Canned WET goods:
Low-energy BSM constraints for model builders

Heavy flavour aspects – 24/04/2023

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Based on: Leljak, Melić, Novak, MR, van Dyk 2302.05268

Context

- Low-energy analyses deal with **O(100) hadronic nuisance parameters**
  - QCD is non-perturbative
  - Lattice calculations are complicated
  - Other QCD methods (LCSR, QM) have uncontrolled uncertainties

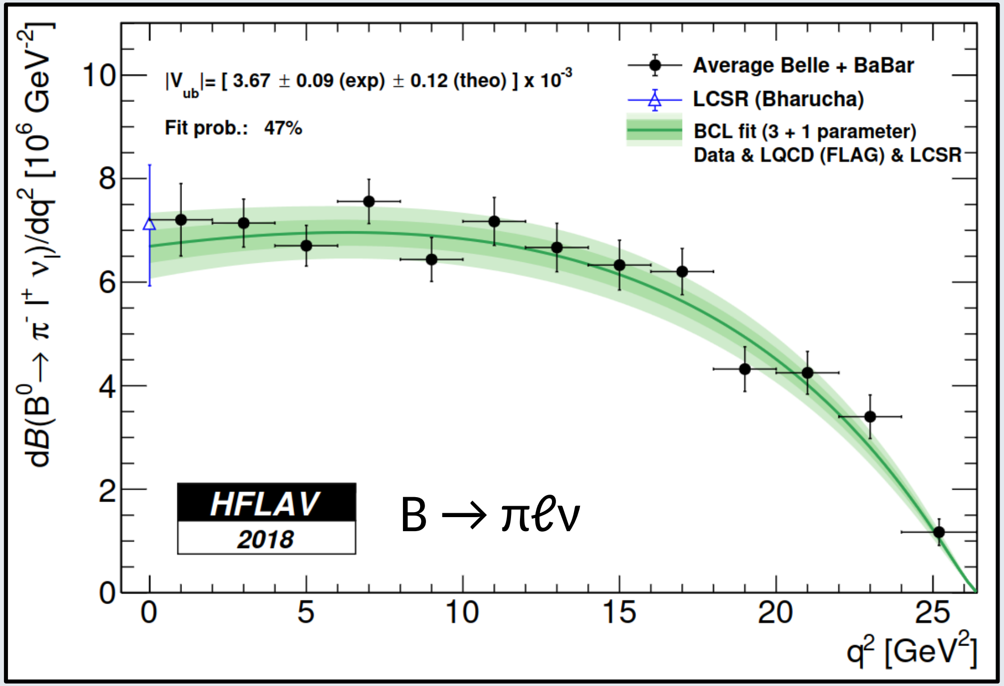
→ This is not something model builders want/should deal with

- **Question**: How can low-energy information be passed on to model builders with minimum dilution and modification?

→ I will try to provide a partial answer in the context of $b \to u\ell\nu$

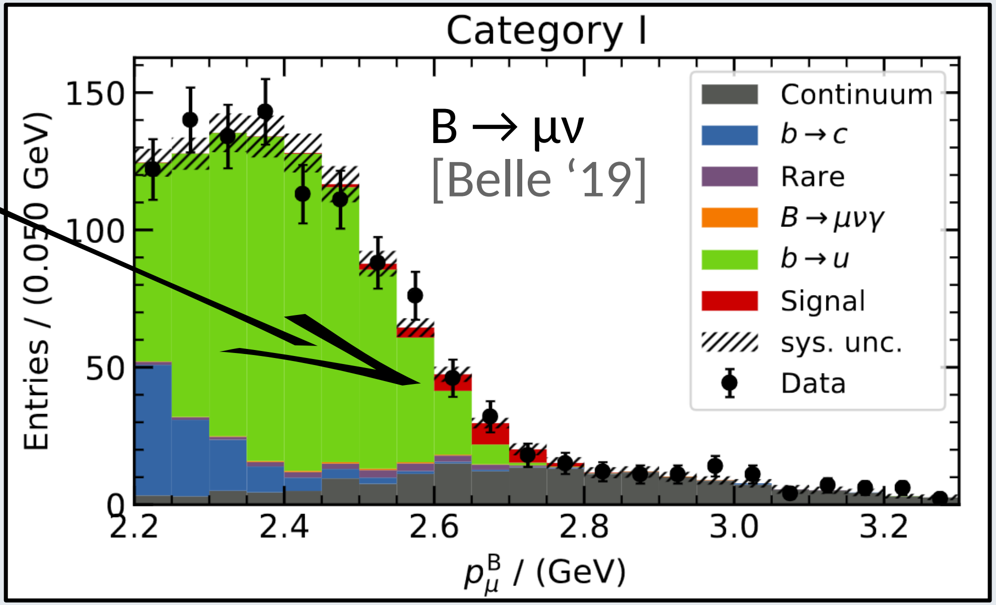
Experimental inputs for $b \to u\ell\nu$ (I)

- **$B \to \pi\ell\nu$**: HFLAV '19 average of BaBar '10 and '12 and Belle '10 and '13 measurements → 13 q^2 bins
- **$B \to \rho\ell\nu$**: average of BaBar '10 and Belle '13 measurements performed by *[Bernlochner et al '21]* → 11 q^2 bins
- **$B \to \omega\ell\nu$**: average of BaBar '12 and Belle '13 measurements performed by *[Bernlochner et al '21]* → 5 q^2 bins



Experimental inputs for $b \to u\ell\nu$ (II)

- We don't add the following data (yet):
  - $B \to \mu\nu$: only observed with 2.8σ significance
  - $B \to \eta^{(\prime)}\ell\nu$: little statistics and poorly known form factors
  - Inclusive $b \to u\ell\nu$: assume SM in the analysis (more details later)
  - $\Lambda_b \to p\ell\nu$ and $B_s \to K^{(*)}\ell\nu$ are measured by LHCb, but normalized to a $b \to c\ell\nu$ mode!



WET

- Assume left-handed neutrinos only

$$\mathcal{H}^{ub\ell\nu} = -\frac{4G_F}{\sqrt{2}}\tilde{V}_{ub}\sum_i \mathcal{C}_i^\ell \mathcal{O}_i^\ell + \cdots + \text{h.c.}\,.$$

- B → π (pseudoscalar) and B → ρ, B → ω (vectors) are sensitive to different combinations of the operators

$$\begin{aligned}
\mathcal{O}^\ell_{V,L} &= \left[\bar{u}\gamma^\mu P_L b\right]\left[\bar{\ell}\gamma_\mu P_L \nu\right], & \mathcal{O}^\ell_{V,R} &= \left[\bar{u}\gamma^\mu P_R b\right]\left[\bar{\ell}\gamma_\mu P_L \nu\right], \\
\mathcal{O}^\ell_{S,L} &= \left[\bar{u}P_L b\right]\left[\bar{\ell}P_L \nu\right], & \mathcal{O}^\ell_{S,R} &= \left[\bar{u}P_R b\right]\left[\bar{\ell}P_L \nu\right], \\
\mathcal{O}^\ell_{T} &= \left[\bar{u}\sigma^{\mu\nu} b\right]\left[\bar{\ell}\sigma_{\mu\nu} P_L \nu\right].
\end{aligned}$$

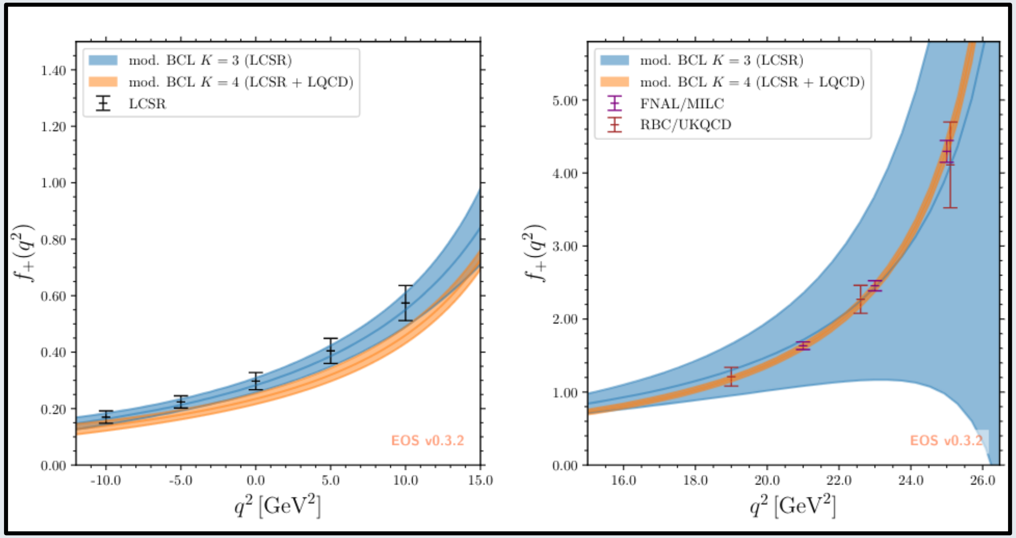
- Only one relevant operator in the SM, normalized to V_{ub}

$$\mathcal{C}^\ell_{V,L} = 1 + \frac{\alpha_e}{\pi}\ln\left(\frac{M_Z}{\mu}\right)$$

Hadronic inputs

- All the non-perturbativity of QCD appears in the *hadronic form factors*. These functions are known from LQCD and/or LCSR calculations:
  - B → π, we used the same inputs as [Leljak, Melić, van Dyk ‘21]
    - LQCD [FNAL+MILC ‘15] [UKQCD ‘15] and LCSR [Leljak, Melić, van Dyk ‘21]
    - BCL parametrization
      → 12 parameters
  - B → ρ and B → ω
    - LCSR [Bharucha, Straub, Zwicky ‘15]
    - BSZ parametrization
      → 2*19 parameters

→ 50 nuisance parameters



[Leljak, Melić, van Dyk ‘21]

Methodology

- Our goals:

  1) Determine the consistency of exclusive data and the quality of a $|V_{ub}|$ extraction

  2) Determine whether a BSM explanation of the data is favored over the SM

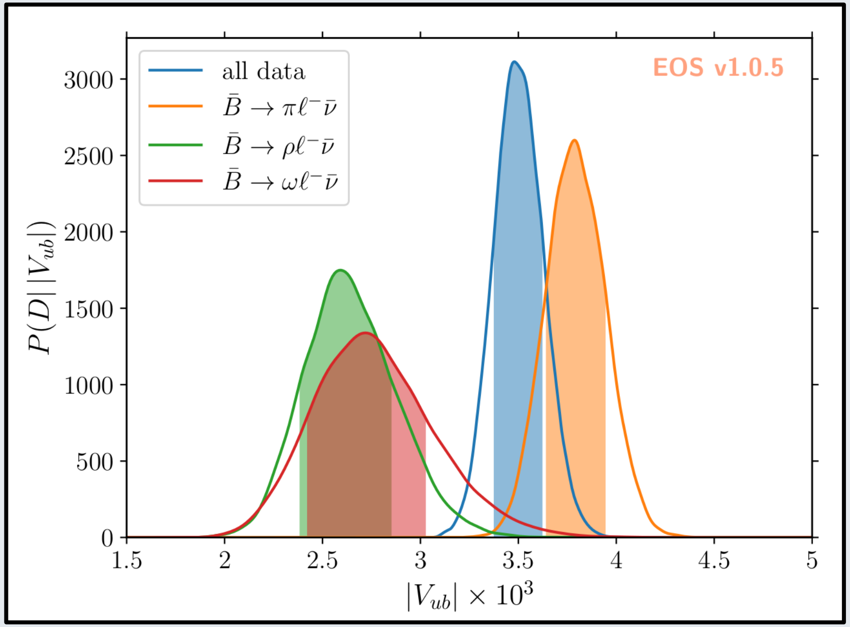
  3) Provide the posterior likelihood of the WCs C_i

- We perform 3 Bayesian analyses:
  - **SM** → only float hadronic inputs: *null hypothesis*
  - **CKM** → float hadronic inputs and extract $|V_{ub}|$
  - **WET** → float hadronic inputs and extract the WCs C_i

- We sampled using *nested sampling* and **EOS**: eos.github.io

Results: Extraction of $|V_{ub}|$

- Good fits: p values > 52%
- Form factors uncertainties propagate to $|V_{ub}|$



Data set	Goodness of fit χ^2	d.o.f.	p value [%]	$|V_{ub}| \times 10^3$
$\bar{B} \to \pi \ell \nu$	27.83	31	62.98	$3.79^{+0.15}_{-0.15}$
$\bar{B} \to \rho \ell \nu$	5.08	10	88.60	$2.63^{+0.25}_{-0.22}$
$\bar{B} \to \omega \ell \nu$	3.19	4	52.66	$2.74^{+0.33}_{-0.28}$
all data	52.31	47	27.53	$3.50^{+0.13}_{-0.12}$

- State-of-the-art determinations:
  - Inclusive [HFLAV, PDG, … '22]
    $|V_{ub}| = 4.13(12)(13)(18)\ 10^{-3}$
  - Exclusive [HFLAV, PDG, … '20]
    $|V_{ub}| = 3.70(10)(12)\ 10^{-3}$

Results: Predictions for B → ℓν

- We can post-dict values for all relevant b → uℓν observable, e.g.

$$\mathcal{B}(\bar{B}^- \to \tau^- \bar{\nu}) = \left(7.87^{+0.58}_{-0.54}\big|_{|V_{ub}|} \pm 0.12\big|_{f_B}\right) \times 10^{-5}\,,$$

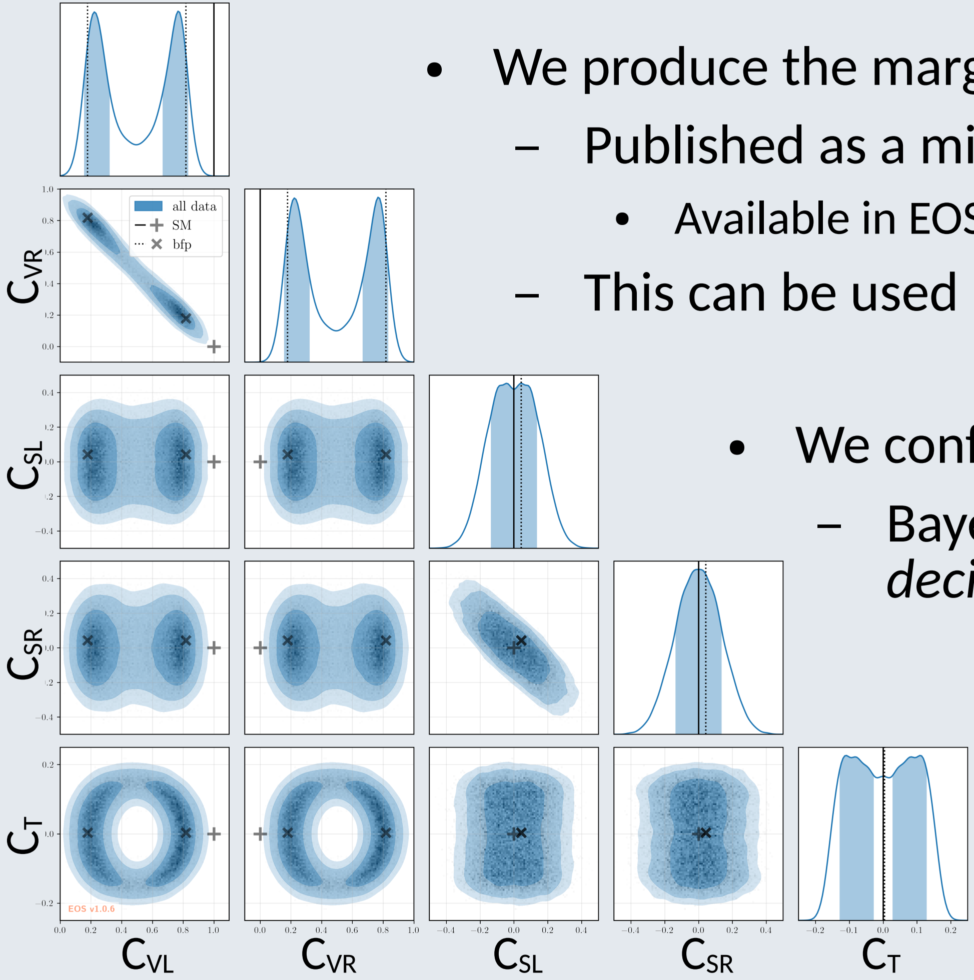
$$\mathcal{B}(\bar{B}^- \to \mu^- \bar{\nu}) = \left(3.54^{+0.26}_{-0.24}\big|_{|V_{ub}|} \pm 0.05\big|_{f_B}\right) \times 10^{-7}\,,$$

$$\mathcal{B}(\bar{B}^- \to e^- \bar{\nu}) = \left(8.28^{+0.61}_{-0.56}\big|_{|V_{ub}|} \pm 0.12\big|_{f_B}\right) \times 10^{-12}\,.$$

- To be compared with the experimental result:

$$\mathcal{B}(\bar{B}^- \to \mu^- \bar{\nu})\big|_{\text{Belle '19}} = (5.3 \pm 2.2) \times 10^{-7}$$

Results: Global likelihood



- We produce the marginalized posterior distribution of the Wcs
  - Published as a mixture density of multivariate Gaussians
    - Available in EOS as `ublnu::P(WET)@LMNRvD:2023A`
  - This can be used by model builders to study BSM scenarios

- We confirm the (known) tension in the C_{VL} – C_{VR} plane
  - Bayesian model comparison finds the **WET** model *decisively in favour* over the **SM** and **CKM** ones

- Future (angular) analyses will help breaking the degeneracy in the C_{VL} – C_{VR} plane

Conclusion (I)

- Yes, the $|V_{ub}|$ inclusive vs. exclusive tension is still present, albeit diminished
- Yes, NP contributions consistently improve the $b \to u\ell\nu$ fit
- But more important (in my opinion): this analysis is meant as a **benchmark for future work**:

  Testing BSM models cannot be done with O(100) hadronic nuisance parameters

  → The theory community will need such (up-to-date) WET likelihoods

  → The theory **and** experimental communities will need to agree on
  (1) an exchange format for non Gaussian likelihoods
  (2) hadronic inputs
  (3) observables of interest…

Conclusion (II)

Examples of problems we need to solve/avoid:

- $b \to u\ell\nu$ inclusive (and exclusive, to a smaller extent) analyses need to **assume SM** for MC production, efficiency calculation…
  - This makes a WET analysis *impossible at present*
  - One possible solution is to reweight MC samples with BSM weights (Hammer, EOS…)
  - But all the analysis steps have to be adapted
- Some experiments suggest an unbinned fit of the WET WC
  - This should only be an **additional piece of information**

    → Global analyses would require the full posterior, including all nuisance parameters which is very hard if not impossible to achieve.