Hadron Spectroscopy
Results from LHCb

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Spectroscopy: *no longer stamp collection*

In the last 15 years many new states not fitting the expectations for qqq and $q\bar{q}$ states.

for a recent review see for example 1708.04012

The nature of the new states is still not obvious: three main domains of investigation open

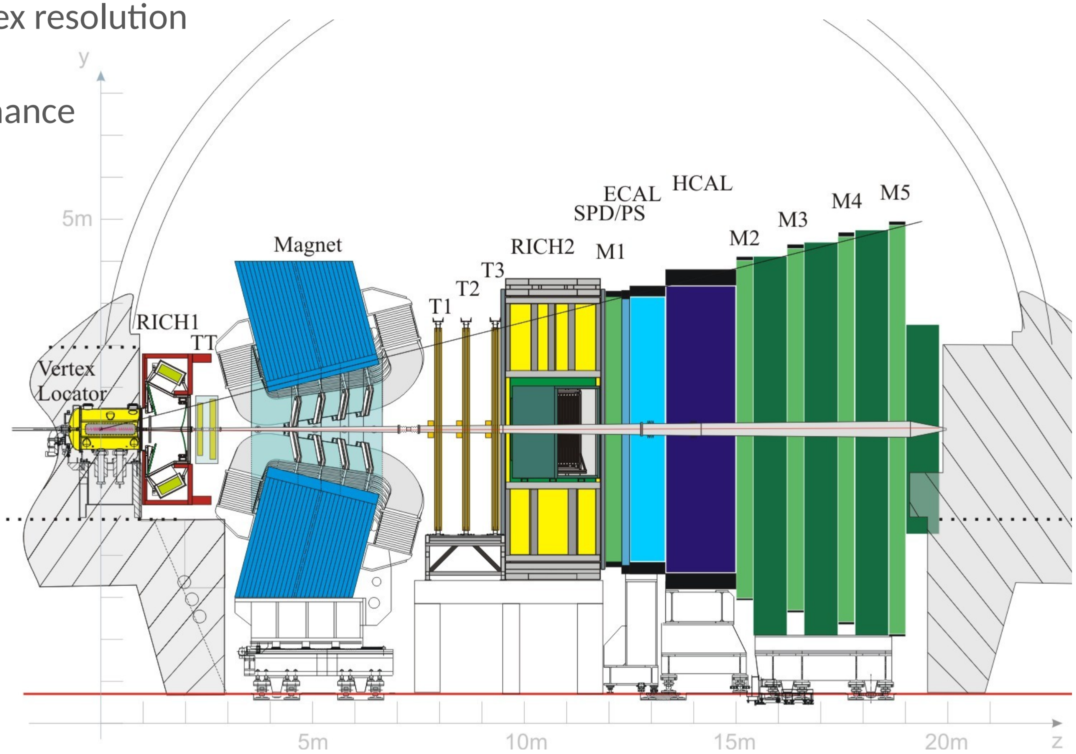
- ➪ Search for new exotic states
  to complete isospin multiplets and confirm quark-model interpretation
- ➪ Study of the excitations of known states
  to constrain and gain confidence the QCD models used to describe heavy hadrons
- ➪ Study the production mechanisms of exotic states (relative to conventional states)
  different interpretations of the exotic states result into different predictions for production

The LHCb experiment: *designed for heavy flavours*

Originally designed to search indirect evidence of new physics in CP violating a rare *b* and *c* decays, LHCb is today a general purpose detector in the forward region.

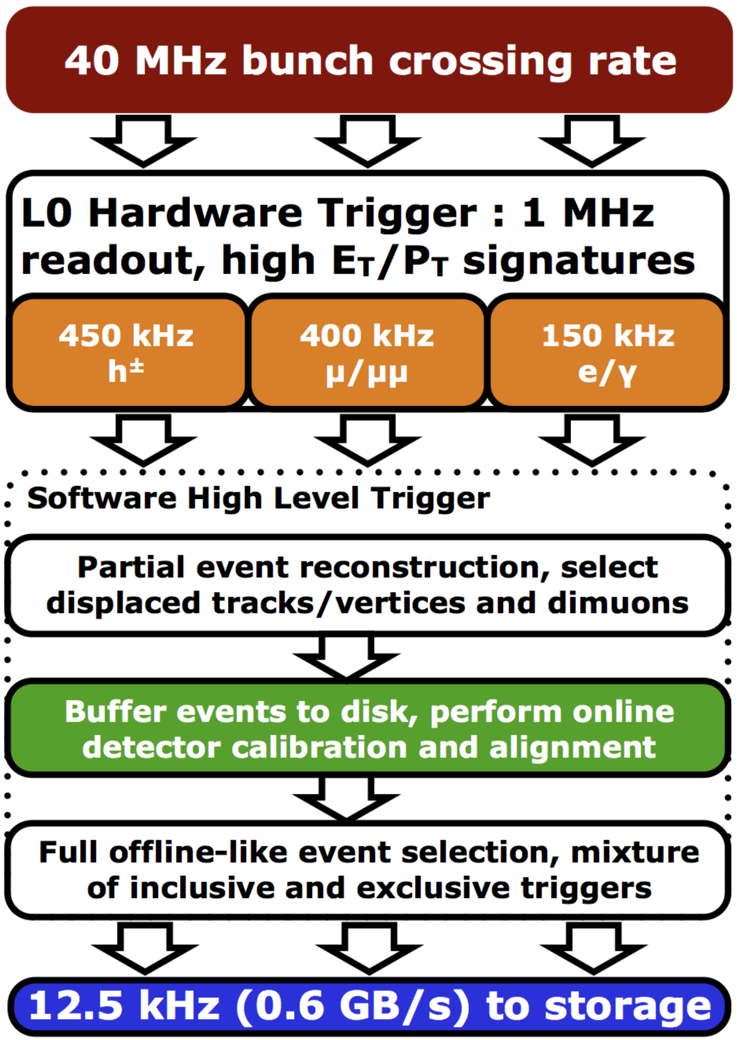
- ➔ unique geometrical coverage
- ➔ outstanding track momentum and vertex resolution
- ➔ excellent Particle Identification performance
- ➔ unique trigger strategy

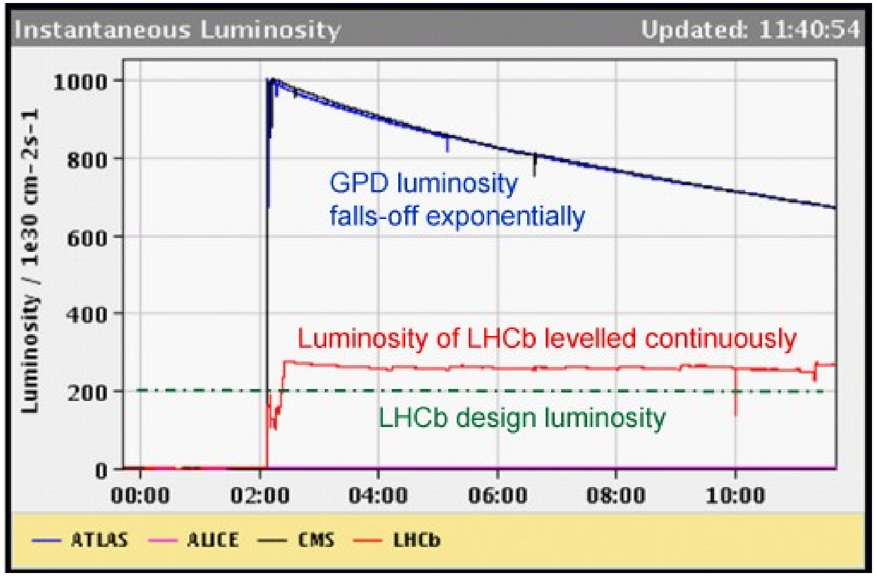
Tracking efficiency	> 96 %
Decay time resolution	45 fs
Momentum resolution	0.5 - 1.0 %
Software trigger input	10^6 events / s



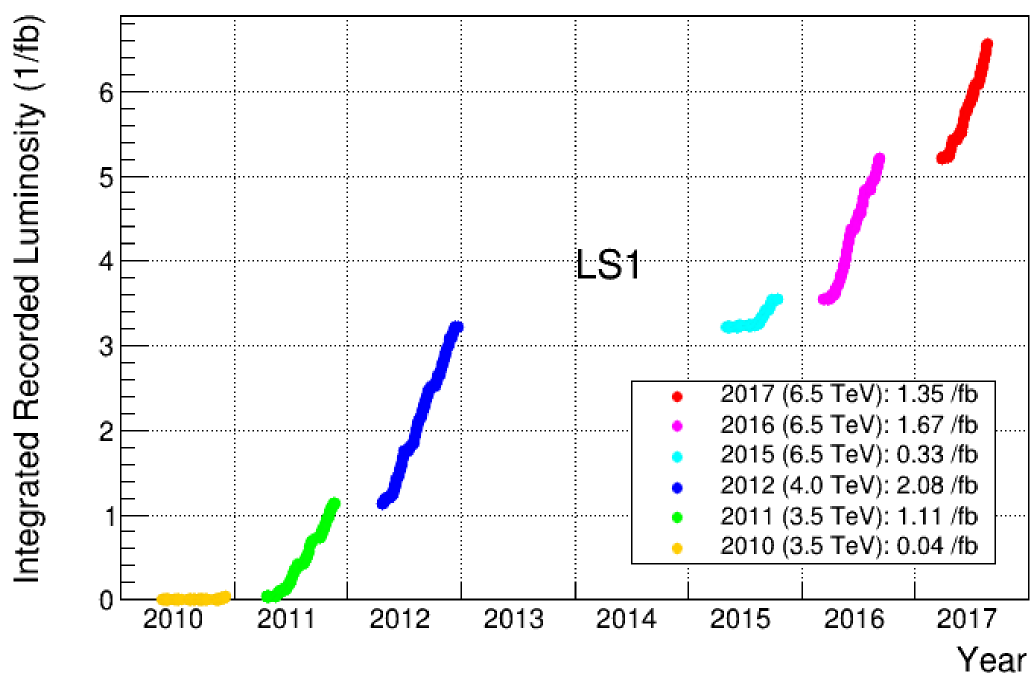
Trigger and data-processing

LHCb-Run2 Trigger scheme





LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2017



Quarkonium(-like) Spectroscopy at the hadron colliders

Production through heavy meson decays
c- and b-mesons long lifetime is sufficient to well separate most tracks of decay products from the primary proton-proton interaction.
Often requires amplitude analysis, in some cases Dalitz analysis is enough.
Competitive with b-factories.

Covered in Andrii's talk

Production through heavy baryon decays
b-baryons have long lifetime and measurable decay length, c-baryons are more challenging.
Requires amplitude analysis due to ½ - spin of the initial state
Unique to hadron colliders.

Covered in Mengzhen's talk

Direct production in *pp* collisions
Often requires dedicated trigger to select the final state.
Great progress made in Run 2 making RICH-based particle identification available at trigger level
The production cross-sections are usually very large compared to $\sigma(b) \times$ BF, but the background can be larger.

Covered in this talk

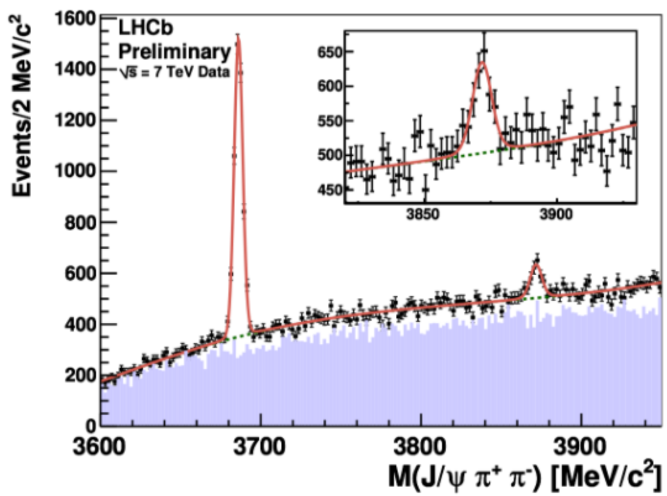
Other LHCb talks on Spectroscopy by *Daniel Vieira* on baryons

EPJ C 72 (2012) 1972

Spectroscopy at LHCb (as from the *LHCb News*)

27 October 2010: Exotic mesons

In 1964 Murray Gell-Mann and George Zweig proposed the quark model (QM) in which mesons, like π mesons, are formed from quark and anti-quark pairs and baryons (like protons) from three quarks. The model is very succesful, but recently particles which could not be classified in this model have been discovered. LHCb has observed one of these exotic state candidates called X(3872) using its decay into a J/ψ meson (see 6 September news) and a π± π- pair. The J/ψ decays in turn into a μ± and μ- pair. The invariant mass of J/ψ π± π- is shown in the figure below. The left enhancement at the mass of 3686 GeV is consistent with the QM bound state ψ' of charm and anti-charm quarks, the right one at the mass of 3872 GeV has properties that are very difficult to reconcile with the Gell-Mann Zweig QM. Possible explanations include a meson-meson molecule (DD* for experts) or multi quark anti-quark system (diquark-diantiquark tetraquark meson for experts).



this plot was made using all data taken in 2010, click in the image to get it in higher resolution, click here to see original plot.

The particle with the mass of 3872 Gev was first observed by the BELLE collaboration in 2003 and is called X(3872). The observation of this particle at this early stage of data taking by LHCb confirms the excellent performance of the LHCb detector and data analysis.

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13 October 2010: LHCb control room in action

Spectroscopy at LHCb (as from the *LHCb News*)

13 September 2017: New avenue to precision mass measurements of the χ_{c1} and χ_{c2} mesons.

[$m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09$ MeV; $m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11$ MeV]
[$\Gamma(\chi_{c2}) = 2.10 \pm 0.20 \pm 0.02$ MeV]

Today, at the open session of the Large Hadron Collider Committee, LHCC, the LHCb collaboration presented the result of a precise mass measurements of χ_{c1} and χ_{c2} mesons, performed for the first time by utilising the newly discovered decay $\chi_{c1,2} \to \mu^+\mu^- J/\psi$.

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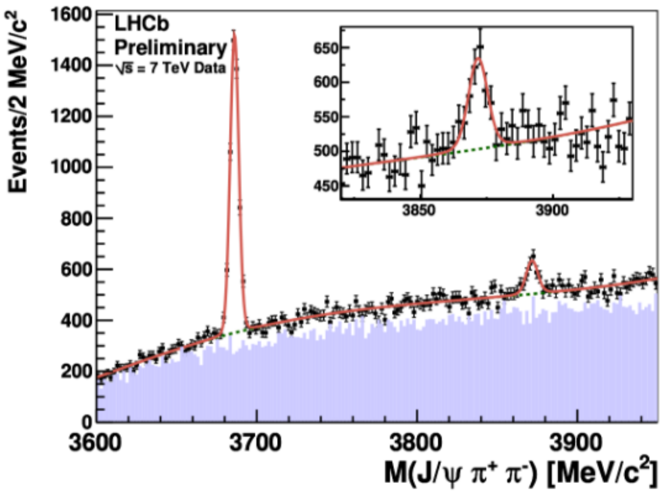

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13 October 2010: LHCb control room in action

Dalitz decay $\chi_{cJ} \to J/\psi\, \mu^+ \mu^-$

Observed a new decay of χ_{c1} and χ_{c2} states: $\chi_c \to J/\psi\, \mu^+ \mu^-$ with $J/\psi \to \mu^+ \mu^-$.

A very important decay for experiments at hadron colliders:

no-photon, low energy release:

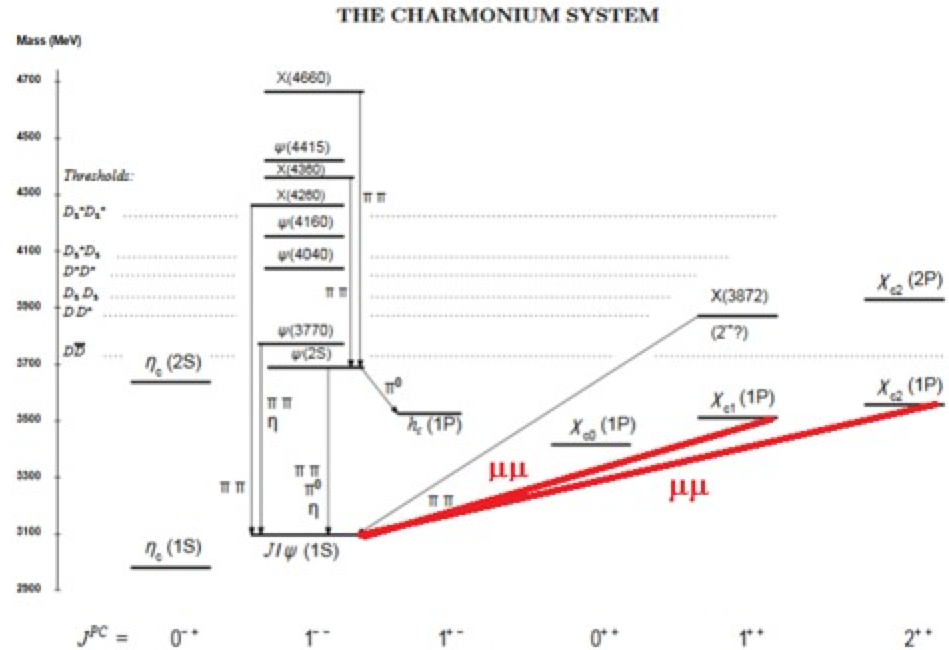
mass & width measurements competitive with full annihilation experiments

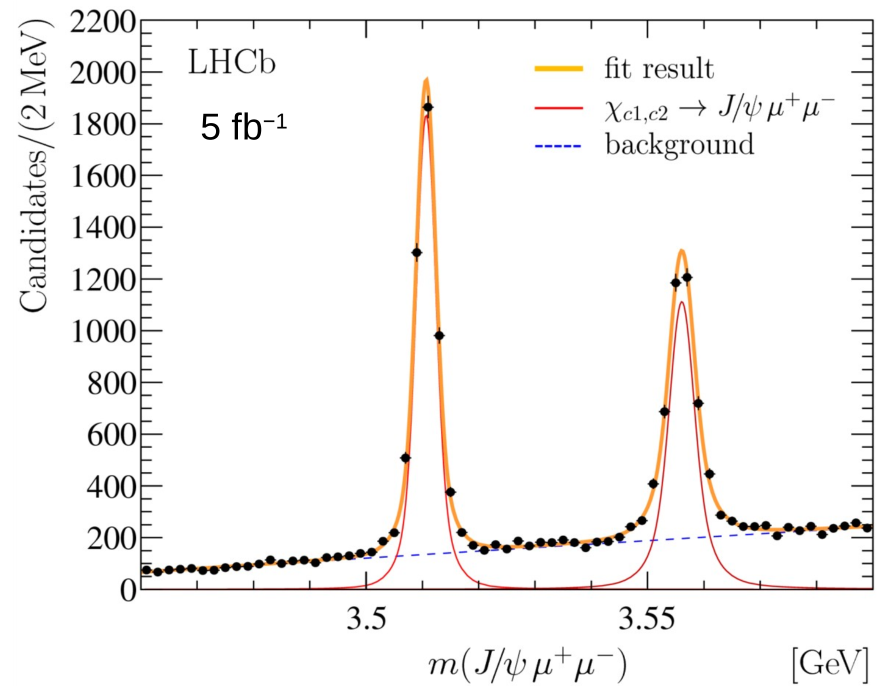
4-muon final state

very effective muon-identification allows significant signal down to low p_T allowing interesting production & polarization measurements

Exotics found through the μ-Dalitz decay?

no evidence so far.





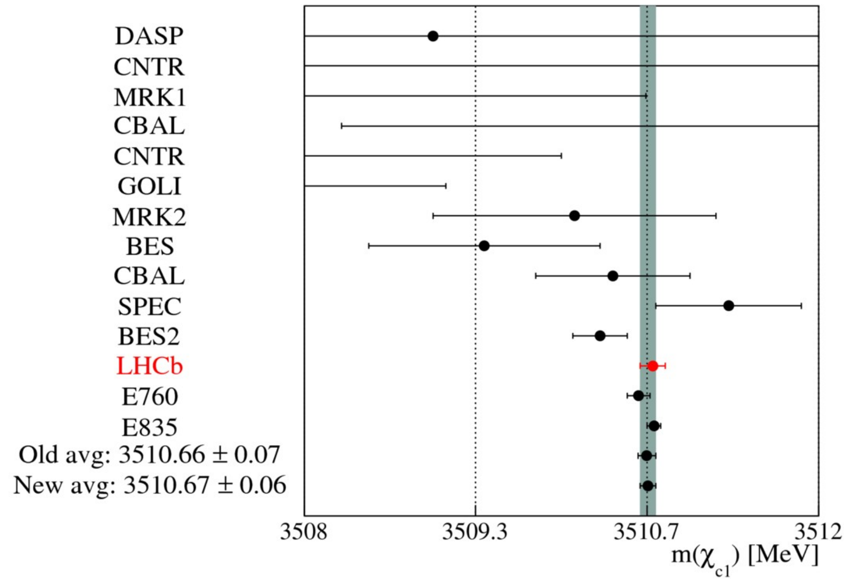
Precision measurements on the χ_c parameters

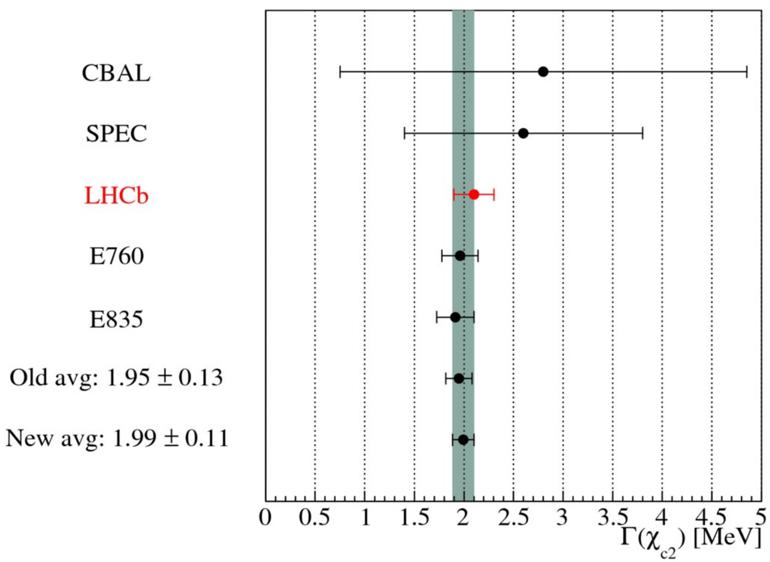
Dominant uncertainty:

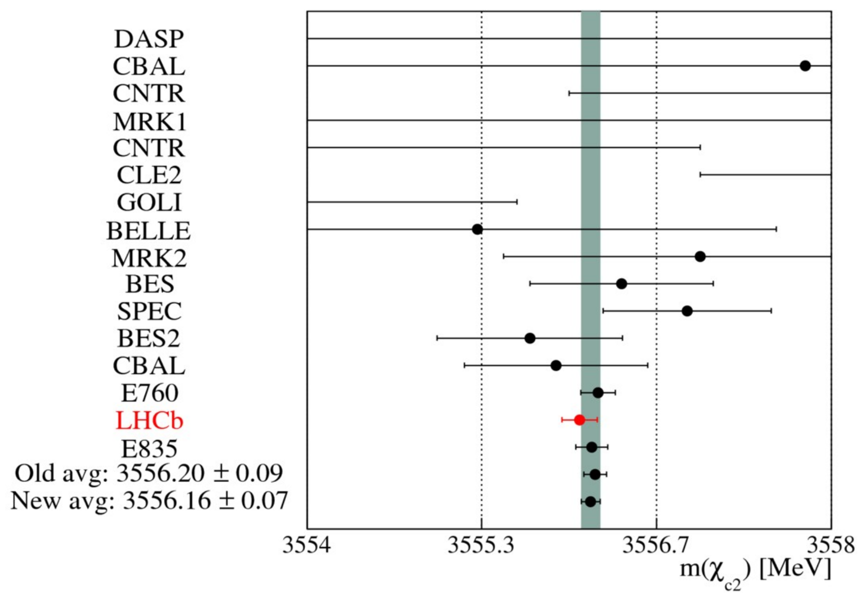
on masses: ***momentum scale***

on mass-difference and width: ***statistics***

$$m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09\,\text{MeV},$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11\,\text{MeV},$$
$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03\,\text{MeV},$$
$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{MeV}.$$







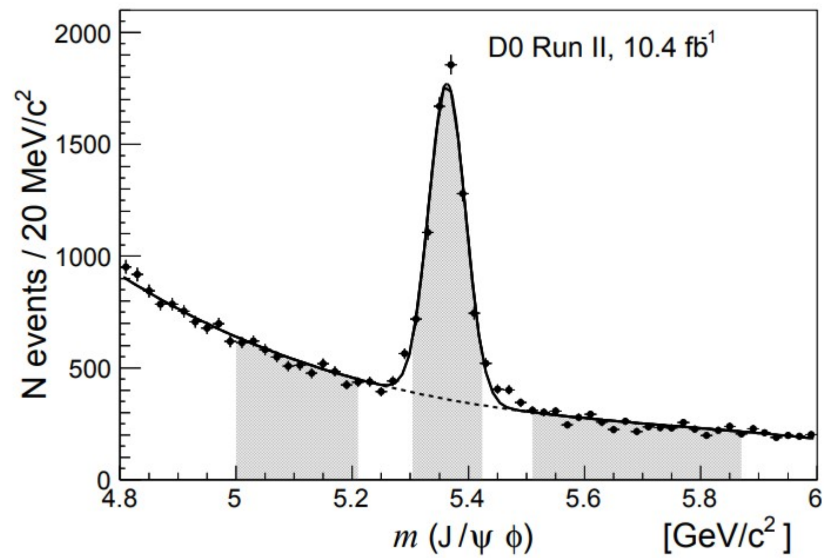
Evidence for $X(5568) \rightarrow B_s\,\pi^+$ at the TeVatron

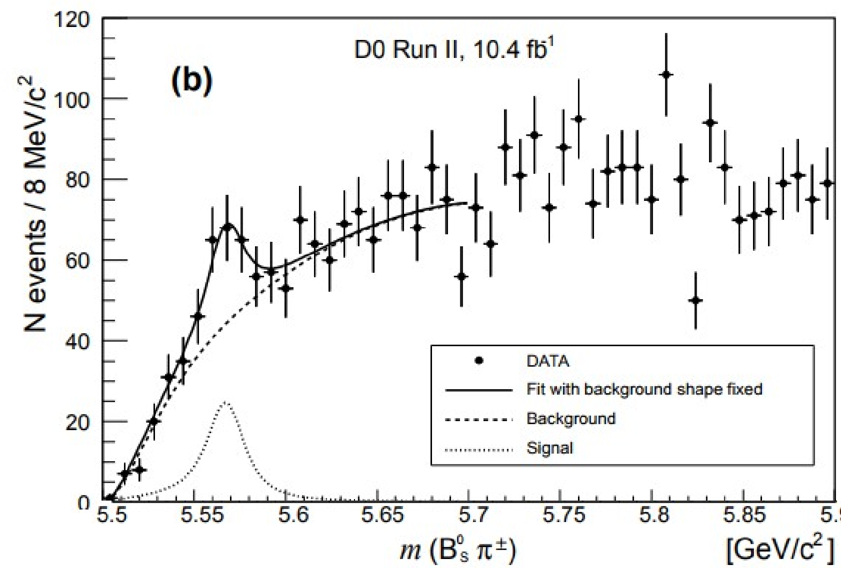
On February, 2016 the D0 Collaboration reports an evidence for a charged state decaying to $B_s\pi^{\pm}$ with $B_s \rightarrow J/\psi\ \phi$.

The state is interpreted as the first *b*-flavoured tetraquark ($b\bar{s}u\bar{d}$) decay by strong interaction.

A puzzling “production” property: about 8% of the B_s mesons would be produced in the decay of *X*(5568).

→ Never spotted for flavour tagging?

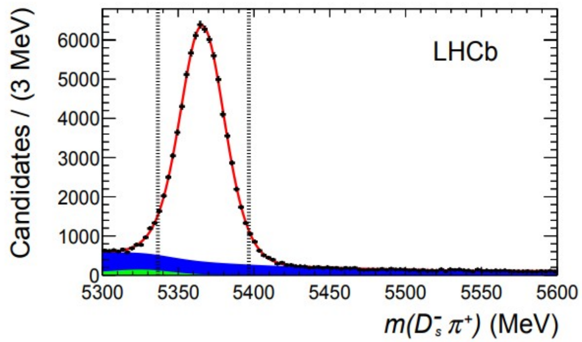


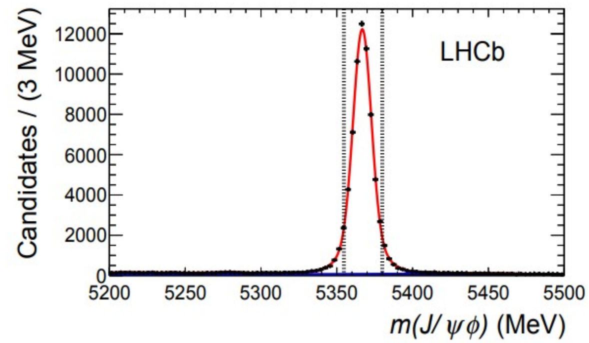


Non-confirmation of *X*(5568) at the LHC

Combining $B_s \to D_s\,\pi$ and $B_s \to J/\psi\,\phi$ in the Run 1 dataset (3 fb^{-1}),

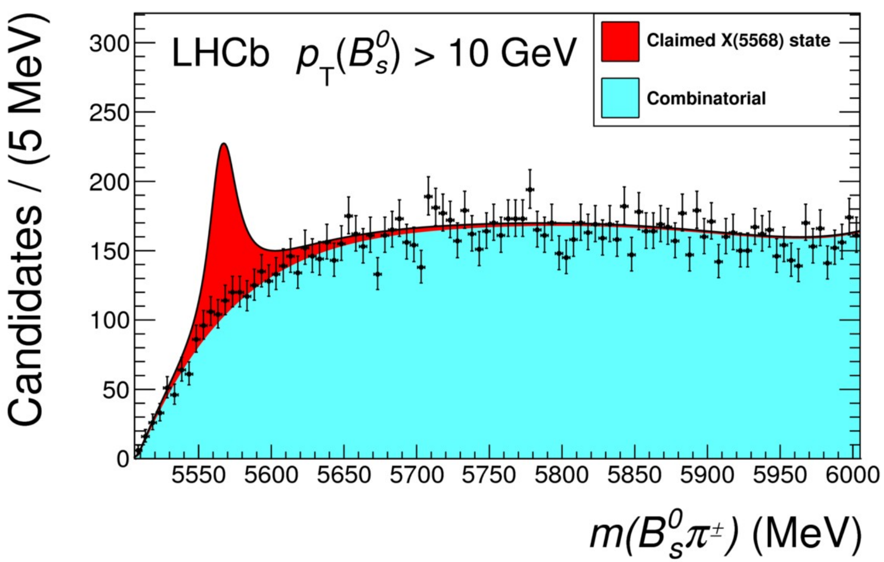
much larger sample than D0

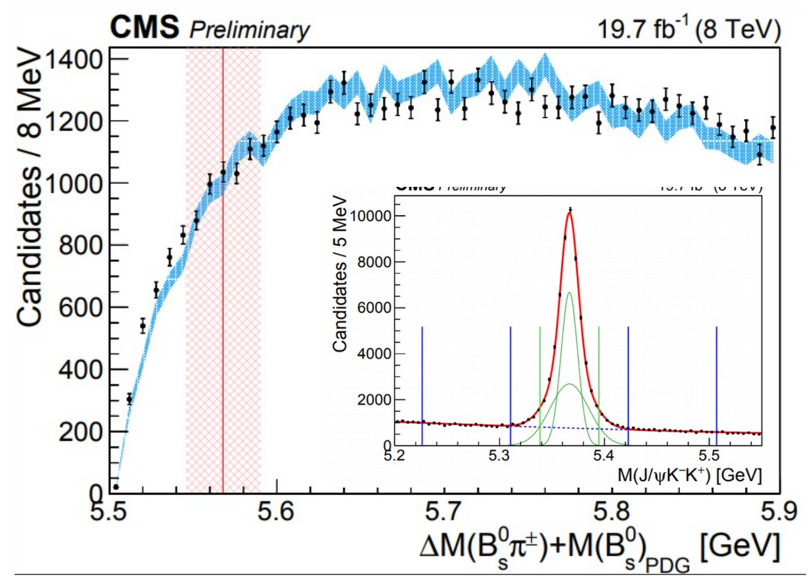




and assuming the same production rate, LHCb should observe a huge signal,

while no significant deviation from background-only is observed

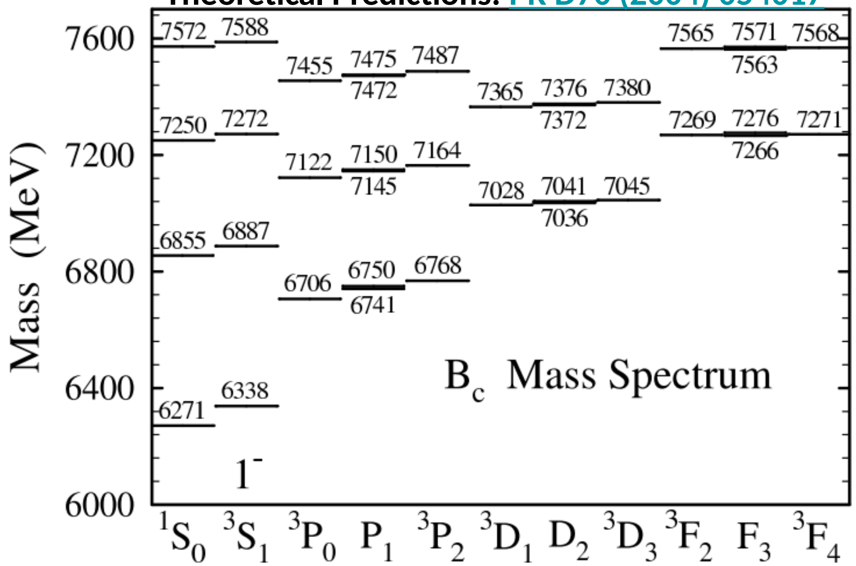


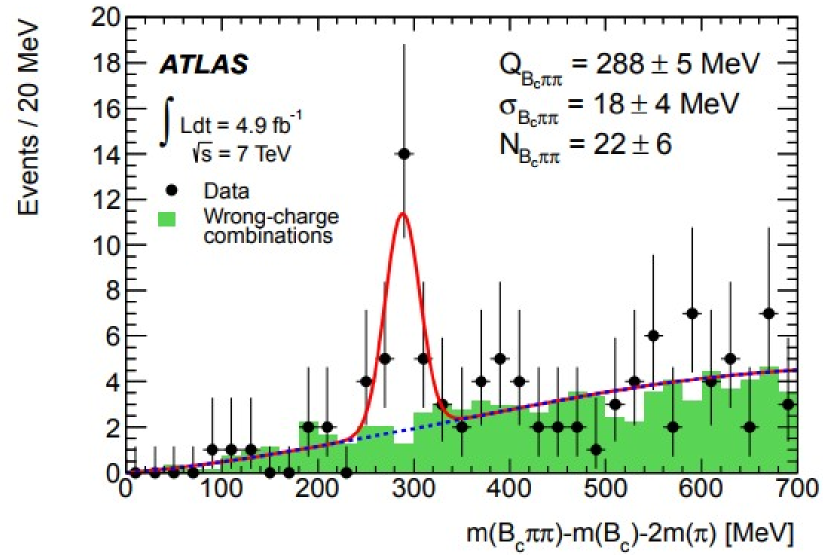


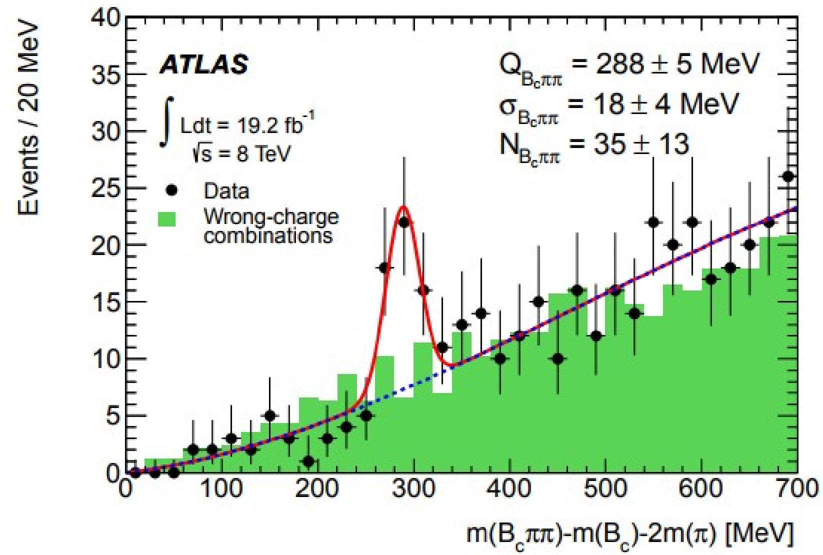
Observed $B_c^{**}(2S) \to B_c\, \pi^+ \pi^-$ with the ATLAS experiment

ATLAS observed on both 2011 and 2012 datasets a bump in the distribution of $m(B_c\ \pi^+ \pi^-)$.

Theoretical Predictions: PR D70 (2004) 054017







If interpreted as observation of the decay $B_c^{**}(2S) \to B_c\, \pi^+ \pi^-$, the mass of the new state would be:

$$6842 \pm 4 \pm 5\ \text{MeV}/c^2$$

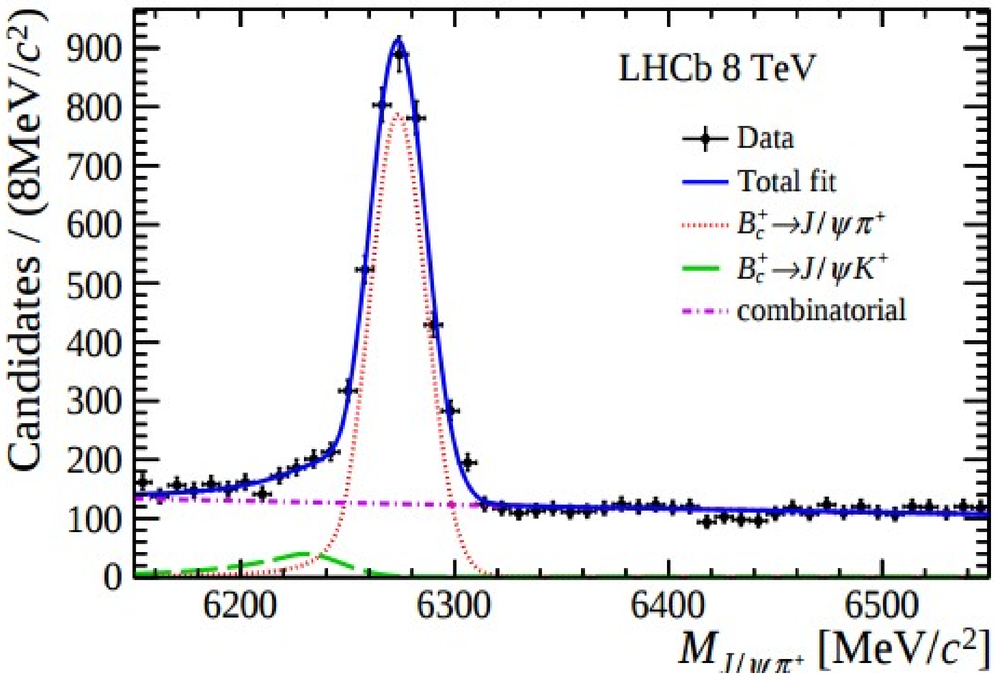
The large B_c collected by the LHCb experiment

LHCb collected roughly 10 times the statistics of ATLAS for the decay

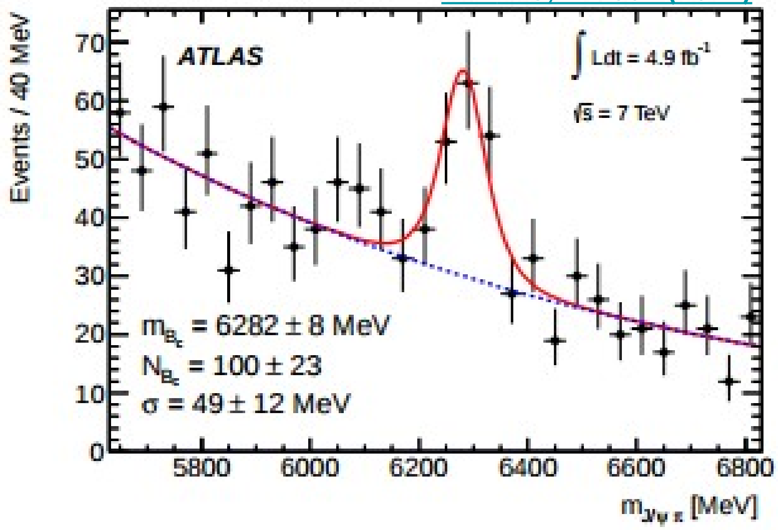
$$B_c \to J/\psi\ \pi$$

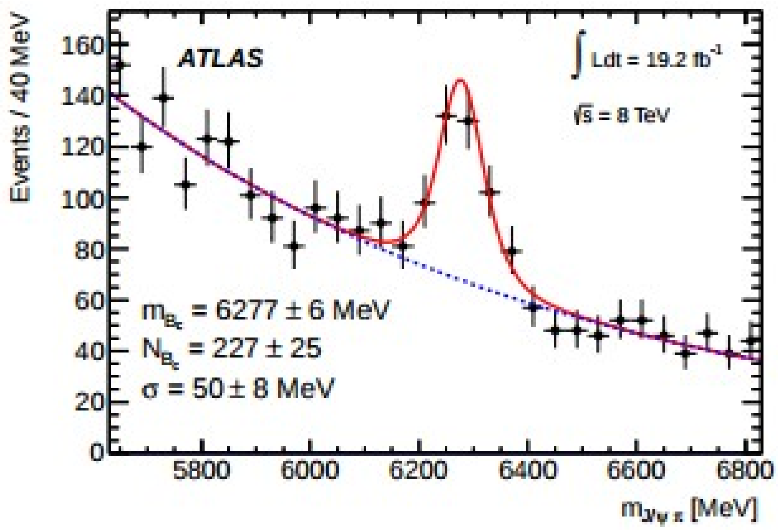
But in a different kinematic region

$p_T < 20$ GeV/c $\quad 2 < \eta < 4.5$



PRL 113, 212004 (2014)

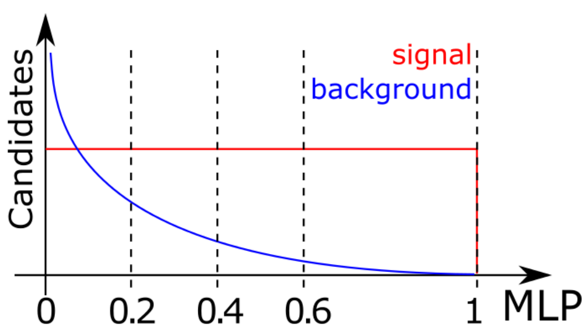


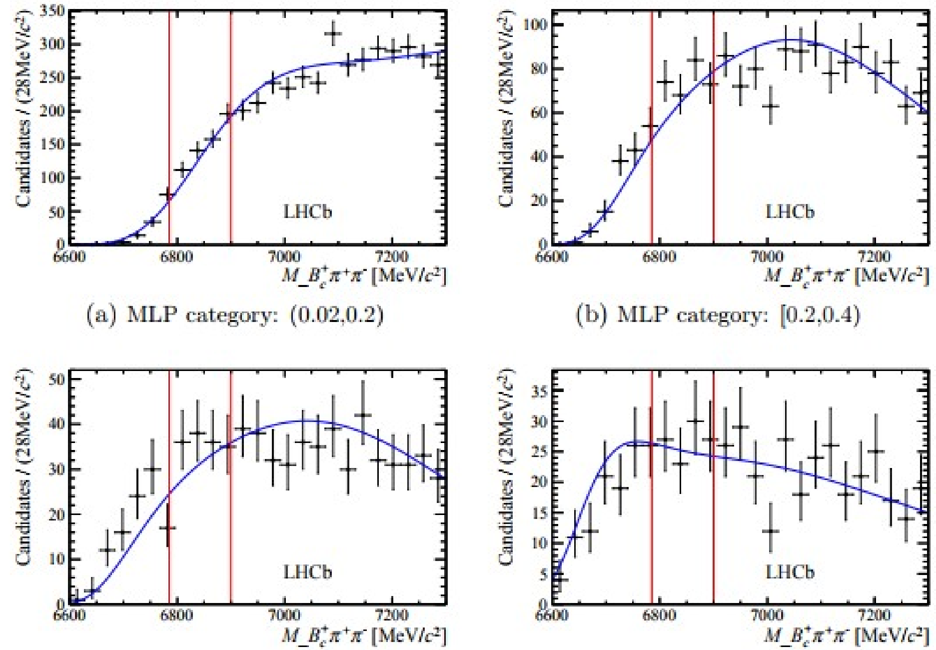


Non-confirmation of $B_c^{**} \rightarrow B_c\, \pi^+ \pi^-$ with 8 TeV LHCb data

Integrated luminosity: 2 fb^{-1}

The analysis is performed in four bins of a flattened MLP trained on a simulated sample for signal and sidebands for the background (cross-checked with wrong-sign combinations Bc $\pi^+ \pi^-$)





(a) MLP category: (0.02,0.2)
(b) MLP category: [0.2,0.4)
(c) MLP category: [0.4,0.6)
(d) MLP category: [0.6,1.0]

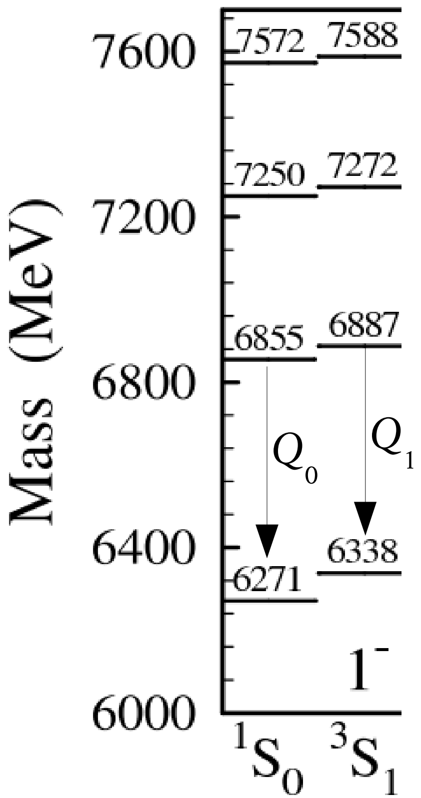
No evidence of signal.

An upper limit is set on the relative production

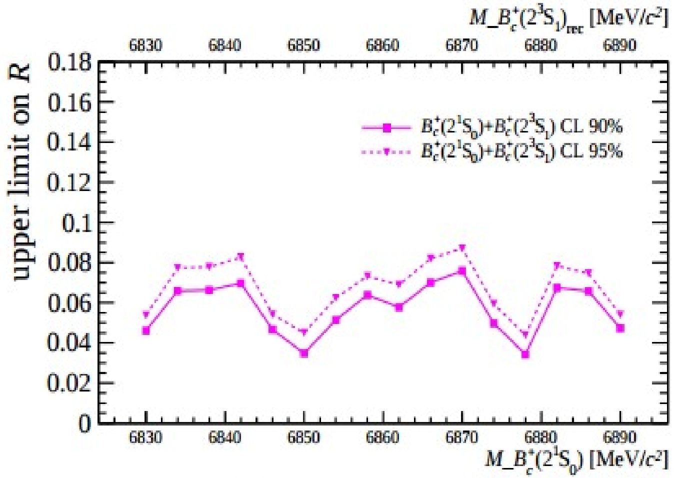
$$\mathcal{R} = \frac{\sigma_{B_c^{(*)+}(2S)}}{\sigma_{B_c^+}} \cdot \mathcal{B}_{B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-}$$
$$= \frac{N_{B_c^{(*)+}(2S)}}{N_{B_c^+}} \cdot \frac{\varepsilon_{B_c^+ \to J/\psi\, \pi^+}}{\varepsilon_{B_c^{(*)+}(2S) \to B_c^+(\to J/\psi\, \pi^+)\pi^+\pi^-}}$$

Upper limit set with LHCb data

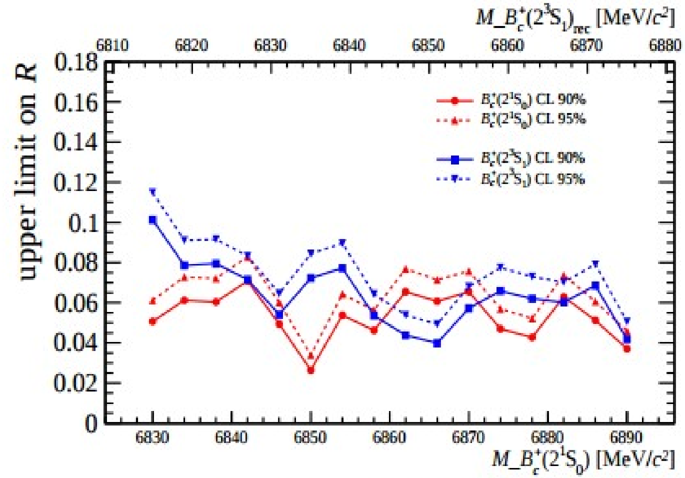
PR D70 (2004) 054017



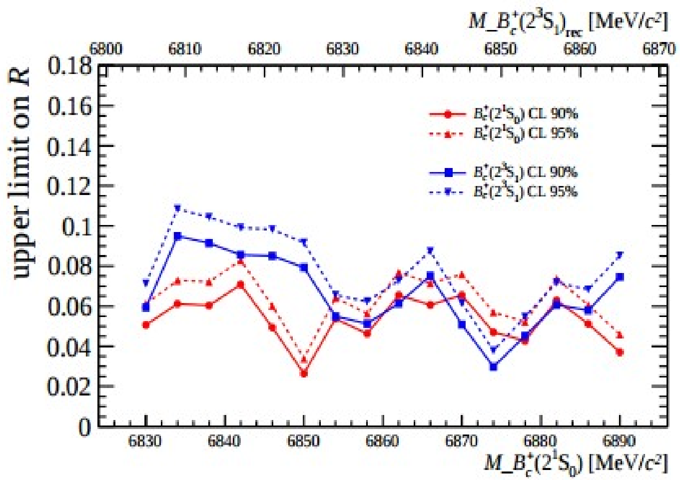
$\Delta M = Q_1 - Q_0$



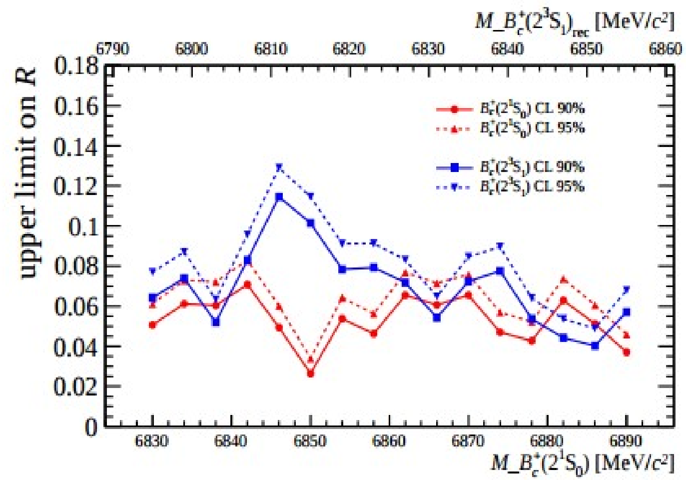
(a) $\Delta M = 0\,\text{MeV}/c^2$



(b) $\Delta M = 15\,\text{MeV}/c^2$



(c) $\Delta M = 25\,\text{MeV}/c^2$



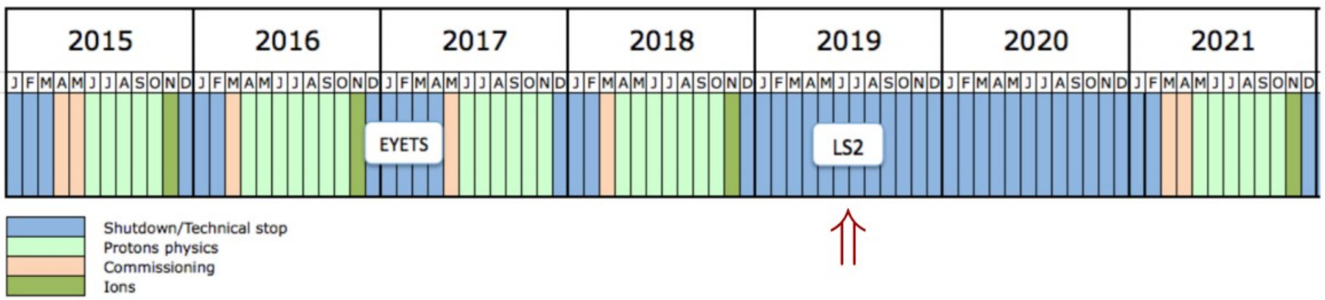
(d) $\Delta M = 35\,\text{MeV}/c^2$

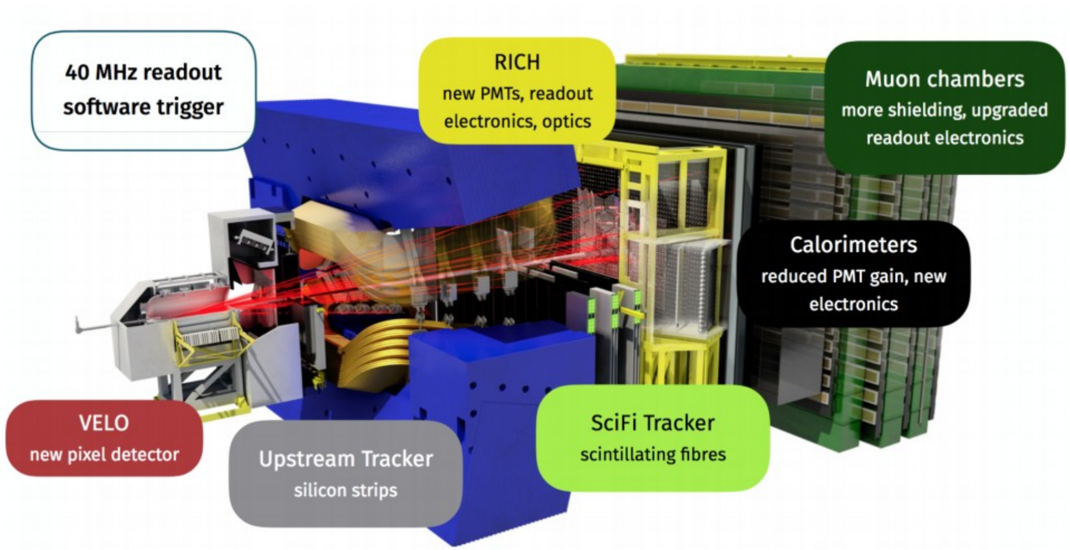
Spectroscopy with the upgraded LHCb

LHCb is going through an upgrade phase which will allow higher integrated luminosity by processing with the software trigger all events at the bunch-crossing energy of 40 MHz.

Teasers: *hadron identification will be available at the trigger level: great increase of trigger efficiency on **prompt decays** to purely hadronic final states including of low* p_T *particles.*

Challenges: *a new computing approach to data-analysis is needed to move as much as possible to exclusive selections.*





Summary

LHCb is a key player in the field of heavy hadron spectroscopy.

Prompt production is being explored to study

- new decay mode of well known states, as $\chi_c \to J/\psi\, \mu^+ \mu^-$
- exotic states, as the $X(5568)$ pointed out by D0
- excited states of known hadrons $B_c(2S)$

The upcoming **LHCb upgrade** is very promising for completing the puzzle:

- larger statistics for from-*b* production of new states
- better efficiency on prompt decays to purely hadronic final states

Backup

$B_c^+ \to J/\psi\ \pi^+$ in the ATLAS and LHCb searches for Bc(2S)