The Lure of Baryons

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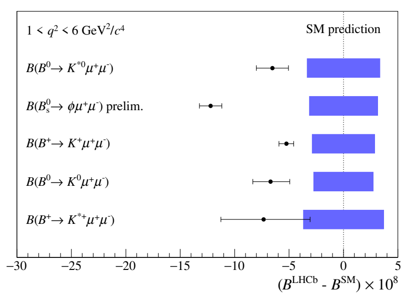
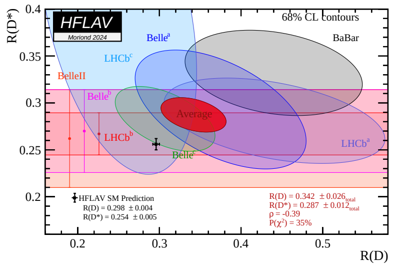
Why should we investigate baryon decays?

- plenty of anomalies seen in meson decays
- why bother?
- seems more complicated!?





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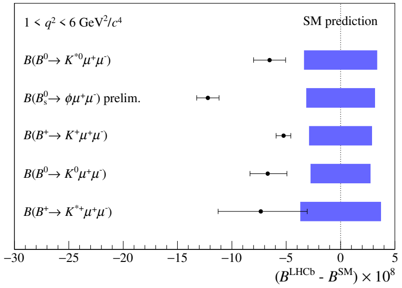
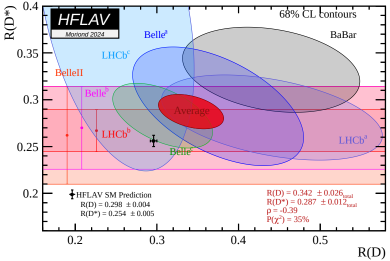
nonsense... baryon decays provide extremely useful information





here: focus on semileptonic decay of ground state to ground state baryons, e.g.

- $\Lambda_b^0 \to \Lambda_c^+(\to p\pi^0)\ell^-\bar{\nu}$ to complement $R_{D^{(*)}}$ and similar
- $\Lambda_b^0 \to \Lambda^0(\to p\pi^-)\ell^+\ell^-$ to complement P_5' and $\mathcal{B}(\bar{B} \to \bar{K}^{(*)}\ell^+\ell^-)$

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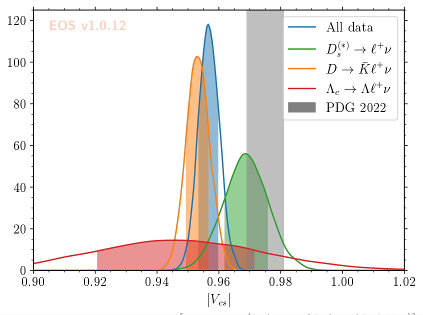

[2407.06145 (Bolognani,Reboud,DvD,Vos)]

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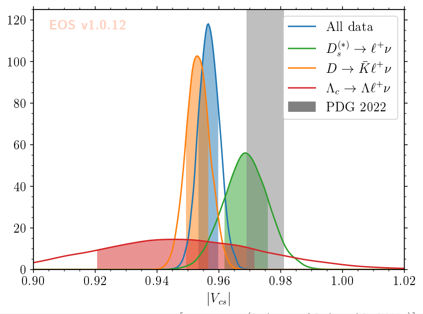

[2407.06145 (Bolognani,Reboud,DvD,Vos)]

- Meril's talk will partially address excited baryonic final states
- discussion session on hadronic spectrum in $\Lambda_b^0 \to \Lambda_c^+ X^0 \ell^-\bar{\nu}$, which deserves investigation both from the theory and the experimental side

- experiment: baryon analyses provide an independent probe (and possible corroboration) of the extant anomalies in meson decays
  - different analyses, different sources of systematic uncertainties useful to check work

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- theory(hadronic): predictions for baryons provide independent check on theory systematics
  - e.g., approximate symmetry relations between hadronic form factors are more predictive for (ground state) baryons
  - pheno analysis in this direction of $\Lambda_b^0 \to \Lambda_c^+$ form factors

[see 1808.09464 (Bernlochner,Ligeti,Robinson,Sutcliffe)]

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- theory(BSM): decay cascades with a secondary weak decay of baryon ground states provide complementary constraints on BSM couplings
  - unique to baryons

$\Lambda_b \to \Lambda\ell^+\ell^-$ – corroboration of the anomalies

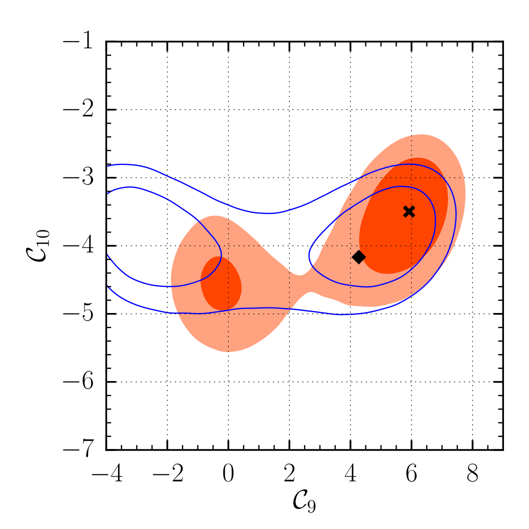
- $\Lambda_b \to \Lambda\ell^+\ell^-$ is a $b \to s\ell^+\ell^-$ mediated decay
  - model-independent analyses constraint at least two parameters C_9 and C_{10}
  - they are a measure of Beyond the Standard Model effectes in vectorial (C_9) and axial (C_{10}) couplings of $\bar{s}b$ to $\ell^+\ell^-$
- in the Standard Model

$$C_9^{\text{SM}} \simeq +4.3 \qquad\qquad C_{10}^{\text{SM}} \simeq -4.1$$

- global analyses of all available meson $b \to s\ell^+\ell^-$ decays see a signficant BSM contribution

$$C_9 - C_9^{\text{SM}} \simeq -1$$

2016 [1603.02974 (Meinel,DvD)]



2019 [1912.05811 (Blake,Meinel,DvD)]

orange: 68% (95%) regions due to $\Lambda_b \to \Lambda\ell^+\ell^-$ (LHCb 2015)

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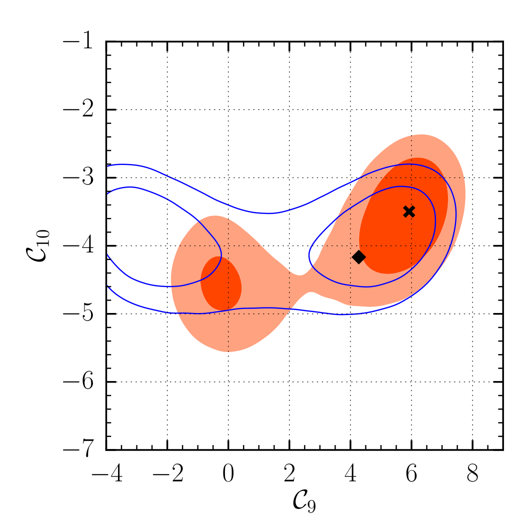

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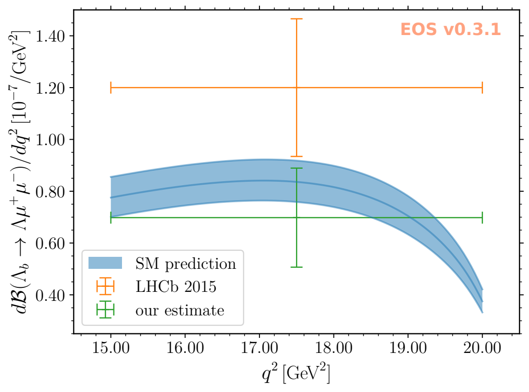
adjusted $\mathcal{B}$ for LHCb-specific Λ_b production fraction



also: LHCb corrected error in angular analysis

$\Lambda_b \to \Lambda\ell^+\ell^-$ – corroboration of the anomalies

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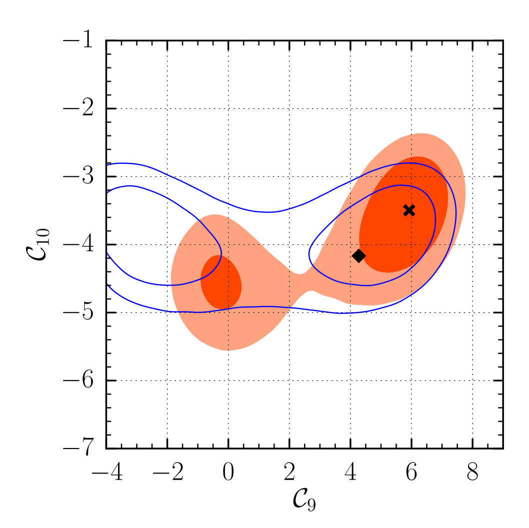

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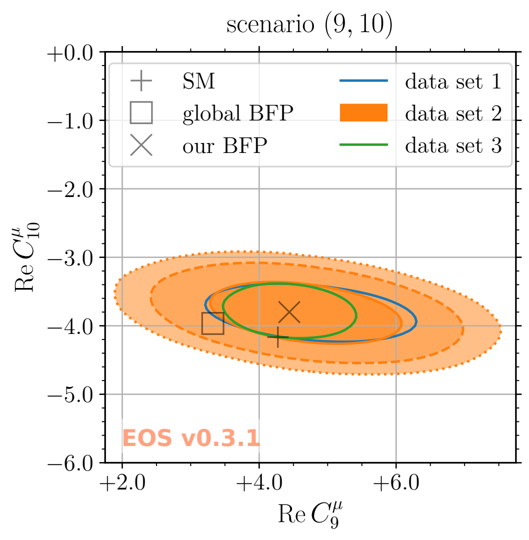

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- in heavy-quark to heavy-quark semileptonic decays, the form factors admit an expansion in terms of $\frac{\alpha_s}{\pi}$ and $\frac{\Lambda_{\text{had}}}{2m_Q}$, where $Q = b, c$
- for the six $\bar{B} \to D^{(*)}$ form factors in SM studies, this leads to ten indep. functions

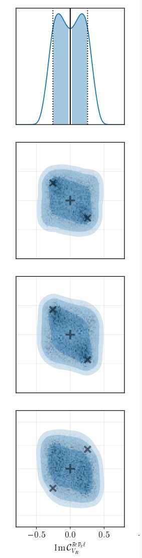
  [hep-ph/9209269 (Falk,Neubert); see e.g. 1912.09335 (Bordone et al.) for need for $1/m_Q^2$ FFs]

  - one at leading-power in $1/m_Q$
  - three at next-to-leading power in $1/m_Q$
  - six at next-to-next-to-leading power in $1/m_Q$ (needed to describe the data!)
- for the six $\Lambda_b \to \Lambda$ form factors in SM studies, this leads to three indep. functions

  [hep-ph/9209269 (Falk,Neubert); 1812.07593 (Bernlochner,Ligeti,Robinson,Sutcliffe)]

  - one at leading-power in $1/m_Q$
  - zero at next-to-leading power in $1/m_Q$
  - two at next-to-next-to-leading power in $1/m_Q$
- as a consequence, $R(\Lambda_c)$ could be predicted with higher precision than possible with the lattice QCD results for the form factors alone! [1812.07593 (Bernlochner,Ligeti,Robinson,Sutcliffe)]

$\Lambda_c^+ \to \Lambda(\to p\pi^-)\ell^+\nu$ – complementary and clean BSM constraints



- recent study finds a puzzle in (semi)leptonic charm decays, specifically $c \to s\ell^+\nu$ [2407.06145 (Bolognani,Reboud,DvD,Vos)]
  - global analysis of meson decays finds a significant deficit in the 2nd-row and 2nd-column unitarity relations of the CKM matrix
- a possible BSM explanation involves CP-violating contributions to right-handed $\bar{s}c$ currents.
  - impossible to test for in $D_s^+ \to \ell^+\nu$ or $D \to K\ell^+\nu$ decays
  - can be tested through angular distributions in $D \to K\pi\ell^+\nu$ or $\Lambda_c^+ \to \Lambda^0(\to p\pi^-)\ell^+\nu$
- $\Lambda_c^+ \to \Lambda^0(\to p\pi^-)\ell^+\nu$ is unique in providing constraints of the form $|C_L|^2 - |C_R|^2$ for the $sc\nu\ell$ coefficients
  - due to parity violation in the secondary $\Lambda^0 \to p\pi^-$ decay

Angular distribution / expressions available for $b \to c\ell^-\nu$ [1907.12554 (Böer,Kokulu,Toelstede,DvD)]

$$K(q^2, \cos\theta_\ell, \cos\theta_{\Lambda_c}, \phi) \equiv \frac{8\pi}{3} \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{\Lambda_c}\, d\phi}\,.$$

$$\begin{aligned}K(q^2, \cos\theta_\ell, \cos\theta_{\Lambda_c}, \phi) = & \left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\ & + \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_{\Lambda_c} \\ & + \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_{\Lambda_c}\sin\phi \\ & + \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_{\Lambda_c}\cos\phi\,,\end{aligned}$$

- K_{3s} is exactly zero in the SM and sensitive to new weak phases in right-handed currents
- theory predictions for K_{3s} are very clean thanks to existing lattice QCD analyses

[1611.09696 (Meinel)]

- integrated over the entire dilepton-mass spectrum, it could be as large 0.12, a smoking gun for BSM physics $c \to s\ell^+\nu$ decays

Conclusions

Usefulness of baryon decays in flavour physics is self-evident

- provide independent set of experimental analyses to probe and potentially corroborate the flavour anomalies
- provide opportunity to challenge theory predictions, to find and diagnose potential issues
- provide complementary constraints for BSM searches

Looking forward to many more showcases delivered by the LHC experiments and BESIII!