XYZ States at LHCb

WPCF2018

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1. LHCb spectrometer - a tool for heavy hadron spectroscopy
2. Standard vs exotic heavy hadron states

3a. Pentaquarks in $\Lambda_b \to J/\psi\, p\, K$ decay: $P_c(4380)$ and $P_c(4450)$
3b. Search for P_c states in $\Lambda_b \to J/\psi\, p\, \pi$ decay
3c. Search for P_c states in $\Lambda_b^0 \to \chi_{c(1,2)}\, p\, K^-$ decays
3d. Observation of $\Xi_b^- \to J/\psi\, \Lambda\, K^-$ Decay
3e. Search for b-flavoured pentaquarks

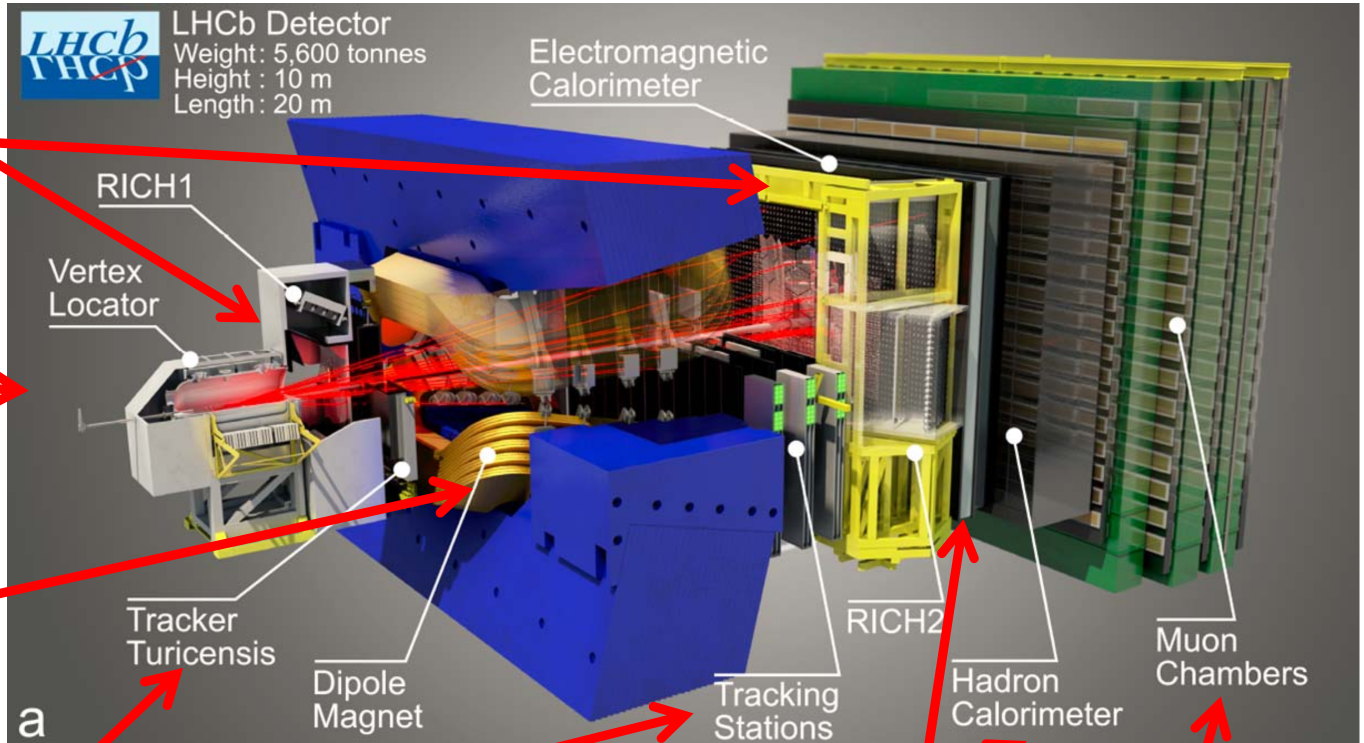
4a. The puzzling states $X \to J/\psi\, \phi$
4b. Tetraquark X(5568) ?

5. Charged Exotic State $Z(4430)^-$

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”

Pros and Cons of Heavy Flavour Spectroscopy with LHCb

+

➢ General advantages (pp interaction):

- **High production cross-sections for HF** (at the LHC are 10^3 larger than at the e^+e^- B factories)
- **Simultaneous accumulation of huge B_d, B_s, B_c and b-baryons data samples**
- **The decay vertices are well separated from the production point** (high boost of the b- and c-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
- LHCb – forward detector ($p >> p_T$): **efficient muon identification for lower P_T values**
- **Space to accomodate excellent RICH detectors** (flavour tagging, background suppression)

-

➢ General drawbacks:

- **The instantaneous luminosity is limited** ($4x10^{32}$ $cm^{-2}s^{-1}$)
- **The efficiencies of γ, π^0 and η reconstruction are much lower** to compare with the e^+e^-

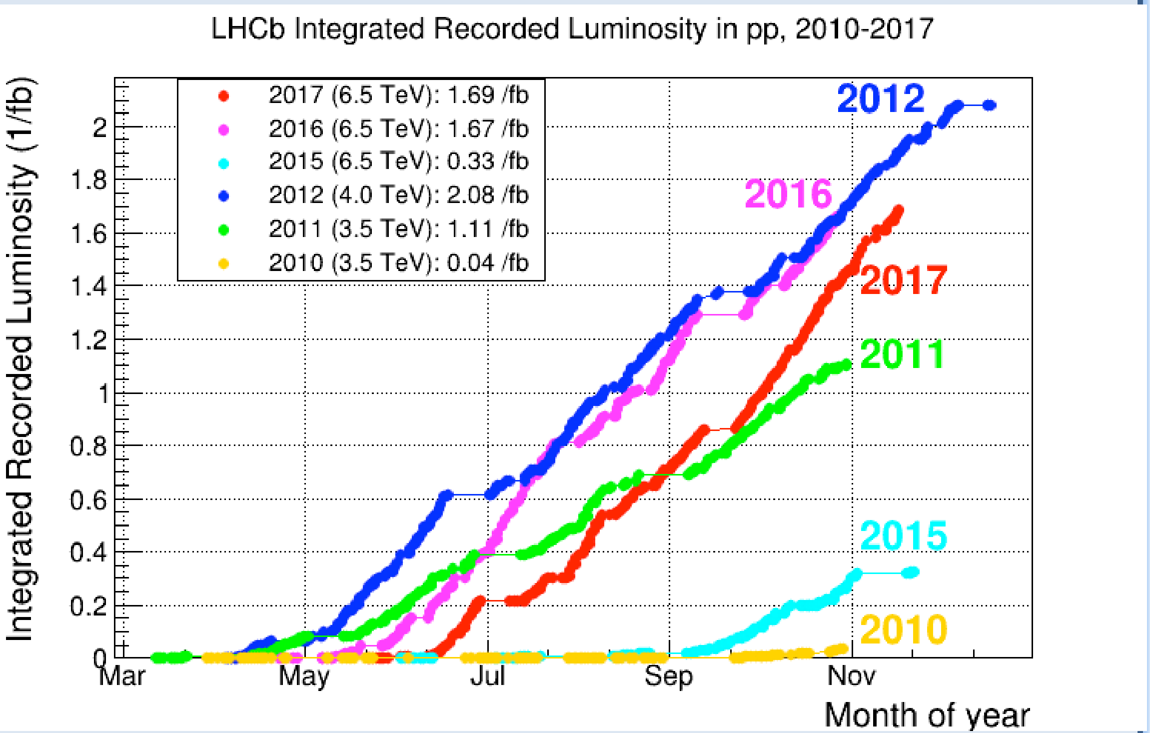
LHCb Data Sample

Run	Years	Lum. $[\text{fb}^{-1}]$	$\sqrt{s}$ [TeV]	$\sigma_{b\bar{b}}$ [μb]	$\sigma_{c\bar{c}}$ [μb]
1	2011-12	3.0	7,8	70	1400
2	2015-17	3.7	13	150	2400

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

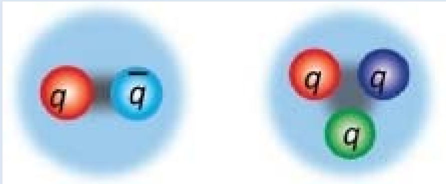
$2 < \eta < 4.5$

- **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**

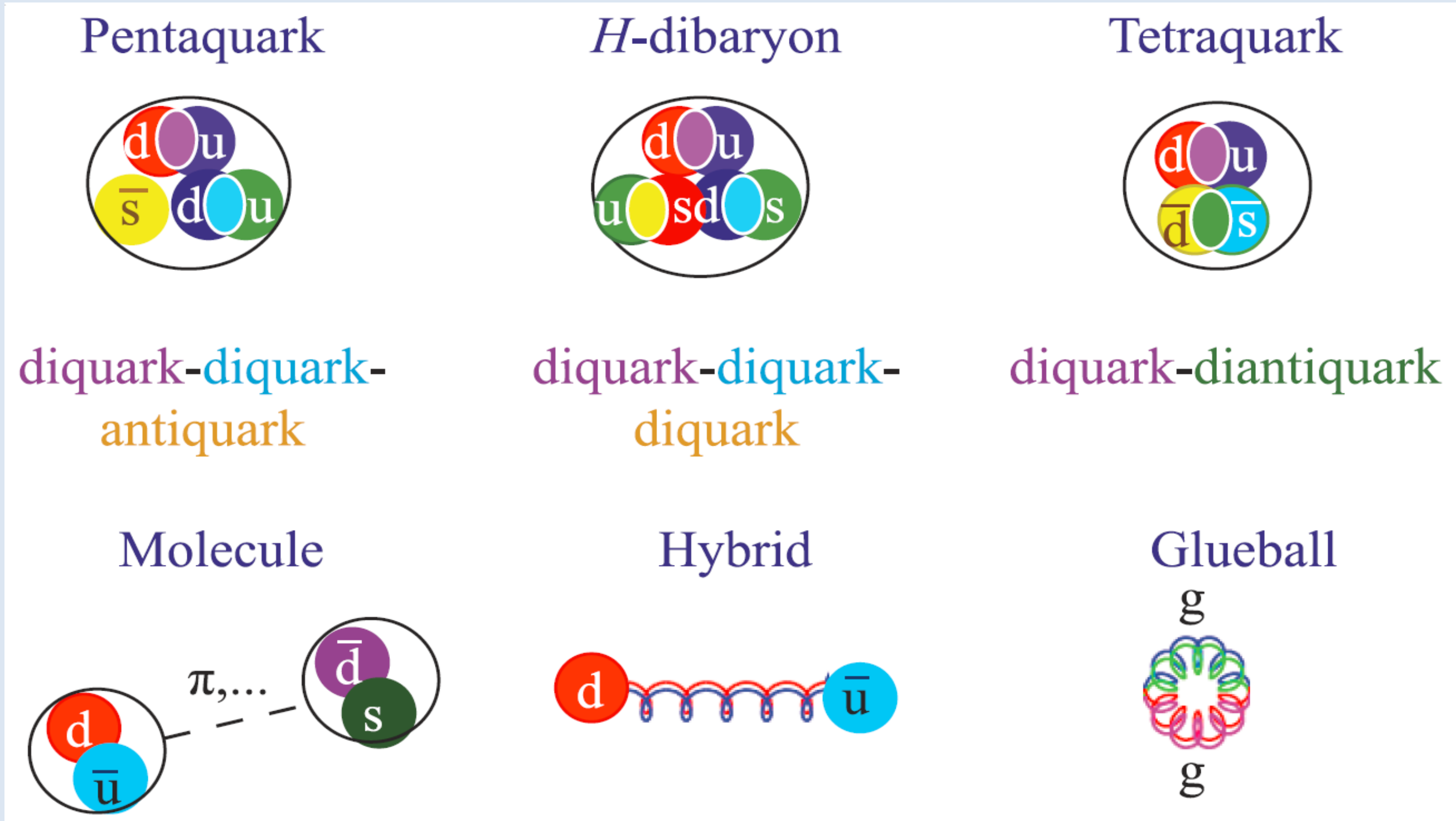


„Standard" vs „Exotic" States

- **Standard states:**



- **Exotic states:**



Front. Phys. **10** 101401

Exotic states (with heavy quarks)

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

- **Quantum numbers:**

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

Unconventional: e.g mesons with 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}

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, Dalitz and Argand plots, amplitude analysis, model independent approach…

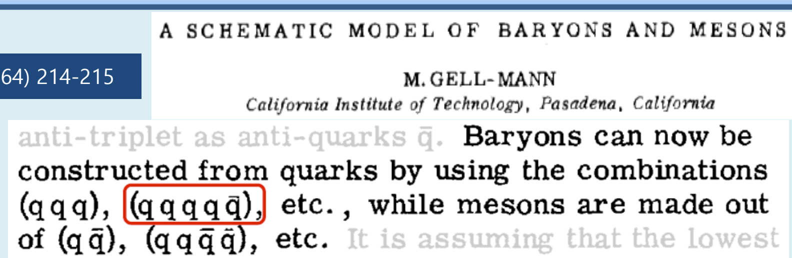
- **Taxonomy** (general, not universally accepted, guidelines):

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)

Pentaquarks in $\Lambda_b^0 \to J/\psi\, p\, K^-$ Decays

- Pentaquarks stay with us from the onset of the quark model...
- Intense experimental searches (rumour about the $\Theta^+(1540)$ state...)

Phys. Lett. 8 (1964) 214-215


A SCHEMATIC MODEL OF BARYONS AND MESONS

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

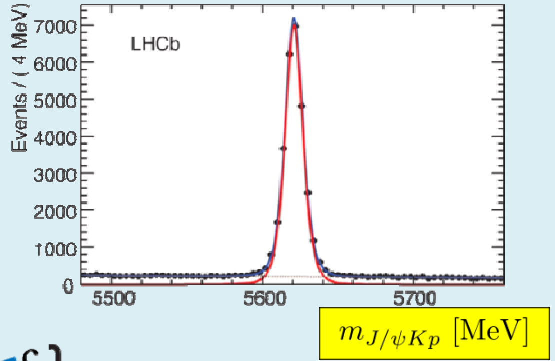
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

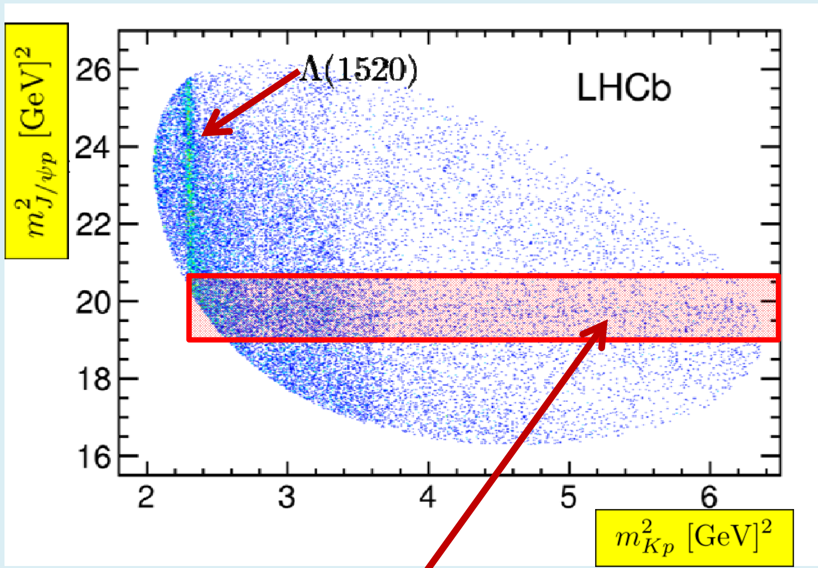
- **LHCb** (2015, Run 1 data, 3fb^{-1}) :

PRL 115 (2015) 072001

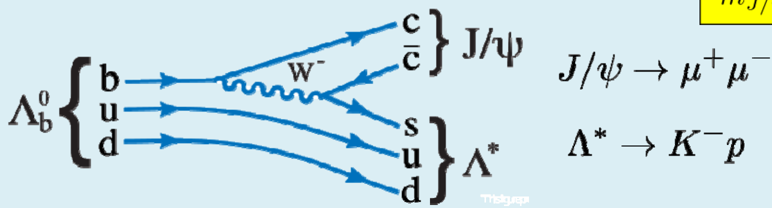
study of the decay $\Lambda_b \to [J/\psi\, p]\, K^-$ $(J/\psi \to \mu^+\mu^-)$

Huge, very clean sample of Λ_bs: 26 007+-166 signal events, background fraction: 5.4%





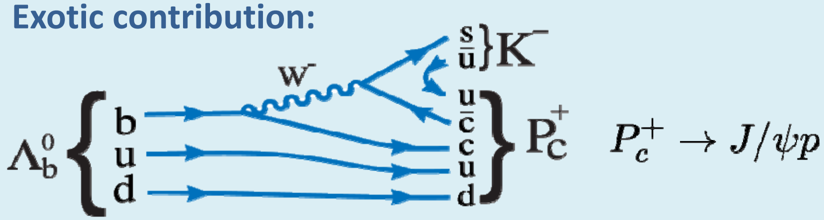
Standard contribution:



$J/\psi \to \mu^+\mu^-$

$\Lambda^* \to K^- p$

Exotic contribution:



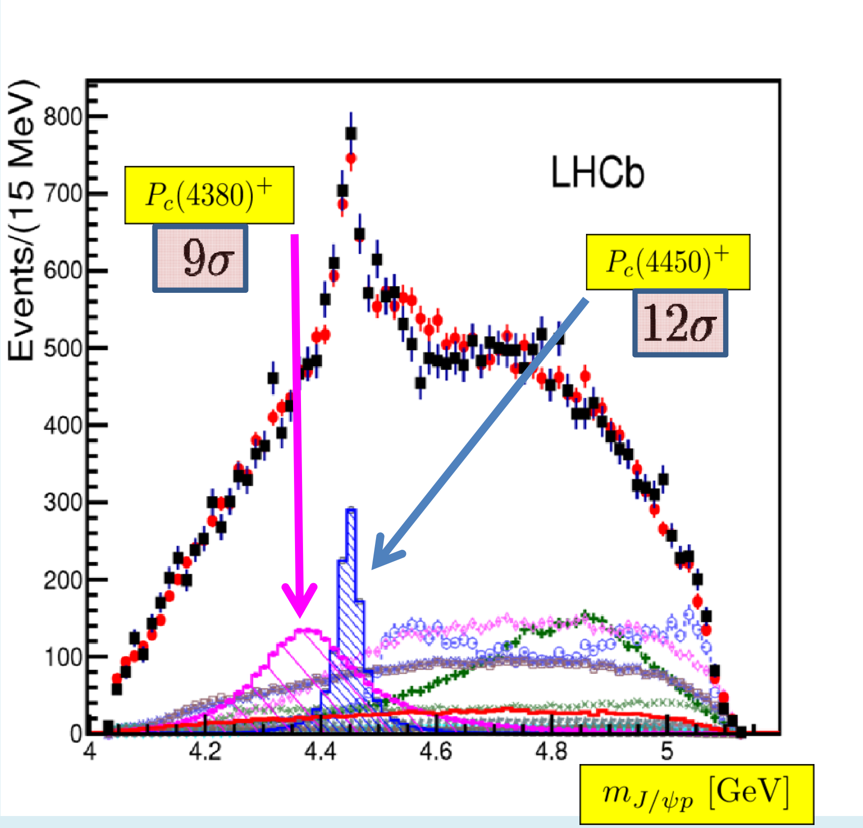
$P_c^+ \to J/\psi p$

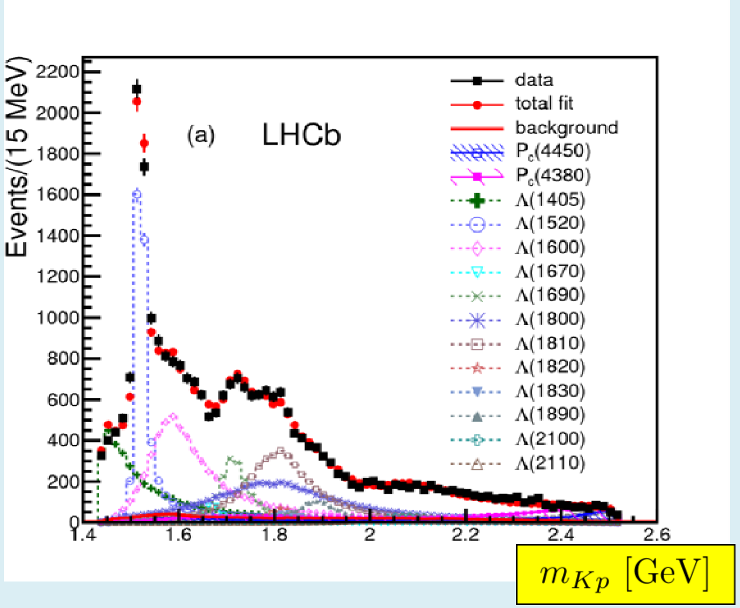
- **Surprising structure in m(J/ψ p)** ⇒ **P_c^+ - the minimal valence quark content: uudc$\bar{c}$**

Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$ Decays

PRL 115 (2015) 072001

- **discovery of two hidden-charm pentaquark-like states $P_c(4380)^+$ and $P_c(4450)^+$**
  - **The full 6D amplitude analysis using the helicity formalism and Breit-Wigner (BW) amplitudes**
    - observables: resonance mass, three helicity angles, two angles between decay planes;
    - takes into account 14 well-defined Λ* states and interference between both decay sequences
  - **The satisfactory description only after including two additional BW amplitudes of P_c states:**





State	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$\frac{3}{2}^-$ $(\frac{3}{2}^+)$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$\frac{5}{2}^+$ $(\frac{5}{2}^-)$

Opposite parities

Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$ Decays

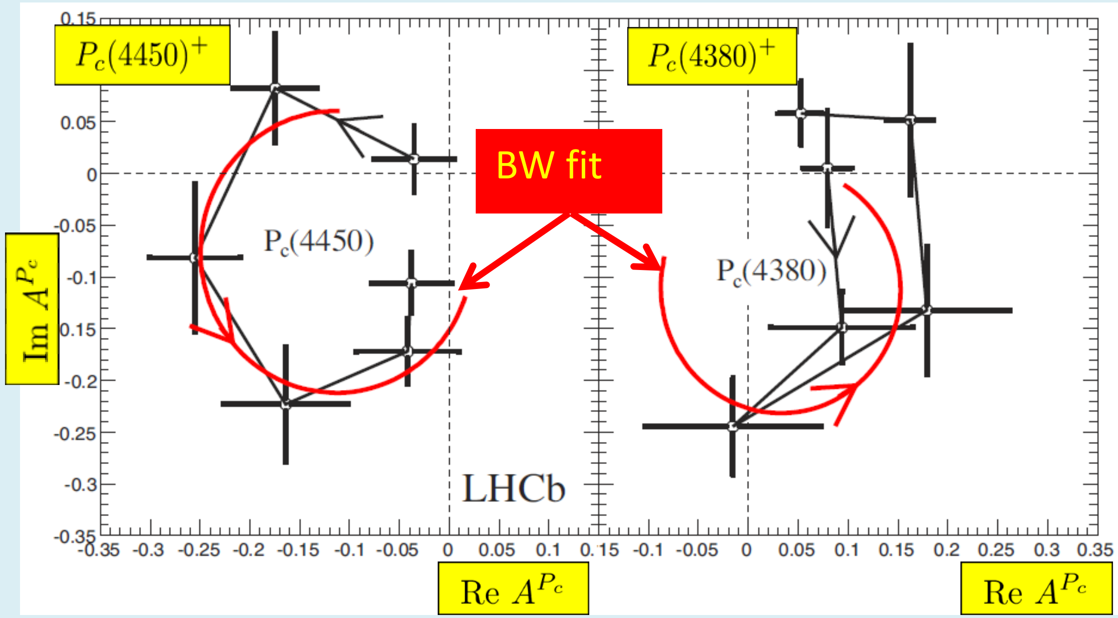
- **Argand Diagrams** (for $3/2^-$ and $5/2^+$ hypothesis)

PRL 115 (2015) 072001

Data points in the six equidistant bins of m(J/ψp) in the range from (–Γ) to (+Γ)

$P_c(4450)^+$:
Consistent with resonant behaviour
(rapid counter-clockwise change
of the phase around the maximum)

$P_c(4380)^+$: needs more statistics



- **The amplitude method is powerful but**

  - **requires the Λ* model** (spectroscopy of these states is complicated)

  - **can provide the detailed info about new states** (mass, width, J^{PC}…)

Pentaquarks in $\Lambda_b^0 \to J/\psi\, p\, K^-$ Decays

PRL 117 (2016) 082002

- **LHCb: fortification of the P_c states observation: Model independent approach**

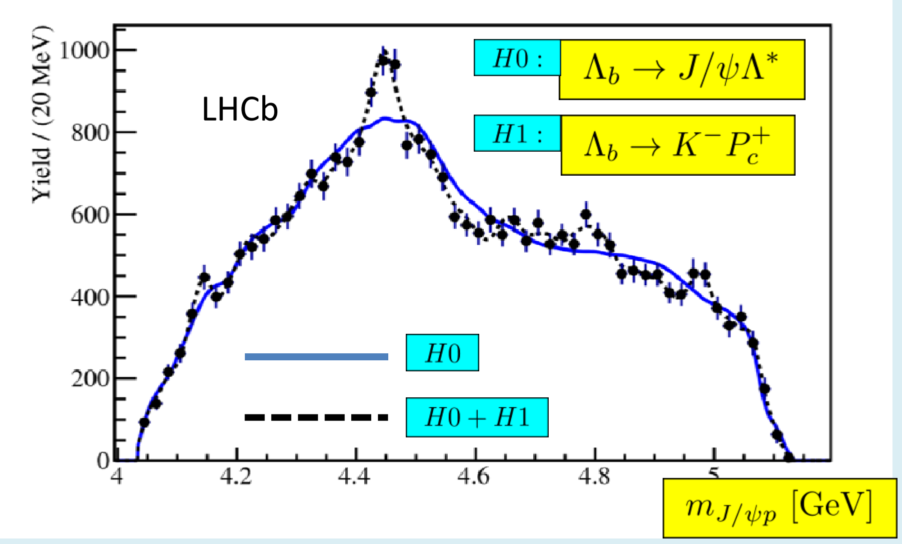
  - **- no need for the Λ* model;** **- can only indicate the presence of exotic states**
  - **2D analysis in terms of** $(m(Kp),\ \cos\theta_{\Lambda^*})$ (θ_{Λ^*}- helicity angle of the K-p system)
  - The $\cos\theta_{\Lambda^*}$ ang. Distribution is expanded in Legendre polynomials (in bins of m(Kp)):

$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

Λ^* resonances can contribute only to low order moments up to $l_{max} = 2J_{max}$

J_{max} – the highest spin of any Kp contribution at the given m_{kp} bin

- $< P_l^U >$ **- Legendre moments:** contain all the information of the angular structure of the system as well as the spin of Λ* resonances



- The [Kp] mass and angular distributions are projected as reflection into the J/ψ p system

- **9σ discrepancy with data, assuming only Λ^* contributions (H0 hypothesis)**

- **The discrepancy concentrated in the region of mass corresponding to the P_c states** (best seen on the m(J/ψ p) distribution)

Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi\, p\, \pi^-$ Decays

- The Cabibbo suppressed mode $\frac{\mathcal{B}(\Lambda_b \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)} = 0.0824 \pm 0.0024 \pm 0.0042$ 1885+-50 Λ_b candidates
- The background fraction is higher by a factor of three

PRL 117 (2016) 082003

Run 1 data, 3fb^{-1}

- The amplitude analysis again
- Four contributions - three of them exotic - considered :

$N^* \to p\pi^-$

$P_c(4380)^+ \to J/\psi p$

$P_c(4450)^+ \to J/\psi p$

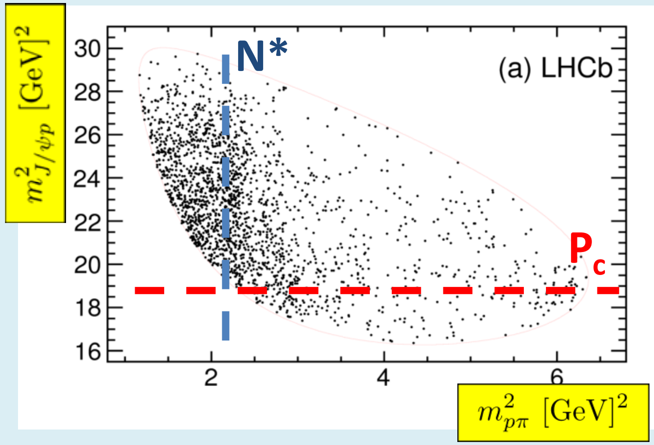
$Z_c(4200)^- \to J/\psi \pi^-$

Reported by Belle in (J/ψ π) (2014)

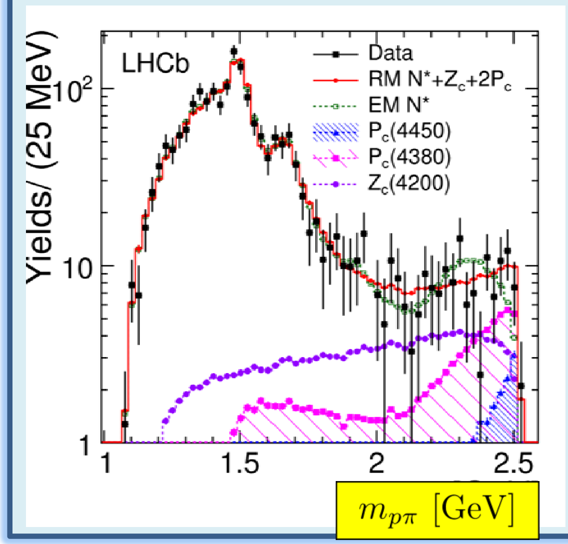
$$M = 4196^{+31}_{-29}\ ^{+17}_{-13}\ \text{MeV}$$

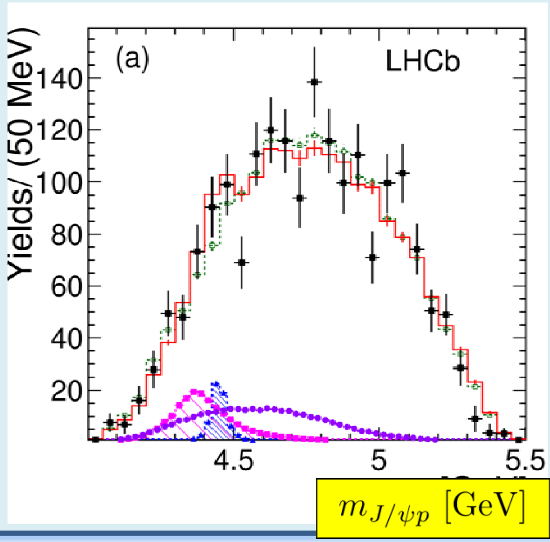
$$\Gamma = 370 \pm 70^{+70}_{-132}\ \text{MeV}$$

$$J^P = 1^+$$



(The masses and widths of N* and P$_c$ states are fixed; Z$_c$(4200)$^-$ parameters set free)





- The data favour the existence of exotic contributions
- 3.1σ significance if both types of exotic resonances are included: P$_c$(4380)$^+$ & P$_c$(4450)$^+$ & Z$_c$(4200)$^-$
- 3.3σ for the P$_c$s, assuming that the Z$_c$(4200)$^-$ contribution is negligible: P$_c$(4380)$^+$ & P$_c$(4450)$^+$

The First Observation of $\Lambda_b^0 \rightarrow \chi_{c(1,2)}\, p\, K^-$

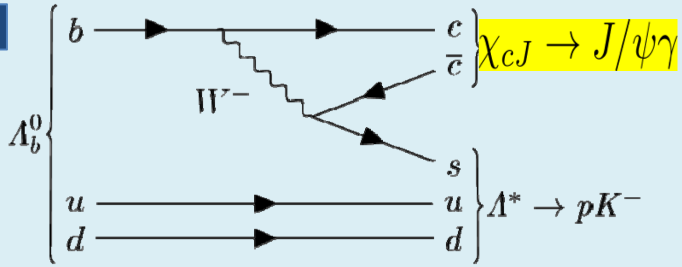
➤ **Motivation:** LHCb: 3fb^{-1} PRL 119 (2017) 062001

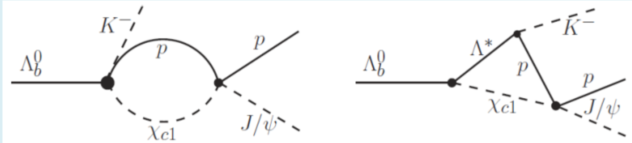
1. **Test the kinematic rescattering effect (KRE) hypothesis**

   - The mass of $P_c(4450)$ is very close to the $[\chi_{c1}p]$ threshold

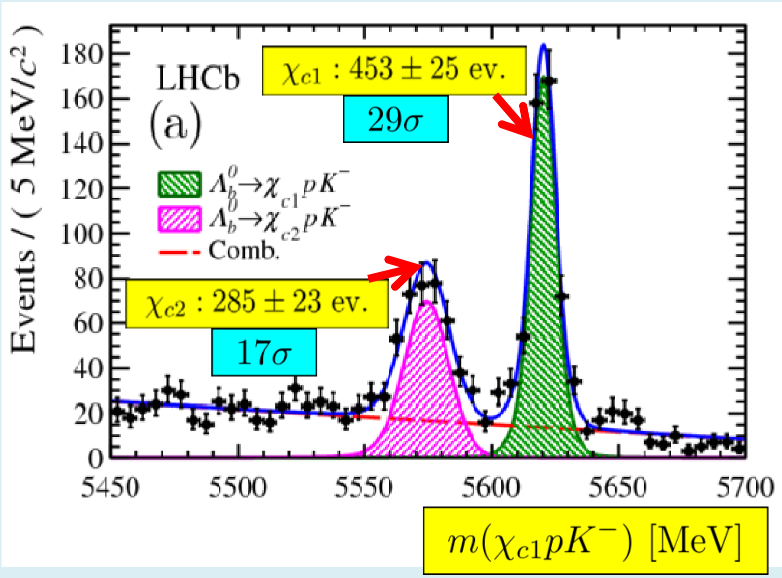
   $$m_{P_c^+(4450)} - m_{\chi_{c1}} - m_p = (0.9 \pm 0.3)\ \mathrm{MeV}$$

   - If $P_c(4450)^+$ is due to KRE ➔ should NOT be observed as a narrow enhancement near the $[\chi_{c1}p]$ threshold in the $\Lambda_b \to \chi_{c1} p K^-$ mode PRD 92 (2015) 071502





2. **Test the factorisation approach:** the decay with χ_{c2} is expected to be suppressed w.r.t. that with χ_{c1}



LHCb: **both $\Lambda_b \to \chi_{c1} pK^-$ and $\Lambda_b \to \chi_{c2} pK^-$ observed for the first time**

Ad 1. distributions of $m(\chi_{c1}p)$ and $m(pK)$ studied
– more statistics needed for the amplitude analysis
Run 1 & 2: >1000 χ_{c1} candidates

Ad. 2. $$\frac{\mathcal{B}(\Lambda_b \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b \to \chi_{c1} pK^-)} = 1.02 \pm 0.11$$ **-no χ_{c2} suppression,**

differs from $$\frac{\mathcal{B}(B^0 \to \chi_{c2} K^{*0})}{\mathcal{B}(B^0 \to \chi_{c1} K^{*0})} = 0.17 \pm 0.05$$

Nucl. Phys. B874 (2013) 663

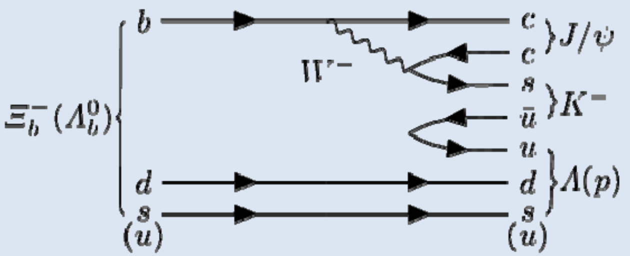
Observation of $\Xi_b^- \to J/\psi \Lambda K^-$ Decay

- **Motivation: search for possible (udsc$\bar{c}$) states, decaying to ($J/\psi \Lambda$) pair**
- **LHCb:** the first observation of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay

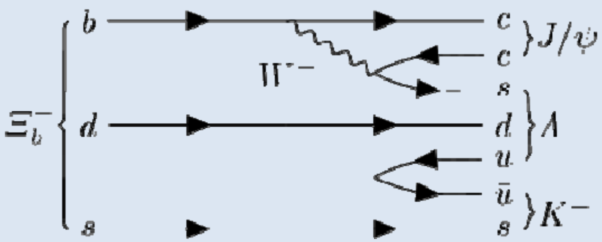
21σ

PRL 117 (2016) 082002

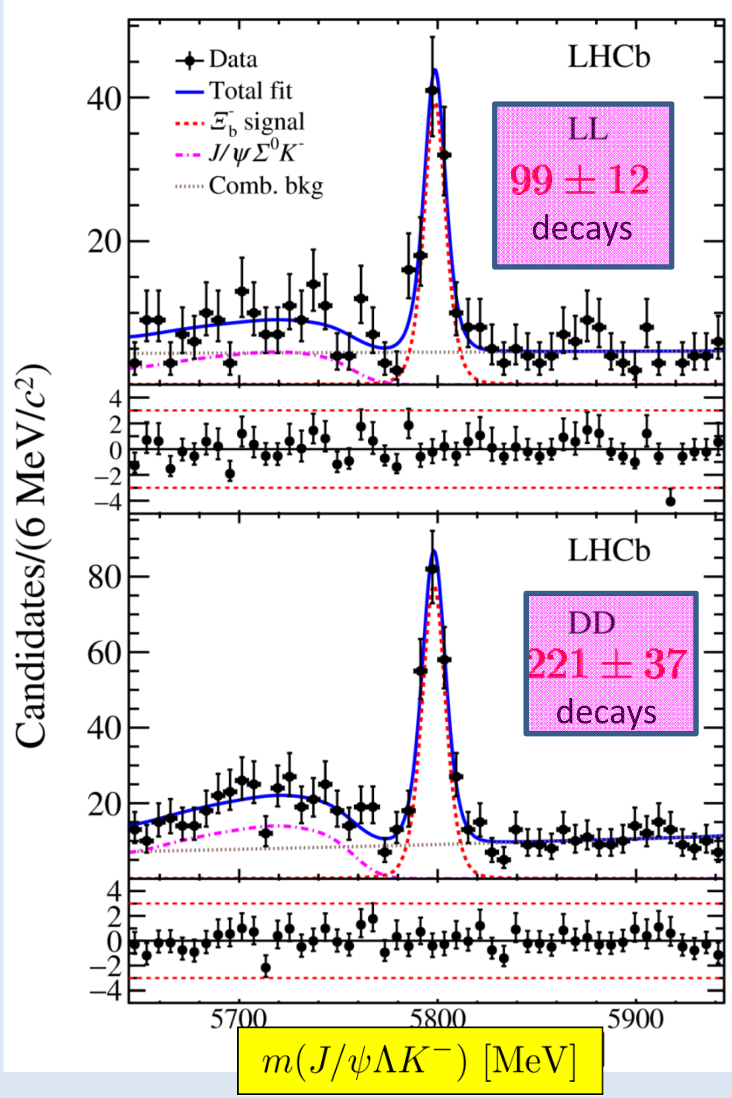
Run 1 data, 3fb^{-1}



LL (Λ candidates): both tracks combined for the $\Lambda^0 \to p\pi^-$ are **long** – include segments in VELO



DD (Λ candidates): both tracks are **downstream** – reconstructed using only the tracking stations downstream of the VELO



- **Results:**

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

$$m(\Xi_b^-) - m(\Lambda_b^0) = (177.08 \pm 0.47 \pm 0.16)\ \text{MeV}$$

- **The amplitude analysis, in search for (udsc$\bar{c}$) states, feasible with the full data sample of Run 2**

Search for b-flavoured Pentaquarks

- **The (uud$c\bar{c}$) states observed (decaying strongly)**

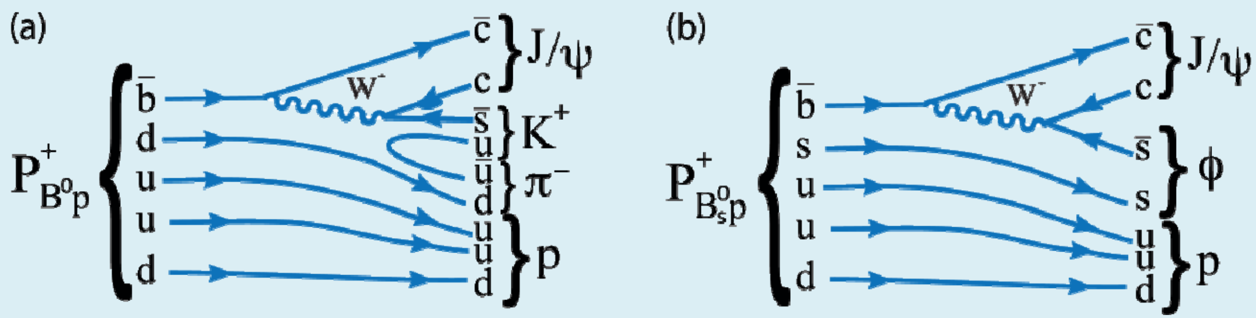
- **The Skyrme model:** Proc. Roy. Soc. London A 260 (1961) 127
  expectation of b-flavoured pentaquarks P_b($b\bar{q}qqq$/$\bar{b}qqqq$), that decay via the weak interaction and are
  - **tightly bound** (Skyrme model: the binding grows with the mass of the constituent quarks)
  - **narrow** ($\Gamma \approx$ 6 MeV, to compare with (40-200) MeV for P_cs)

- **LHCb:** the search for four types of P_b states PRD 97 (2018) 032010 Run 1 data, 3fb^{-1}

new

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	$b\bar{u}udd$	$P^-_{\Lambda^0_b \pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b \pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

below the threshold for strong decays

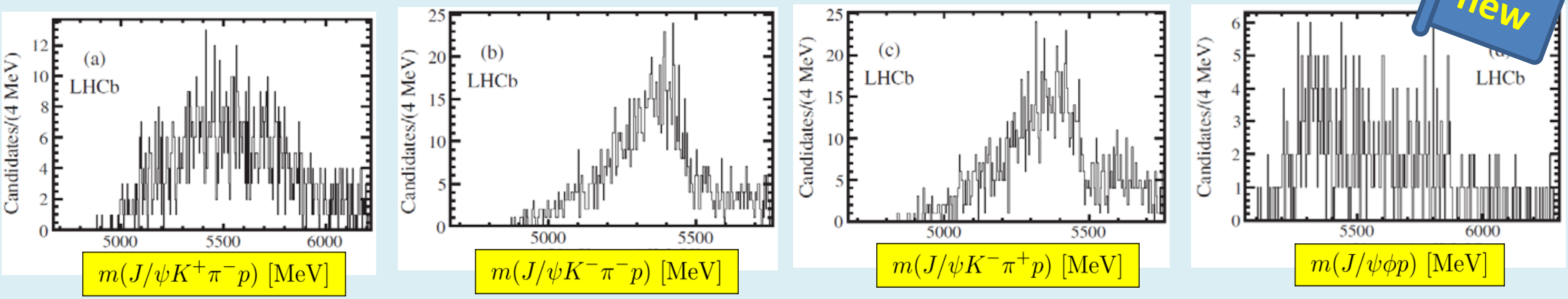


Search for b-flavoured Pentaquarks

- No signal observed

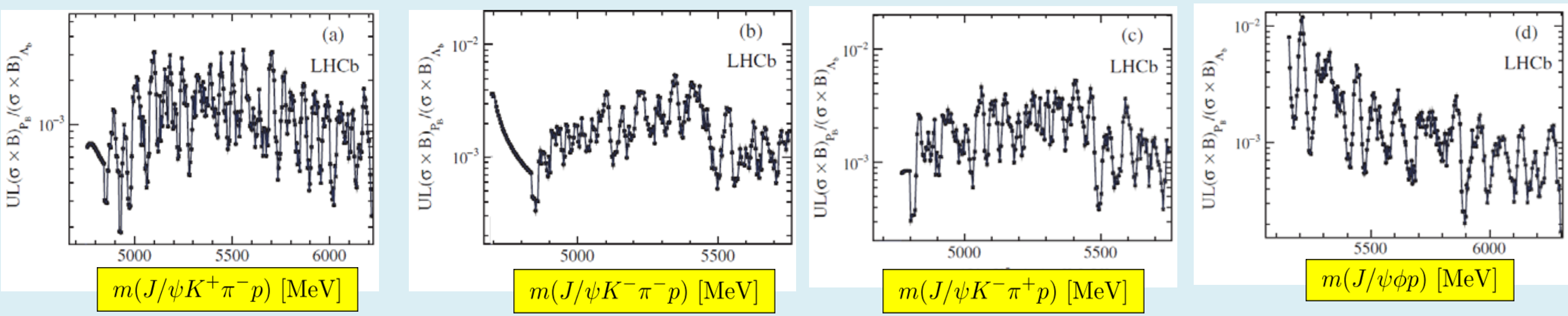
PRD 97 (2018) 032010

new



- Upper limits on the P_b production ratio w.r.t. $\Lambda_b^- \to J/\psi K^- p$

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

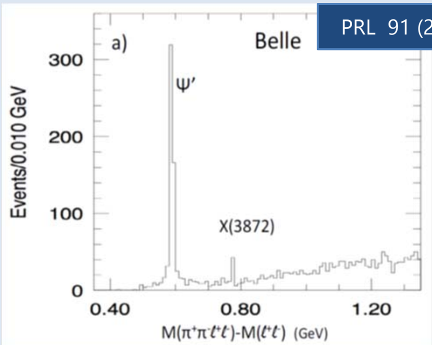


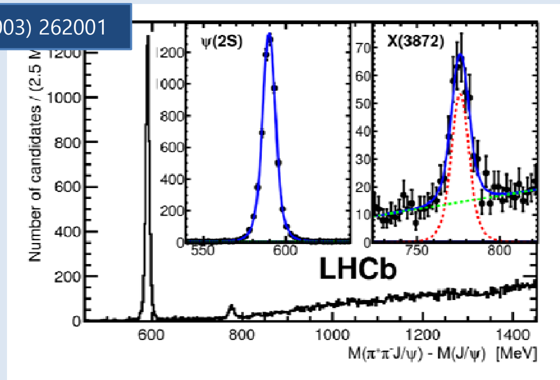
- The limits (90% CL) on R are at the level 10^{-2} - 10^{-3}

The Puzzling States X → J/ψϕ

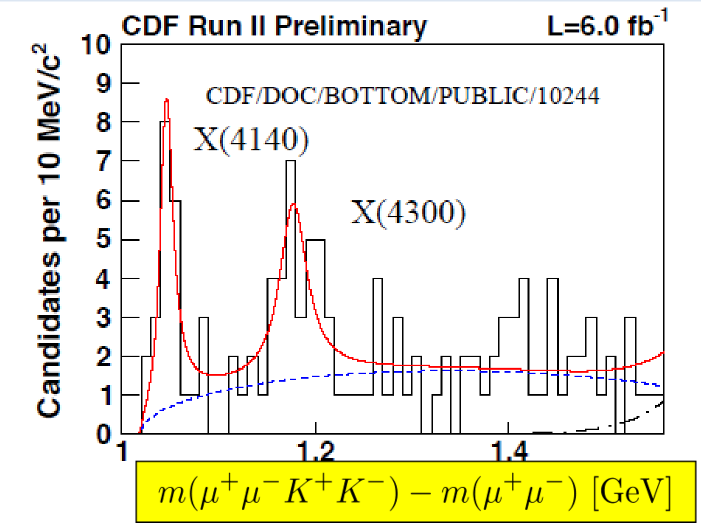
- **Reminder: the X(3872) revolution**
- Belle (2003): observation of narrow state X in $B \to [\pi^+\pi^- J/\psi]\, K$ decay
- The most studied exotic state
- LHCb: $J^{PC} = 1^{++}$ PRL 110 (2013) 222001
- X is most probably a mixture of $\chi_{c1}(2P)$ and of $D\bar{D}^*$ molecule

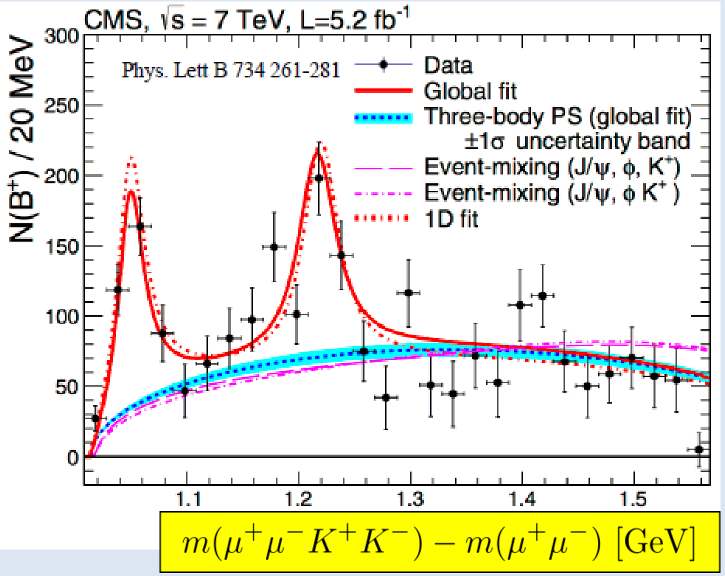
PRL 91 (2003) 262001





- **The X(4140) - evidence for a narrow near threshold structure in B⁺ → (J/ψ ϕ) K⁺ decays: CDF, D0, CMS**
- **The X(4274) – the second relatively narrow [J/ψ ϕ] state – evidence from CDF and CMS**
- **Negative results from other experiments (B-factories)**





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

CMS:
PL 734 (2014) 261

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

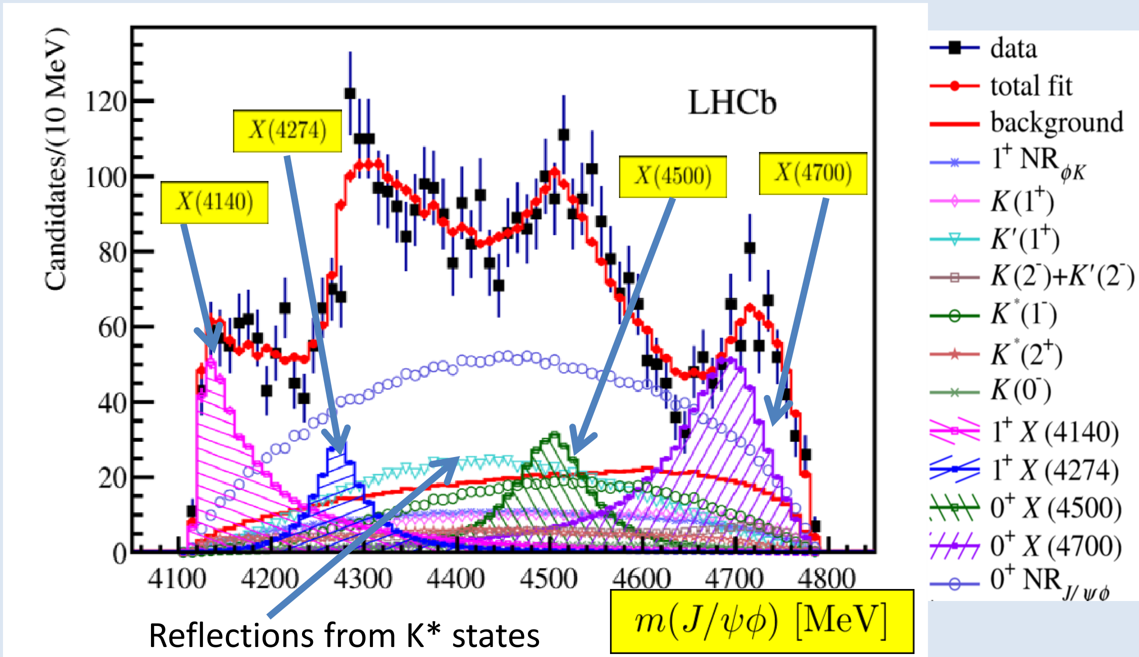
The Puzzling States X → J/ψφ

LHCb: the first amplitude analysis of $B^+ \to [J/\psi\ \phi]\ K^+$ decays

Run 1 3fb^{-1}

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**



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

- The X(4140) width is substantially larger than previously determined (average of other meas.: 15.7+-6.3 MeV)
- X(4140) and X(4274) – J^{PC} incompatible with cusps and molecular bound states - possible interpretation as tetraquarks $c\bar{c}s\bar{s}$ (no light valence quarks) or $\chi_{c1}(3P)$
- X(4500) and X(4700) – $D_s^{*+}D_s^{*-}$ state or $\chi_{c1}(4P)$, $\chi_{c1}(5P)$

Controversy About the Tetraquark X(5568)

➢ **D0 (2016): reports a narrow structure X(5568) in the $B_s^0\,\pi^+$ spectrum** PRL 117 (2016) 022003

$$X^{\pm}(5568) \to B_s^0 \pi^{\pm}, \quad B_s^0 \to J/\psi\phi$$

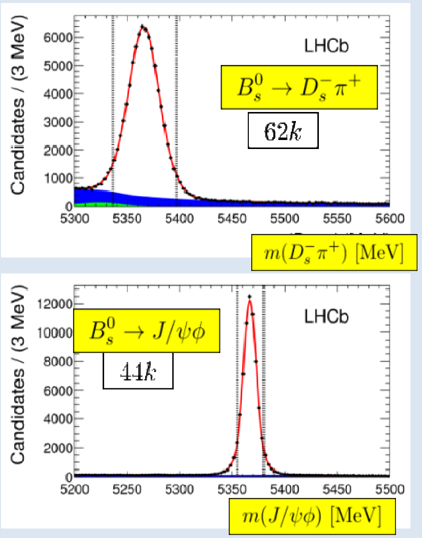
$$\rho_X = \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi^{\pm})}{\sigma(pp \to B_s^0 + \text{anything})} = (8.6 \pm 1.9 \pm 1.4)\ \%$$

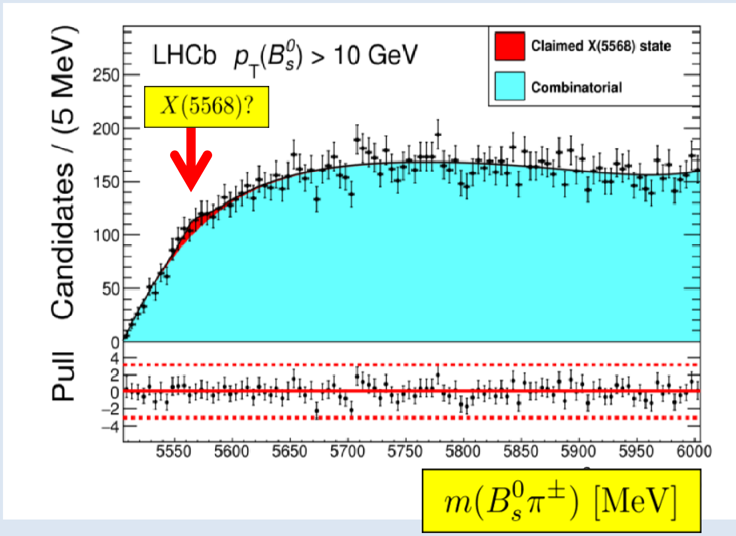
(5.1 σ)

A system (tetraquark or molecule) containing valence (anti)quarks with four different flavours (b,s,d,u) ?

➢ **LHCb (2016):** 20x more D_s than D0 collab. PRL 117 (2016) 152003

- **lack of observation of any X(5568)-like signal** 3fb^{-1}





$$\rho_X < 2\ \% \quad (95\ \%\ C.L.)$$

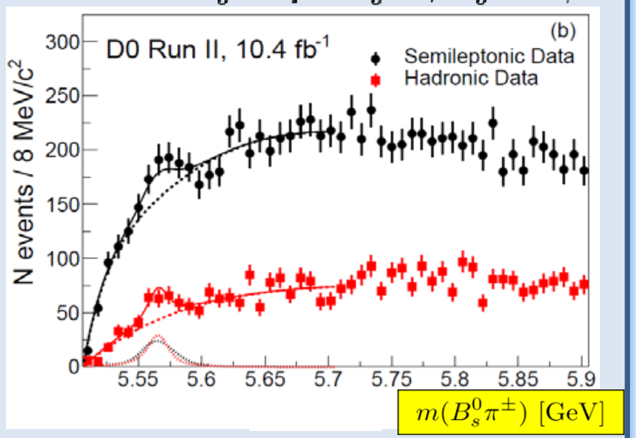
- Similar negative result from CMS: CMS-PAS-BPH-16-002 (2016)

➢ Not seen by CDF (27.Dec.2017): arXiv: 1712.09620 [hep-ex]

➢ Seen again by D0 (29.Dec.2017): arXiv: 1712.10176 [hep-ex]

$$X^{\pm}(5568) \to B_s^0 \pi^{\pm}$$

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



$$m = 5566.9^{+3.2+0.6}_{-3.1-1.2}\ \text{MeV}$$

$$\Gamma = 18.6^{+7.9+3.5}_{-6.1-3.8}\ \text{MeV}$$

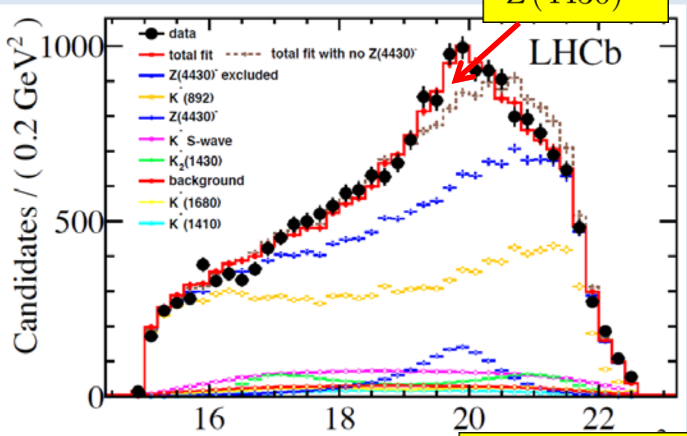
(6.7 σ)

Charged Exotic State Z(4430)$^-$

- **Belle (2008): evidence for Z(4430)$^-$ in ψ’π mass distribution** $(B^0 \to \psi(2S)\pi^- K^+$ decays)
- LHCb (2014): tenfold increase in signal yield (25176+-174 decays); Run 3fb^{-1}

PRL 112 (2014) 222002

4D amplitude analysis:



$m(Z(4430)^-) = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma(Z(4430)^-) = 172 \pm 13^{+37}_{-34}$ MeV

$J^P = 1^+$ assignment established relative to:

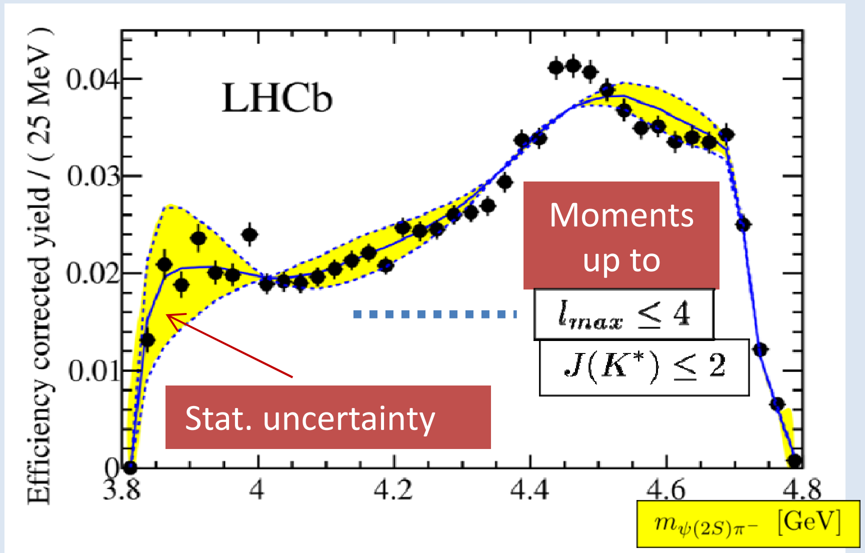
J^P	0^-	1^-	2^+	2^-
sign. $[\sigma]$	9.7	15.8	16.1	14.6

Positive parity → hypothesis of threshold effect $\overline{D}^*(2007)D_1(2420)$ and $\overline{D}^*(2007)D_2^*(2460)$ ruled out

PRD 92 (2015) 112009

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 Kπ reflections with $J(K^*) \le 2$ excluded (>8σ)**



- **The most plausible interpretation of Z(4430): a tetraquark; the minimal quark content $c\bar{c}d\bar{u}$**

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 recently provided valuable contributions to heavy flavour spectroscopy of exotic states:**
  - Observation of hidden-charm pentaquarks P_c; searches for b-flavoured states P_b
  - Observation of candidates for tetraquark $c\bar{c}s\bar{s}$ states in the J/ψϕ final state
  - Non-confirmation of a tetraquark X(5568)
  - Confirmation and extensive studies of $Z(4430)^-$ in ψ'π mass distribution

- **More precice 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….**