Recent results from LHCb

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on behalf of the LHCb collaboration

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The LHCb experiment

The LHCb experiment: precision studies of b and c-hadron decays (CP violation, rare decays) $\rightarrow$ test SM/indirect evidence of NP

Requirements:

- High yield $\rightarrow$ efficient trigger and selection, large production cross sections: $\sigma_{\bar{b}b} \sim 110\mu$b, arXiv:1612.05140, $\sigma_{\bar{c}c} \sim 2.4$mb, arXiv:1510.01707, @13 TeV in LHCb accpt.
- Low background $\rightarrow$ mass resolution, particle identification

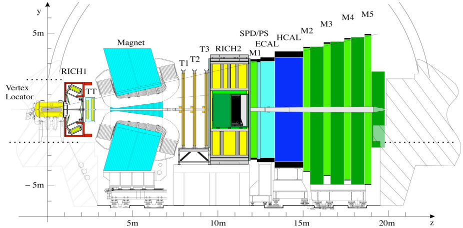
LHCb detector:

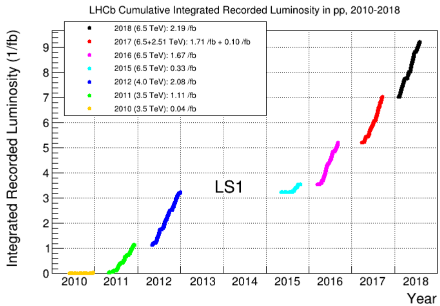
- Vertexing&Tracking: excellent resolutions
- Particle identification: $\pi/K/p$ (RICH), $\pi/e/\gamma$ (E/HCAL), μ (MUON)
- Trigger: L0 (hardware: high p_T e/γ/hadron/μ candidates), HLT1&HLT2 (software)
    - (since Run2) perform an almost run-time detector alignment and calibration

Data Taking:

- operating at a levelled inst. lumi $\mathcal{L} \sim 4 \times 10^{32}\mathrm{cm}^{-2}s^{-1}$
- Run1: $\int \mathcal{L} = 3$ fb^{-1} @7 and 8 TeV
- Run2: $\int \mathcal{L} \simeq 6$ fb^{-1} @13 TeV (x2 $\sigma_{\bar{b}b}$ and increased trigger efficiency)

2008 JINST 3 S08005, Int. J. Mod. Phys. A30 (2015) 1530022.





Outline

Selection of most recent/relevant/interesting LHCb measurements:

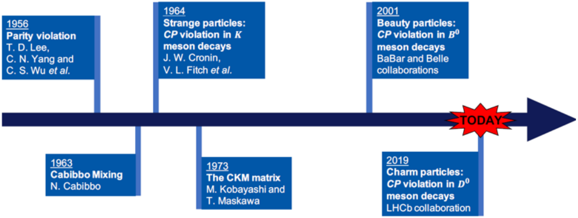
- **CP violation** in b and $c-$hadron decays
- **Precision** measurements of heavy-flavor hadron properties
- **Hadron spectroscopy**

Not covered by this talk:

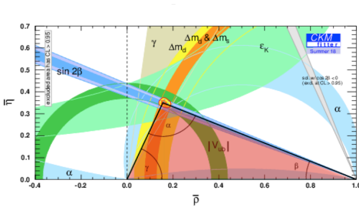
- Tests of fundamental symmetries (LFU) $\rightarrow$ see the talk by Jacopo Pinzino this afternoon
- QCD, Jets $\rightarrow$ see the talk by Christine Angela Aidala this afternoon
- Rare decays
- Heavy Ion & fixed-target physics results
- Electroweak measurements

see the LHCb public results web page for more information

CP violation



CKMfitter



CP violation is one of the key ingredients needed to explain why today's universe is only composed of matter particles

- is described by the Standard Model through one parameter in the CKM matrix, but insufficient
- was established experimentally in K and B meson decays since many years
- is expected to be tiny in **charm meson decays**: $10^{-3} - 10^{-4}$
- physics beyond the the SM (NP) could contribute to CP violation

CP violation: first observation of CP violation in D^0 meson decays

CP violation may manifest itself in decays where two or more amplitudes with different weak-phases interfere.

The asymmetry in the decays of D^0 and $\bar{D}^0$ to a common final state

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \sim a_{CP}^{dir} - \frac{\langle t(f) \rangle}{\tau(D^0)} a_{CP}^{ind}$$

is sensitive to both **direct** ($|\bar{A}_f|^2 \neq |A_f|^2$) and **indirect CPV** (through $D^0 - \bar{D}^0$ mixing or the interference between decay and mixing)

Time integrated measurement:

- huge statistics of D^0 from either **prompt** $D^{*+} \to D^0 \pi^+$ or $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$ decays
- efficient D^0 tagging
- large suppression of the systematic uncertainties by measuring

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

result (including previous LHCb measurement, Run1)

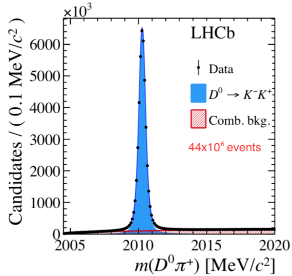
$\Delta A_{CP} = (-15.2 \pm 2.9) \times 10^{-4}$ deviates from 0 by $> 5\sigma$

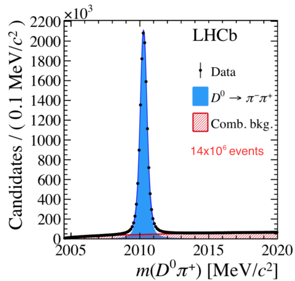
first observation of CPV in charm decays involving up-type quarks

roughly compatible with SM predictions (uncertainties)

Phys. Rev. Lett. 122 (2019) 211803

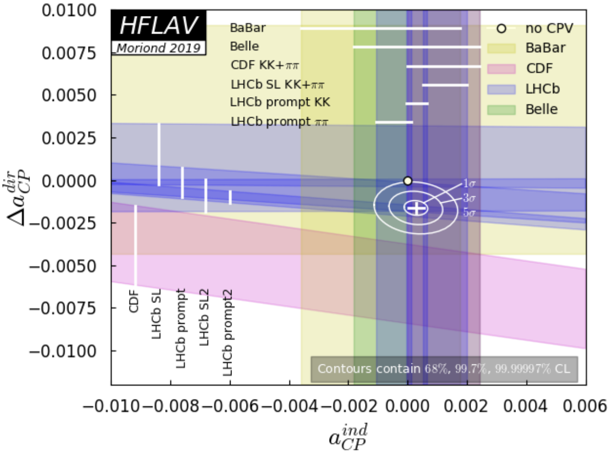
$\int \mathcal{L} = 5.9$ fb^{-1} – Run2





CP violation: first observation of CP violation in D^0 meson decays

HFLAV



$$\Delta A_{CP} \sim \Delta a_{CP}^{dir} + \frac{\Delta\langle t\rangle}{\tau(D^0)} a_{CP}^{ind}$$

Results from a global fit

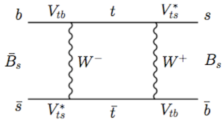
Agreement with no CP violation CL $= 5.4 \times 10^{-8}$

ΔA_{CP}^{dir} deviates from 0 by $> 5\sigma$

a_{CP}^{ind} consistent with 0 within 1σ

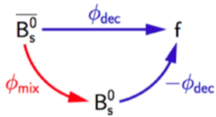
CP violation in B_s^0 decays: measuring the mixing-induced phase ϕ_s

- In the SM neutral B_s^0 meson can oscillate to its antiparticle via short-distance box-diagram.
- Mixing-induced CP violation can arise in the interference of the decay amplitudes to a common final state f with or without mixing and is measured by the asymmetry:

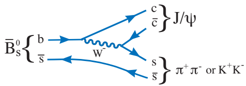


$$A_{CP}(f,t) = \frac{\Gamma(B_s^0(t)\to f) - \Gamma(\bar{B}_s^0(t)\to f)}{\Gamma(B_s^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)} \sim \eta_f \sin\phi_s \sin(\Delta m_s t)$$

where $\phi_s = -Arg(\frac{q}{p}\frac{\bar{A}_f}{A_f})$ contains contributions from both the mixing and the decay



- For decays dominated by a single weak transition $\phi_s = \phi_{\rm mix} - 2\phi_{\rm dec}$ and can be expressed in terms of CKM matrix elements.
- $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays are dominated by $\bar{b}\to\bar{c}cs$ transitions [a]. $\phi_s = 2Arg((V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)) = -2\beta_s$ (UT angle) is precisely known $\phi_s^{SM} = (-37.0 \pm 1.0)$ mrad UTfit



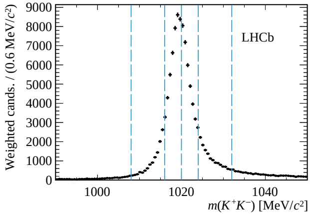
- Any possible contribution of NP in the mixing can cause a deviation from $-2\beta_s$: $\phi_s = -2\beta_s + \Delta\phi_s^{NP} + \Delta\phi_s^{Peng.}$

([a]) The contribution of penguin or other transitions is measured to be small Phys. Lett. B742 (2015) 38

CP violation in B_s^0 decays: improved measurements of the mixing-induced phase ϕ_s

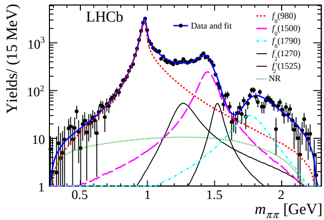
Two decay channels:

- $B_s^0 \to J/\psi K^+K^-$ arXiv:1906.08356
  different CP eigenstates contributing
- $B_s^0 \to J/\psi \pi^+\pi^-$ arXiv:1903.05530
  wide range of $m(\pi^+\pi^-)$ (several resonances), mainly CP-odd
- 1.9 fb^{-1} of Run2 data



Time-dependent tagged and angular analysis:

- High yields, low background
- Excellent decay-time resolution $\sigma_t \sim 45$ fs
- Efficiency to tag the initial $B_s^0/\bar{B}_s^0$ flavour $\sim 5.0\%$



results (combined with previous LHCb measurements, Run1)

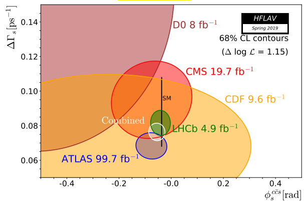
LHCb combination: $\phi_s = (-41 \pm 25)$ mrad

HFLAV combination: $\phi_s = (-55 \pm 21)$ mrad

SM predictions: $\phi_s^{SM} = (-37.0 \pm 1.0)$ mrad (UTfit)

will approach SM precision after Upgrade Phase II

HFLAV



also sensitive to Γ_s=0.6562±0.0021ps^{-1} , $\Delta\Gamma_s$=0.0816±0.0048ps^{-1} , $|\lambda|$=0.993±0.010

CP violation in $B_s^0 \to \phi\phi$ decays: measurement of the mixing-induced phase $\phi_s^{s\bar{s}s}$

$B_s^0 \to \phi\phi$ decay is a $b \to s\bar{s}s$ FCNC process that can proceed only via gluonic penguin diagrams
$\to$ enhanced sensitivity to possible NP contributions.

$$A_{CP}(f,t) \sim \eta_f \sin\phi_s^{s\bar{s}s} \sin(\Delta m_s t)$$

- SM predictions $|\phi_s^{s\bar{s}s}| < 20$mrad arXiv:0810.0249, Phys. Rev. D 80 (2009) 114026
- Measuring a different value of $\phi_s^{s\bar{s}s}$ from expectations would be a clear indication of NP

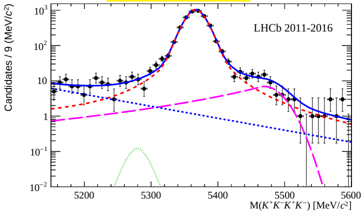
Time-dependent tagged and angular analysis similar to that for $B_s^0 \to J/\psi K^+K^-$

- Different CP eigenstates contributing
- $\phi\phi$ reconstruction more complicated
- Background contribution suppressed thanks to excellent PID and mass resolution
- Excellent decay-time resolution $\sigma_t \sim 43$ fs
- Efficiency to tag the initial $B_s^0/\bar{B}_s^0$ flavour $\sim 5.7\%$

results

$\phi_s^{s\bar{s}s} = -73 \pm 115(\text{stat}) \pm 27(\text{syst})$ mrad
$|\lambda| = 0.99 \pm 0.05 \pm 0.01$
consistent with SM expectations, improved measurement will eventually reveal NP

arXiv:1907.10003



. signal, $\Lambda_b^0 \to \phi p K^-$, $B_d^0 \to \phi\phi$, comb. bkg.

Precision measurement of $D^0 - \bar{D}^0$ mixing

In the SM D^0 can oscillate to $\bar{D}^0$ (and viceversa) via short-distance box-diagram.

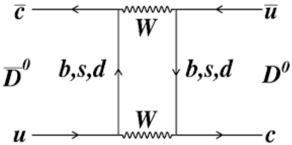
- Physical mass eigenstates are a mixture of flavor eigenstates:

$$D_{1,2} = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

  with mass $m_{1,2}$ and width $\Gamma_{1,2}$

- Oscillation rate depends on (assuming CP conservation):

$$x \equiv \frac{(m_1 - m_2)c^2}{\Gamma} \quad \text{and} \quad y \equiv \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma}$$



Expectation:

- $D^0 - \bar{D}^0$ mixing short-distance transitions are very small (CKM-suppressed and GIM).
- Long distance processes should dominate (but difficult to calculate).

Measurements WA HFLAV:

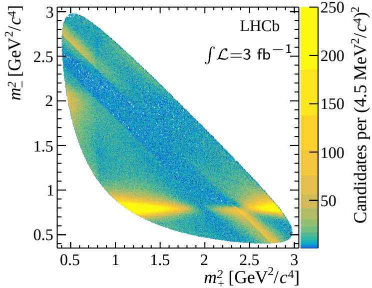
- $x = (3.6^{+2.1}_{-1.6}) \times 10^{-3}$, $y = (6.7^{+0.6}_{-1.3}) \times 10^{-3}$
- and are consistent with CP conservation in mixing: $|q/p|$=$0.94^{+0.17}_{-0.07}$, ϕ=$Arg(q/p)$=$-0.13^{+0.26}_{-0.17}$

Precision measurement of $D^0 - \bar{D}^0$ mixing

Phys. Rev. Lett 122 (2019) 231802

Use self-conjugate multibody $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decays

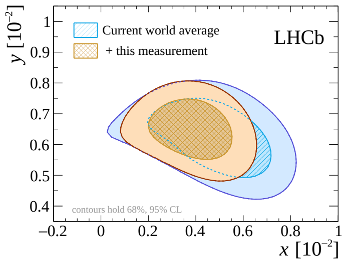
- from prompt D^* (π-tagged) and b-hadron decays (μ-tagged)
- novel model-independent approach (bin-flip):
  - Ratios between decays reconstructed in bins of phase-space regions and decay-time
  - Minimize need of external decay model or accurate efficiency
  - External inputs from CLEO.



CP-averaged results

$y_{\mathrm{CP}} = [7.4 \pm 3.6(\mathrm{stat}) \pm 1.1\ (\mathrm{syst})] \times 10^{-3}$
$x_{\mathrm{CP}} = [2.7 \pm 1.6(\mathrm{stat}) \pm 0.4\ (\mathrm{syst})] \times 10^{-3}$ most precise single measurement, still consistent with zero.

New global average $x = (3.9^{+1.1}_{-1.2}) \times 10^{-3}$ → **first evidence of nonzero mass difference**
Global constraints improve also CP parameters $|q/p|$ and ϕ.

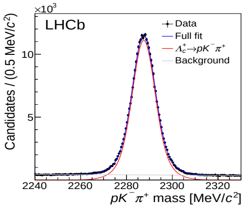


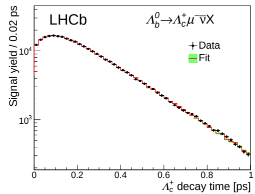
Precision measurements of heavy flavor hadrons

LHCb is a factory of heavy flavor hadrons. Precision measurement of the lifetime of charmed baryons Ω_c^0, Λ_c^+, Ξ_c^+ and Ξ_c^0.
Theoretical predictions based on HQE (expansions in m_Q) + higher order (non perturbative, due to spectator quarks) Phys. Rev. D88 (2013) 034004, Phys. Rept. 289 (1997) 1

- Use semileptonic b-hadron decays $H_b \to H_c \mu \bar{\nu}_\mu X$ (Run1)
  - $\Xi_c^+ \to pK^-\pi^+$
  - $\Lambda_c^+ \to pK^-\pi^+$
  - $\Omega_c^0 \to pK^+K^-\pi^+$
  - $\Xi_c^0 \to pK^+K^-\pi^+$

  Larger statistics of signal than any previous measurements.
- Measure lifetime relative to that the D^+ (reduce systematic uncertainties)

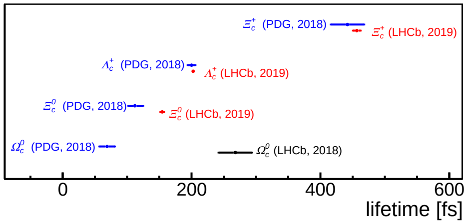




Phys. Rev. D100 (2019) 032001 Phys. Rev. Lett. 121 (2018) 092003

results:

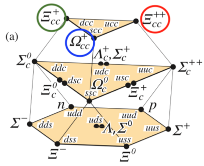
$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1$ fs
$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4$ fs
$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0$ fs 3.3σ from PDG
$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2$ fs 4$\times$ the previous WA
Changes lifetime hierarchy: $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$
$\to$ implication for theory



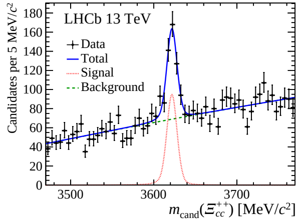
Hadron spectroscopy: doubly charmed Ξ_{cc}^{++} state

Quark model predictions for doubly charmed baryons ground states: one isospin doublet ($\Xi_{cc}^{++} = ccu$ and $\Xi_{cc}^{+} = ccd$) of states almost degenerate in mass and with large lifetimes and one singlet ($\Omega_{cc}^{+} = ccs$) of $J^P = 1/2^+$

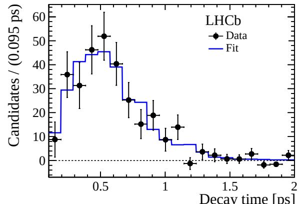
- Claim of Ξ_{cc}^{+} observation in $\Lambda_c^+ pK^-$ and $D^+ pK^-$ final states by SELEX, not confirmed by other experiments
- LHCb observed a significant ($> 12\sigma$) peak in $\Lambda_c^+ K^- \pi^+ \pi^+$ invariant mass consistent with the Ξ_{cc}^{++} state



Phys.Rev.Lett.119 (2017) 112001



Phys.Rev.Lett. 121 (2018) 052002



results

$m_{\Xi_{cc}^{++}} = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c^+)\mathrm{MeV}/c^2$

Phys.Rev.Lett.119 (2017) 112001

$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022}(stat) \pm 0.014(syst)\mathrm{ps}$

Phys.Rev.Lett. 121 (2018) 052002

Mass and lifetime are consistent with expectations

Also observed in: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ with a $\mathcal{B}$ consistent with predictions

Phys.Rev.Lett. 121 (2018) 162002

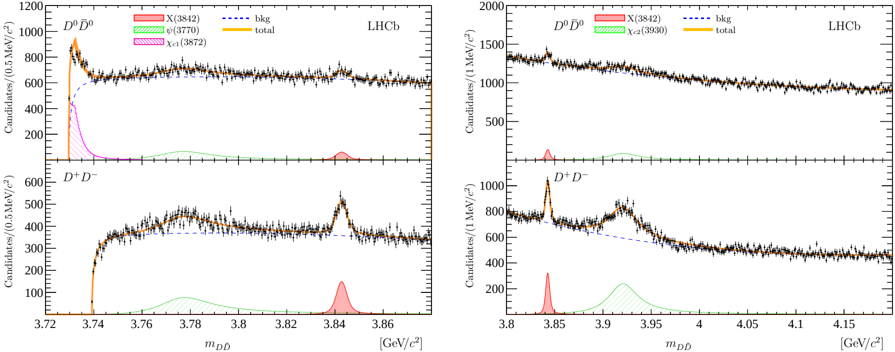
while no signal in $\Xi_{cc}^{++} \to D^+ pK^- \pi^+$ so far

arXiv:1905.02421

Opening of a new environment to test QCD models.

Hadron spectroscopy: $D\bar{D}$ spectroscopy & new charmonium states

Studying the invariant-mass distributions of charm mesons pairs promptly produced reveals interesting structures:



$\psi(3770)$, $\chi_{c1}(3872)$, $\chi_{c2}(3930)$ and

NEW narrow **X(3842)** state — JHEP 07 (2019) 035 — Run1+Run2

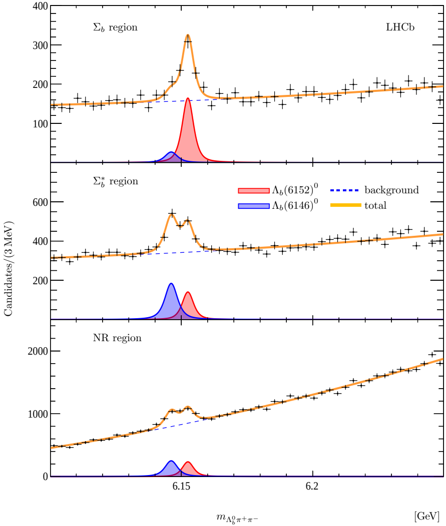
$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12$ MeV/c^2, $\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35$ MeV

decays to $D^0\bar{D}^0$ and D^+D^-

mass and Γ consistent with the predicted $\bar{c}c$ state with $J^{PC}=3^{--}$: $\psi_3(1^3D_3) \rightarrow$ First Observation!!

Hadron spectroscopy: new resonances in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum

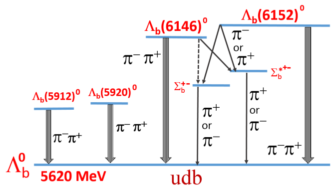
The study of the invariant-mass distributions of $\Lambda_b^0\pi^+\pi^-$ mesons reveals a structure that clearly split in two almost degenerate narrow states if one selects events with $\Lambda_b^0\pi^\pm$ mass consistent with $\Sigma_b^\pm$, $\Sigma_b^{*\pm}$ resonances or the rest (NR)



arXiv.1907.13598 (Run1+Run2)

NEW narrow $\Lambda_b^0(6146)$ and $\Lambda_b^0(6152)$ states

$m_{\Lambda_b^0(6146)} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16$ MeV/c^2,
$\Gamma_{\Lambda_b^0(6146)} = 2.9 \pm 1.3 \pm 0.3$ MeV
mainly decays via $\Sigma_b^*\pi$,
$m_{\Lambda_b^0(6152)} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16$ MeV/c^2,
$\Gamma_{\Lambda_b^0(6152)} = 2.1 \pm 0.8 \pm 0.3$ MeV
decays via $\Sigma_b\pi$ and $\Sigma_b^*\pi$
possible interpretation as a doublet of $\Lambda_b^0(1D)$

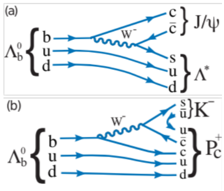


Hadron spectroscopy: Discovery of two pentaquark states

Conventional hadrons made of $\bar{q}q$ (mesons) or qqq (baryons). Exotic hadrons such as pentaquarks ($qqq\bar{q}q$) or tetraquarks ($\bar{q}q\bar{q}q$) were predicted since 1964 by Gell-Mann and Zweig.

In 2015 LHCb announced the discovery of two pentaquark states.

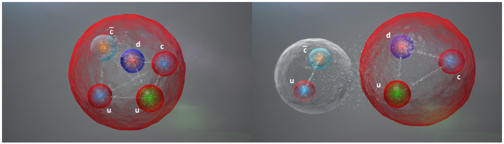
Phys. Rev. Lett. 115 (2015) 072001



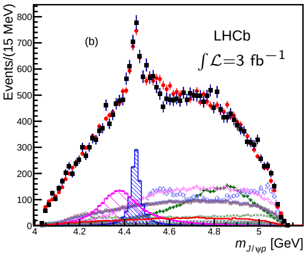
Full angular analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays in Run1 data. Two states decaying to $J/\psi p$ with a clear resonant structure:

- $P_c(4450)^+$ (narrow) and $P_c(4380)^+$ (broad)

Attracted lots of interest from the theorists. Two main explanations on their nature: tightly bound VS loosely bound molecular states.



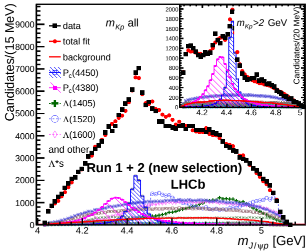
● data ● fit



Searched also in different decay modes: $\Lambda_b^0 \to J/\psi K^\pm \pi^\pm p$, $J/\psi K^\pm \pi^\mp p$, $J/\psi \phi p$, $J/\psi \pi p$ → upper limits

Phys. Rev. Lett. 122 (2019) 222001

NEW results from the analysis on the full data sample (Run1+Run2) of $\Lambda_b^0 \to J/\psi p K^-$ decays: $9\times$ the statistics

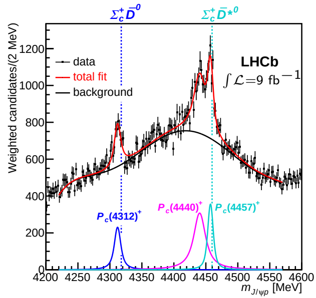


Larger data set is consistent with the old one, but more accurate $\to$ allows finer binning

Perform a 1D fit to the $m(J/\psi p)$. Contribution from several Λ^{**} $\to$ different strategies to deal with

results

- $P_c(4450)^+$ narrow state is resolved in two states: $P_c(4440)^+$ and $P_c(4457)^+$ with widths $\sim$ mass resolution
- Evidence for a 3$^{\text{rd}}$ narrow state: $P_c(4312)^+$ (was one bin fluctuation)
- 1D mass fit is inconclusive about the presence of broad states ($P_c(4380)^+$) $\to$ working to the full angular analysis



The minimal quark content of the 3 states is $duuc\bar{c}$
All 3 states are narrow and just below the $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ mass thresholds $\to$ possible evidence for baryon-meson bound states

Summary

Plenty of interesting measurements were performed by LHCb with Run1+2 data and more are in the pipeline.

- Physics program dramatically extended with respect to the initial program.
- Superseded WA precision in several measurements of heavy flavour
- Finally established CP violation in Charm decays
- Lots of suprising results in hadron spectroscopy

An interesting future is ahead of us with the LHCb upgrade and new data taking Upgrade TDRs

- 2019-2020: replacement of most of the sub-detectors
- Run3: 5x the instantaneous luminosity and a completely new readout/trigger
- Aim to collect 50 fb^{-1} by end of Run4
- A second major upgrade for the HL-LHC era is also being proposed with the aim to collect 300fb^{-1} document