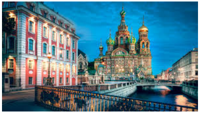
Spectroscopy of b- and c-hadrons

Lucio Anderlini
on behalf of the LHCb Collaboration
including contents from ATLAS, BABAR, BELLE, BESIII, CDF, and CMS

The Third Annual Conference on Large Hadron Collider Physics

LHCP 2015



Friday September, 04th – St. Petersburg, Russia

Outline

Introduction

New c-hadrons

- In prompt $D^{(*)}K$ combinations
- $B \to Dhh$ studies (spin-3 D mesons)
- $B \to DDh$ studies

New b-hadrons

- $B_c^+(2S)$ observation
- Excited b-mesons at LHCb and CDF
- Excited b-baryons

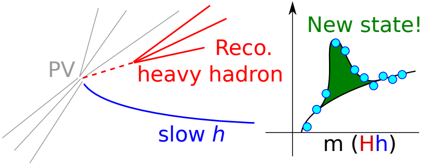
Quarkonia(-like) spectroscopy

- New Z_c states from BESIII
- $X_b^+ \to \Upsilon(1S)\pi^+$ searches
- Study of $X(3872) \to \rho^0 J/\psi$
- Tetraquark $Z_c(4430)^-$
- ~~Pentaquarks observation P_c~~ (covered in Anton's highlights)

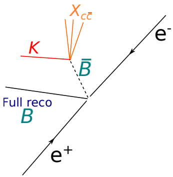
Conclusion and outlook

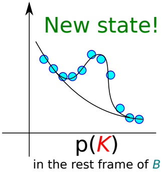
Don't miss the HF-3 session this afternoon, with theoretical and experimental reports on Heavy Flavour spectroscopy.

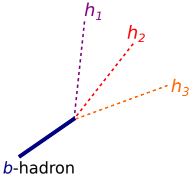
Important test for QCD theories.
Several concurrent techniques to explore heavy flavours excited states.

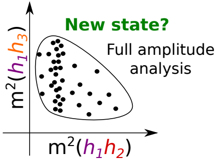


ATLAS & CMS	pp with $\sqrt{s} = 7 - 8\,\mathrm{TeV}$
LHCb	pp with $\sqrt{s} = 7 - 8\,\mathrm{TeV}$
CDF	$p\bar{p}$ with $\sqrt{s} = 1.96\,\mathrm{TeV}$
Belle & Babar	e^+e^- with $\sqrt{s} = 10.58\,\mathrm{GeV}$
BESIII	e^+e^-, lower $\sqrt{s}$









Principle of amplitude analyses

1. Define a *pure sample* of $R \to abc$ decays ($R \equiv c-$ or b-hadron).
   Background can be
   - Statistically subtracted with **sPlot** (in binned analyses)
   - Statistically subtracted with **sFit** (in unbinned analyses)
   - Modeled and included in the analysis (**cFit**)
2. Define the decay amplitude $\mathcal{M}$ as sum of resonant contributions M_r, depending on the set of variables $\boldsymbol{\sigma}$ (invariant masses, and decay angles).
3. Compute the decay width as a function of $\boldsymbol{\sigma}$:

   $$\mathrm{d}\Gamma(\boldsymbol{\sigma}) = K(\boldsymbol{\sigma}) \left| \sum_r \mathcal{M}_r(\boldsymbol{\sigma}) \right|^2 \mathrm{d}\boldsymbol{\sigma}$$

   $K(\boldsymbol{\sigma})$ corrects for kinematics; it depends on the choice of $\boldsymbol{\sigma}$.
4. Compute efficiency $\varepsilon(\boldsymbol{\sigma})$, usually using flat-dynamics simulation.
5. Fit the pdf

   $$pdf(\boldsymbol{\sigma})\mathrm{d}\boldsymbol{\sigma} = \varepsilon(\boldsymbol{\sigma})\Gamma(\boldsymbol{\sigma})\mathrm{d}\boldsymbol{\sigma}$$

   to the *pure sample* defined above.

Changing the recipe of the $\mathcal{M}_r$ contributions, one draws conclusions on

- Existence of resonant states
- Quantum numbers of resonant states

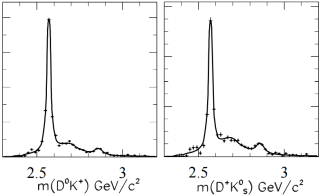
Taking into account the interference between the resonant states!

c-hadron spectroscopy

A DK structure at $m \sim 2.86 \mathrm{GeV}/c^2$ seen at Babar, confirmed at LHCb

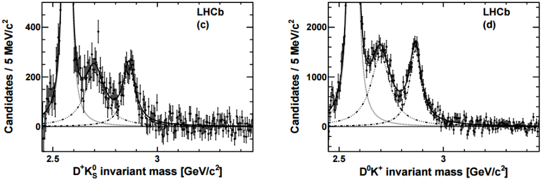
BaBar (2009) [PRD80:092003]

Inclusive study of $e^+e^- \to D^{(*)}K$



LHCb (2012) [JHEP 1210 (2012) 151]

Inclusive study of $pp \to DK$



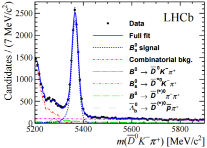
The three peaks are

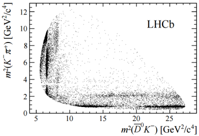
- $D_{s2}^{*+}(2573) \to D^0K^+$ and $D_{s2}^{*}(2573)^+ \to D^+K_S^0$;
- $D_{s1}^{*+}(2710) \to D^0K^+$ and $D_{s2}^{*}(2710)^+ \to D^+K_S^0$; observed by Babar (2009)
- $D_{sJ}^{*+}(2860) \to D^0K^+$ and $D_{sJ}^{*}(2860)^+ \to D^+K_S^0$; observed by Babar (2009)

BaBar also observed $D_{s1}^{*}(2710)^+$ and $D_{s1}^{*}(2860)^+$ to D^*K final states.

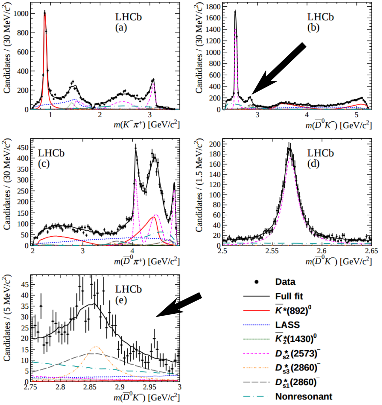
$\bar{B}^0_s \to D^0 K^- \pi^+$: an abundant decay with **rich resonant sub-structure**

Full amplitude analysis using the *cFit* technique, fitting the fake B^0_s component (Combinatorial, Partial reco, and mis-id Λ^0_b) together with the **15 resonant and non-resonant** signal amplitudes.





The structure at $m \sim 2860 \text{MeV}/c^2$ contains both spin-1 and spin-3 components (significance $> 10\sigma$)!
Components were named $D^*_{s1}(2860)^-$ and $D^*_{s3}(2860)^-$

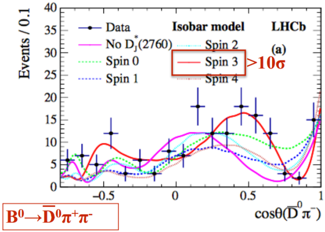


LASS shape: parametrization of the S-wave component.

This is the **first observation** of a spin-3 heavy flavour hadron.

Rich c-meson spectroscopy from other $B \to Dhh$ decays @LHCb

Decay mode	Branching fraction	Reference
$B^0 \to \bar{D}^0\pi^+\pi^-$	$8.46 \pm 0.14 \pm 0.29 \pm 0.40$	[PRD 92, 032002]
$B_s^0 \to \bar{D}^0 f_0(980)$	$0.017 \pm 0.010 \pm 0.005 \pm 0.001$	[JHEP 08(2015)005]
$B^0 \to \bar{D}^0 K^+\pi^-$	$0.92 \pm 0.06 \pm 0.07 \pm 0.06$	[PRD 92, 012012]
$B_s^0 \to \bar{D}^0 K^-\pi^+$	$10.0 \pm 0.4 \pm 1.0 \pm 1.0$	[PRD 90, 072003]
$B^0 \to \bar{D}^0 K^- K^+$	$0.47 \pm 0.09 \pm 0.06 \pm 0.05$	[PRL 109, 131801]
$B_s^0 \to \bar{D}^0 K^- K^+$	0.42 ± 0.19	[PRL 109, 131801]
$B^- \to D^+ K^-\pi^-$	$0.731 \pm .019 \pm 0.022 \pm 0.039$	[PRD 91, 092002]



$\theta(\bar{D}^0\pi)$ defined in the rest frame of D^*

Observed D^* mesons

$D_0(2400)$, and $D_s(2460)$ dominant in all analyses

$D^*(2650)$, $D^*(2760)$, $D^*(3000)$

spin-3 $D^*(2800)^+$ in $B^0 \to \bar{D}^0\pi^+\pi^-$

spin-1 $D^*(2791)^+$ in $B^- \to \bar{D}^+K^-\pi^-$

Observed D_s^* mesons

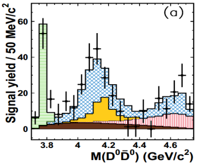
$D_{s1}^*(2700)^-$

$D_{s1}^*(2860)^0$ and $D_{s3}^*(2860)^0$ (cf. above)

$D_{sJ}^*(3040)^-$

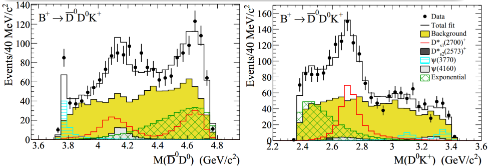
$$B^0 \to D^+ D^0 K^- \qquad \text{and} \qquad B^+ \to D^0 \bar{D}^0 K^+$$

Belle (2008) [PRL 100:092001]



- Observed resonance $D^*_{sJ}(2700)^+$
- Found it dominates $B^+ \to D^0 \bar{D}^0 K^+$ decays
- **Need for unexplained non-resonant contribution**, modeled as an **exponential** in $m(D^0 K^+)$.

Babar (2015) [PRD 91, 052002]



- Confirms all Belle's conclusions with higher statistics
- Improves precision in mass and width measurements
- Extends the observation of the *non-resonant* contribution to $B^0 \to D^- D^0 K^+$

Nature of $D^*_{sJ}(2700)^+$ is still unclear. It has been suggested it is:

- the first radial excitation of the $D^*_s(2112)$ meson [PRD 86, 054024]
- an 1^3D_1 $c\bar{s}$ state [PRD 89, 074023], possibly mixing with the former
- two resonances overlapping

News from LHCb coming soon!

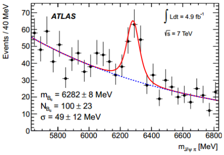
b-hadron spectroscopy

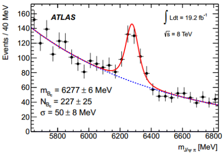
A charmed and beauty excited state: $B_c^+(2S)$

Observed the decay

$$B_c^+(2S) \to B_c^+\pi^+\pi^-$$

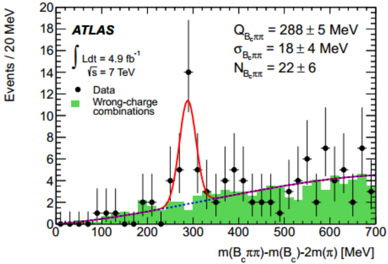
Full Run-1 data sample

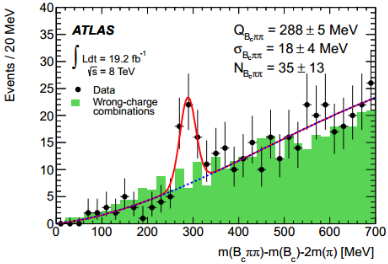




$B_c^+(2S)$ candidates reconstructed using B_c^+ candidates in mass window $m(B_c^+)_{PDG} \pm 3\sigma$

Mass	$6842 \pm 4 \pm 5$ MeV$/c^2$
$N(B_c^+)$ in 2011	100 ± 23
$N(B_c^+)$ in 2012	227 ± 25
$N(B_c^+(2S))$ in 2011	22 ± 6
$N(B_c^+(2S))$ in 2012	35 ± 13
Significance	5.2 σ



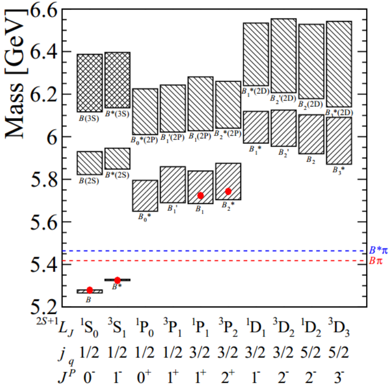


Observation of a B resonance at CDF

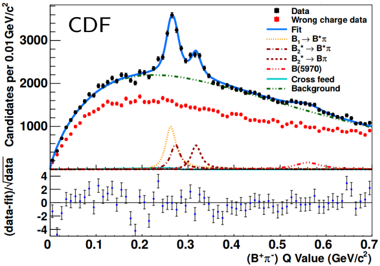
[PRD 90, 012013]

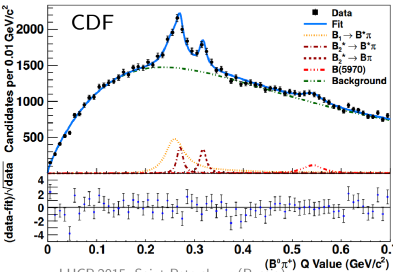
Reanalysis combining B^+ meson from

- $B^- \to J/\psi K^-$;
- $B^{-,0} \to D^{0,-}\pi^+$
- $B^{-,0} \to D^{0,-}\pi^+\pi^-\pi^+$
- $B^0 \to J/\psi K^*(892)^0$;
- $B^0 \to J/\psi K^0_S$;



Structures in the plots are:
$B_1 \to B^*\pi$
$B_2^* \to B^*\pi$ (FIXED shape&yield)
$B_2^* \to B\pi$
$B(5970) \to B\pi$ (NEW!)





More B resonances at LHCb

LHCb analysis of the Run-1 pp dataset.
Using decays:

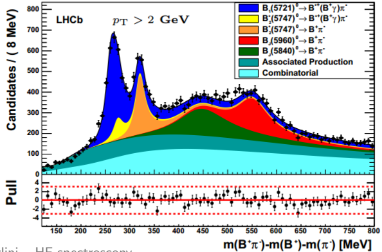
- $B^- \to J/\psi K^-$;
- $B^{-,0} \to D^{0,-}\pi^+(\pi^+\pi^-)$ with $D^0 \to K^-\pi^+(\pi^-\pi^+)$
- $B^0 \to J/\psi K^*(892)^0$;

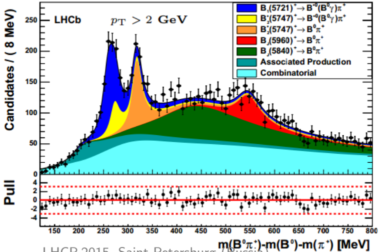
Improved measurement of the masses of $B_1^{0,+}$ and $B_2^{*\,0,+}$.

Fit parameter	$B^+\pi^-$	$B^0\pi^+$
$B_1(5721)^{0,+}$ μ	263.9 ± 0.7	260.9 ± 1.8
$B_1(5721)^{0,+}$ Γ	30.1 ± 1.5	29.1 ± 3.6
$B_2^*(5747)^{0,+}$ μ	320.6 ± 0.4	318.1 ± 0.7
$B_2^*(5747)^{0,+}$ Γ	24.5 ± 1.0	23.6 ± 2.0

First evidence (3.7 σ) of $B_2^* \to B^*\pi^+$.

Enhancement at 5.97 GeV$/c^2$ reported by CDF is confirmed and labeled $B(5960)$.



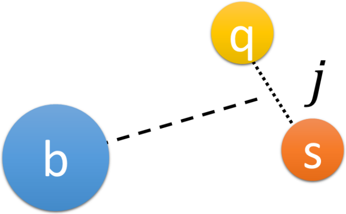


[PRL 114, 062004]

LHCb studies the $\Xi_b^0 \pi^-$ combinations where

$$\Xi_b^0 \to \Xi_c^+ \pi^- \quad \text{and} \quad \Xi_c^+ \to \Lambda_c^+ p K^-$$

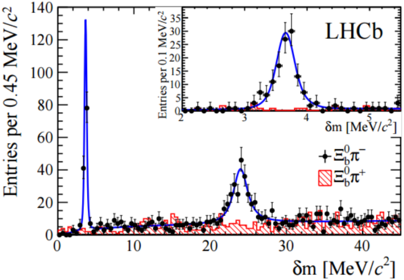
Taking wrong-sign combination as background proxy.



LHCb observes two new states, labeled Ξ_b' and Ξ_b^*.

Angular analysis does not exclude quark model interpretation:

Ξ_b	$J^P = \frac{1}{2}^+$	$j = 0$
Ξ_b'	$J^P = \frac{1}{2}^-$	$j = 1$
Ξ_b^*	$J^P = \frac{3}{2}^+$	$j = 1$



Very precise mass measurement:

$$m(\Xi_b'^-) = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50 \text{ MeV}/c^2$$
$$m(\Xi_b^{*-}) = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50 \text{ MeV}/c^2$$

Last uncertainty propagated from $m(\Xi_b^0)$ [PDG]: $m(\Xi_b^0) = 5971 \pm 0.50$ MeV$/c^2$

An excited Ξ_b at CMS

A Ξ_b^* state was already reported at CMS studying $\Xi_b^- \pi^+$ combinations.

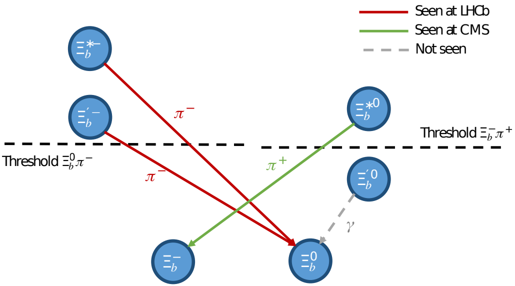
Measured mass:

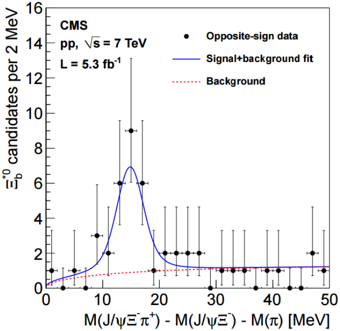
$$m(\Xi_b^{*0}) = 5945.0 \pm 0.7 \pm 0.3 \pm 2.7 \text{ MeV}/c^2$$

where the last uncertainty is propagated from $m(\Xi_b^-)$.

Analysis based on 2011 data, $\sqrt{s} = 7$ Tev

A possible interpretation...

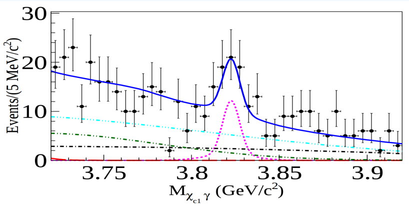




$N_{\text{sig}} \sim 18$ candidates
Significance (including LEE): 5.3 σ

$Q\bar{Q}$ and $Q\bar{Q}$-like spectroscopy

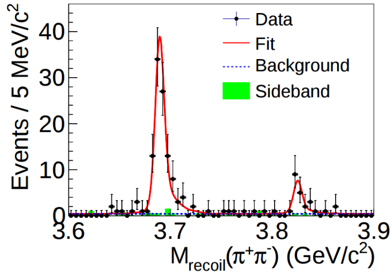
In 2013, Belle reports an evidence (3.8σ) for a state $X(3823) \to \chi_{c1}\gamma$. [PRL 111, 032001]



Its mass $(3823.1 \pm 1.8 \pm 0.7$ MeV$/c^2)$ was found consistent with the interpretation as $\psi_2(1^3D_2)$ state.

No peak seen in $D\bar{D}$: also consistent with $\psi_2(1^3D_2)$.

In 2015, BESIII confirms the state (6.2σ).



Improved measurement of mass and width:

$$M = 3821 \pm 1.3 \pm 0.7 \text{ MeV}/c^2$$

$$\Gamma < 16 \text{ MeV}/c^2 (90\% C.L.)$$

$$R = \frac{\mathcal{B}(X(3823) \to \chi_{c2}\gamma)}{\mathcal{B}(X(3823) \to \chi_{c1}\gamma)} < 0.43(90\%\text{C.L.})$$

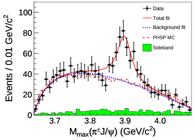
Potential model predictions for $\psi_2(1^3D_2)$ [PRD 69:094019]

$M \sim 3815$ MeV$/c^2$ $\quad$ $R \sim 0.2$

Γ small ($D\bar{D}$ suppressed for P violation)

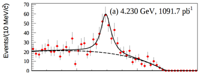
Z_c states at BESIII

$Z_c(3900)^{\pm}$?	$Z_c(3900)^0$?	$Z_c(4020)^{\pm}$?	$Z_c(4020)^0$?



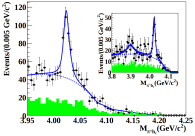
$e^+e^- \to \pi^-\pi^+J/\psi$

[PRL 110, 252001]



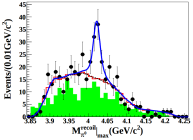
$e^+e^- \to \pi^0\pi^0J/\psi$

[1506.06018]



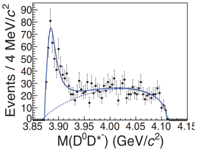
$e^+e^- \to \pi^-\pi^+h_c$

[PRL 111, 242001]



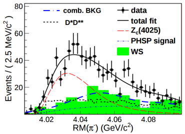
$e^+e^- \to \pi^0\pi^0h_c$

[PRL 113, 212002]



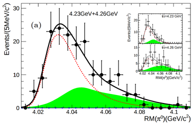
$e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$

[PRL 112, 022001]



$e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$

[PRL 112, 132001]



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

[1507.02404]

Most of these papers were submitted in 2014 and 2015. No angular analysis yet.

Search for $X_b \to \Upsilon(1S)\pi^+\pi^-$ at ATLAS and CMS

ATLAS and CMS report a search for a state analogue to the $X(3872)$ in the b-sector.

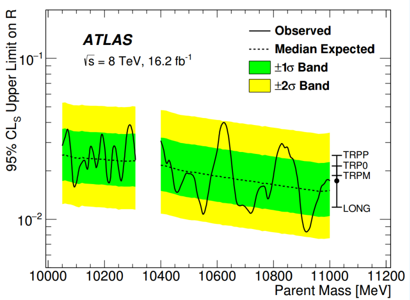
In analogy to $X(3872) \to J/\psi\pi^+\pi^-$ they look for $X_b \to \Upsilon(1S)\pi^+\pi^-$, using $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ as control channel.

In absence of signal, they put an upper limit (at 95% of C.L.) on

$$R = \frac{\mathcal{B}(X_b \to \Upsilon(1S)\pi^+\pi^-)}{\mathcal{B}(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)}$$

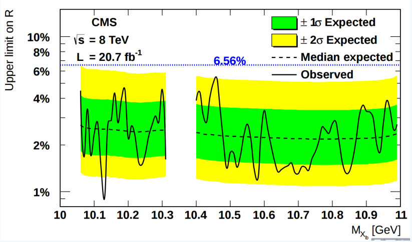
ATLAS

[PLB 740 199]



CMS

[PLB 727 57]



For comparison: $$R = \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi(1S)\pi^+\pi^-)} = 6.56 \pm 0.29 \pm 0.65\%$$

$X(3872)$ quantum numbers using $J/\psi\rho$ decays

[PRD 92 1, 011102]

Making short a long history

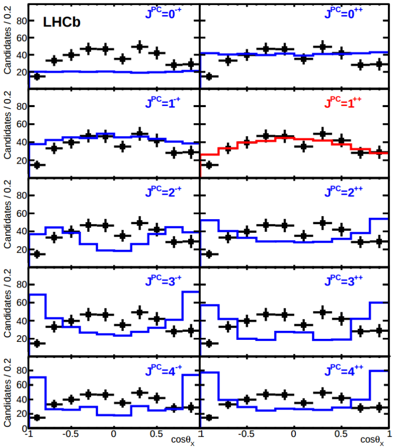
- $X(3872)$ observed at Belle (2003)
- CDF, D0, and Babar confirm it exists
- $X(3872) \to J/\psi\gamma$ implies $C = +$
- $X(3872) \to J/\psi\rho^0$ implies $J_{\pi\pi} = 1$
- Angular analysis at CDF finds $J^{PC} = 1^{++}$ or 2^{-+}
- With 2011 LHCb data: $J^{PC} = 1^{++}$.

Extension to full Run1 dataset (LHCb)

LHCb and CDF analyses rely on the assumption of a matrix element dominated by the lowest angular momentum ($L_{\min}$) between products.

Exotic nature of $X(3872)$ can introduce contribution of $L_{\min} + 2$, invalidating 1^{++} assignment.

This is the first analysis with no assumption on L.



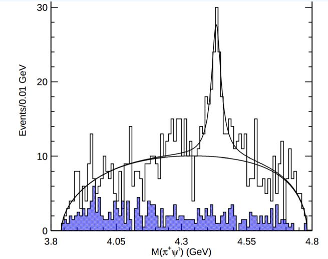
$\theta_X \equiv$ helicity angle of $X(3872)$

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

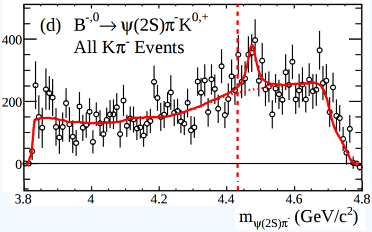
All alternative hypotheses discarded by 16σ or more.

$Z_c(4430)^-$ at Belle, Babar and LHCb

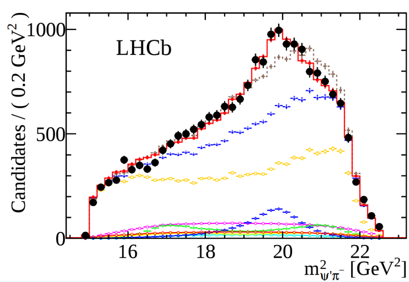
Observation at Belle [PRL 100:142001]



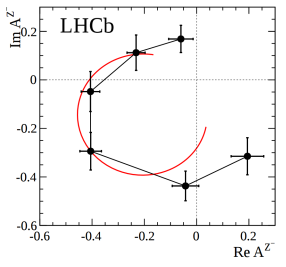
2.7σ excess at Babar (inconsistent mass) [PRD 79 112001]



Confirmation at LHCb (with Babar's mass) [PRL 112, 222002]



with unambiguous resonant behaviour



PRELIMINARY RESULT!

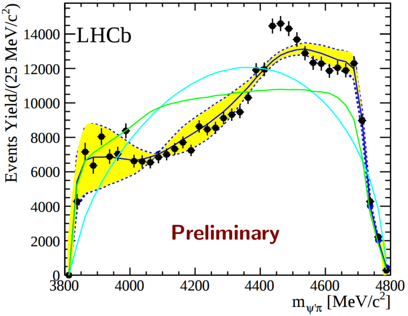
Following the example of the Babar's analysis, LHCb attempts to describe the $\psi(2S)\pi^-$ mass in terms of reflections of the $K\pi$ system.

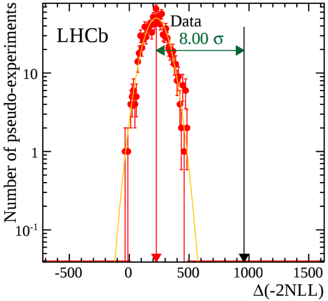
- In fine bins of $m(K\pi)$, decompose distribution $\cos(\theta^*_K)$ on the first $\ell_{\max}$ spherical harmonics (**moments**).
- Generate phase-space simulation (cyan)
- Reweight MC to reproduce $m(K\pi)$ distribution (green)
- Reweight MC according to the moments (yellow)

K^* resonance with ℓ larger than 6 are unphysical: $\ell_{\max} = 6$.

Conclusion: $K\pi$ structures with reasonable angular momentum are insufficient to explain the $m_{\psi'\pi}$ distribution.

The null hypothesis, with no $Z_c(4430)$ is rejected by 8σ, or more.





LHCb extended the study of the $\psi(2S)\pi^-$ system to the $\bar{B}_s^0 \to \psi(2S)K^+\pi^-$ decay.

The decay is largely dominated by $\bar{B}_s^0 \to \psi(2S)K^*(892)^0$.

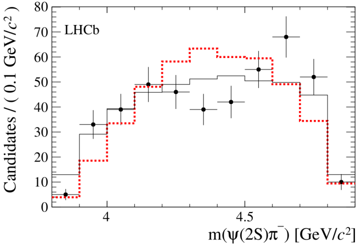
LHCb reports the first observation of the non resonant decay.

The small relative branching ratio

$$\frac{\mathcal{B}(\bar{B}_s^0 \to \psi(2S)K^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^+\pi^-)} = 5.38 \pm 0.36 \pm 0.22 \pm 0.31 \left(\frac{f_s}{f_d}\right)$$

makes the statistics limited.

No structure observed in $m(\psi(2S)\pi^-)$ spectrum.



solid histogram: amplitude fit model
dotted histogram: phase-space

Summary

Spectroscopy studies are very active at the LHC and all over the world.

In the last year

- New excited b-mesons and b-baryons were observed,
- The first spin-3 charm mesons were found in b-decays,
- An excited B_c^+ state was seen,
- A tetraquark was unambigously identified as such,
- Two pentaquarks were observed.

Enhance interest in $B \to DDX$ decays as probe of over-threshold charmonia, and as play-ground for excited charmed states (*e.g.* $D_s^*(2700)^+$).

All of the studies presented here are dominated by statistical uncertainties.

The higher HF production cross-section, and the increased luminosity make the **second run of the LHC extremely promising** for spectroscopy studies.

Teasers include:

- Double heavy baryons (Ξ_{cc}, Ξ_{bc}, ...)
- More B_c excited states
- $B_c^+ \to D_{(s)}^{(*)+} D_{(s)}^{(*)+} h^-$ decays

Spare slides

Study of B decays to final states containing η_c at Belle

[JHEP 1506(2015)132]

Molecular interpretation of $X(3872)$ suggests other $D\bar{D}$ states may exist.

Belle searches for $X_1(3872)$, $X(3730)$, and $X(4014)$ to final states: $\eta_c\pi^+\pi^-$, $\eta_c\pi^0$, and $\eta_c\eta$ (where $\eta \to \gamma\gamma$ or $\eta \to \pi^+\pi^-\pi^0$).

The analysis strategy is based on **unseen** $B^\pm \to K^\pm\eta_c + nh$ decays.

Upper limits are given at 90% of C.L.

$\mathcal{B}(B^\pm \to K^\pm\eta_c\pi^+\pi^-)$	39 $\times 10^{-5}$
$\eta_c\pi^+\pi^-$ from $X_1(3872)$	3.0 $\times 10^{-5}$
$\eta_c\pi^+\pi^-$ from $Z_c(3900)$	4.7 $\times 10^{-5}$
$\eta_c\pi^+\pi^-$ from $Z_c(4020)$	1.6 $\times 10^{-5}$
$\mathcal{B}(B^\pm \to K^\pm\eta_c\omega)$	53 $\times 10^{-5}$
$\eta_c\omega$ from $X_1(3872)$	6.9 $\times 10^{-5}$
$\eta_c\omega$ from $Z_c(3900)^0$	4.7 $\times 10^{-5}$
$\mathcal{B}(B^\pm \to K^\pm\eta_c\eta)$	22 $\times 10^{-5}$
$\eta_c\eta$ from $X(3730)$	4.6 $\times 10^{-5}$
$\eta_c\eta$ from $X(4014)$	3.9 $\times 10^{-5}$
$\mathcal{B}(B^\pm \to K^\pm\eta_c\pi^0)$	6.2 $\times 10^{-5}$
$\eta_c\pi^0$ from $X(3730)$	0.6 $\times 10^{-5}$
$\eta_c\pi^0$ from $X(4014)$	1.2 $\times 10^{-5}$
$\eta_c\pi^0$ from $X(3915)$	1.8 $\times 10^{-5}$

Assumptions

	Molecule
$X_1(3872)$	$D^0\bar{D}^{*0} - \bar{D}^0D^{*0}$
$X(3730)$	$D^0\bar{D}^0 + \bar{D}^0D^0$
$X(4014)$	$D^{*0}\bar{D}^{*0} + \bar{D}^{*0}D^{*0}$

	J^{PC}	Modes
$X_1(3872)$	1^{+-}	$\eta_c\omega, \eta_c\rho$
$X(3730)$	0^{++}	$\eta_c\eta, \eta_c\pi^0$
$X(4014)$	0^{++}	$\eta_c\eta, \eta_c\pi^0$