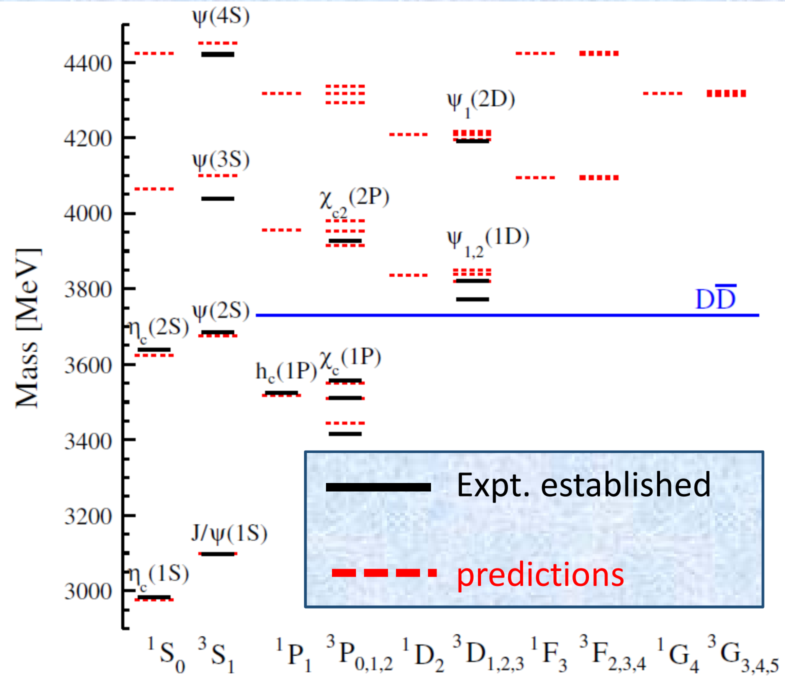
➢ **The properties of new states to be determined**

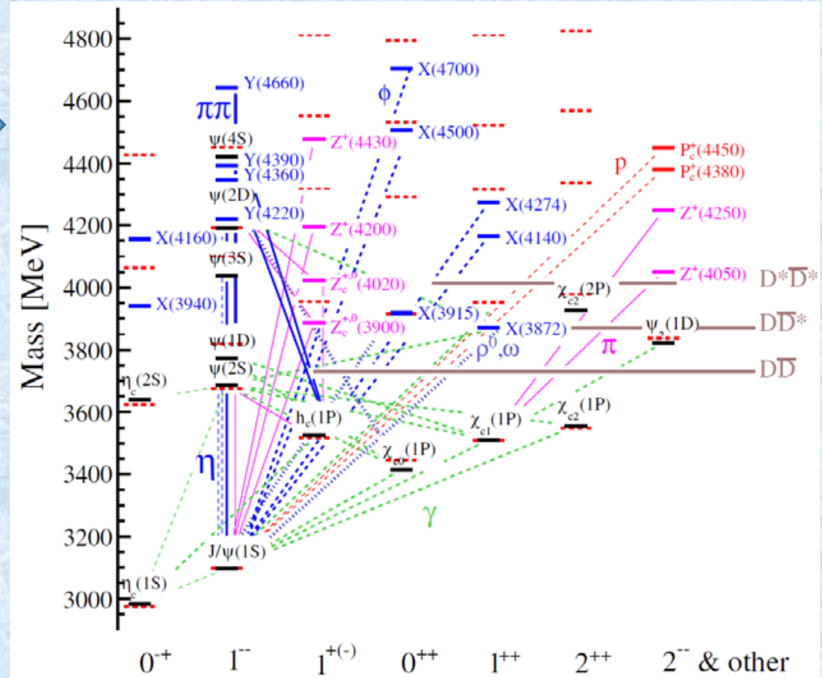
- Mass and width
- Spin, parity, C-parity….
- Production rates
- Decay channels, branching fractions….

➢ **Notation of quarkonium states**

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

n – $Q\bar{Q}$ radial quantum number
S – combined spin of the $Q\bar{Q}$ pair
L – the relative angular momentum of the pair (S: L=0, P: L=1, D: L = 2)
J – the total angular momentum





Exotic states (with heavy quarks)

- **Quantum numbers:**

J^{PC}

Unconventional ← J^{PC} → **Conventional**

e.g mesons with 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+} …

Conventional → Supernumerary / atypical production and/or decays

- **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)

LHCb Spectrometer

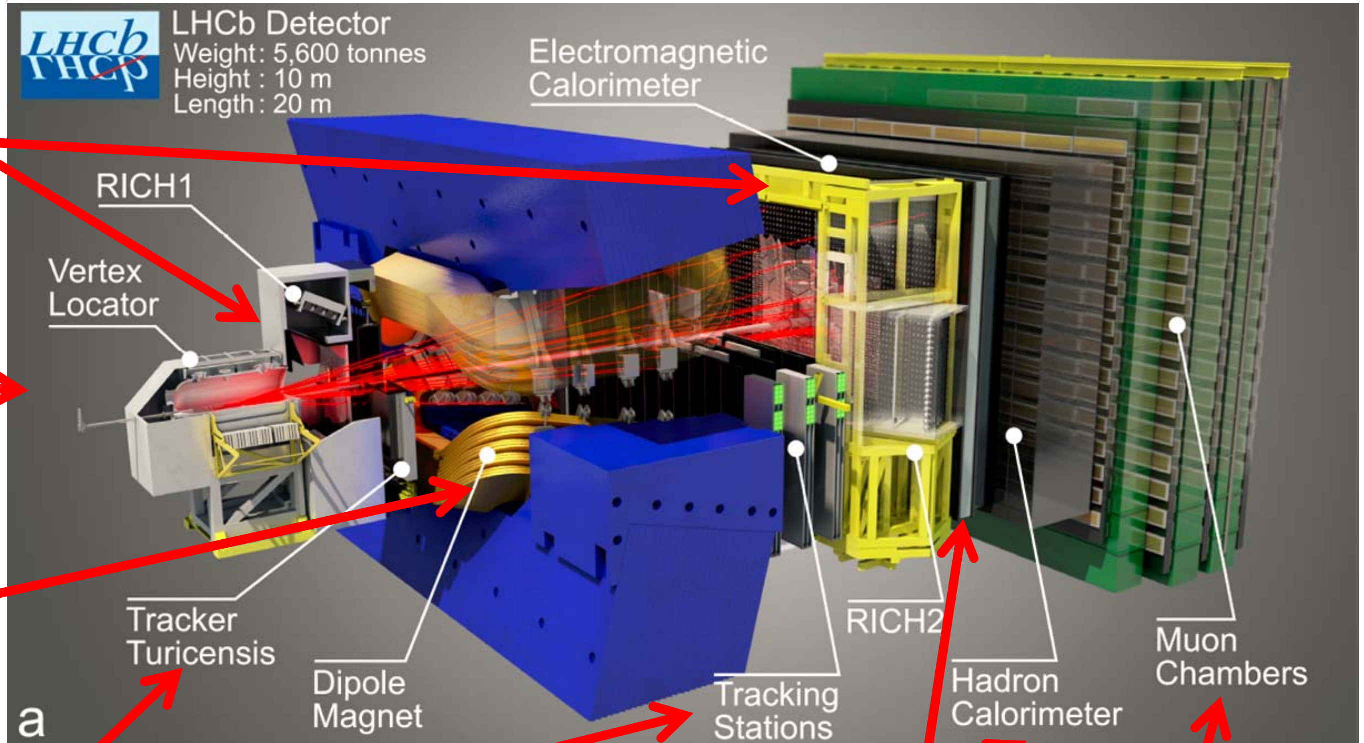
➢ The first hadron-collider experiment that is dedicated to heavy flavour (HF) physics

➢ The geometry of forward spectrometer

RICH:
Separation of K, p from π:
ε(K→K) ≈ 95 %   ε(π →K) ≈ 5 %
ε(p→p) ≈ 95 %   ε(π →p) ≈ 5 %

Vertex Detector:
Impact parameter resolution:
$\sigma_{IP} = 20\ \mu m$
Decay time resolution:
heavy hadrons: ≈50 fs

Dipole magnet:
Bending power: 4 Tm



Precise tracking system:
ε(trk) ≈ 96 %
Momentum resolution:
$$\frac{\Delta p}{p} = 0.5\ \%\quad p = 20\ \mathrm{GeV}$$
$$0.8\ \%\quad p = 100\ \mathrm{GeV}$$

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

Electromagnetic and hadronic calorimeters
ECAL: $\frac{\sigma_E}{E} = 1\ \% \oplus \frac{10\ \%}{\sqrt{E[\mathrm{GeV}]}}$

Muon system:
ε(μ → μ) ≈ 97 %
ε(π → μ) ≈ (1-3) %

Spectrometer:
very good mass resolution $\sigma(m_{B\to hh}) \approx 22\ \mathrm{MeV}$

Trigger:
Highly flexible, currently have "offline quality"

LHCb Spectrometer

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

+

- **High production cross-sections for HF** ($2x10^4$ 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: $0.8^o < \Theta < 15.4^o$) **:**

+

- **LHCb captures a HF production cross-section, comparable to that of ATLAS and CMS (high-p_T range) in MUCH SMALLER SOLID ANGLE →** smaller number of electronic channels → smaller event size → larger trigger bandwith to store (dominated by b and c physics)
- LHCb – forward detector ($p >> p_T$): **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** ($4x10^{32}$ $cm^{-2}s^{-1}$)
- **The efficiencies of γ, π^0 and η reconstruction are much lower,** compared with the e^+e^-

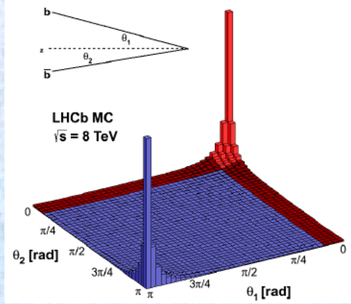
LHCb Data Sample

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}

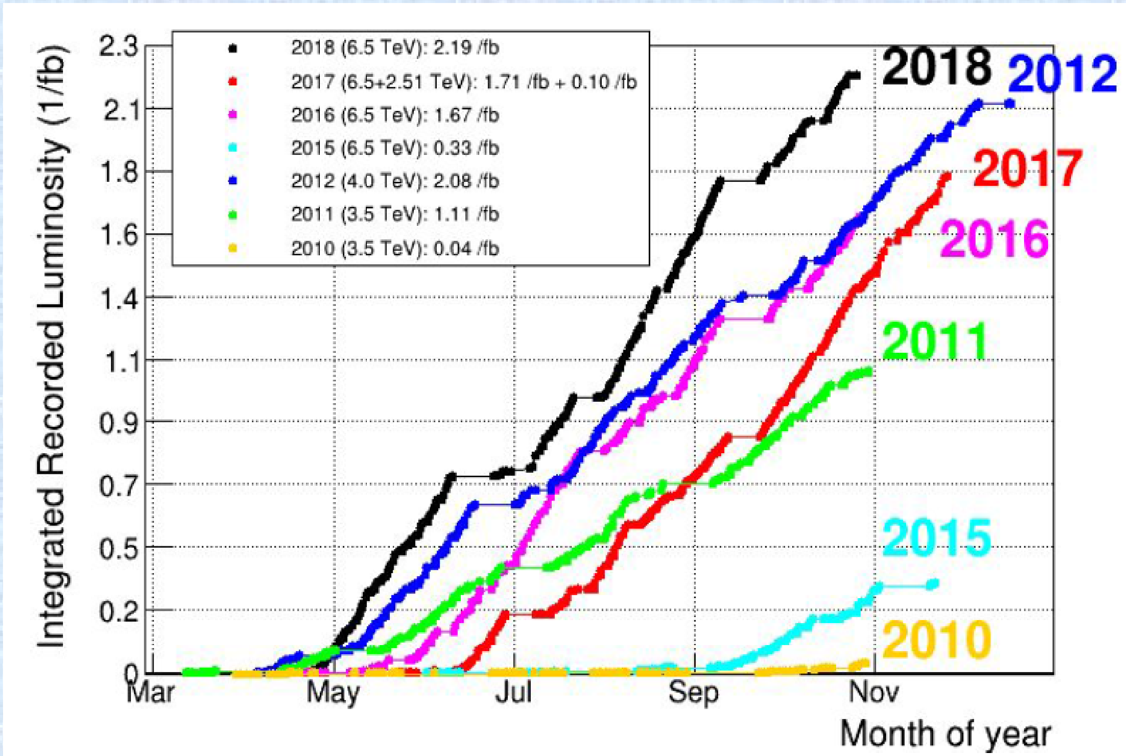
$$2 < \eta < 4.5$$

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



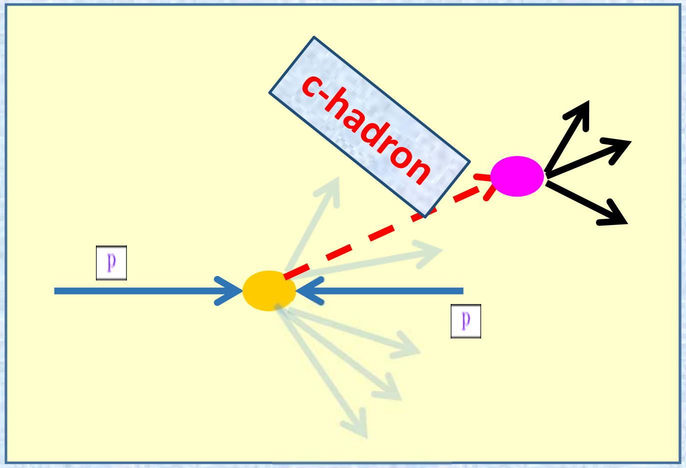
- **All results presented here correspond to Run 1 data:**
  3 fb^{-1}
  4 x 10^{12} b-hadrons produced

- **Run 2 vs Run 1:**
  - more abundant production of b-hadrons
  - improvements in trigger and selection efficiencies



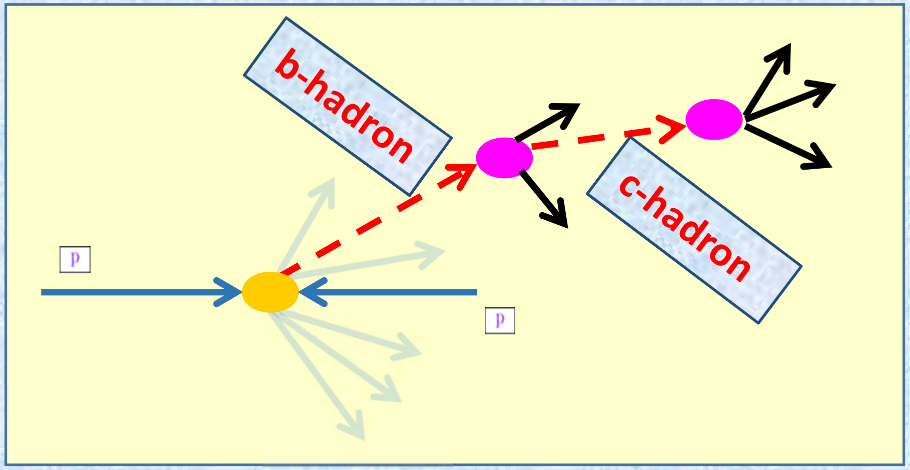
Production of Charmed Hadrons

➢ Direct (prompt) production



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

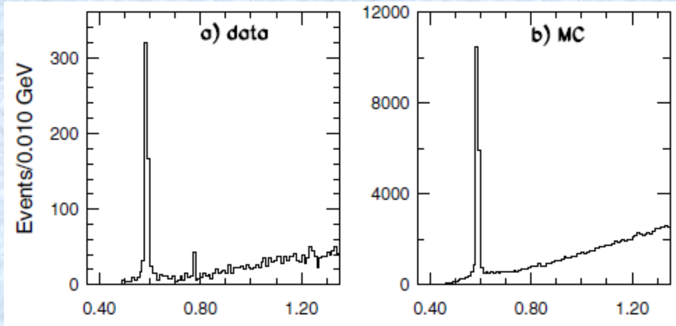
➢ Production in weak decays of beauty hadrons



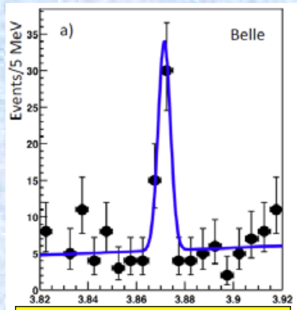
- Smaller yields, but much reduced background
- More tools e.g. kinematical constraints, detached vertices…
- Knowledge about the initial state → determination of quantum numbers of the observed states
- Only states, with specific spin-parities can be observed
- The c-hadron can show up in high(-er)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

X(3872): Past and Latest Measurements

- **X(3872) - the trigger of exotic revolution**
  - Belle (2003): PRL 91 (2003) 262001
  - observation of narrow state X in $B \to [\pi^+\pi^- J/\psi]\, K$ decay
- **The current nomenclature of the PDG:** $X(3872) \equiv \chi_{c1}(3872)$



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



$M(\pi^+\pi^- J/\psi)$ [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

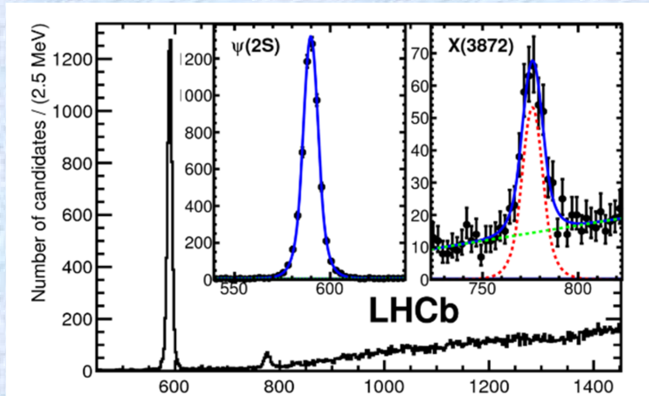
   the first observation of the inclusive production of the X(3872) in the process: $pp \to X(3872) + \text{anything}, \quad X(3872) \to \pi^+\pi^- J/\psi$

   $$M(X(3872)) = 3871.95 \pm 0.48 \pm 0.12\ \mathrm{MeV/c^2}$$

   PDG: $\mathbf{M(X(3872)) = 3871.69 \pm 0.17}\ \mathrm{MeV/c^2}$

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

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



$M(\pi^+\pi^- J/\psi) - M(J/\psi)$ [MeV/c^2]

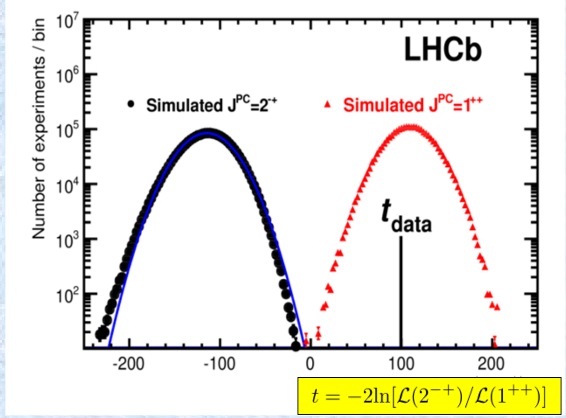
2. **Narrow width in decays to charmonia:** $\mathbf{\Gamma < 1.2}\ \mathrm{MeV/c^2}$ (Belle PR D84 (2011) 052004)

X(3872): Past and Latest Measurements

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

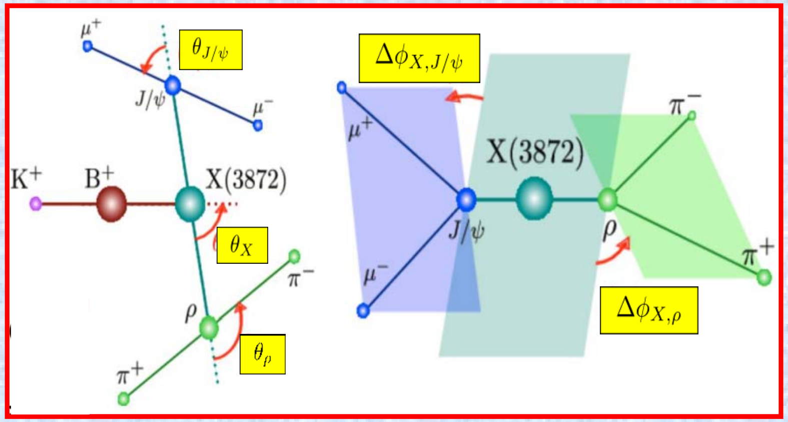
PRL 110 (2013) 222001

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

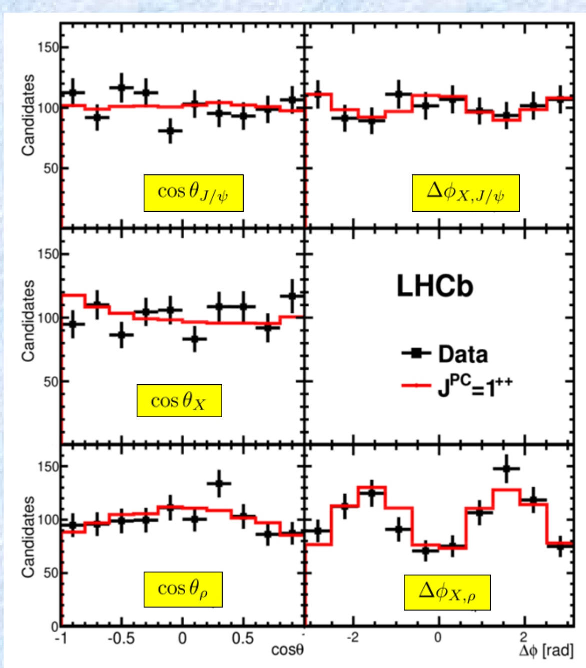


The variables:

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



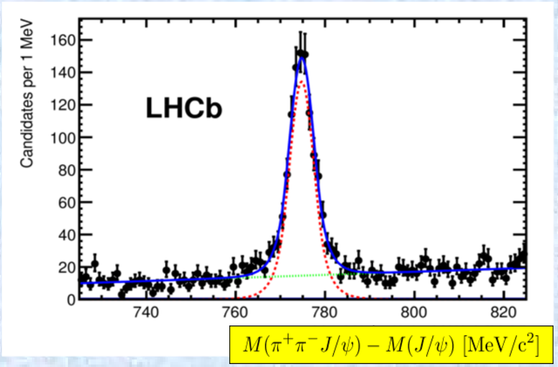
The last remaining controversy (2^{-+} vs 1^{++}) solved:
The 2^{-+} hypothesis excluded with a significance > 8σ



LHCb (2015): PRD 92 (2015) 011102

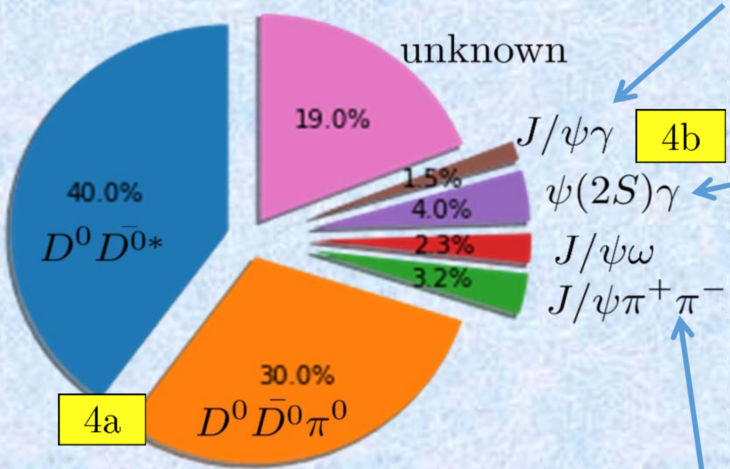
data 3 fb^{-1}, 1011±38 events

For the first time, no assumption about the orbital angular momentum in the X(3872) decay
$J^{PC}=1^{++}$ confirmed



X(3872): Past and Latest Measurements

4. Decay modes



4a 4b 4b*

BaBar (2009): $\mathcal{B}(X(3872) \to J/\psi\gamma) > 4\%$ PRL 102 (2009) 132001

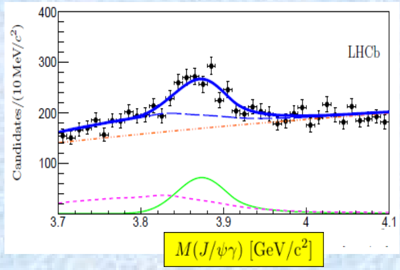
LHCb (2014): NuclPhys B886 (2014) 665

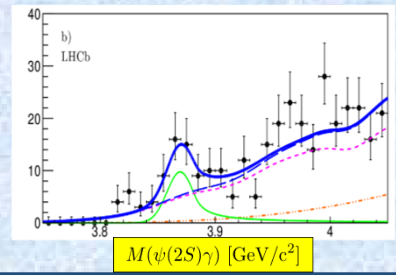
$$R_{J/\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

$\mathrm{C} = 1$

PLB 588 (2004) 189

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





But BESIII:

$R_{J/\psi\gamma} < 0.59$

(90% C.L.)

arXiv:2001.01156

5. In the decay $X(3872) \to \pi^+\pi^- J/\psi$ **the M(ππ) is concentrated around the ρ mass**
The X decays to J/ψρ and J/ψω with comparable branching fractions → isospin violation

EPJC 72 (2012) 1972
PRD 92 (2015) 011102

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

PRD 92 (2015) 011102

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

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

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

PLB 769 (2017) 305

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

EPJ C77 (2017) 609

Observation of $\Lambda_b \to \chi_{c1}(3872)pK^-$

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

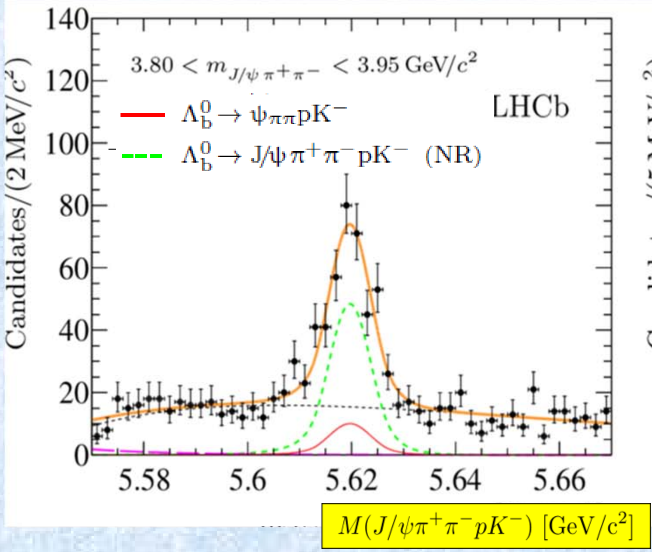
- **LHCb (2019):**

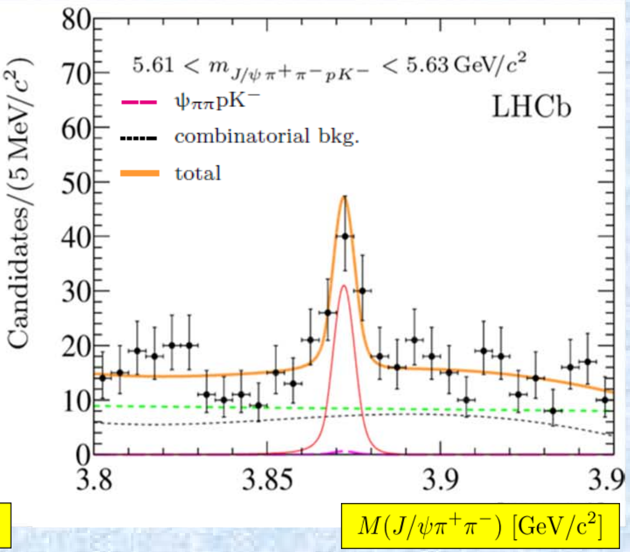
  search for the decay

$$\Lambda_b^0 \to \chi_{c1}(3872)pK^-$$
$$\chi_{c1} \to J/\psi\pi^+\pi^-$$

(2011-12, 2016 data 4.9 fb^{-1})

JHEP 09 (2019) 028

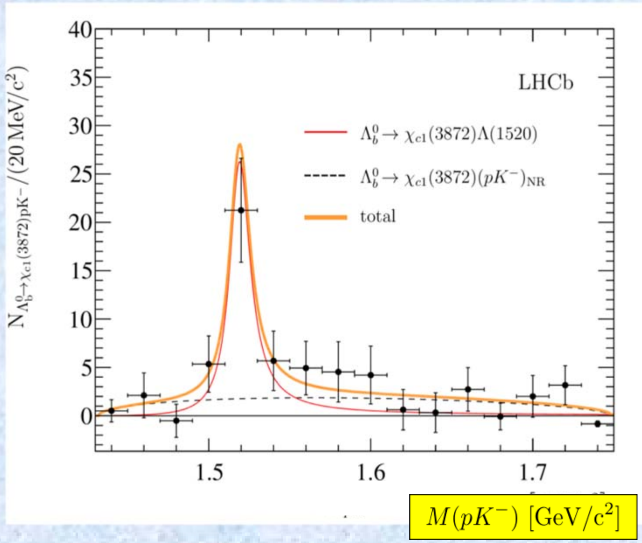




Fit to $J/\psi\pi^+\pi^-pK^-$ and $J/\psi\pi^+\pi^-$ mass spectra:
the signal of 55±11 events; 7.2σ

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

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



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

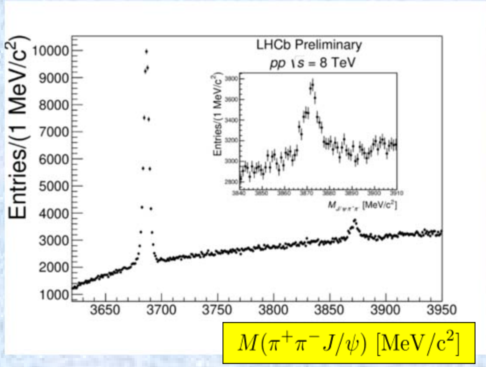
$$\Lambda_b^0 \to \chi_{c1}(3872)\Lambda^0(1520)(\to pK^-)$$

Multiplicity Dependence $\chi_{c1}(3872)$ and $\psi(2S)$ Production

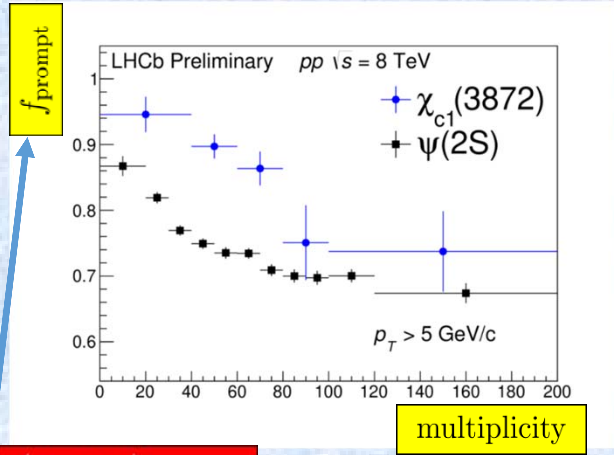
10. The relative production of $\chi_{c1}(3872)$ and $\psi(2S)$ vs particle multiplicity

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

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



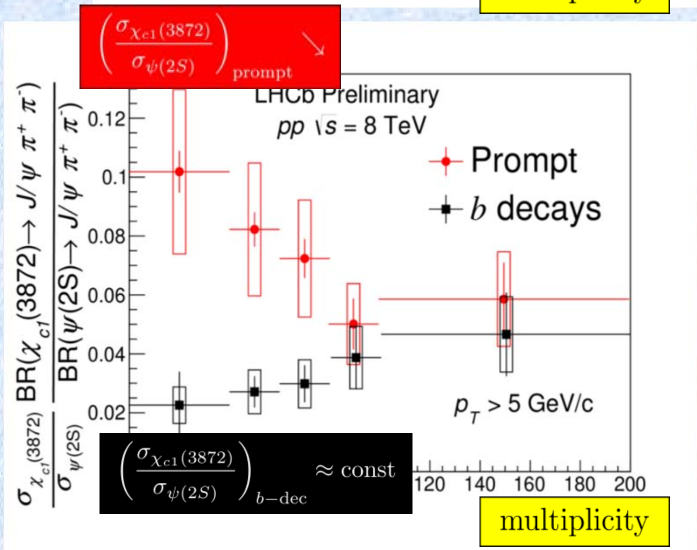
$f_{\text{prompt}}=$ the fraction of $\chi_{c1}(3872)$ and $\psi(2S)$ that are produced promptly



❑ **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

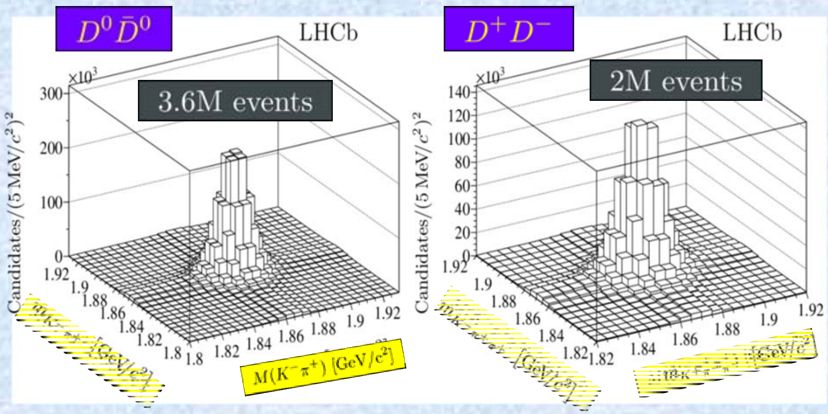


Interpretation: **X(3872) is likely a mixture of a $\chi_{c1}(2^3P_{1++})$ charmonium and of $D^0\bar{D}^{0*}$ molecule**
Molecule: properties 1, 2, 3, 4a, 5 (→ only a small admixture of $D^+\bar{D}^{+*}$, compare with $D^0\bar{D}^{0*}$), 6 and 10
Charmonium: radiative decays (4b*), 7 and observation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

New Charmonium State X(3842) in D$\bar{D}$

- **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:**
   $X(3872) \equiv \chi_{c1} \to D^{*0}\bar{D}^0,\ D^{*0} \to D^0\pi^0$ or $D^{*0} \to D^0\gamma$
2. **A broad maximum:** $\psi(3770) \to D\bar{D}$ - the 1st observation of hadroproduction of $\psi(3770)$

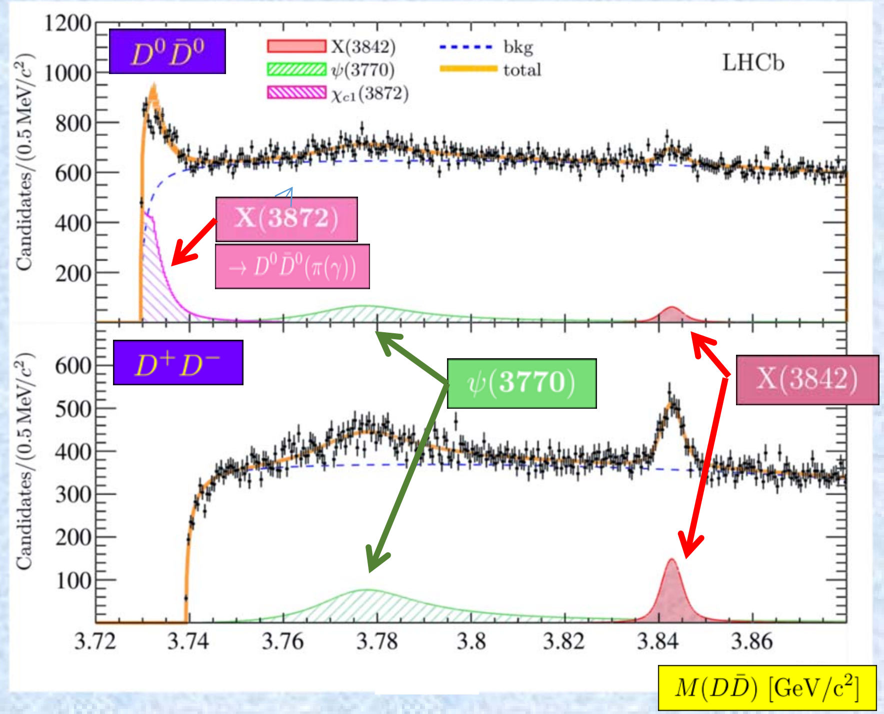
   $$M_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6\ \text{MeV}/c^2$$

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 $J^P = 3^{--}$



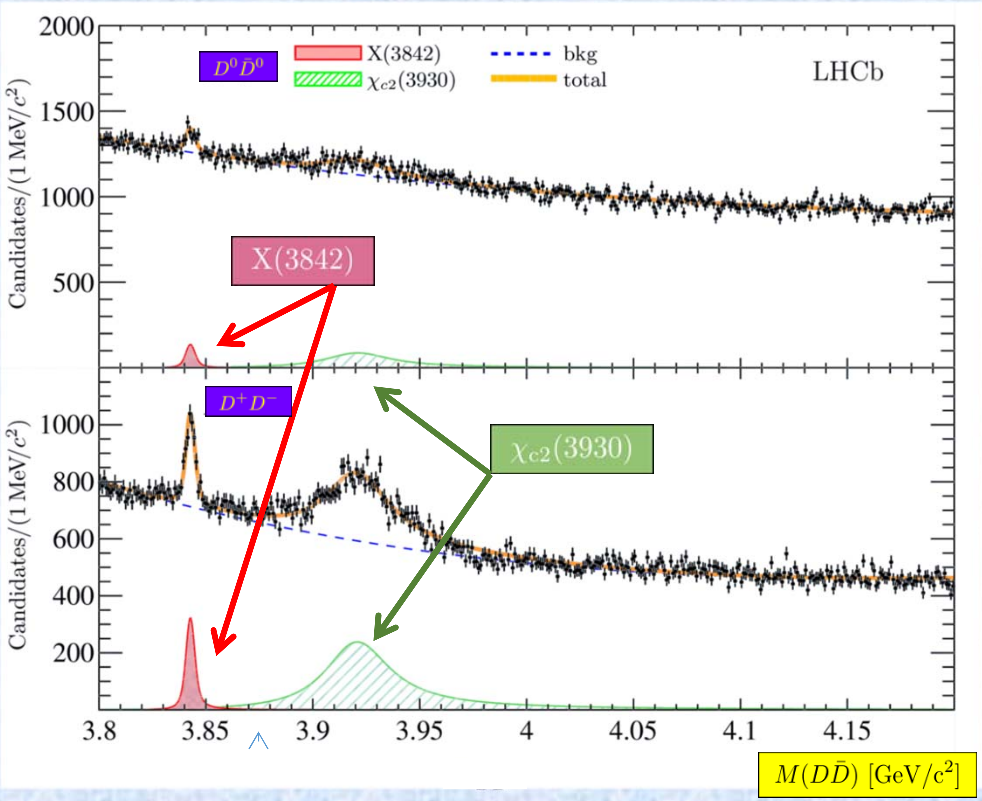
New Charmonium State X(3842) in $D\bar{D}$

4. A wide structure, mostly in the D^+D^- mass spectrum at ≈3920 MeV/c², interpreted as:

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

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

$$\Gamma_{\chi_{c2}(3920)} = 36.6 \pm 1.9 \pm 0.9\ \mathrm{MeV/c^2}$$



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

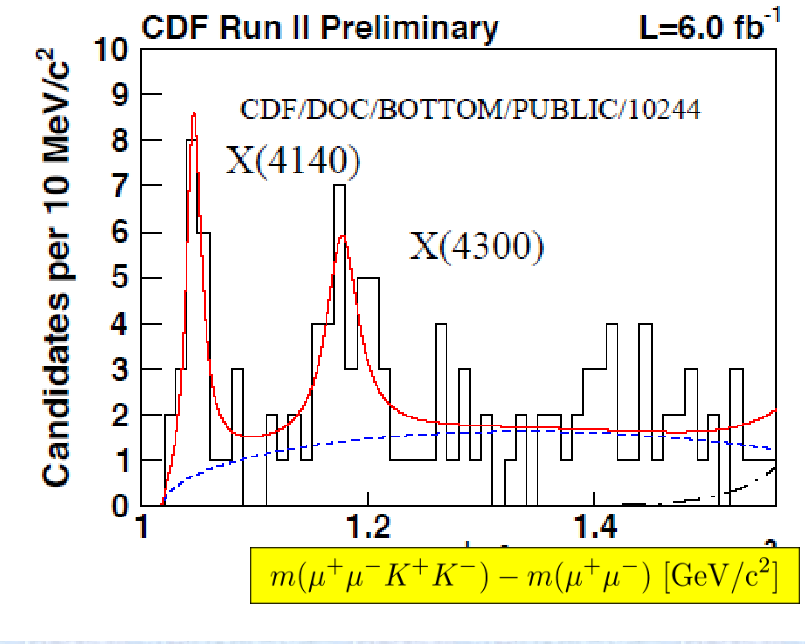
The Puzzling States X → J/ψϕ

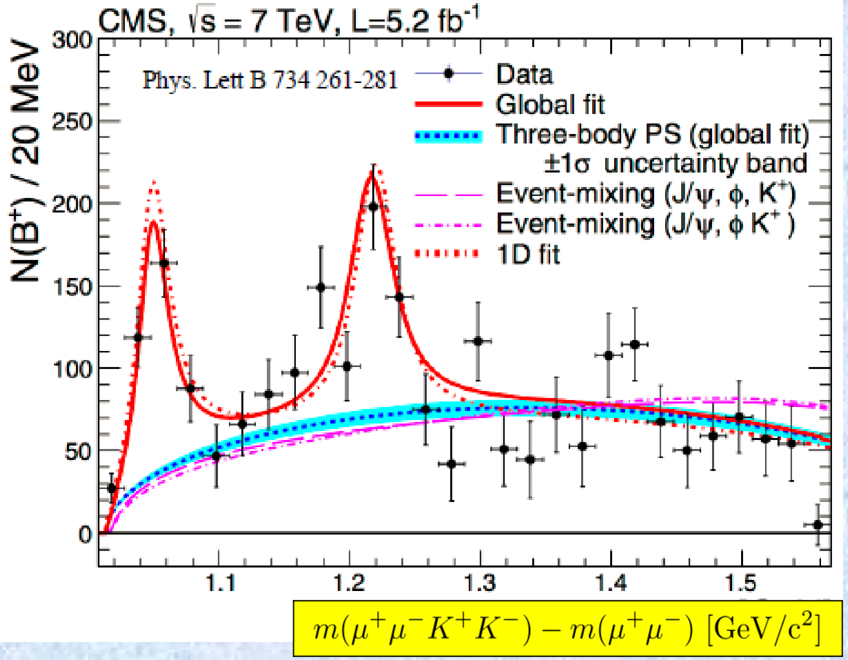
- **X(4140)** - evidence for a narrow near threshold structure in $B^+ \to (J/\psi\ \phi)\ K^+$ decays: CDF, D0, CMS
- **X(4274)** – the second relatively narrow [J/ψ ϕ] state – evidence from CDF and CMS

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

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

CMS:
PL 734 (2014) 261





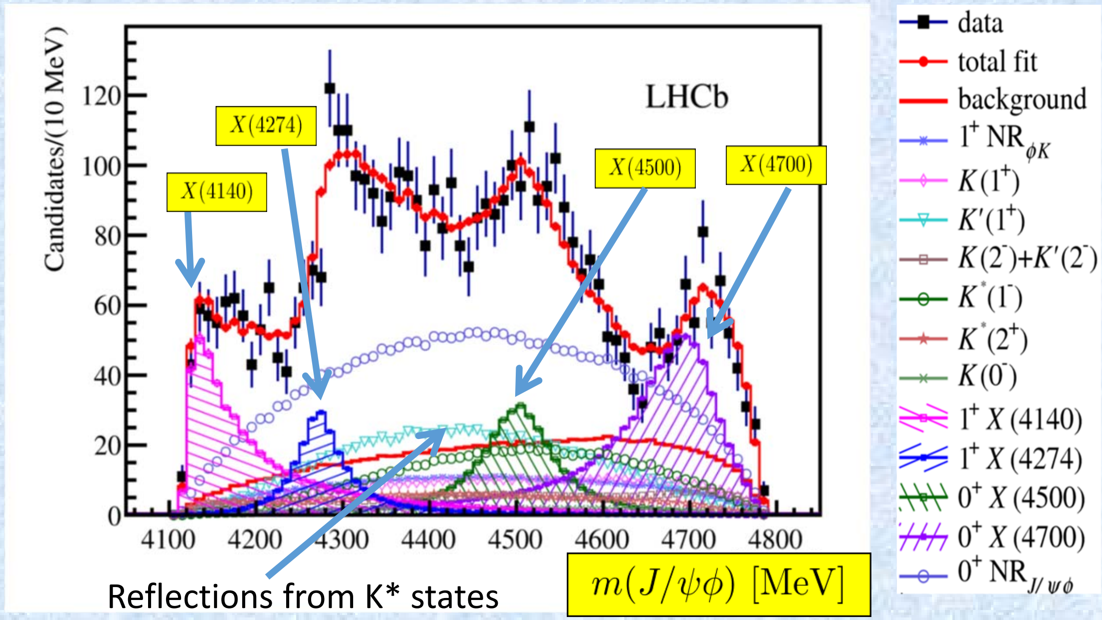
- **Negative results from B-factories**

The Puzzling States X → J/ψϕ

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

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

- 4289+-151 candidates; nearly background free
- 6D phase space composed of m(ϕK), helicity angles and Δϕ angles
- The amplitude analysis aimed to resolve K*→ K ϕ from the potential X→ J/ψ ϕ resonances
- **The model with excited K*s (→ Kϕ) 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)



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

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

- 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

Controversy About the Tetraquark X(5568)

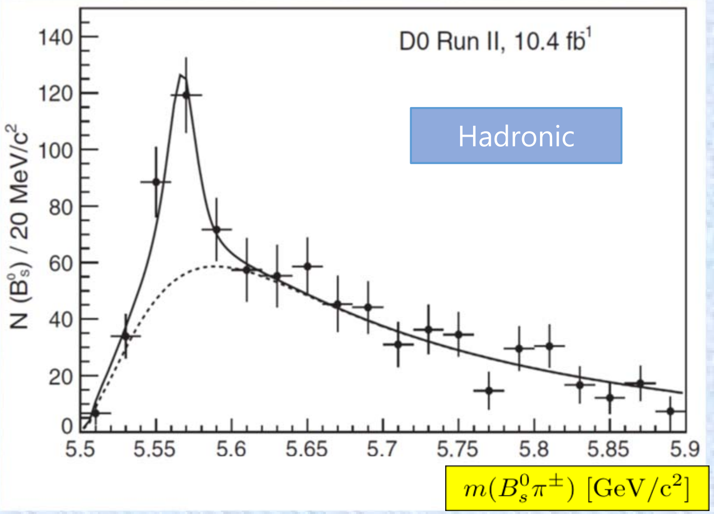
- **D0 (2016): reports a narrow structure X(5568) in the B_s^0 π^+ spectrum** $X^{\pm}(5568) \to B_s^0 \pi^{\pm}$

PRL 117 (2016) 022003 $B_s^0 \to J/\psi \phi$

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

- The ratio of yields: X(5568) w.r.t. B_s $\rho_X = \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0 \pi^{\pm})}{\sigma(pp \to B_s^0 + \text{anything})}$

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



- **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) ?

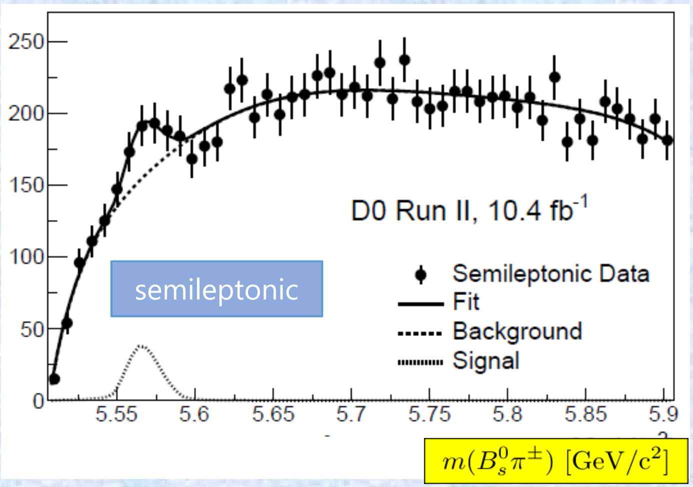
- **D0 (2017): the second evidence for the state X(5568) in the decay** $X^{\pm}(5568) \to B_s^0 \pi^{\pm}$

$$B_s^0 \to \mu^{\mp} D_s^{\pm} X, D_s^{\pm} \to \psi \pi^{\pm}$$

- **Combining hadronic and semileptonic data:**

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

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



Controversy About the Tetraquark X(5568)

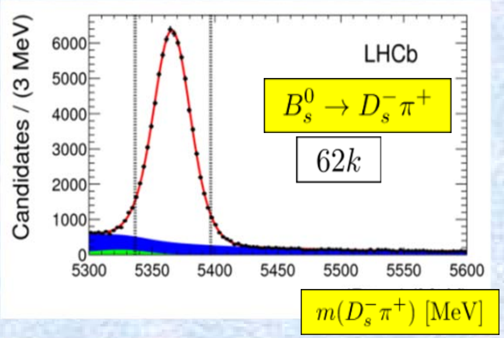
➢ **LHCb (2016):** 20x more D_s than D0 collab. - lack of observation of any X(5568)-like signal

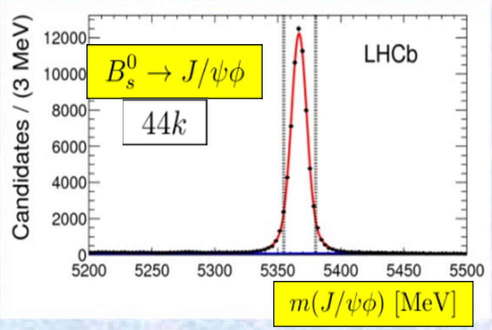
PRL 117 (2016) 152003

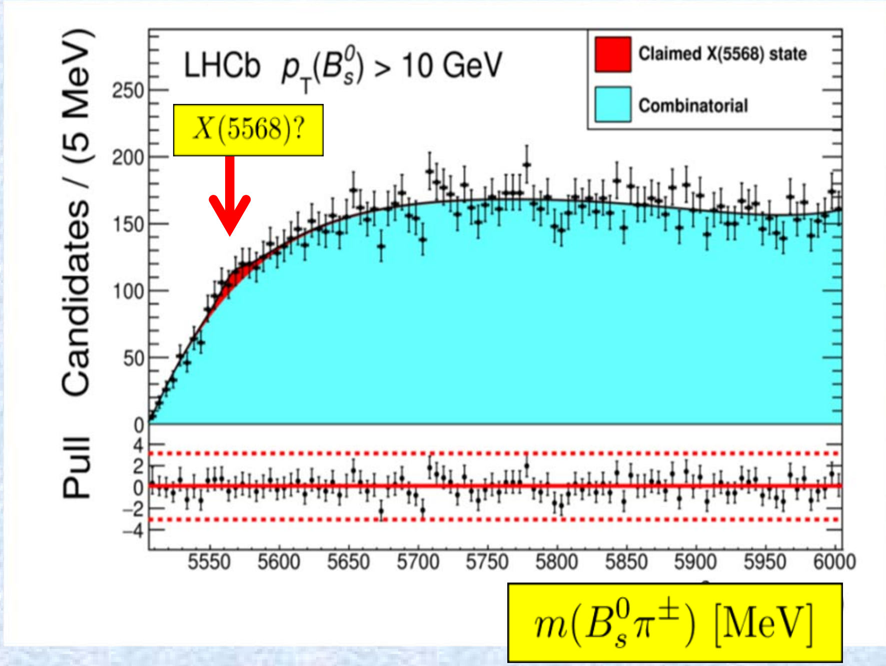
$3fb^{-1}$

$\rho_X < 2\ \%$

(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.)

Charged Exotic State $Z_c(4430)^-$

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

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

PRL 100 (2008) 142001 | PR D80 (2009) 031104 | PR D88 (2013) 074026

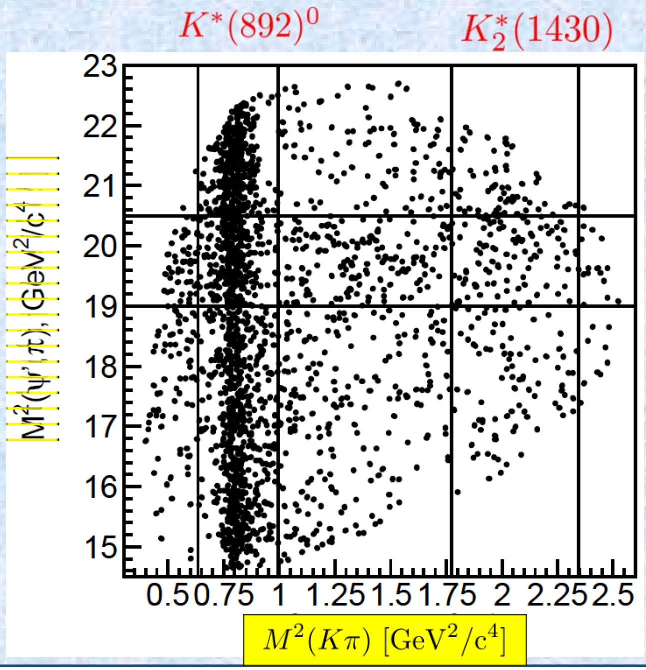
$\Gamma_{Z_c(4430)^-} = 200^{+41+26}_{-46-35}\ \mathrm{MeV/c^2}$

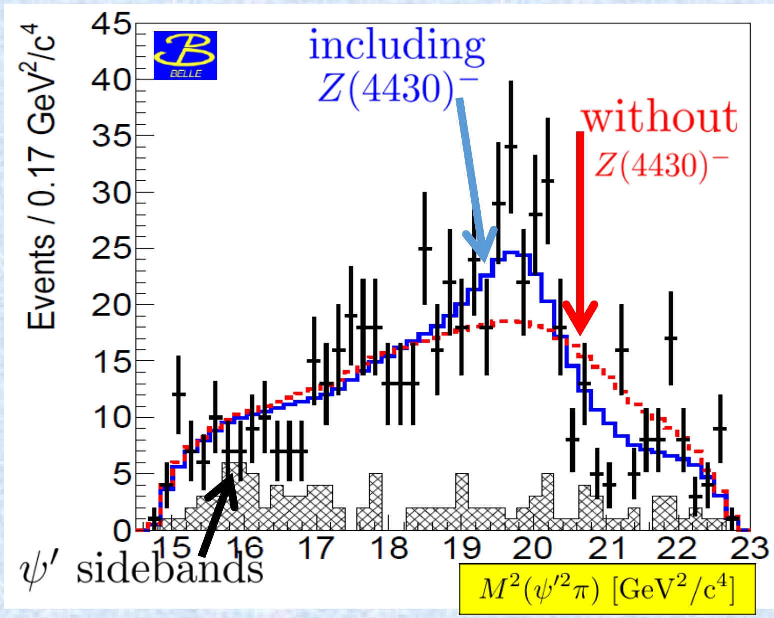
$\mathcal{B}(B^0 \to Z_c(4430)^-(\to \psi'\pi^-)K^+) = (6.0^{+1.7+2.5}_{-2.0-1.4}) \times 10^{-5}$

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

- 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

Charged Exotic State $Z_c(4430)^-$

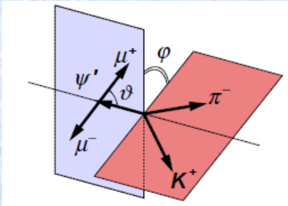
➤ **LHCb (2014-15): tenfold increase in the signal yield** (25 000 decays; Run1 3fb^{-1}); **two approaches:**

4D amplitude analysis

PRL 112 (2014) 222002

- The variables:

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

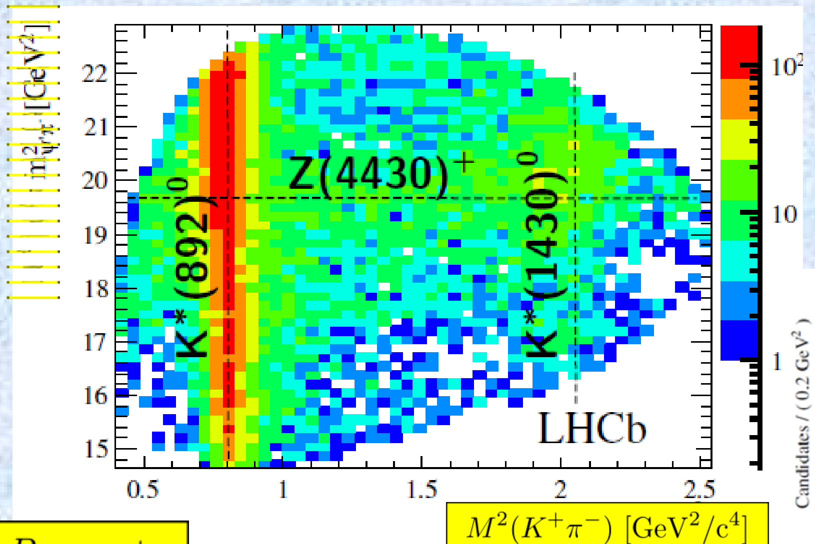


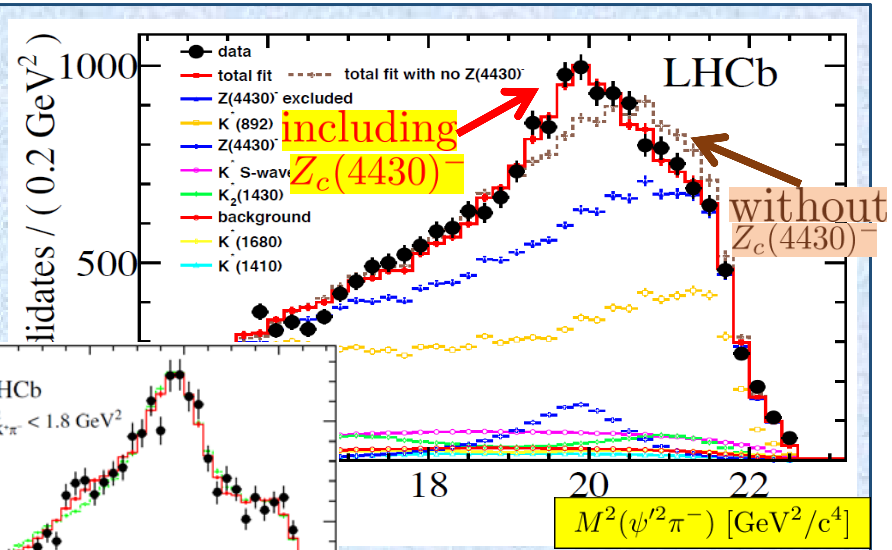
Model independent approach:

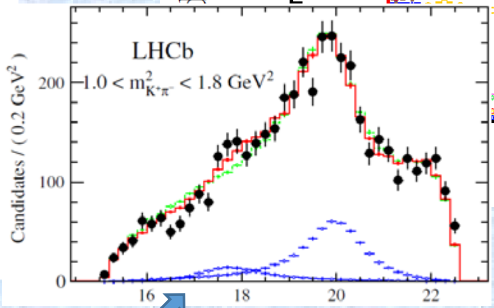
PRD 92 (2015) 112009

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

4D amplitude analysis cont







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

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

$J^P = 1^+$

Assignment fully established

relative to:

J^P	0^-	1^-	2^+	2^-
sign. [σ]	9.7	15.8	16.1	14.6

The second state (Z_0^-) ?

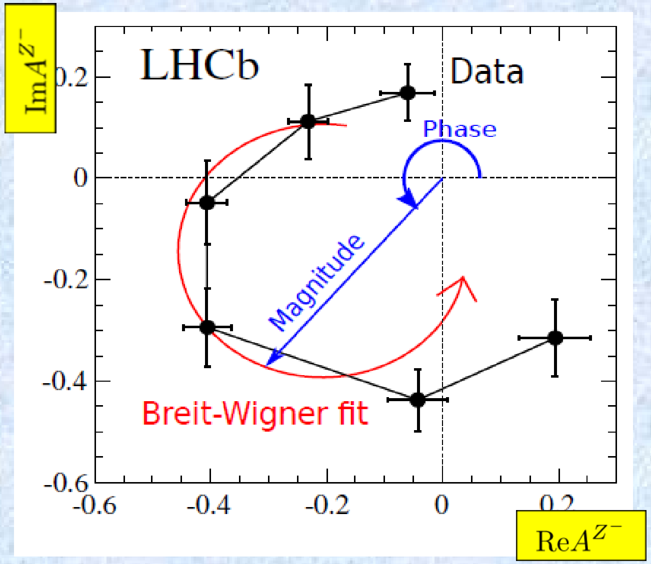
$J^P = 0^-$ | $M(Z_0^-) = 4239 \pm 18^{+45}_{-10}$ MeV/c^2 | $\Gamma(Z_c(4430)^-) = 220 \pm 47^{+108}_{-74}$ MeV/c^2 | 6σ

Charged Exotic State $Z_c(4430)^-$

4D amplitude analysis cont

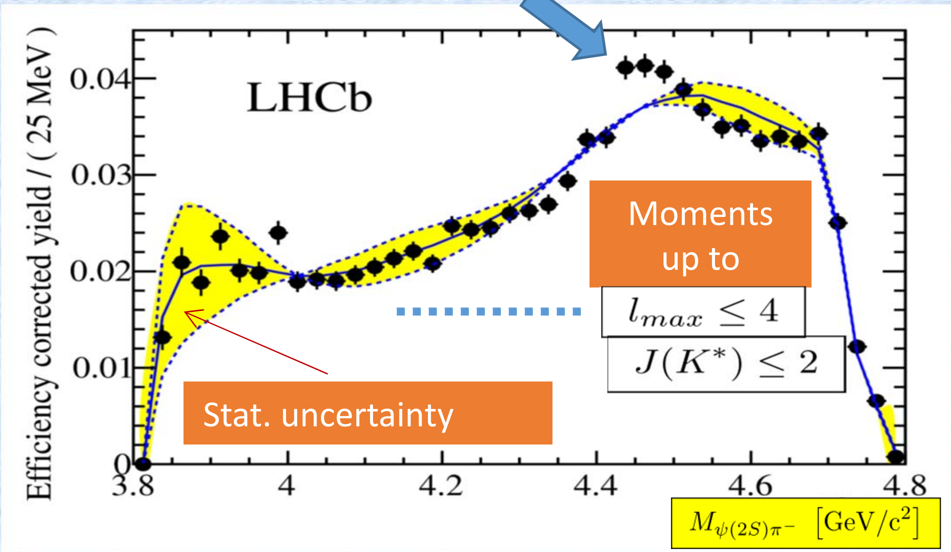
Argand plot: clear resonant behavior

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



Model independent approach:

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



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

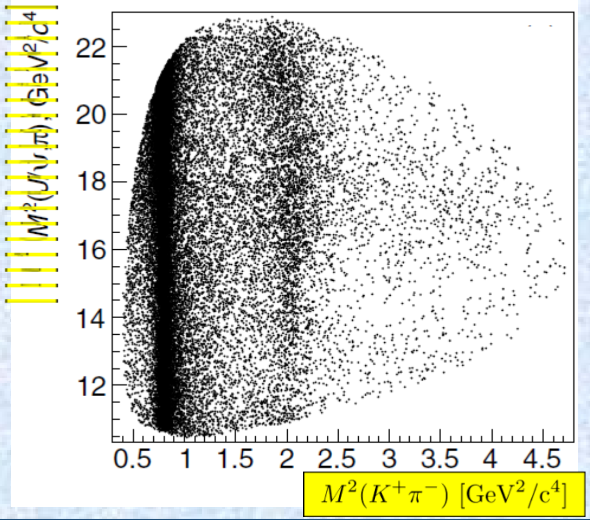
$Z_c(4200)^-$ in $B^0 \to J/\psi\, \pi^- K^+$ Decays

- **Belle (2014): the 1st evidence for $Z_c(4200)^-$ in $J/\psi\pi$ mass distribution** (~3×10^4 $B^0 \to J/\psi\pi^- K^+$ decays)
  In addition, the first evidence for $Z_c(4430)^- \to J/\psi\pi^-$

PR D90 (2014) 112009

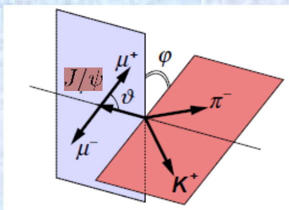
- $M_{Z_c(4200)^-} = 4196^{+31+17}_{-29-13}\ \mathrm{MeV/c^2}$

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

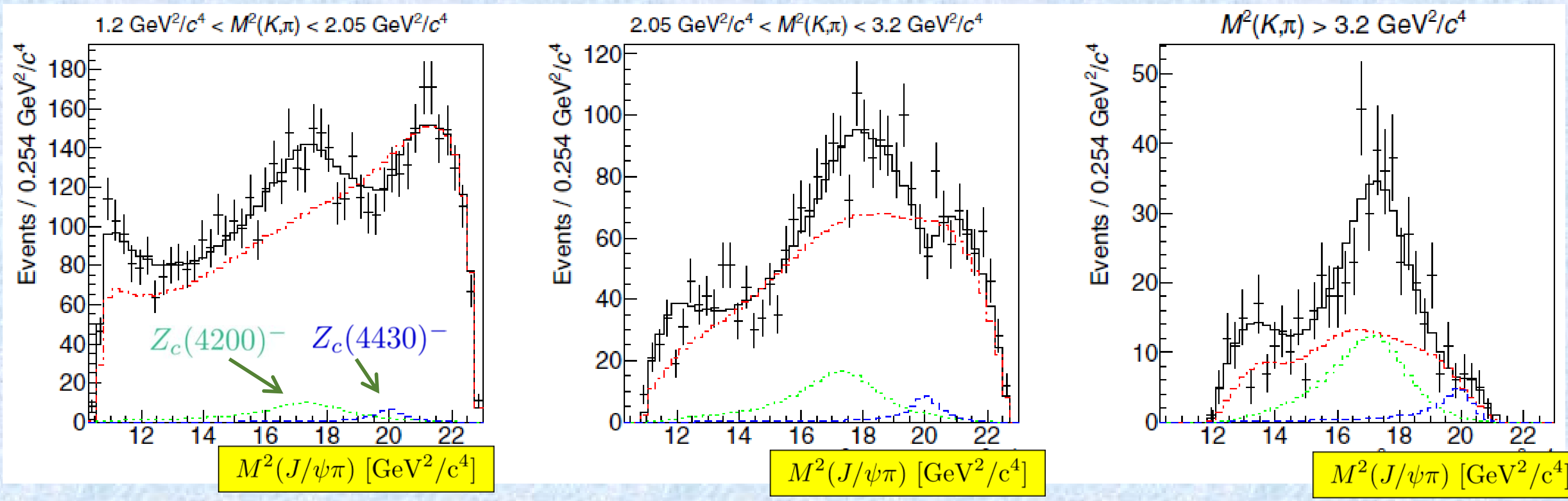


- **4D amplitude analysis** with the set of variables:

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



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



$Z_c(4200)^-$ in $B^0 \rightarrow J/\psi\, \pi^- K^+$ Decays

➢ **LHCb (2019): twentyfold increase in the signal yield** (~5.5x10^5 $B^0 \rightarrow J/\psi \pi^- K^+$ decays, Run1 3fb^{-1})

- The decay $B^0 \rightarrow J/\psi \pi^- K^+$ is known to be dominated by K^*_J 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

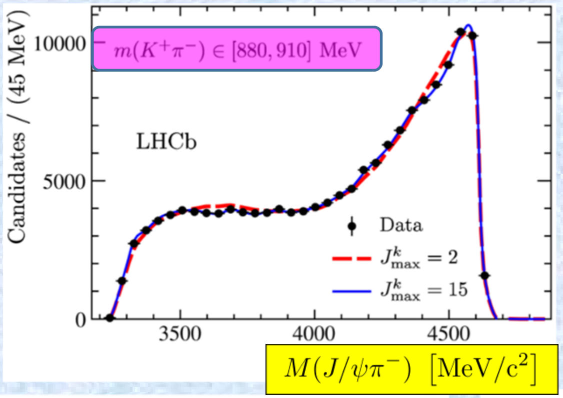
- **Model independent approach** – no information about the exact content of the K^*_J states is needed

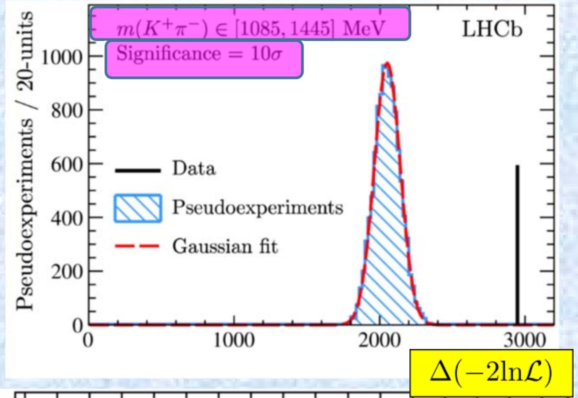
➢ 4D study ($M(K^+\pi^-)$, $\cos\theta_{K^*}$, $\cos\theta_l$, ϕ))

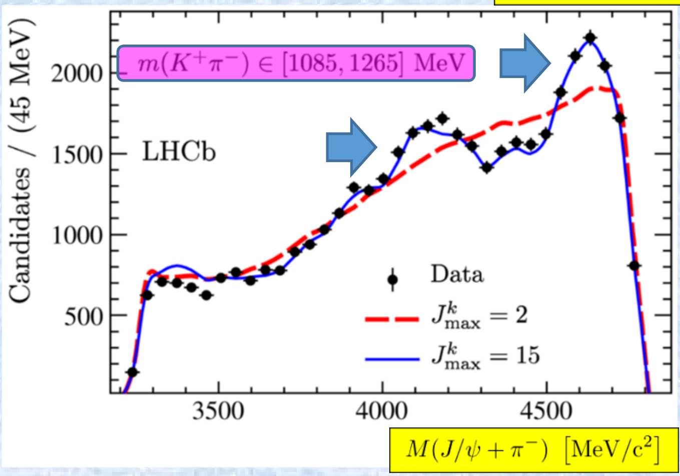
➢ **Data inconsistent with K^*_J reflections only at 10σ level**

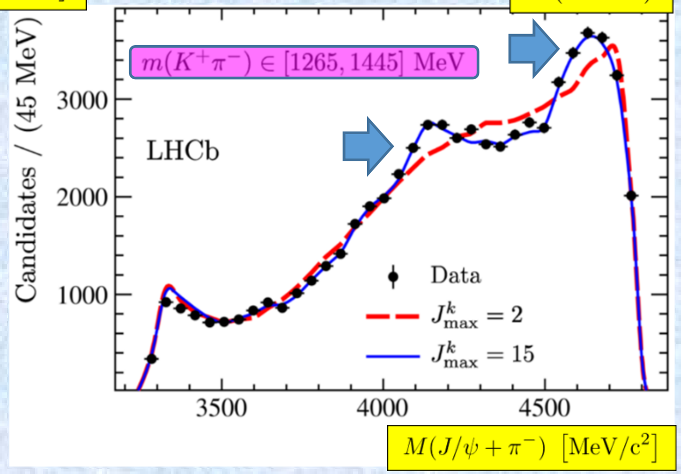
➢ Unphysical $J^k_{max} = 15$ states are needed to describe the data

Confirmation of the presence of exotic contribution









LHCb:

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

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

➤ **LHCb (2018): Dalitz plot analysis of** $B^0 \to \eta_c(1S)(\to p\bar{p})K^+\pi^-$ **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**

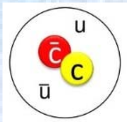
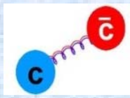


Image from Godfrey & Olsen, Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

➡ expectation of a new charmonium-like state with a mass of ~3800 MeV/c^2, decaying into $\eta_c\pi^-$

✓ **Quarkonium hybrid**

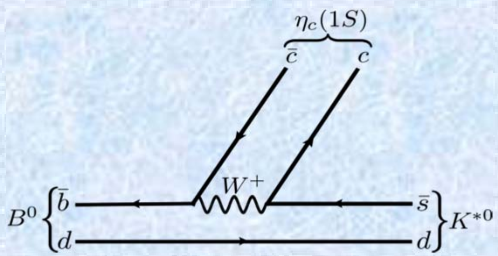


(with the valence gluon replaced by I=1 excitation of the gluon and light quarks)

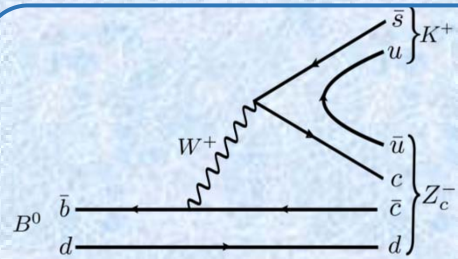
➡ expectation of several charmonium tetraquarks in the mass range (3800,4500) MeV/c^2, decaying into $\eta_c\pi^-$

✓ **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 $\eta_c\pi^-$

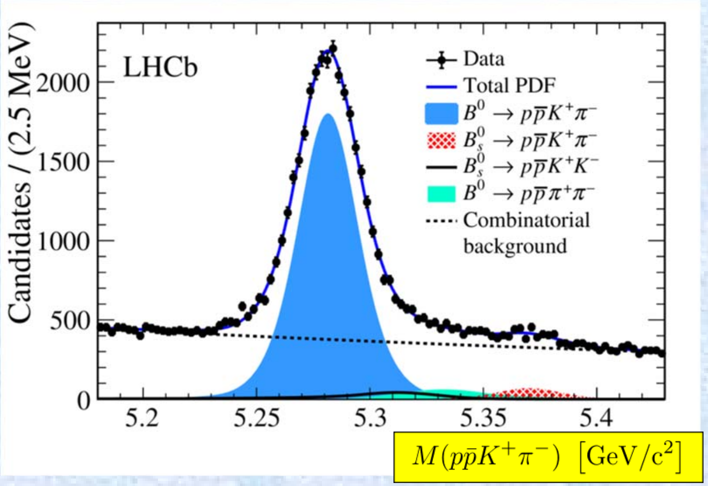


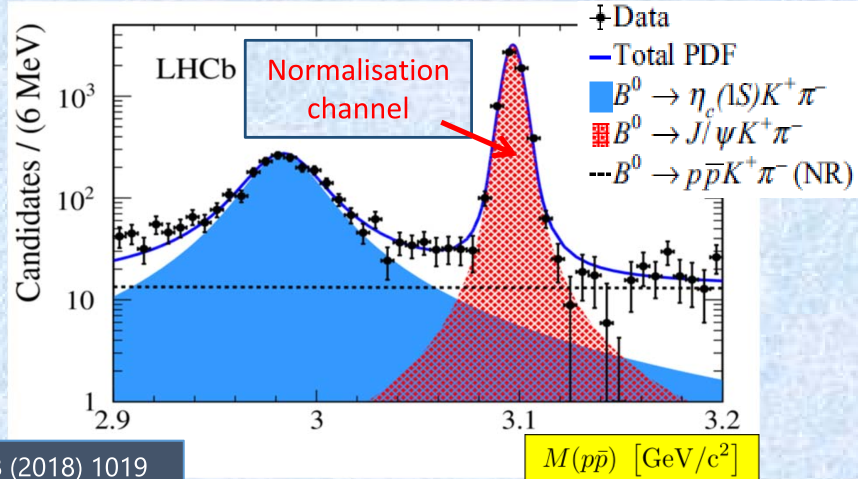
„Standard" K^*_J resonances dominate the decay $B^0 \to \eta_c(1S)K^+\pi^-$



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

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





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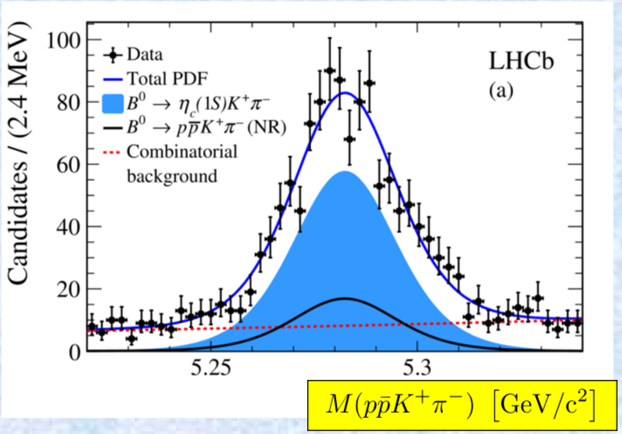
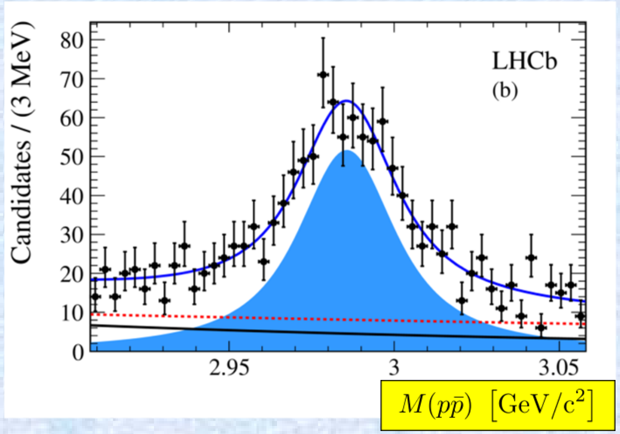
$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.73 \pm 0.24(\text{stat}) \pm 0.13(\text{syst}) \pm 0.66(\mathcal{B})) \times 10^{-4}$ - the first measurement

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





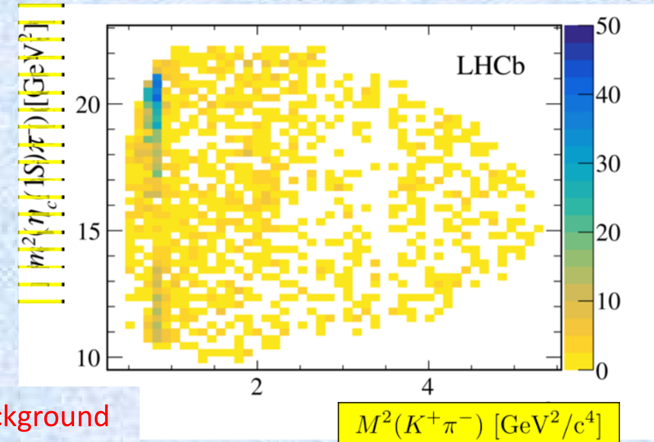
(plots for Run1 data)

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

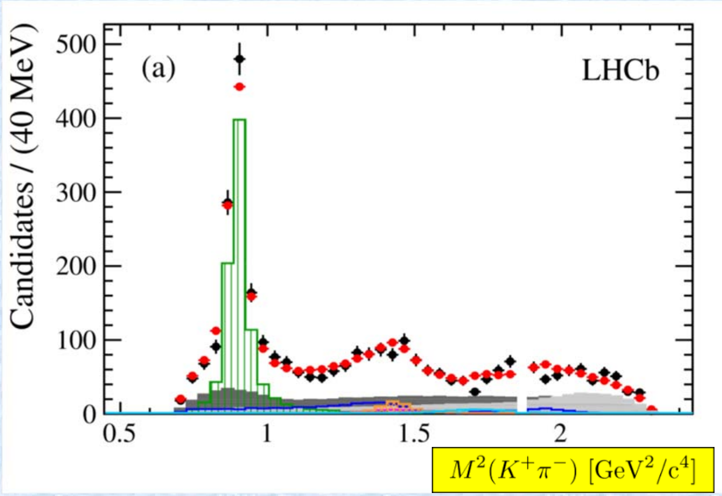
$Z_c(4100)^-$ in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ Decays

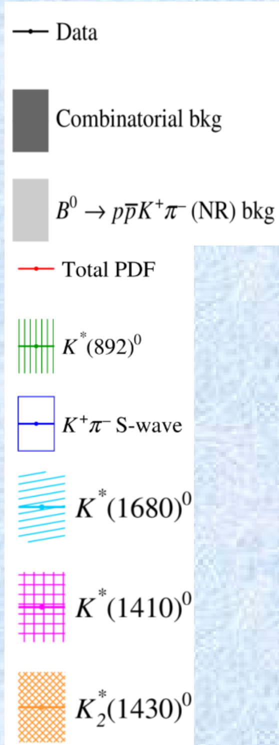
➢ **Dalitz plot analysis: baseline fit – only K^*_J contributions**

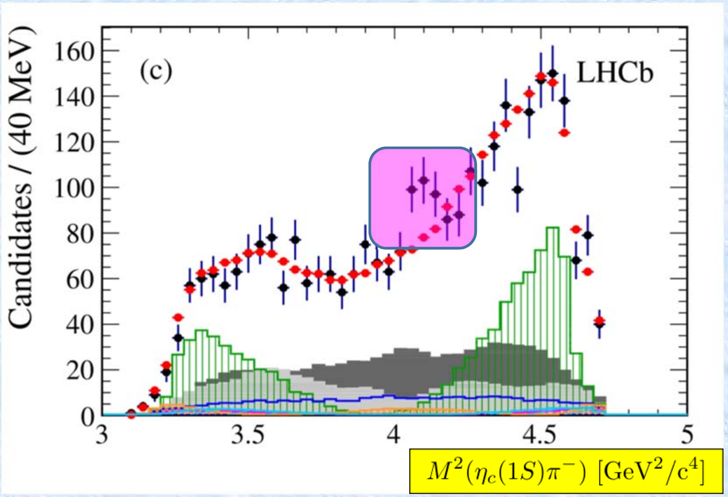
EPJC 78 (2018) 1019

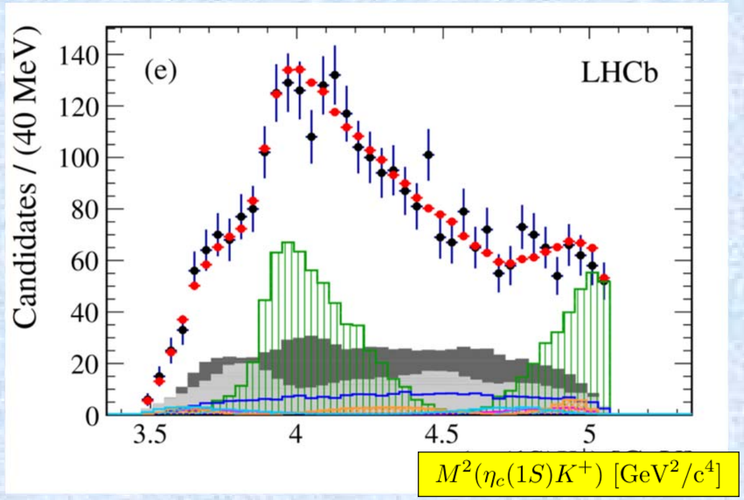


(background subtracted)









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

➢ **Dalitz plot analysis: the fit including an exotic contribution**

EPJC 78 (2018) 1019

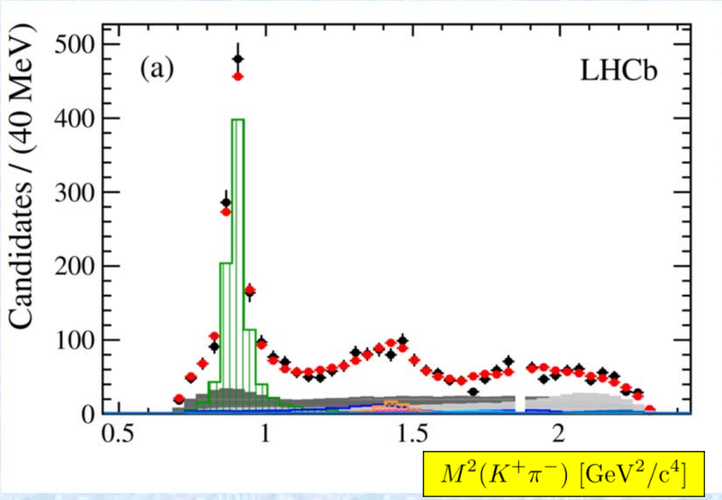
- The addition of a $J^P=1^-$ resonance in $\eta_c\pi^-$ improves the fit by $\Delta(-2\ln\mathcal{L}) = 41.4 \quad (4.8\sigma)$

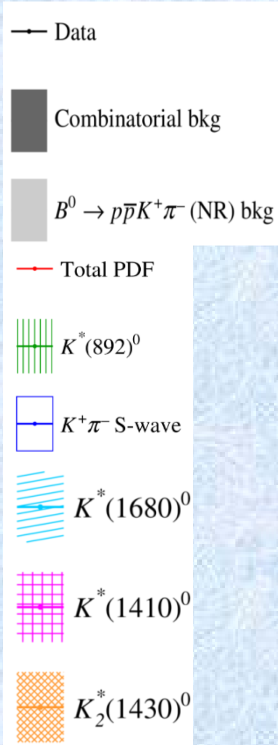
$$M_{Z_c(4100)^-} = 4096 \pm 20^{+18}_{-22}\ \mathrm{MeV/c^2}$$

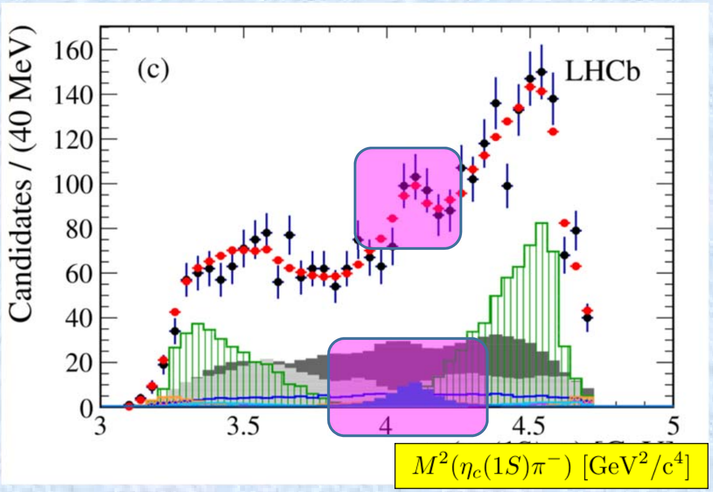
$$\Gamma_{Z_c(4100)^-} = 152 \pm 58^{+60}_{-35}\ \mathrm{MeV/c^2}$$

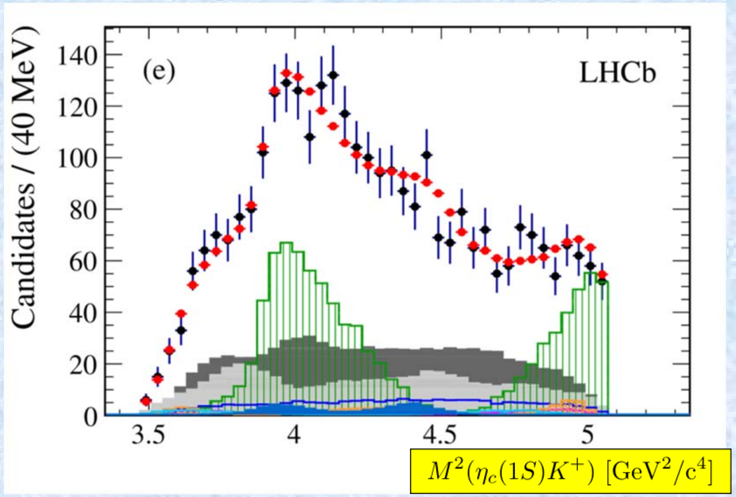
Significance 3.4σ (4.8σ – stat. only)

- **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

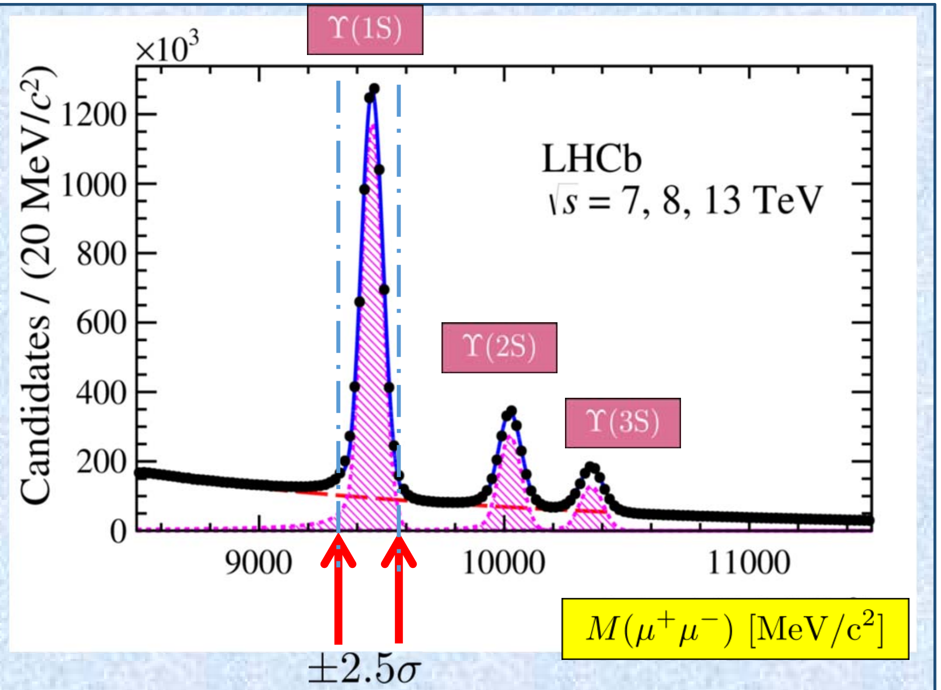
Search for Beautiful Tetraquarks

- 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] GeV/c^2, close but below the $\eta_b\eta_b$ threshold (18.798±0.005) GeV/c^2
  - ➔ The expected, experimentally favorable, decay mode: $X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)l^+l^-, \quad (l = e, \mu)$
  - Lattice QCD calculations: no indication for the X state in the hadron spectrum

LHCb(2018): JHEP 10 (2018) 086

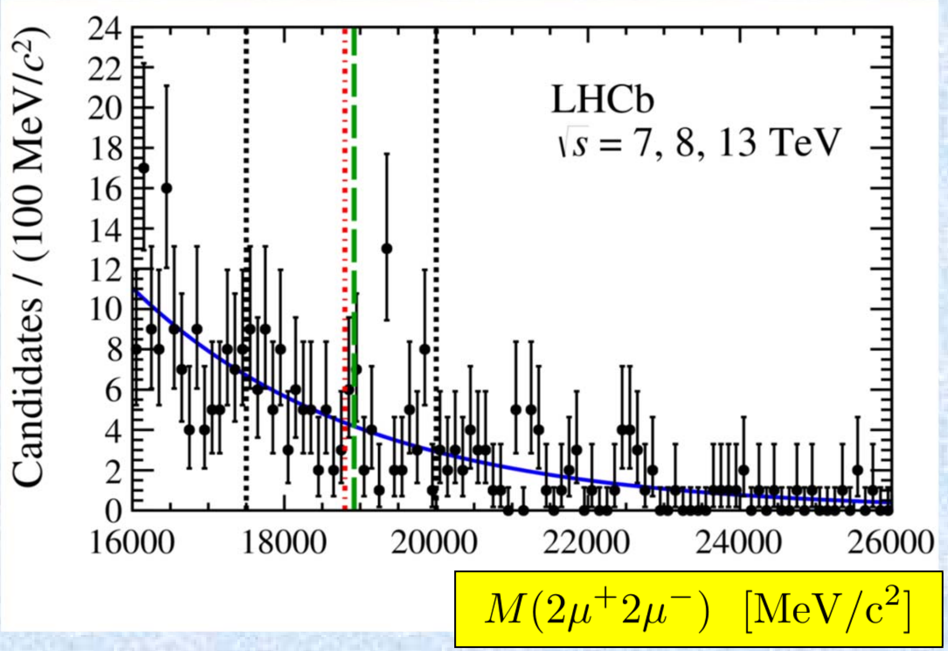
- 6.3 fb^{-1} of data recorded between 2011 and 2017
- the search for the X state decaying to $\Upsilon(1S)(\to \mu^+\mu^-)\mu^+\mu^-$
- the normalization decay channel: $\Upsilon(1S) \to \mu^+\mu^-$

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

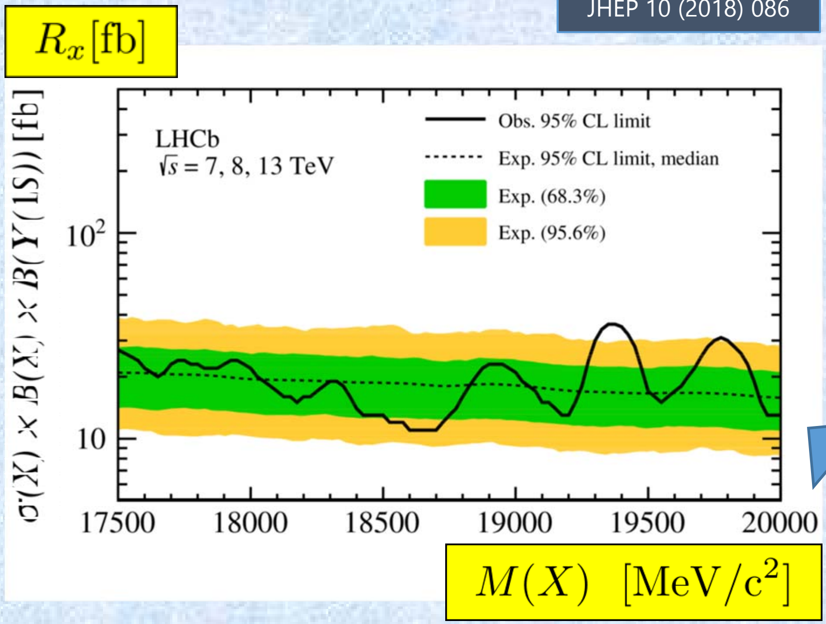


Search for Beautiful Tetraquarks

- 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: $M(\mu^+\mu^-) \notin [3050, 3150]$ MeV/c^2



JHEP 10 (2018) 086



- **No significant excess is observed in data in the mass range [17.5, 20] GeV/c^2**
- **An upper limit is set for**

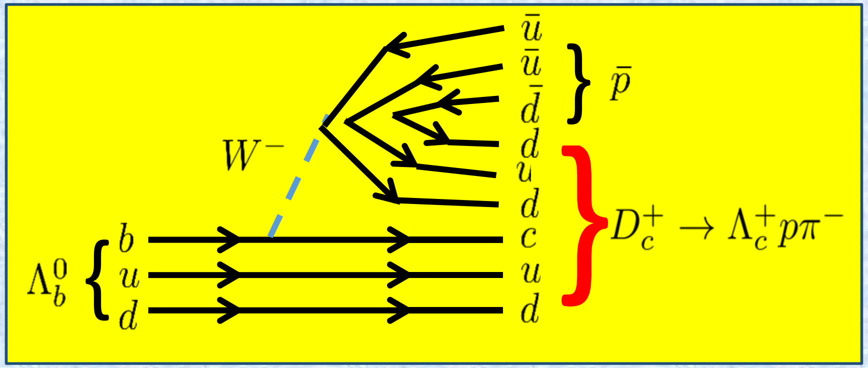
$$R_X = \sigma(pp \to X) \times \mathcal{B}(X \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$$

Search for Dibaryon States in $\Lambda_b \to \Lambda_c^+ p \bar{p} \pi^-$

- **LHCb (2018): search for the dibaryon states in** $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-(\Lambda_c^+ \to pK^-\pi^+)$ PL B784 (2018) 101

Run1 3 fb^{-1}

- Motivated by the paper by L.Maiani, A.D.Polosa and V.Riquer PL B750 (2015) 37
- **The lightest charmed dibaryon D_c^+** (quark content [cd][ud][ud]) with the mass below 4682 MeV/c^2 is expected to participate in the decay $\Lambda_b^0 \to D_c^+ \bar{p}$:



- Two options for the subsequent decays of the D_c :

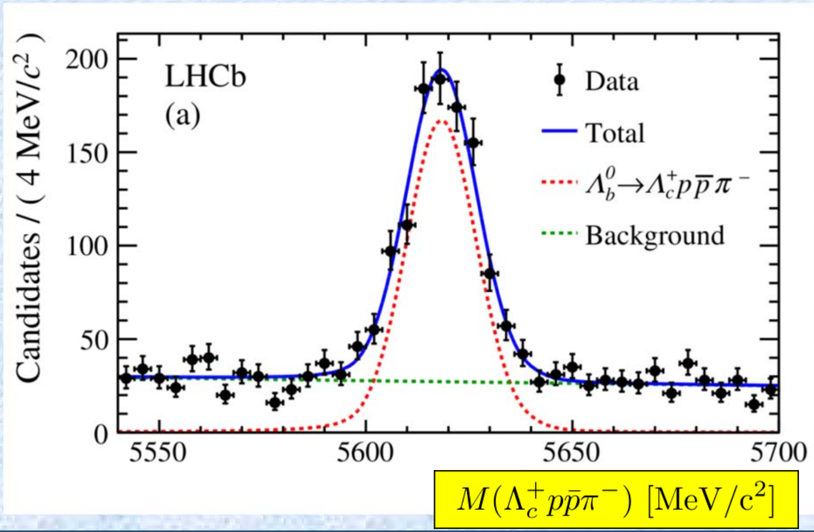
$$D_c^+ \to p\Sigma_c^0, \quad \Sigma_c^0 \to \Lambda_c^+\pi^-$$
$$D_c^+ \to pP_c^0, \quad P_c^0 \to \Lambda_c^+\pi^-$$

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

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

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

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



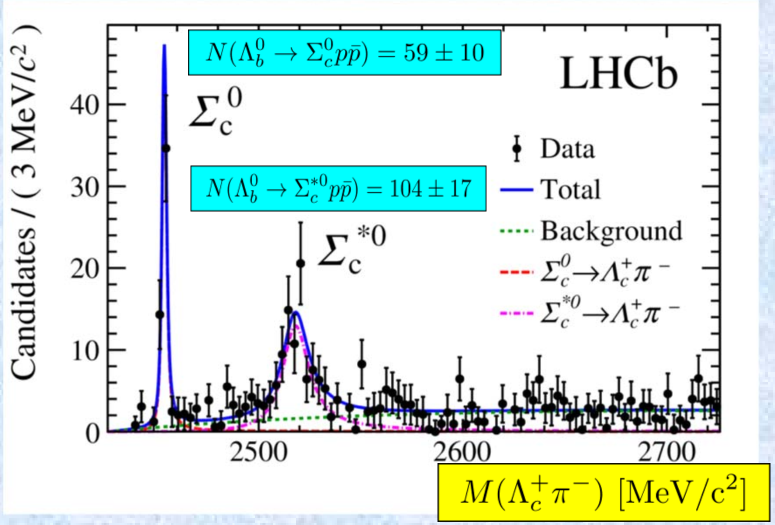
Search for Dibaryon States in $\Lambda_b \rightarrow \Lambda_c^+ p \bar{p} \pi^-$

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

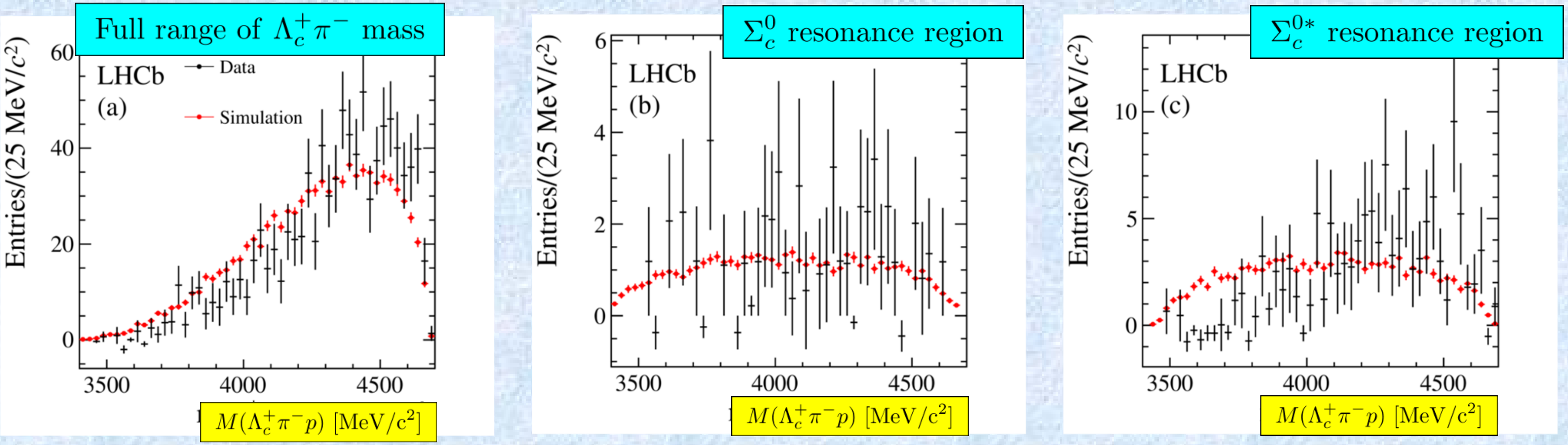
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^0(\to \Lambda_c^+\pi^-)p\bar{p})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.089 \pm 0.015 \pm 0.006$$

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

PL B784 (2018) 101



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

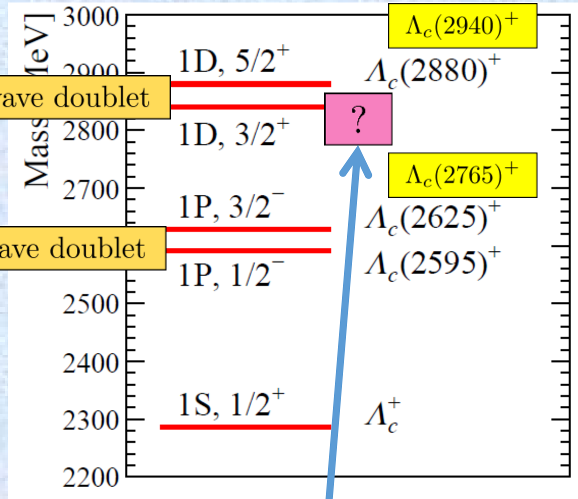


- **No evidence of peaking structures found**

Open-charm Exotic States in Λ_c^+ Excitations ?

➢ **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)

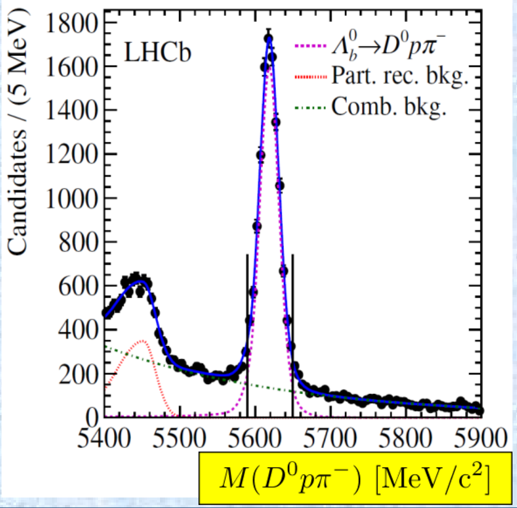


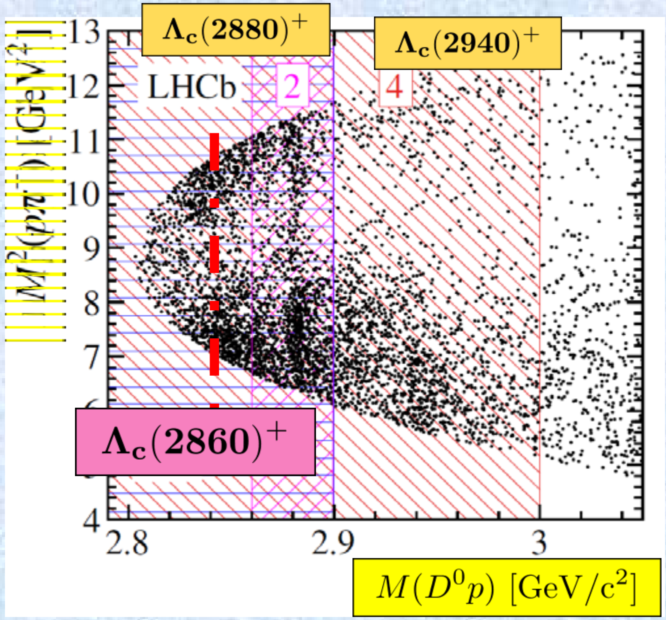
➢ **LHCb (2017)** JHEP 1705 (2017) 030

The first study of excited Λ_c^+ states in exclusive Λ_b decays

$\Lambda_b^0 \to D^0 p\pi^-,\ D^0 \to K^-\pi^+$ (5D amplitude analysis)

11212 ± 126 signal events (16% of background)





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

The first, most likely assignment for the $\Lambda_c(2940)^+$: $J^P = 3/2^-$ → 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

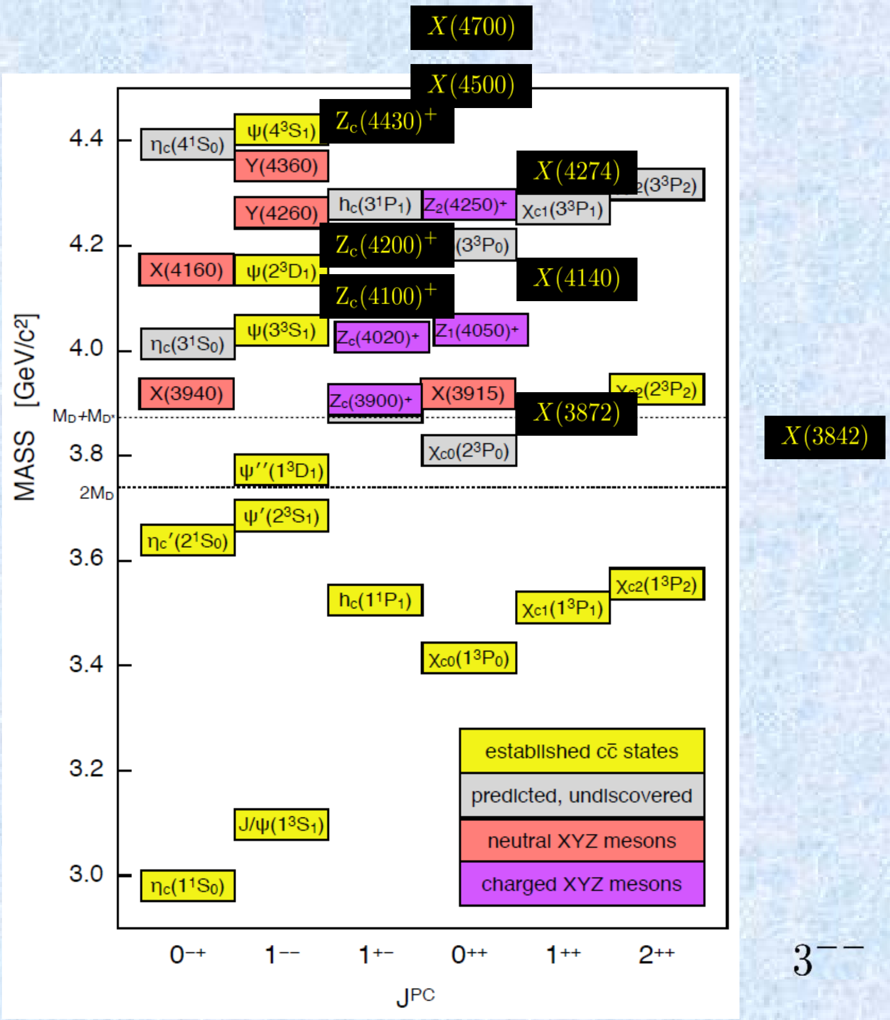
Conclusions

- **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….**



and

$X(5568)$ $\Lambda_c^+(2860)$