Opportunities with *b*-baryons at LHCb

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Challenges in Semileptonic Decays

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Baryons

- Mesonic decays well studied at B-factories
- Unique capability with baryonic decays at LHC
  - Copious amount of Λ_b at LHCb (~ 40% of b-hadron produced at LHCb are Λ_b baryons)
- Compared to b-meson decays allows us to probe different spin dynamics (e.g. particularly sensitive to tensor NP currents)
  [PRD 99 (2019) 055008, JHEP 08 (2017) 131]

LHCb (recent) semileptonic results with baryons

- **Published measurements:**
  - Observation of the decay $\Lambda^0_b \to \Lambda_c^+ \tau^- \nu$ with $\tau \to \pi\pi\pi(\pi)\nu$
    [Phys. Rev. Lett. 128 (2022) 191803]
  - $d\Gamma/dq^2$ measurement of $\Lambda^0_b \to \Lambda_c^+ \mu\nu$
    [Phys. Rev. D 96 (2017) 112005]
  - Fragmentation fractions of Λ^0_b
    [Phys. Rev. D 100 (2019) 031102(R)]

- **Ongoing measurements:**
  - Angular analysis of $\Lambda^0_b \to \Lambda_c^+ \mu\nu$
  - Form factor measurement in $\Lambda^0_b \to \Lambda_c^* \mu\nu$
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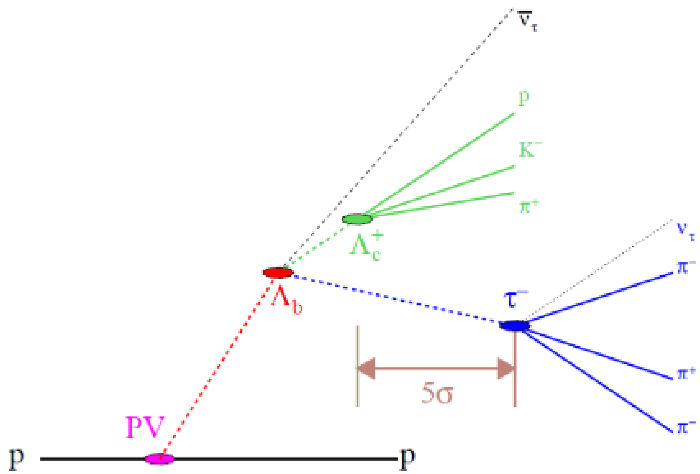
$R(\Lambda_b)$ measurement

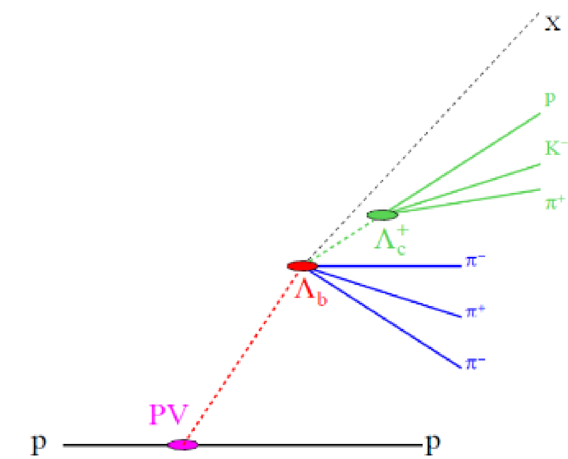
[Phys. Rev. Lett. 128 (2022) 191803]

- First LFU test in a baryonic b → clν decay
- Initial state spin 1/2 ⇒ could couple to different physics beyond SM
- Three-prong hadronic decays τ→ πππ(π^0)ν
- Dataset: run1 LHCb data

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



$\Lambda_b^0 \to \Lambda_c^+ 3\pi$



$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}$$

$$R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \left\{ \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} \right\}_{\text{ext. input}}$$

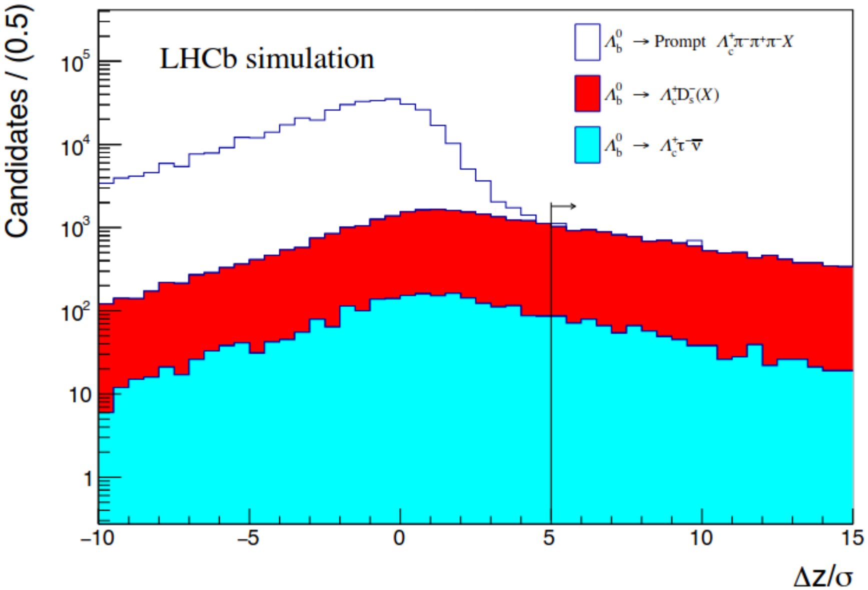
[PDG 2020]

$R(\Lambda_b)$ analysis workflow

[Phys. Rev. Lett. 128 (2022) 191803]

- Tight Λ_c^+ particle identification selection.
- Λ_c^+ sideband template used in the signal fit to remove the background under the peak
- Combine with detached πππ triplet forming τ candidates
- Reconstruct decay kinematics
- Prompt background rejection thanks to vertex topology
  - $\Lambda^0_b \rightarrow \Lambda_c^+ \pi\pi\pi X$
  - Suppressed by requiring the τ
    - vertex to be downstream wrt Λ^0_b vertex along beam direction with a 5σ significance

$$\Delta z = z(3\pi) - z(\Lambda_c) > 5\,\sigma_{vtx}$$

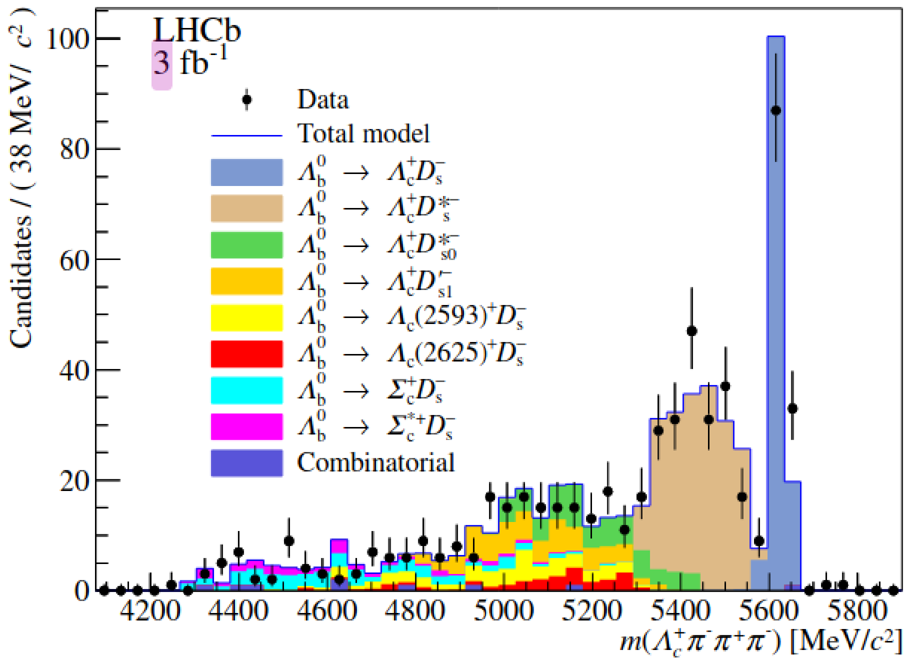


$R(\Lambda_b)$ measurement

[Phys. Rev. Lett. 128 (2022) 191803]

- $\Lambda^0_b \to \Lambda_c^+ D_s (\to \pi\pi\pi X)$
  - Suppressed using a BDT:
  - exploit τ decay dynamics and taking into account the resonant structure of the 3π system
  - the energy carried by neutral particles within the cone around the 3π direction
  - kinematic variables from partial reconstruction
  - Validated on with control samples: $\Lambda^0_b \to \Lambda_c^+ \pi\pi\pi$, $\Lambda^0_b \to \Lambda_c^+ D^-(X)$, $\Lambda^0_b \to \Lambda_c^+ D^0\text{bar}(X)$

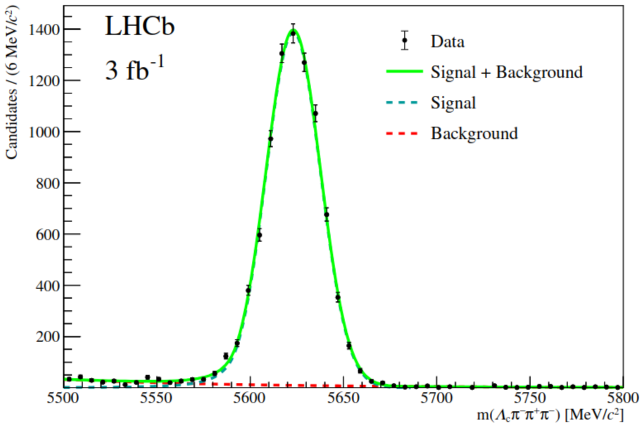
- Exclusive $\Lambda^0_b \to \Lambda_c^+ D_s (\to \pi\pi\pi X)$ control sample to constrain the double charm decays



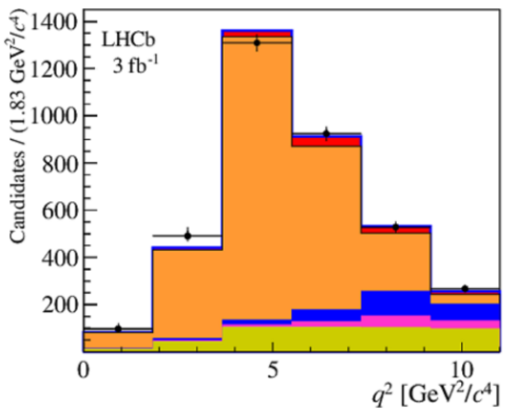
$R(\Lambda_b)$ measurement

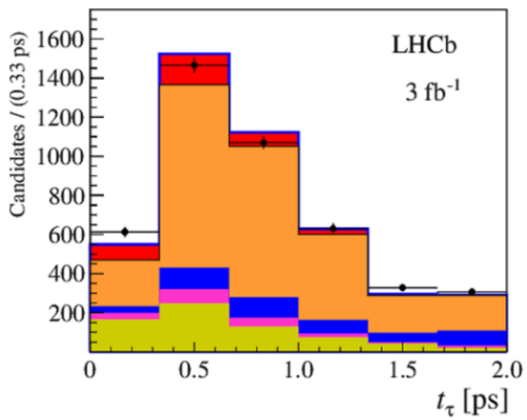
[Phys. Rev. Lett. 128 (2022) 191803]

- $\Lambda^0_b \rightarrow \Lambda_c^+ \pi\pi\pi$ yield extracted from fit to the invariant mass

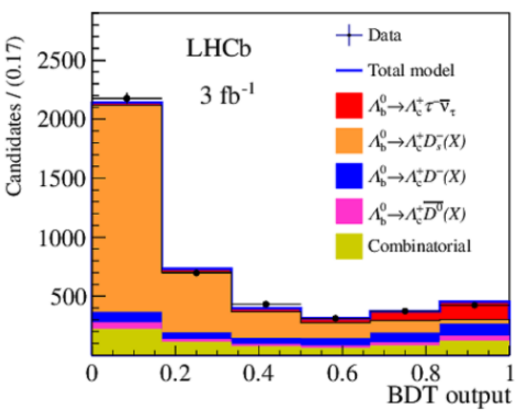


- Signal yield extrated from fit to
  - q^2
  - τ decay time
  - Isolation BDT output





- First observation of the mode $\Lambda^0_b \rightarrow \Lambda_c^+ \tau^- \bar{\nu}$ with a 6σ significance



$R(\Lambda_b)$ measurement

[Phys. Rev. Lett. 128 (2022) 191803]

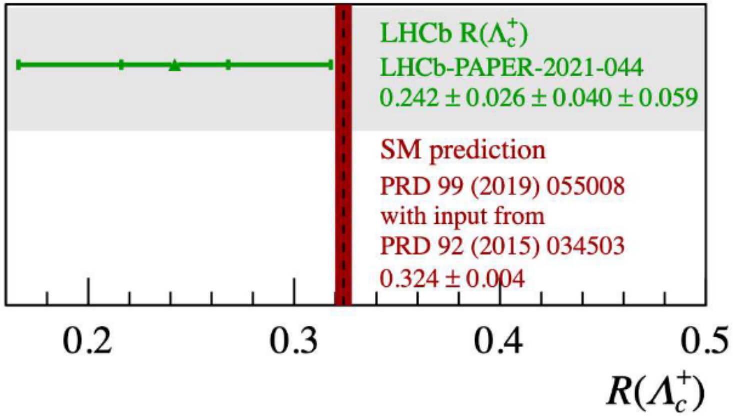
- $\mathcal{K}(\Lambda_c) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst})$
- Dominant source of systematic uncertainty is double charm background template shapes

Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\overline{\nu}_\tau$ feeddown	2.5
$D_s^- \to 3\pi Y$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^- , D^- , $\overline{D}^0$ template shapes	13.0
Efficiency ratio	2.8
Normalisation channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

- $\mathcal{B}(\Lambda_b^0 \to \Lambda_c \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16(\text{stat}) \pm 0.25(\text{syst}) \pm 0.23(\text{ext}))\ \%$

$\mathcal{R}(\Lambda_c) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$

- In agreement with SM prediction within 1σ



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Form Factor measurements

[Phys. Rev. D 100 (2019) 031102(R)]

- Differential distributions key for comparisons with Heavy Quark Effective Theory and Lattice QCD
- Necessary to measure CKM parameters ($|V_{cb}|$ in overall factor G)
- Measure form-factors as one Isgur-Wise function ξ(w)

$$w = \frac{m^2_{\Lambda_b^0} + m^2_{\Lambda_c^+} - q^2}{2 m_{\Lambda_b^0} m_{\Lambda_c^+}}$$

- In the static approximation the differential decay with is given by

$$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w)$$

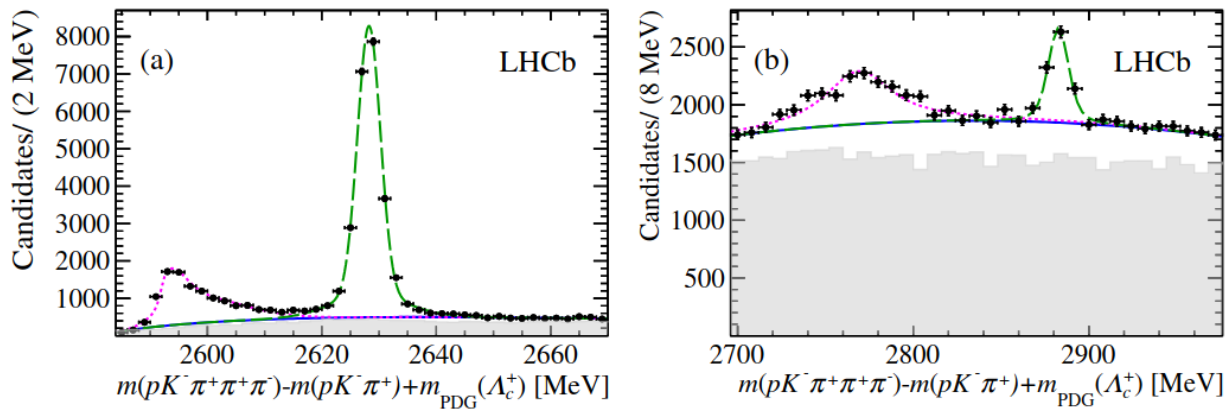
- Considering the non perturbative correction to the static limit:

$$\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma^2(w-1)^2 + \ldots$$

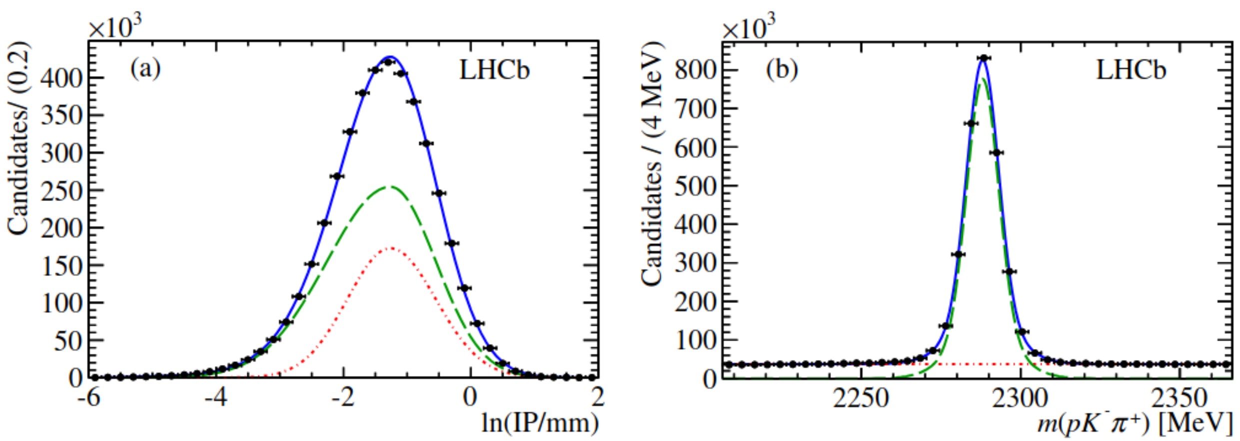
Form Factor measurements

[Phys. Rev. D 100 (2019) 031102(R)]

- Dataset: run1 LHCb data
- Inclusive $\Lambda^0_b \to \Lambda_c^+ \mu\nu X$ with $\Lambda_c^+ \to pK\pi$
- Excited state are backgrounds to ground state decay



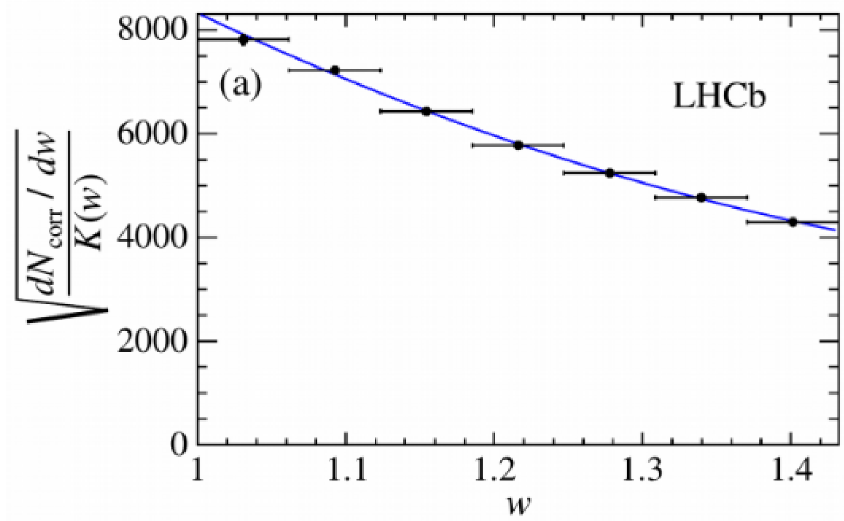
- 2D fit to the m(pKπ) and ln(IP/mm)

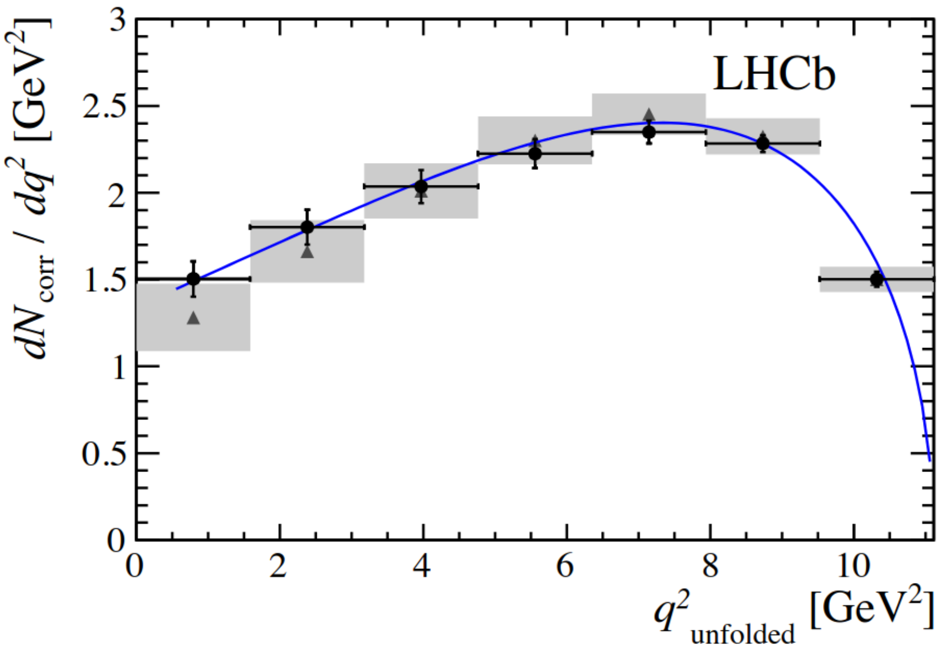


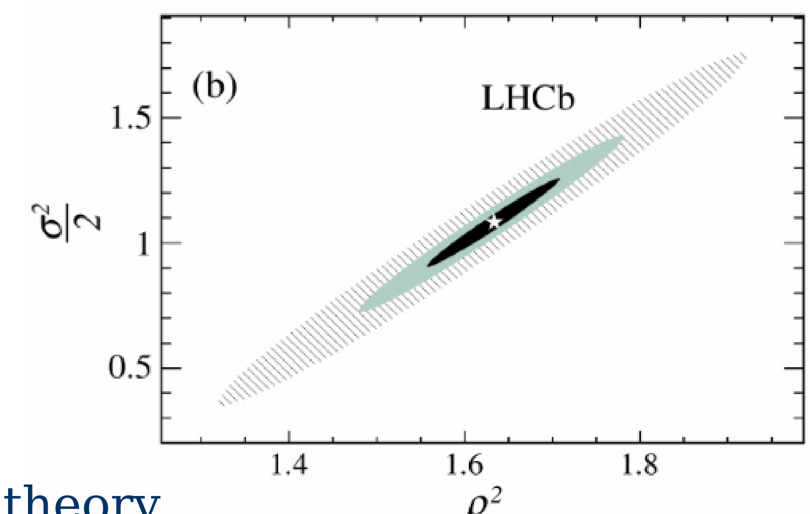
Form Factor measurements

[Phys. Rev. D 100 (2019) 031102(R)]

- The raw spectrum is unfolded for:
  - detector resolution
  - *w* smeraring effects
  - Single value decomposition
- Correct for acceptance and efficiency
- Unfold also for q^2







- Results compatible with the expectaion from theory
- Ongoing studies with normalization channel to extract |Vcb|

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b-hadron fractions measurement @13 TeV

[Phys. Rev. D 100 (2019) 031102(R)]

- Knowledge of b-hadron fragmentation fractions is essential in many aspects:
  - To allow for relating the pp production cross-section from pQCD to the observed hadrons
  - To convert the observed B_s and Λ^0_b production ratios at the LHC into absolute branching fractions
  - To characterize the signal (background) composition in inclusive (exclusive) b-hadron analyses
- These fractions must be determined experimentally because they are driven by strong dynamics in the non-perturbative regime.

b-hadron fractions measurement @13 TeV

[Phys. Rev. D 100 (2019) 031102(R)]

- The measured ratios are:

$$\frac{f_s}{f_u + f_d} \; ; \; \frac{f_{\Lambda_b^0}}{f_u + f_d}$$

$$f_q \equiv \mathcal{B}(b \to B_q)$$
$$f_{\Lambda_b} \equiv \mathcal{B}(b \to \Lambda_b)$$

- Data sample: 1.67 fb^{-1} (2016)
- Inclusive semileptonic decays: $H_b \to H_c X \mu \nu$
- Theoretical basis: Semileptonic widths for all b hadrons are almost equal [I.Bigi et al., JHEP 09 (2011) 012] → $G_{SL}(H_b) = G_{SL}$
  - Differences predicted to be around 1% (HQE)

  → we can use the measured lifetime to relate measured yield to hadron fragmentation.

$$\frac{f_s}{f_u + f_d} = \frac{n_{\text{corr}}(\overline{B}_s^0 \to D_s \mu)}{n_{\text{corr}}(B \to D^0 \mu) + n_{\text{corr}}(B \to D^+ \mu)} \frac{\tau_{B^-} + \tau_{\overline{B}^0}}{2\tau_{\overline{B}_s^0}} (1 - \xi_s) - \frac{\mathcal{B}(B \to D_s K \mu)}{\langle \mathcal{B}_{SL} \rangle} \frac{\epsilon(B \to D_s^+)}{\epsilon(\overline{B}_s^0 \to D_s^+)}$$

Corrected yields of $\bar{B}_s^0$, $\bar{B}^0$, B^-

SU(3) breaking correction $\xi_s = (-1 \pm 0.5)\%$

Subtraction of $\bar{B}^0(B^-) \to D_s^+ K \mu^- \bar{\nu}_\mu X$ contributions in $\bar{B}_s^0$ signals

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = \frac{n_{\text{corr}}(\Lambda_b^0 \to H_c \mu^-)}{n_{\text{corr}}(B \to D^0 \mu^-) + n_{\text{corr}}(B \to D^+ \mu^-)} \frac{\tau_{B^-} + \tau_{\overline{B}^0}}{2\tau_{\Lambda_b^0}} (1 - \xi_{\Lambda_b^0})$$

Corrected yields of Λ_b^0, $\bar{B}^0$, B^-

Chromomagnetic correction $\xi_{\Lambda_b^0} = (3 \pm 1.5)\%$

b-hadron fractions measurement @13 TeV

[Phys. Rev. D 100 (2019) 031102(R)]

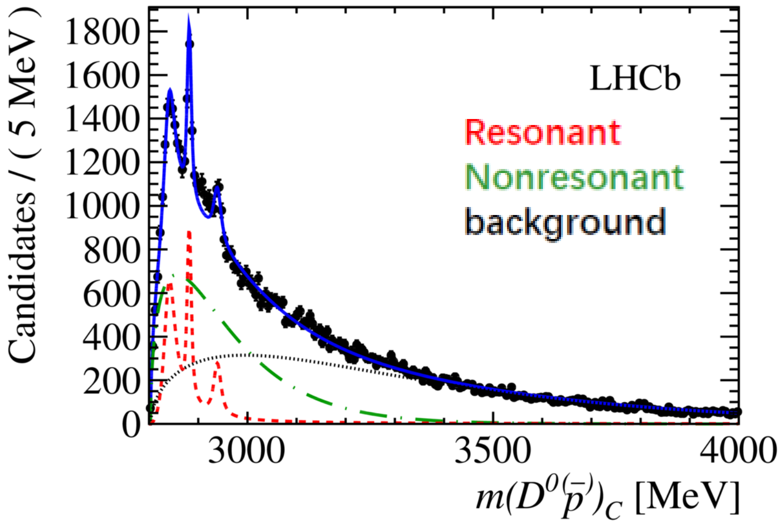
$$n_{\rm corr}(B \to D^0\mu^-) = \frac{1}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(B \to D^0)} \times$$
$$\left[n(D^0\mu) - n(D^0K^+\mu^-)\frac{\epsilon(\overline{B}{}^0_s \to D^0)}{\epsilon(\overline{B}{}^0_s \to D^0K^+)} - n(D^0p\mu^-)\frac{\epsilon(\Lambda^0_b \to D^0)}{\epsilon(\Lambda^0_b \to D^0p)} \right]$$

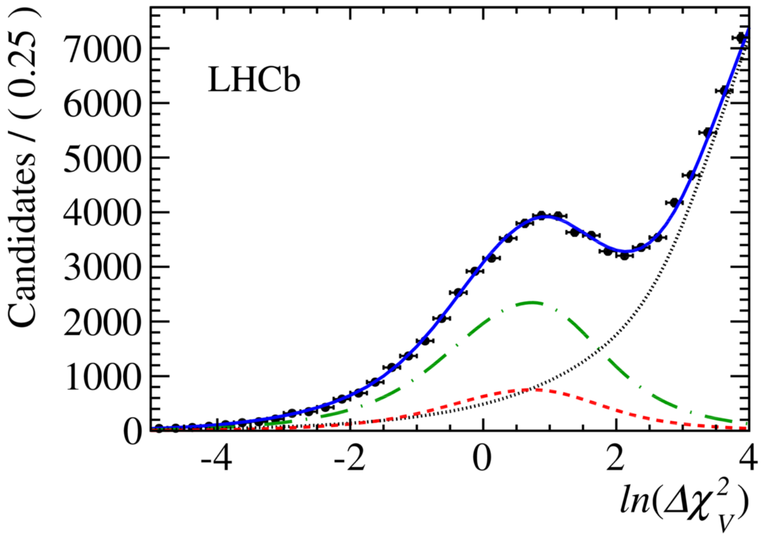
Inclusive yield

Subtracted yield of $B_s \to D^0 K X\mu\nu$

Subtracted yield of $\Lambda_b \to D^0 p X\mu\nu$

- $D^0 h X\mu\nu$ are signal for B_s and Λ_b and background for B^0 and B^-
  - 2D Fit to
    - $m(D^0h) - m(D^0) - m(D^0)_{pdg}$ (h=K,p)
    - $\ln(\Delta\chi^2_V)$: logarithm of the vertex χ^2 difference between $Dh\mu$ and $D\mu$

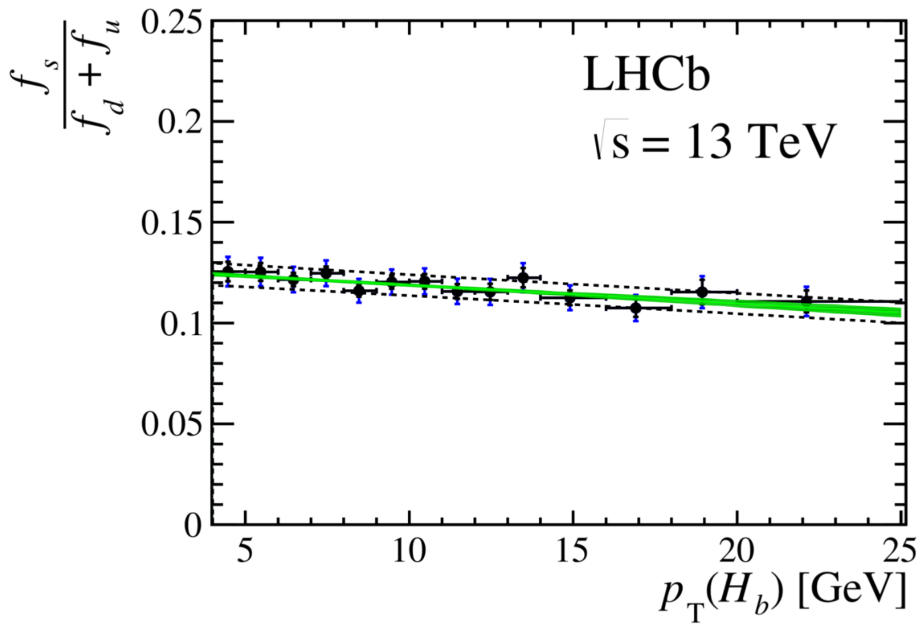


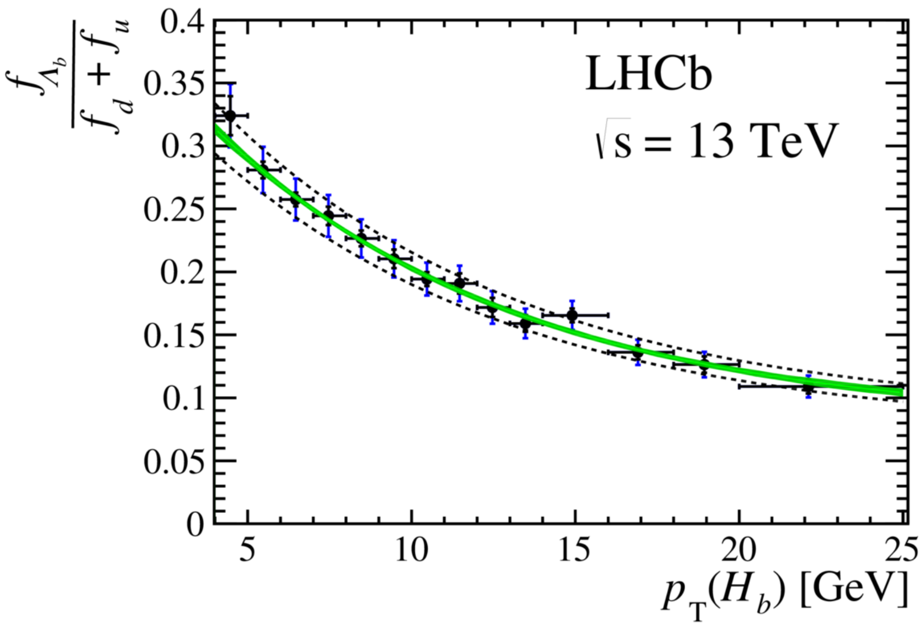


b-hadron fractions measurement @13 TeV

[Phys. Rev. D 100 (2019) 031102(R)]

- Fit to data: linear χ^2 fit to p_T (charm+μ) distributions incorporating a full covariance matrix, which takes into account correlation introduced from the kaon kinematics, PID and tracking systematic uncertainties.





- Averages fractions integrated between the limits $4<p_T$ (charm+μ)<25 GeV and $2<\eta<5$

$$\frac{f_s}{f_u+f_d} = 0.122 \pm 0.006 \qquad \frac{f_{\Lambda_b^0}}{f_u+f_d} = 0.259 \pm 0.018$$

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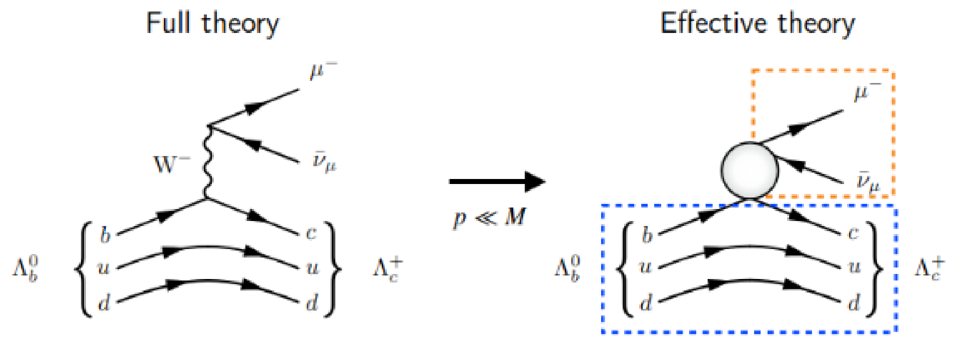
Angular analysis of $\Lambda^0_b \to \Lambda_c^+ \mu\nu$



- Search for new physics in Λ^0_b decays

- Goal of the analysis: probing the UV dynamics of the SM-WET, by measuring the Wilson Coefficients (WC) c_i

$$\mathscr{L}_{NP} \propto \sum_{i,d} \frac{c_i^{[d]}}{\Lambda_{NP}^{d-4}} O_i^{d\geq 5}(\psi_{SM})$$

e.g. C_{VR}, C_{SR}, C_{SL}, C_T, =0 in the SM

New Physics Operators

- By measuring the decay rate in we can access the Wilson Coefficients and the hadronic Form Factors

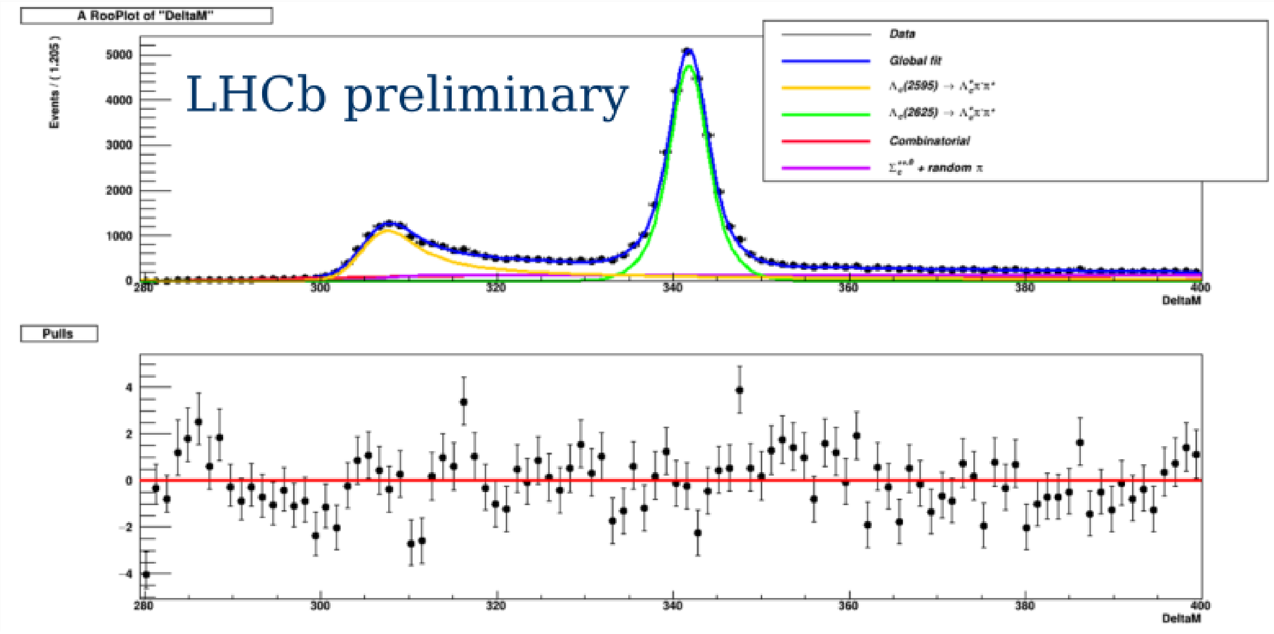
$$\frac{1}{N}\frac{d^2N}{dq^2\, d\cos\theta_\mu} \propto \sum_i c_i(\Lambda) f_i(q^2)$$

- Target: winter conferences

$\Lambda^0_b \rightarrow \Lambda_c^+ \mu\nu$ form factors

- Perform the $\Lambda^0_b \rightarrow \Lambda_c^+ \mu\nu$ form factors measurement from the double differential decay rate with respect to q and cos(θμ)

- The goal is to publish the result from the folded fit and the $\dfrac{BR(\Lambda_b \rightarrow \Lambda_c^+(2595)\mu\nu)}{BR(\Lambda_b \rightarrow \Lambda_c^+(2625)\mu\nu)}$



- Target: summer conferences

Conclusion

- Semileptonic *b*-hadron decays are excellent opportunites to check the SM and look for new phyisics
- Broad SL physics program at LHCb: measurement of CKM matrix elements, angular analysis, Wilson coefficients, LFU tests…
- Successful Run1 and Run2: 3+6 fb^{-1}, still many analysis ongoing
- Upgrade Phase I:10 times more data (20 times more hadronic events) → larger control samples and improved model descriptions will help to control systematic uncertainties

Thank you for your attention!

Original	Upgrade I	Upgrade II
2009-2018	2022-2032	2033-