b-baryons at the LHCb experiment

Luis Miguel Garcia Martin
on behalf of the LHCb collaboration

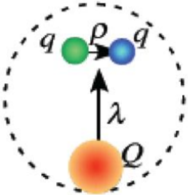
Outline

Introduction: Why heavy baryon decays

Heavy baryons are a useful platform for testing non-perturbative QCD approaches against experimental results

- **QCD** of baryon **simplified in a presence of a heavy quark**
  - $m_{b,c} >> \Lambda_{\text{QCD}} >> m_{qq}$, $m_{b(c)} = 4.8(1.7)\,\text{GeV}/c^2$
- SU(2) flavour symmetry: light qq uncorrelated from heavy Q flavour
  - Λ_c^+ (Σ_c) properties can be related to Λ_b^0 (Σ_b) with $c \leftrightarrow b$
- Spin symmetry: j_{qq} decoupled from J_Q and conserved

- Non-zero spin grants access to more observables [JPG24(1998)979, EPJC79(2019)634]
- Two spectator quarks $\Longrightarrow$ different form factors



Introduction: Why *b*-baryon decays

Must decay outside the third family :

- Long lifetime ($\sim 1.6\,\mathrm{ps}$)
- Many accessible decay channels (small BR's)

Type of processes:

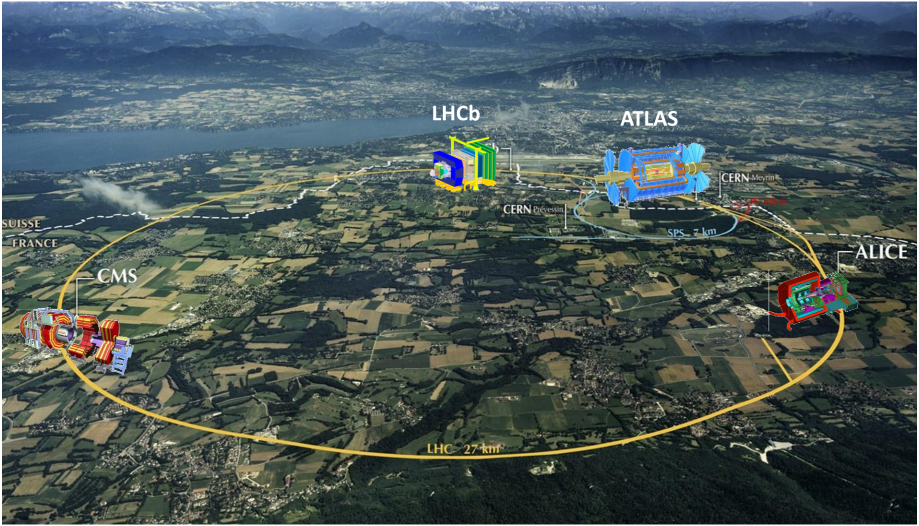
- Dominant: $b \to c$ (favoured) and $b \to u$ (suppressed)
- Rare: Flavour Changing Neutral Current (FCNC): $b \to s, d$
  - Strongly suppressed by the Standard Model (SM)
  - Sensitive to indirect effects of New Physics (NP)

Ideal place to probe New Physics effects!

Caveat:

- Uncertainty on b-baryon fragmentation fractions higher than for b-mesons [PRD104(2021)032005, PRD100(2019)031102, PRD99(2019)052006]
  - $\frac{f_s}{f_d} = 0.2539 \pm 0.0079$ $\quad \frac{f_{\Lambda_b}}{f_u + f_d} = 0.259 \pm 0.018$ $\quad \frac{f_{\Xi_b}}{f_{\Lambda_b}} = (8.2 \pm 2.7) \times 10^{-2}$

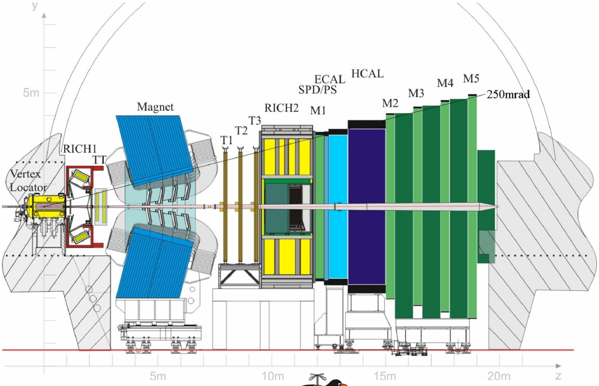
The LHC

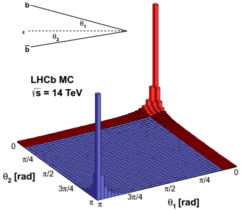


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

The LHCb experiment

- The LHCb idea: Single-arm forward spectrometer [JINST3(2018)S08005]:
  - $\sim$4% of the solid angle ($2 < \eta < 5$)
  - $\sim$30% of the b hadron production





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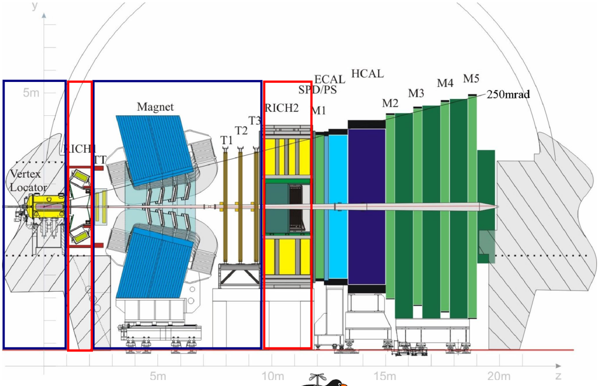

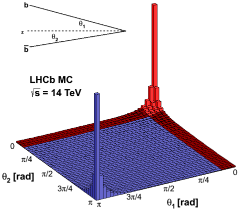

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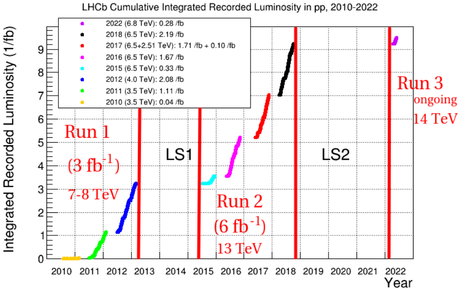

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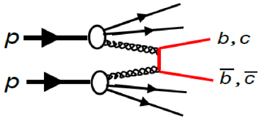
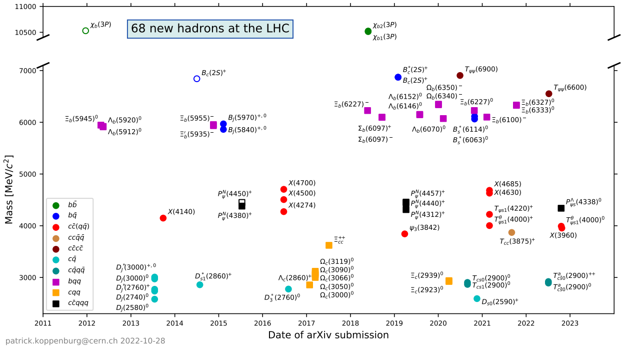
- Largest sample of heavy flavour decays
- Highly complementary to e^+e^- "B-factory" experiments:
  - Produce all types of b,c-mesons and baryons
  - Huge cross-section $\frac{\sigma(pp)}{\sigma(Y(4S))} \sim 10^3 - 10^5$



New hadrons

[Patrick Koppenburg]



26 new baryons

22 new exotic hadrons

- Naming convention proposal
  [arXiv:2206.15233]

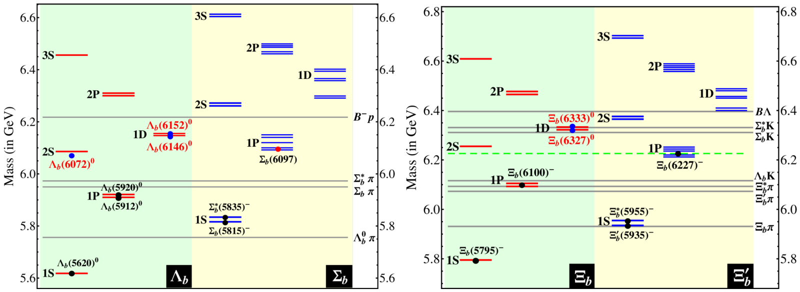
60 new states discovered by LHCb

- **LHCb is a factory of new particles!!**

Spectroscopy

bqq' baryons form multiplets (flavour, spin, and spatial wave functions)

- If qq' = $(u, d) \implies \Lambda_b^0$ $(j_{qq'} = 0)$ or $\Sigma_b^{(*)}$ $(j_{qq'} = 1)$
- (bsq) $\implies \Xi_b$ $(j_{sq} = 0)$ or $\Xi_b^{\prime(*)}$ $(j_{sq} = 1)$
- Expected **rich spectrum** of excited states **at higher masses**



[PRL128(2022)162001]

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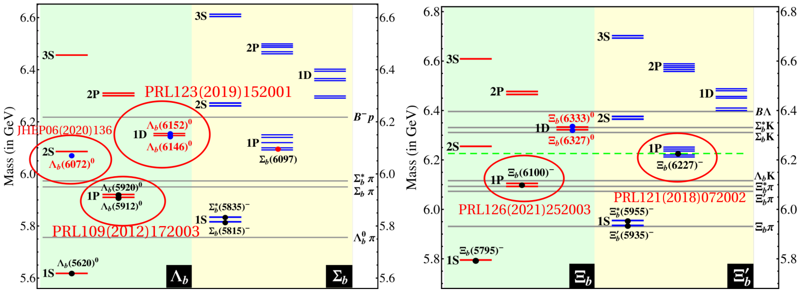
- Expected **rich spectrum** of excited states **at higher masses**
  - Several Λ_b^0, Ξ_b resonances found in recent years
  - Prediction of resonant 1D states $\Xi_b^{0*} \to (\Sigma_b^{(*)} \to \Lambda_b^0\pi^\pm)K$

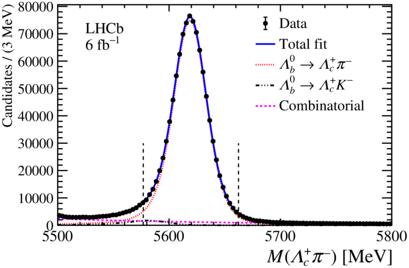


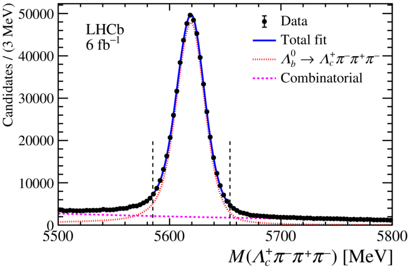
[PRL128(2022)162001]

Spectroscopy: Ξ_b^{0*}

Search for $\Xi_b^{0*} \to \Lambda_b^0 \pi^+ K^-$ [PRL128(2022)162001]

- Reconstruct $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$





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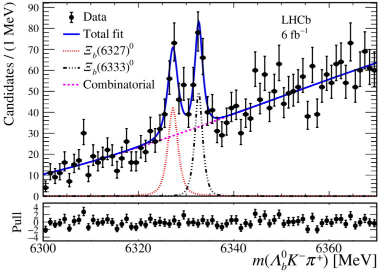
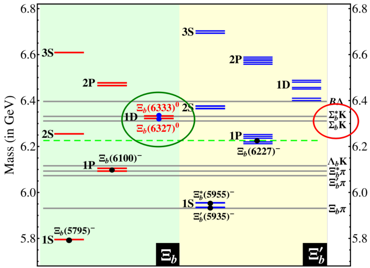
- Add prompt K^- and π^+ candidates
  - Found two peaks with $9(5)\sigma$ significance w.r.t no (one) peak hypothesis
  - Two peaks compatible with the 1D doublet states





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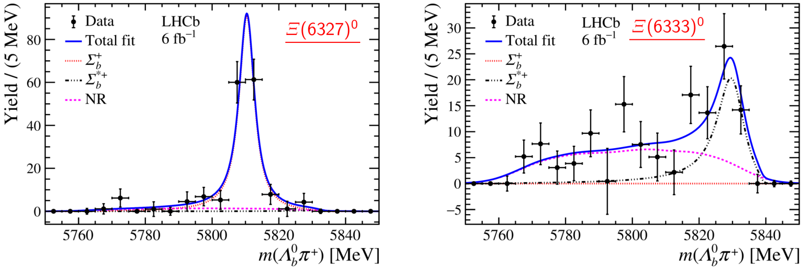
    - Found two peaks with $9(5)\sigma$ significance w.r.t no (one) peak hypothesis
    - Two peaks compatible with the 1D doublet states
- Look for $\Xi_b^{0*} \to \Sigma_b^{(*)+} K^-$, with $\Sigma_b^{(*)+} \to \Lambda_b^0 \pi^+$ contributions
- Masses, widths and decay patterns are consistent with the predictions



Search for the doubly heavy baryons: Ξ_{bc}^{+}

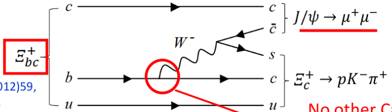
Looking for **charged** $\Xi_{bc}^{+} \to J/\psi\, \Xi_{c}^{+}$ [arXiv:2204.09541]

- Partially motivated by previous search for Ξ_{bc}^{0} and Ω_{bc}^{0} [CPC45(2021)093002]
- Using ratio of produced decays (R) with norm. channel $B_c^{+} \to J/\psi\, D_s^{+}$

$\tau(\Xi_{bc}^{+}) > \tau(\Xi_{bc}^{0}, \Omega_{bc}^{0})$
More efficient prompt-bkg subtraction

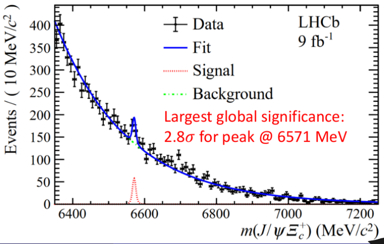
Phys.Usp.45(2022)455, Nul.Phys.A 895(2012)59, EPCJ 16(2000)461, PRD 98(2018)113004, PRD 99(2019)073006

"golden channel" for signal identification (online & offline)

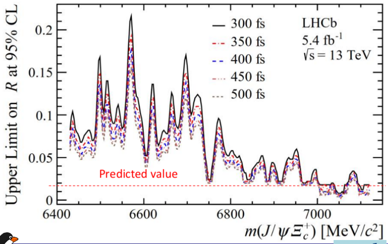


No other Cabbibo suppression than V_{cb}
Relatively large branching fraction

Hint of a bump in mass spectrum

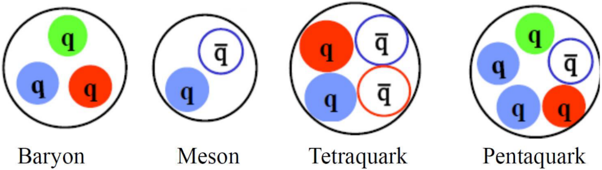


Upper Limit(UL) of R assigned as $f(m, \tau)$



Exotic

Unconventional hadrons (tetra/penta-quarks) predicted since the origin of the Quark Model [PL8(1964)214]



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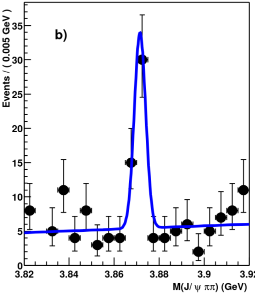

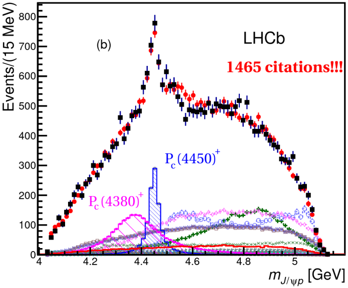

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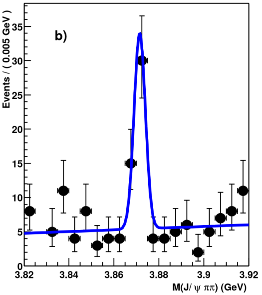
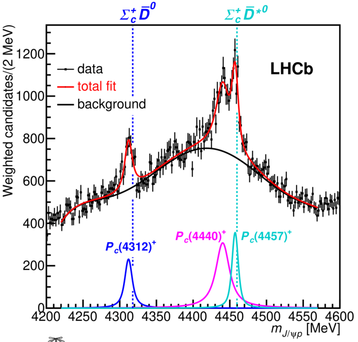
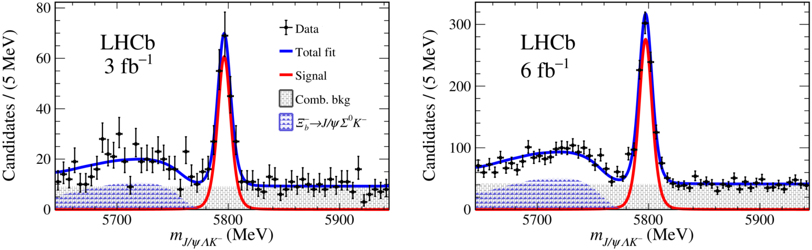
  - Updated analysis with Run 1+2 data [PRL122(2019)222001]
  - Structure at 4312 MeV evident
  - $P_c(4450)$ resolved into 2 narrower structures





Exotic: $P^{\Lambda}_{\psi s}$

Analysis searching for the strange partner $(P^{\Lambda}_{\psi s})$ in $\Xi_b^- \to J/\psi \Lambda K^-$ [SB66(2021)1278]



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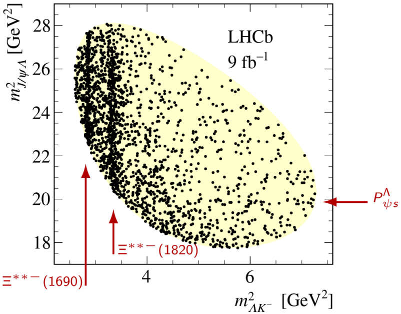

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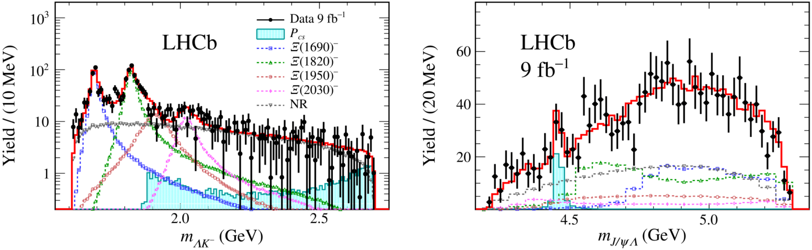
- Significance of $P^{\Lambda}_{\psi s}$ is 3.1σ
- Also improved precision in mass and width of $\Xi(1690^-)$ and $\Xi(1820^-)$

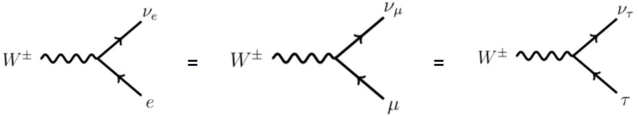


State	M_0 (MeV)	Γ_0 (MeV)	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2}_{-2.6}\,^{+6.7}_{-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2}_{-6.2}\,^{+6.9}_{-4.1}$

Lepton flavour universality (LFU)

In the SM, the EW coupling of the leptons are equal:

- Decay rates to e, μ, τ only differ by phase-space
- Well established for $Z \to \ell\ell$, $J/\psi \to \ell\ell$, $\pi, K \to \ell\nu$



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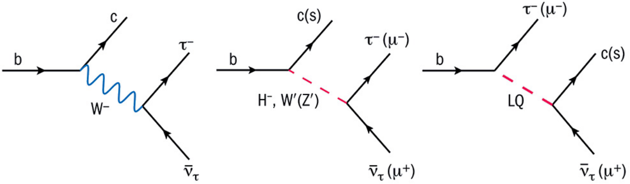
  - LFV could be enhanced up to experimentally accessible levels [PRL114(2015)091801]



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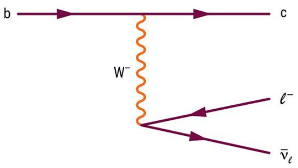
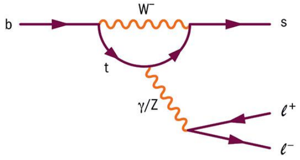
- Two kinds of semileptonic decays can be studied

Charged currents (tree)



FCNC (loop)



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- Contribution from New Physics (NP) can affect this universality
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- Two kinds of semileptonic decays can be studied
- Need observables with negligible uncertainty from QCD (R_H)

$$R_H = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B \to H\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B \to He^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

LFU tests: R_{pK}

LFU test with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ [JHEP05(2020)040]:

- Using 2011-2012 + 2016 dataset ($5\,\text{fb}^{-1}$)
- $R_{pK} = \frac{\mathcal{B}[\Lambda_b^0 \to pK^-\mu^+\mu^-]}{\mathcal{B}[\Lambda_b^0 \to pK^-e^+e^-]}$

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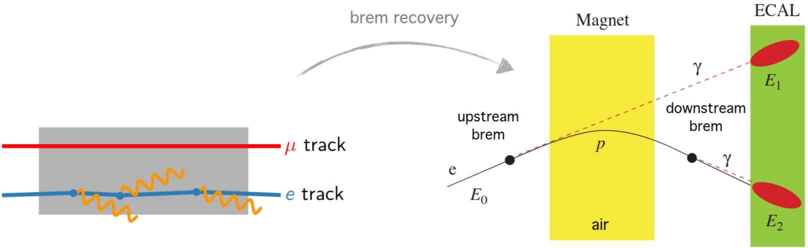
- Significant differences between μ and e reco (e.g. brem, PID, backgrounds



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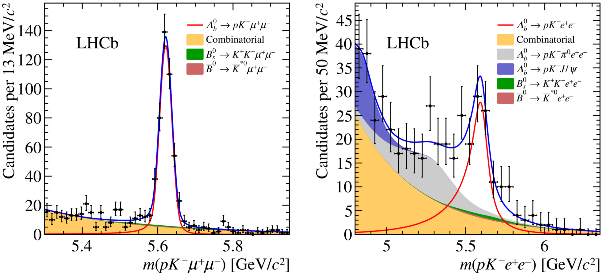

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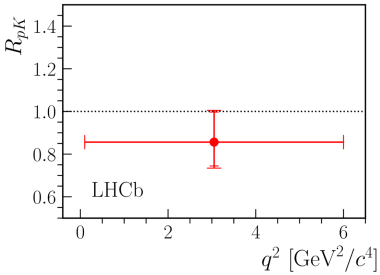
- Significant differences between μ and e reco (e.g. brem, PID, backgrounds
- **First observation** of $\Lambda_b^0 \to pK^-e^+e^-$
- **First and only measurement** $b \to s\ell\ell$ **in baryons** ($R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$)
  - Compatible with SM



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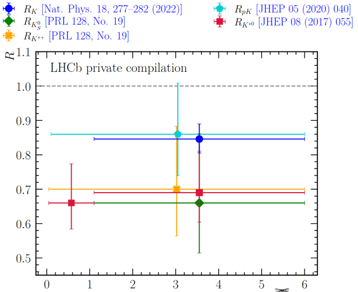
LFU test with $\Lambda_b^0 \to pK^- \ell^+ \ell^-$ [JHEP05(2020)040]:

- Using 2011-2012 + 2016 dataset ($5\,\text{fb}^{-1}$)
- $R_{pK} = \dfrac{\mathcal{B}[\Lambda_b^0 \to pK^- \mu^+\mu^-]}{\mathcal{B}[\Lambda_b^0 \to pK^- J/\psi\,(\mu^+\mu^-)]} \Big/ \dfrac{\mathcal{B}[\Lambda_b^0 \to pK^- e^+e^-]}{\mathcal{B}[\Lambda_b^0 \to pK^- J/\psi\,(e^+e^-)]}$
- Significant differences between μ and e reco (e.g. brem, PID, backgrounds
- **First observation** of $\Lambda_b^0 \to pK^- e^+ e^-$
- **First and only measurement** $b \to s\ell\ell$ **in baryons** ($R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$)
  - Compatible with SM
- Same trend as other LFU tests

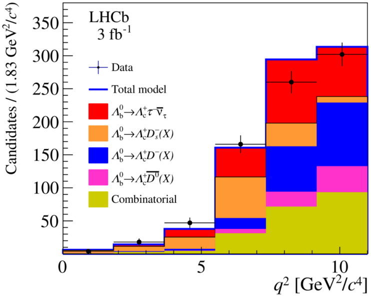


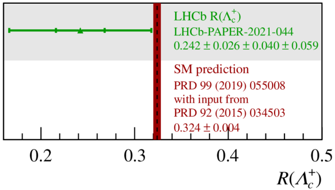
Schmitt@ICHEP

LFU tests: $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$

Aim to observe $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$ tauonic decay [PRL128(2022)191803]:

- Reconstruct $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$
- Using missing energy technique with Λ_b^0 and τ mass constraints
- $q^2 = p^2_{\tau\overline{\nu}_\tau} = (p_{\Lambda_b^0} - p_{\Lambda_c^+})^2$
- **First observation** with 6.1σ significance
- $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau) = 1.50 \pm 0.16(\text{stat}) \pm 0.25(\text{syst}) \pm 0.23(\text{ext})\%$
- First measurement of $R_{\Lambda_c^+} = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}$ (in agreement with SM)

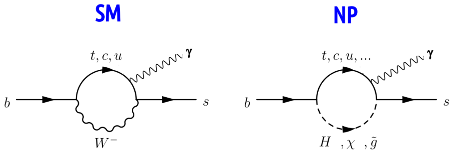




Radiative b-baryon decays

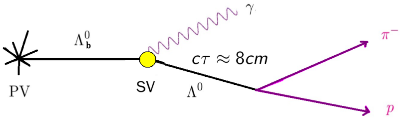
Radiative decays: Complementary tests with $b \to s$ penguins which probe a different set of operators than **leptonic modes**:

- Photon polarization predicted to be mainly left-handed
- New particles can enhance right-handed currents
- Photon polarization accessible through angular distribution (clean observable)



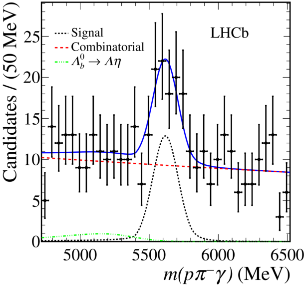
Caveats:

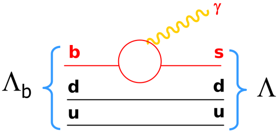
- Challenging reconstruction at LHCb
  - No photon direction and long-lived particle $\implies$ No secondary vertex



Radiative decays: $\Lambda_b^0 \to \Lambda\gamma$

- First radiative *b*-baryon decay observed (2016 data) [PRL123(2019)031801]





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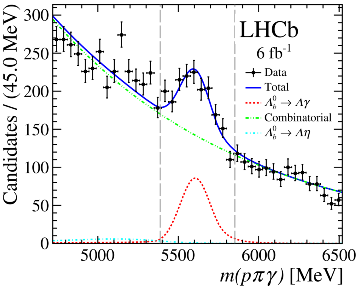
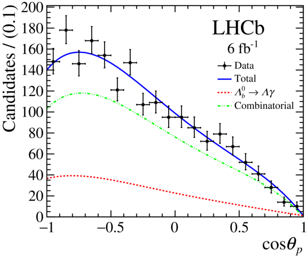
- Analysis using Run 2 data to measure the photon polarization [PRD105(2022)L051104]
  - Using angular distribution $\Gamma(\cos\theta_p) = 1 - \alpha_\Lambda \alpha_\gamma \cos\theta_p$
  - Fixing $\alpha_\Lambda = 0.754 \pm 0.004$ [NP15(2019)631]
- Photon polarization compatible with SM ($\alpha_\gamma^{SM} = 1$)





$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.})$

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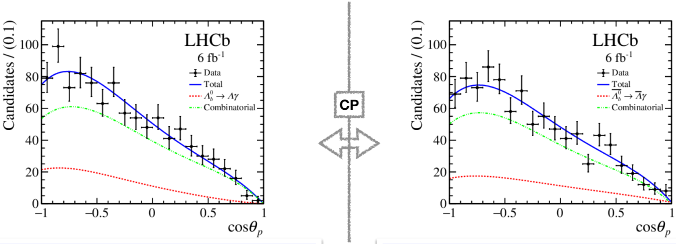
  - Fixing $\alpha_\Lambda = 0.754 \pm 0.004$ [NP15(2019)631]
- Photon polarization compatible with SM ($\alpha_\gamma^{\text{SM}} = 1$)
- Splitting the sample in Λ_b^0 and $\overline{\Lambda}_b^0$ allows to test for CPV
  - Fixing $\alpha_\Lambda^+ = -0.758 \pm 0.012$ and $\alpha_\Lambda^- = 0.750 \pm 0.010$ [NP15(2019)631]
  - No significant CPV found



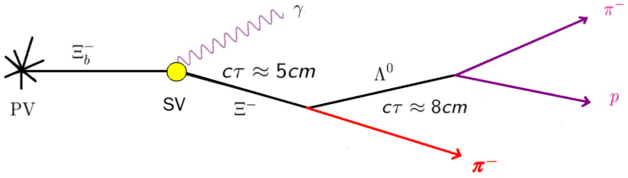
$\alpha_\gamma^- > 0.56$ (0.44) at 90% (95%) CL

$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}\,(stat.)^{+0.16}_{-0.09}\,(syst.)$

Radiative decays: $\Xi_b^- \to \Xi^- \gamma$

First search for the $\Xi_b^- \to \Xi^- \gamma$ radiative decay [JHEP01(2022)069]

- More challenging due to two long-lived particles, and $\frac{f_{\Xi_b}}{f_{\Lambda_b^0}} \sim 0.1$



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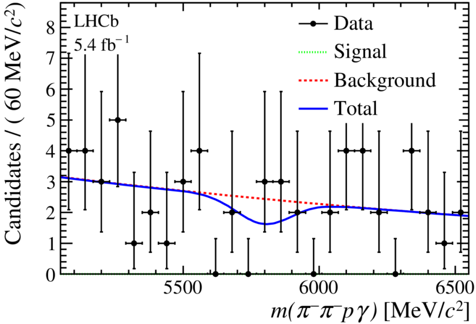

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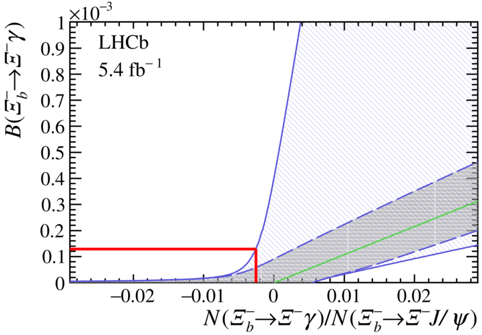
- More challenging due to two long-lived particles, and $\frac{f_{\Xi_b}}{f_{\Lambda_b^0}} \sim 0.1$
- No signal is found
- Using $\Xi_b^- \to \Xi^- J/\psi$ as normalization channel
- **First upper limit is set** $\mathcal{B}(\Xi_b \to \Xi^- \gamma) < 1.3 \times 10^{-4}$
    - Recent predictions $\mathcal{B}(\Xi_b \to \Xi^- \gamma) \sim 10^{-5}$ [PRD105(2022)073007, EPJC82(2022)1,68]



CP violation

- Significant **CP asymmetries observed in B mesons** [PDG2022]
  - $\mathcal{A}^{CP}(B^0 \to K^+\pi^-) = -0.824 \pm 0.0047$
  - $\mathcal{A}^{CP}(B_s^0 \to K^-\pi^+) = 0.236 \pm 0.017$
  - $\mathcal{A}^{CP}(B^0 \to (\pi^+\pi^-)_\rho(K^+\pi^-)_{K^*}) = -0.62 \pm 0.13$
  - $\mathcal{A}^{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.114 \pm 0.007$ [arXiv:2206.07622]
- **No significant CP asymmetry observed in b-baryon decays yet** [PLB787(2018)124]
  - $\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-) = -0.020 \pm 0.023$
  - $\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-) = -0.035 \pm 0.026$
  - Suffer from large statistical uncertainties
- Theory prediction [PRD58(1998)096013, PRD69(2004)017901]: $\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-(\pi^-)) \simeq 3(6)\%$
- Abundant resonant structures are observed in multi-body decays of b-baryons
  - Decay amplitudes interferences may generate significant CP asymmetry

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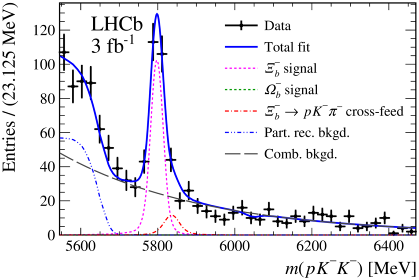
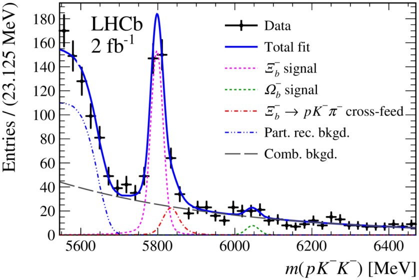
- Abundant resonant structures are observed in multi-body decays of b-baryons
  - Decay amplitudes interferences may generate significant CP asymmetry
- Recently discover $\Xi_b^- \to pK^-K^-$ [PRL118(2017)071801]

CP violation: $\Xi_b^- \to pK^-K^-$

Study of the CPV using $\Xi_b^- \to pK^-K^-$ [PRD104(2021)5,052010]

- Using Run 1 + 2015-2016 data sample
  - Also search for $\Omega_b^- \to pK^-K^-$ (not found)





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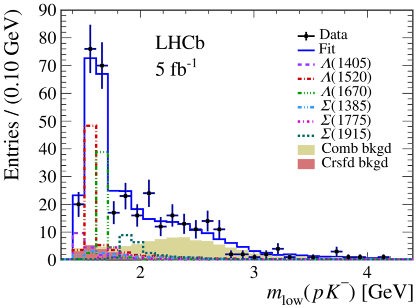

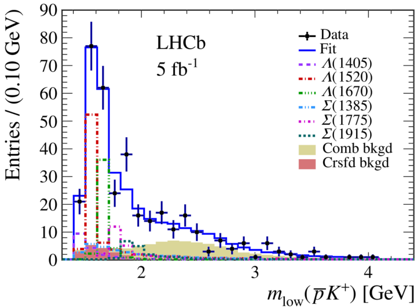

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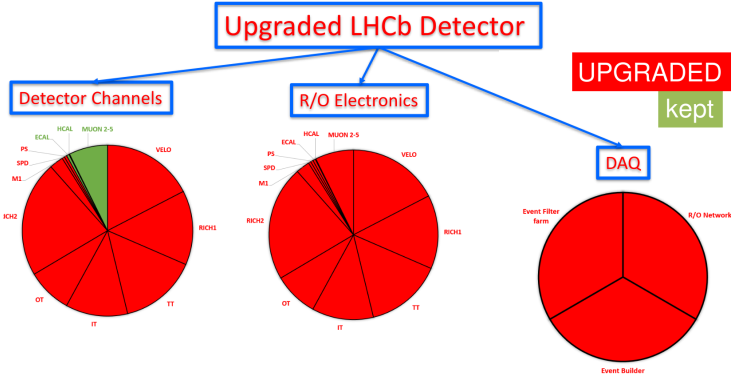
  - Also search for $\Omega_b^- \to pK^-K^-$ (not found)
- Considering contribution from intermediate resonances
- No CP violation is observed

Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

Prospects

- Upgraded detector for Run 3
- Fully-software trigger + Full detector readout at 40 MHz:
  - Highest throughput among HEP experiments
  - Large boost in efficiency for hadronic channels



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- Upgraded detector for Run 3
- Fully-software trigger + Full detector readout at 40 MHz:
  - Highest throughput among HEP experiments
  - Large boost in efficiency for hadronic channels
- x3-5 (x7-10) boost in statistics for Run 3 (Run 4)
  - Access to doubly heavy states
  - Improve precision in measurements [LHCC-G-171]
- We already plan for the next upgrade! [LHCC-2021-012]
- Strong program beyond flavour exploiting unique acceptance
  - Extending the Physics program (e.g. long-lived particles [FBD5(2022)1008737])

R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047

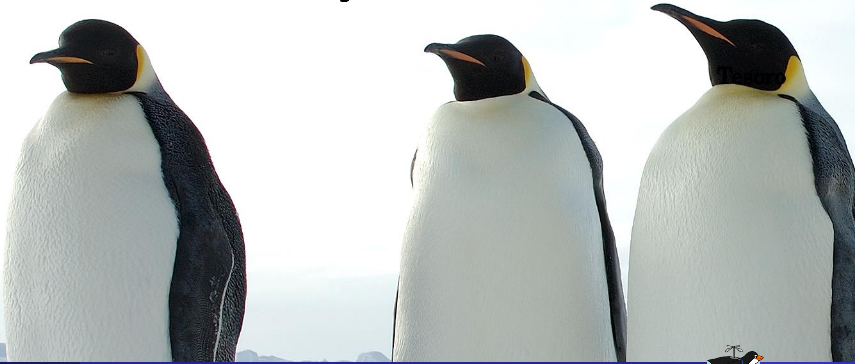
Decay mode	LHCb $23\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$
$\Lambda_b^0 \to J/\psi\, pK^-$	340k	700k	4M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600

Summary

- LHC is a heavy baryon factory
  - LHCb detector well suited for their detection
- New conventional (excited) and exotic hadrons are discovered every year
  - LHCb steadily supplying new discoveries
- Competitive LFU tests from baryon decays
- First photon polarization measurement in *b*-baryons
- Still looking for CPV in baryon decays

- Strong synergy with theory colleagues needed as ever!
- Developments in lattice QCD crucial for LHCb precision measurements
  - form-factors, decay constants, predictions of hadron properties...

Thanks for your attention



Introduction: Observables

Phenomenology perspective

- $\mathcal{B}$**:** affected by hadronic uncertainties
- **Angular observables:** first-order form-factor cancellations
- **LFU:** full cancellations in the SM

Experimental perspective

- $\mathcal{B}$**:** simple extraction, good control of efficiencies through control modes
- **Angular observables:** need to control acceptance, many parameters require large yields
- **LFU:** need control of $e^{\pm}$ vs $\mu^{\pm}$ efficiencies $\Longrightarrow$ very challenging at hadron machines

New naming scheme (proposal) [arXiv:2206.15233v1]

Currently no PDG rule for:

- exotic mesons with *s*, *c*, *b* quantum numbers
- no extension for pentaquark states

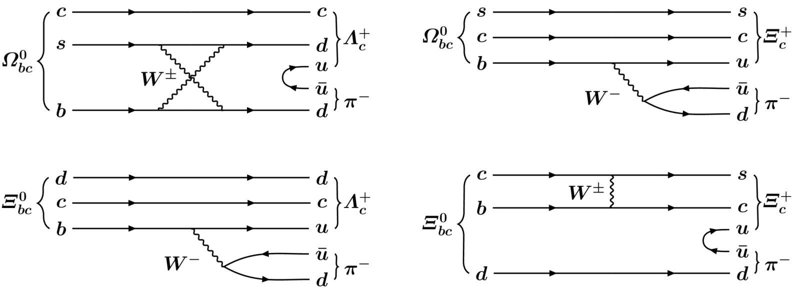
Idea of the proposal:

- T for tetra, P for penta
- Superscript: based on existing symbols, to indicate isospin, parity and G-parity
- Subscript: heavy quark content

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+,\ J^{PC} = 1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2},\ J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2},\ J^P = 1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+,\ J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

Search for the doubly heavy baryons: Ξ_{bc}^0 and Ω_{bc}^0

- **First search for neutral** Ω_{bc}^0 and Ξ_{bc}^0 baryons decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ final states [CPC45(2021)093002]



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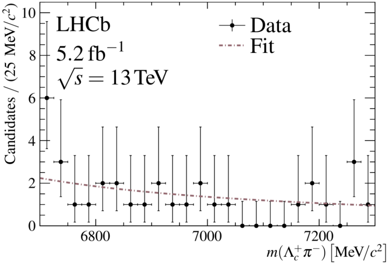
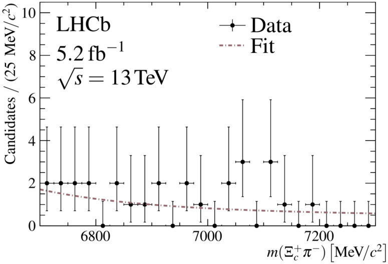
- No excess is found:





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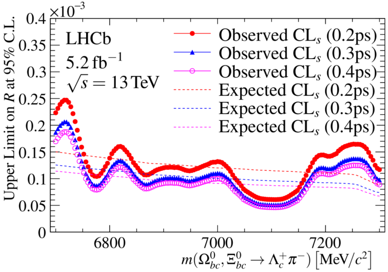
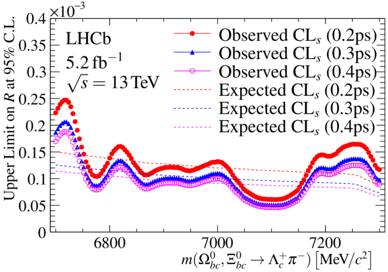
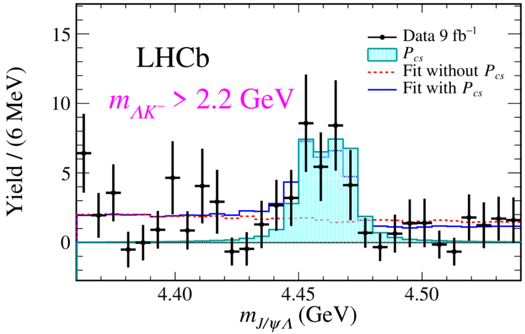
- No excess is found: Setting upper limit





Exotic: $P_{\psi s}^{\Lambda}$

Slices on $m(\Lambda K^{+})$ to disentangle contributions from Ξ^{*-} resonances



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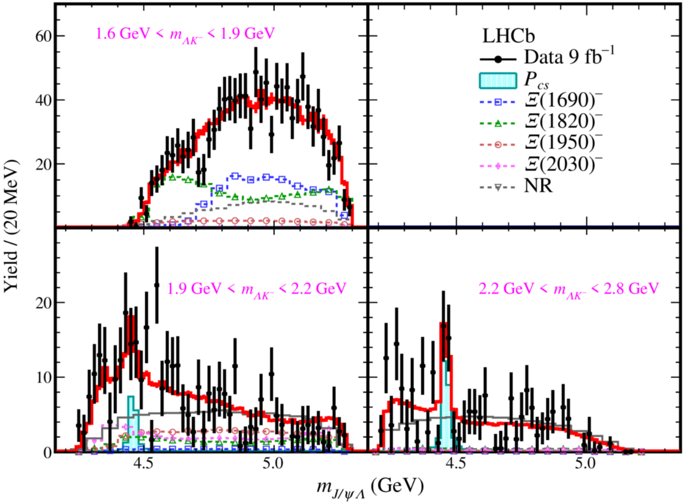
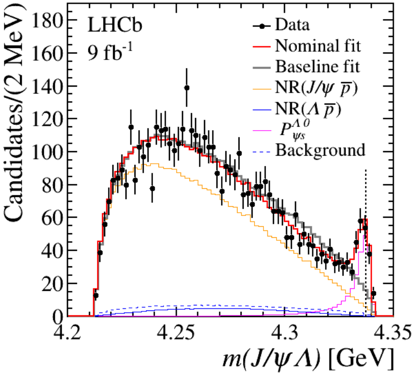


Exotic: $P^{\Lambda}_{\phi s}$

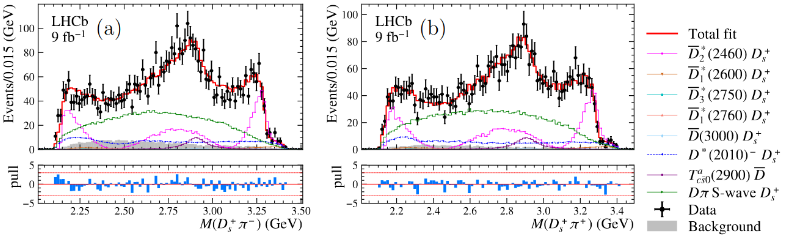
Another $P^{\Lambda}_{\phi s}$ found in $B^- \to J/\psi\,\overline{p}\Lambda$ [arXiv:2210.10346]

- Observed with $> 10\sigma$



Exotic: Tetraquarks

- $T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$ ($c\bar{u}\bar{d}s$) observed in D^-K^+ [PRL125(2020)242001, PRD102(2020)112003]
  - First open-charm tetraquark
- Looking for isospin partners $T^a_{c\bar{s}0}(2900)^{0/++}$ ($c\bar{s}u\bar{d}/c\bar{s}\bar{u}d$) [LHCb-PAPER-2022-026, in preparation]
  - First observation ($> 9\sigma$)
  - Strong preference for $J^P = 0^+$ ($> 7\sigma$)



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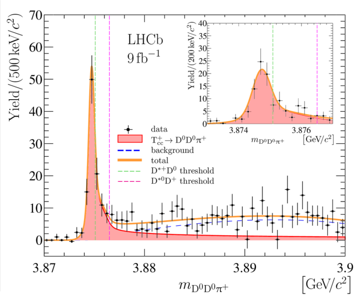
  - First observation ($> 9\sigma$)
  - Strong preference for $J^P = 0^+$ ($> 7\sigma$)
- Doubly-charmed tetraquark T^+_{cc} $(cc\bar{u}\bar{d})$ observed ($> 9\sigma$) [NC13(2022)3351]



LFU tests: $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$

The τ momentum can be estimated, using the constraint that the 3 pions come from the τ decay, up to a two-fold ambiguity, as follows:

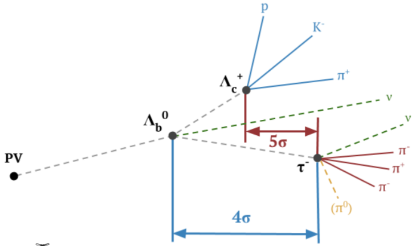
$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}|\cos\theta \pm \sqrt{(m_\tau^2 - m_{3\pi}^2) - 4m_\tau^2|\vec{p}_{3\pi}|\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2\cos^2\theta)}$$

To resolve the two-fold ambiguity, one can tune θ in order for both solutions to become only one using:

$$\theta_{\max} = \arcsin\left(\frac{m_\tau^2 - m3\pi^2}{2m_\tau|\vec{p}_{3\pi}|}\right)$$

Analogous approach for computing Λ_b^0 momentum:

- Using derived p_τ as input

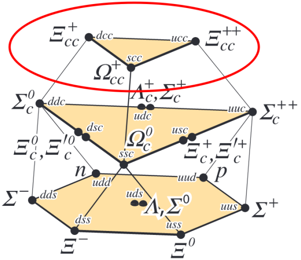


Search for the doubly heavy baryon

Double heavy baryons:

- Ideal systems to test effective QCD theories
- The recent LHCb measurement of Ξ_{cc}^{++} has been used:
  - Calculate the binding energy in a QQ diquark
  - Predict the mass of the recently observed T_{cc}^{+}

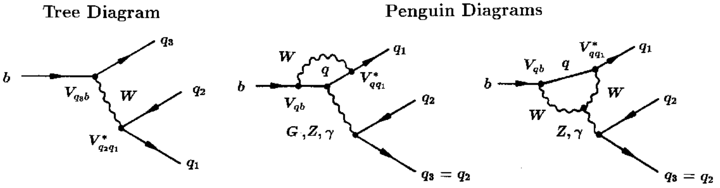
Three weakly decaying qqq states with C = 2 and $J^P = 1/2^+$ are expected:



Non leptonic decays

Nonleptonic decays with multiple hadrons:

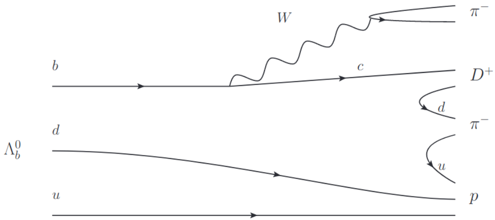
- Mediated by the weak $b \to ccs$ and $b \to cus$ transitions
- Useful for testing non-perturbative QCD
  - c hadronazing separated from the baryon states sensitive to QCD effects in beauty baryon
- Strong interactions hadronic initial and final states
  - More challenging to compute rates than semileptonic partners ($b \to c\ell\overline{\nu}_\ell$)



Non leptonic decays: $\Lambda_b^0 \to D^{(*)+} p\pi^-\pi^+$

Search for the $\Lambda_b^0 \to D^+ p\pi^-\pi^+$ and $\Lambda_b^0 \to D^{*+} p\pi^-\pi^+$ decay modes
[JHEP03(2022)153]

- Using $\Lambda_b^0 \to \Lambda_c^+ \pi^+\pi^-\pi^-$, $\Lambda_c^+ \to pK^-\pi^+$ as normalization channel
  - Same final state
  - Remove dependency with $f_{\Lambda_b^0}$



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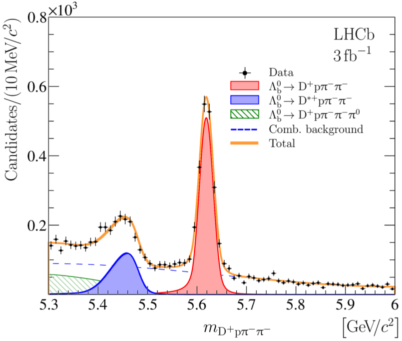
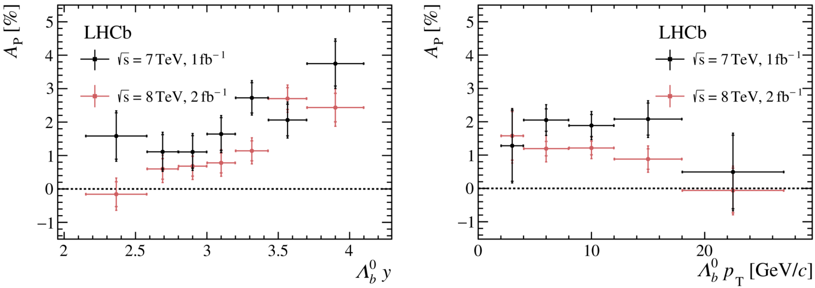
  - Same final state
  - Remove dependency with $f_{\Lambda_b^0}$
- **First observation** of $\Lambda_b^0 \to D^+ p\pi^-\pi^+$ and $\Lambda_b^0 \to D^{*+} p\pi^-\pi^+$
- Can be used as normalization for future $\Xi_b^0 \to D^{(*)+} pK^-\pi^+$ searches



CP violation: Λ_b^0-$\overline{\Lambda}_b^0$ production asymmetry

Study Λ_b^0-$\overline{\Lambda}_b^0$ production symmetry [JHEP10(2021)060]

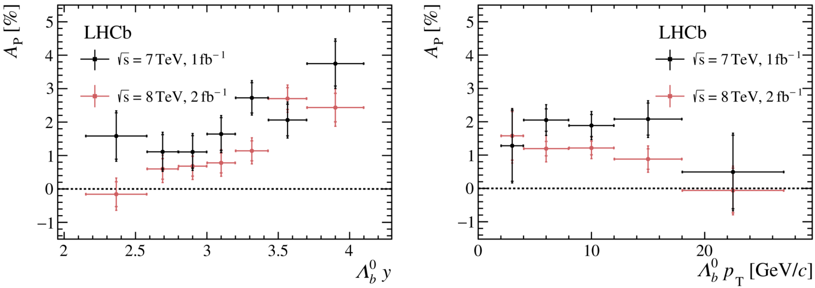
- Using $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu X$
- Assuming CP symmetry in the decay



CP violation: Λ_b^0-$\overline{\Lambda}_b^0$ production asymmetry

Study Λ_b^0-$\overline{\Lambda}_b^0$ production symmetry [JHEP10(2021)060]

- Using $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu X$
- Assuming CP symmetry in the decay
- Results incompatible with production symmetry with 5.8σ
- Evidence for dependence of rapidity with 4σ



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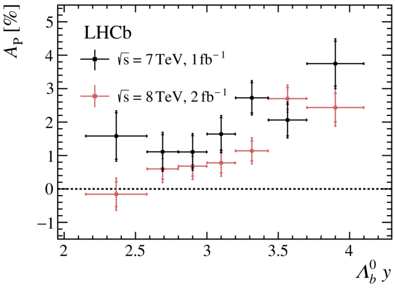
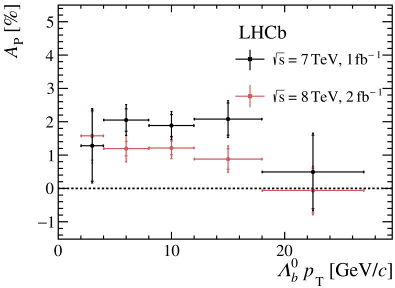
- Results incompatible with production symmetry with 5.8σ
- Evidence for dependence of rapidity with 4σ
- **First observation of a particle-antiparticle asymmetry in *b*-hadron**
- Relevant result for CPV analyses

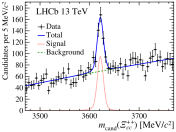


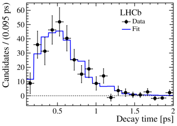


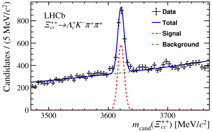
Charm-baryon decays

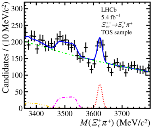
Many interesing results from *c*-baryon decays

- Doubly charmed Ξ_{cc}^{++} first observed [PRL119(2017)112001]
  - Precision measurements of its lifetime [PRL121(2018)052002], mass [JHEP02(2020)049] and production rate [CPC44(2020)022001]
  - Recent observation with new decay channel $\Xi_{cc}^{++} \to \Xi_c^{'+}\pi^+$ [JHEP05(2022)038]









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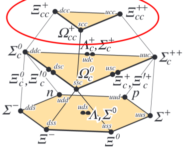
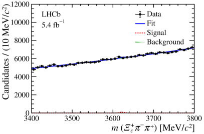
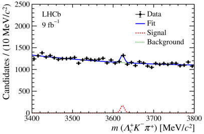
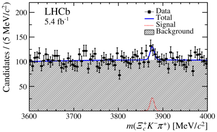
  - Recent observation with new decay channel $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ [JHEP05(2022)038]
- Expected two isospin partners yet to be observed:
  - Search for Ξ_{cc}^{+} [JHEP12(2021)107]
  - Search for Ω_{cc}^{+} [SCPMA64(2021)101062]





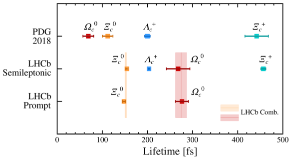




Charm-baryon decays

Many interesing results from c-baryon decays

- Doubly charmed Ξ_{cc}^{++} first observed [PRL119(2017)112001]
    - Precision measurements of its lifetime [PRL121(2018)052002], mass [JHEP02(2020)049] and production rate [CPC44(2020)022001]
    - Recent observation with new decay channel $\Xi_{cc}^{++} \to \Xi_c^{'+}\pi^+$ [JHEP05(2022)038]
- Expected two isospin partners yet to be observed:
    - Search for Ξ_{cc}^{+} [JHEP12(2021)107]
    - Search for Ω_{cc}^{+} [SCPMA64(2021)101062]
- $\tau_{\Omega_c^0}$ measurement of Ω_c^0 in disagreement with previous measurements [SB67(2022)479-487] ($\tau_{\Xi_c^0}$ also measured)



$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7\,\text{fs},$$

$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2\,\text{fs},$$