Heavy Flavour Landscape

Danny van Dyk

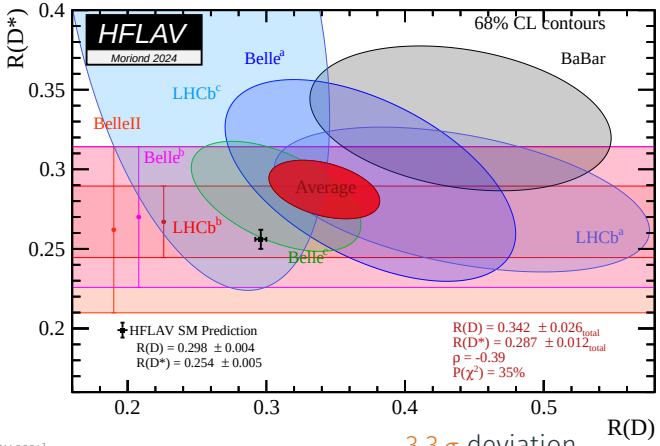
Sep 26th 2024

Institute for Particle Physics Phenomenology, Durham

Aims

- discuss probes for the effects of physics beyond the Standard Model in processes that change quark flavour
- provide context of challenges using three prototypical processes
- compare to some experimental outlooks based on the Belle II physics book and the HL-LHC report [1808.10567,1812.07638]

$$R(X) = \mathcal{B}(B \to X\tau\bar{\nu})/\mathcal{B}(B \to X\mu\bar{\nu})$$



[HFLAV 2024]

3.3 σ deviation

- LHCb expects $\sigma(R_{D^*}) \simeq 0.003$ at 300 fb^{-1}
- Belle II expects $\sigma(R_{D^*}) \simeq 0.006$ at 50 ab^{-1},
- both expect to measure the full angular distribution
- compare current theory uncertainty $\sigma = 0.005$

- main uncertainty: hadronic form factors
  - parametrize mismatch between partonic ($b \to c$) and exclusive hadronic ($\bar{B} \to D^{(*)}$) picture
  - SM predictions depend on 2 (for R_D) and 4 (for R_{D^*}) scalar functions of momentum transfer $m_\ell^2 \leq q^2 \leq (M_B - M_{D^{(*)}})^2$

- main uncertainty: hadronic form factors
  - parametrize mismatch between partonic ($b \to c$) and exclusive hadronic ($\bar{B} \to D^{(*)}$) picture
  - SM predictions depend on 2 (for R_D) and 4 (for R_{D*}) scalar functions of momentum transfer $m_\ell^2 \leq q^2 \leq (M_B - M_{D^{(*)}})^2$
- community made great strides since 2012 heavy-quark symmetry based estimates

[Fajfer,Kamenik,Nisandzic 1206.1872]

- main uncertainty: hadronic form factors
  - parametrize mismatch between partonic ($b \to c$) and exclusive hadronic ($\bar{B} \to D^{(*)}$) picture
  - SM predictions depend on 2 (for R_D) and 4 (for R_{D^*}) scalar functions of momentum transfer $m_\ell^2 \leq q^2 \leq (M_B - M_{D^{(*)}})^2$
- community made great strides since 2012 heavy-quark symmetry based estimates

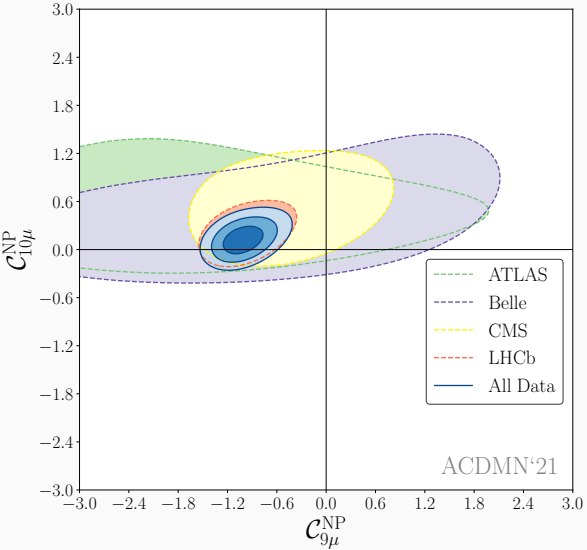
[Fajfer,Kamenik,Nisandzic 1206.1872]

- nowadays: lattice QCD analyses at serveral q^2 points for all form factors w/ correlations
  - Fermilab/MILC (2021), HPQCD (2023), JLQCD (2023) [2105.14019, 2304.03137, 2306.05657]
  - reasonable to combine in joint fit [Bordone,Jüttner 2406.10074]
  - heavy-quark symmetry check not yet carried out

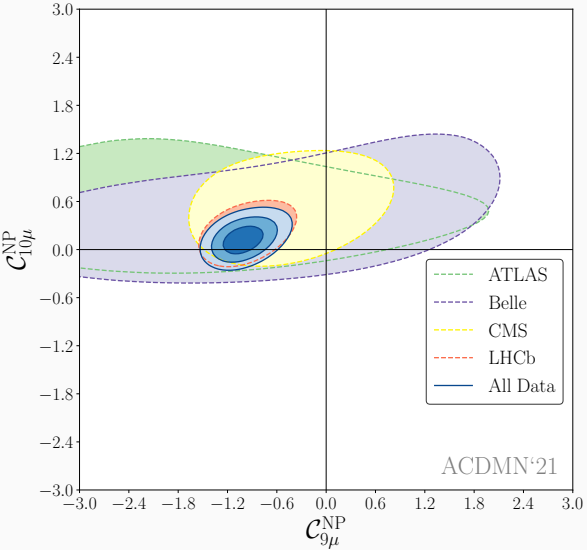
- main uncertainty: hadronic form factors
  - parametrize mismatch between partonic ($b \to c$) and exclusive hadronic ($\bar{B} \to D^{(*)}$) picture
  - SM predictions depend on 2 (for R_D) and 4 (for R_{D^*}) scalar functions of momentum transfer $m_\ell^2 \leq q^2 \leq (M_B - M_{D^{(*)}})^2$
- community made great strides since 2012 heavy-quark symmetry based estimates

[Fajfer,Kamenik,Nisandzic 1206.1872]

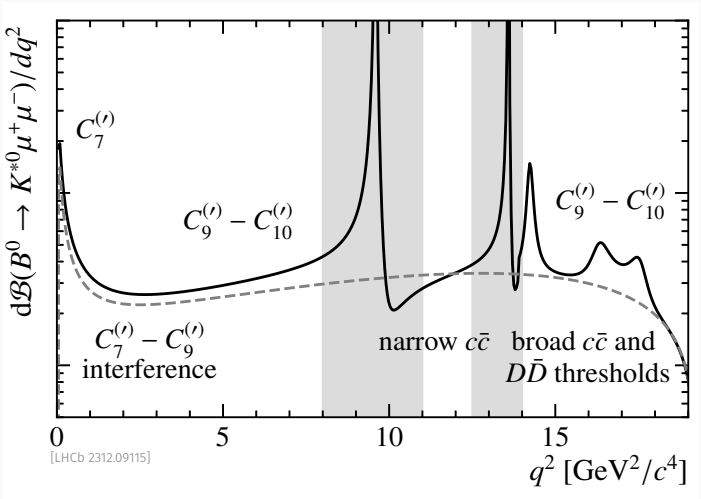
- nowadays: lattice QCD analyses at serveral q^2 points for all form factors w/ correlations
  - Fermilab/MILC (2021), HPQCD (2023), JLQCD (2023) [2105.14019, 2304.03137, 2306.05657]
  - reasonable to combine in joint fit [Bordone,Jüttner 2406.10074]
  - heavy-quark symmetry check not yet carried out
- next big issue: consistent treatment of QED effects, accounting for structure-dependent QED effects



- large number of observables render $R(D^{(*)})$-style combination moot

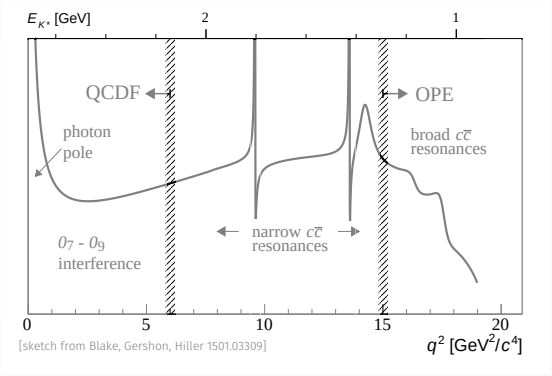


- large number of observables render $R(D^{(*)})$-style combination moot
- instead: BSM sensitivity expressed in EFT coefficients C_9 & C_{10} of $sb\mu\mu$ operators



- large number of observables render $R(D^{(*)})$-style combination moot
- instead: BSM sensitivity expressed in EFT coefficients C_9 & C_{10} of $sb\mu\mu$ operators
- dashed: purely local $sb\mu\mu$ contribution ($\propto$ form factors)
- solid: adds nonlocal contributions due to $sbcc$ operators $O_{1,2}^c$

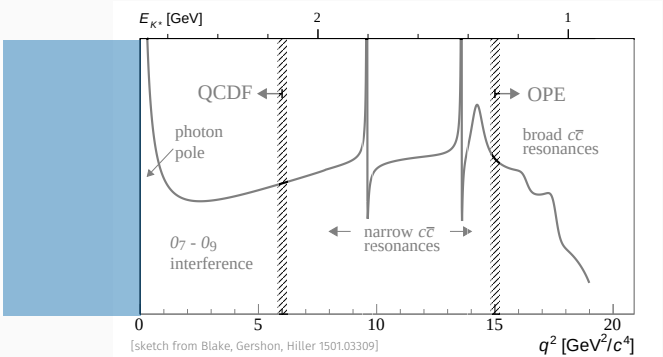
$$\mathcal{H}_\lambda = P(\lambda)_\mu \langle H_s | \int d^4x\, e^{iq\cdot x}\, \mathcal{T}\{ J^\mu_{\text{em}}(x), [C_1 O_1^c + C_2 O_2^c](0) \} | H_b \rangle$$



- $O_{1,2}^c \sim [\bar{s}\Gamma b]\,[\bar{c}\Gamma' c]$

source of dominant systematic uncertainties in theoretical predictions!

$$\mathcal{H}_\lambda = P(\lambda)_\mu \langle H_s | \int d^4x\, e^{iq\cdot x}\, \mathcal{T}\{ J^\mu_{\rm em}(x), [C_1 O_1^c + C_2 O_2^c](0) \} | H_b \rangle$$

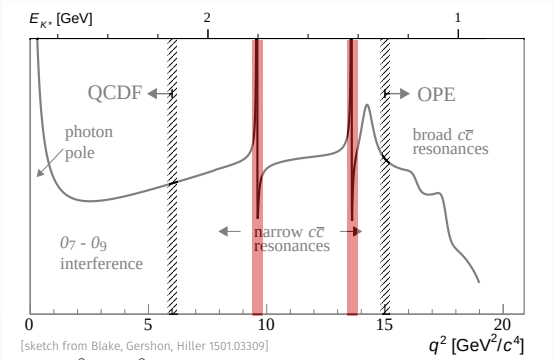


[sketch from Blake, Gershon, Hiller 1501.03309]

- $O^c_{1,2} \sim [\bar{s}\Gamma b]\,[\bar{c}\Gamma' c]$

- leading contributions expressed through local form factors $\mathcal{F}_\lambda$
- correction suppressed by $1/(q^2 - 4m_c^2)$; can by systematically obtained

$$\mathcal{H}_\lambda = P(\lambda)_\mu \langle H_s | \int d^4x\, e^{iq\cdot x}\, \mathcal{T}\{ J^\mu_{\rm em}(x), [C_1 O_1^c + C_2 O_2^c](0) \} | H_b \rangle$$

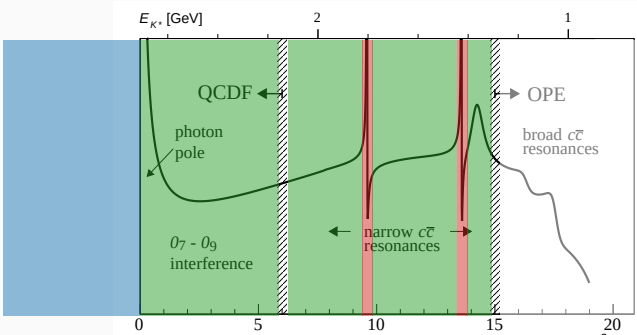


[sketch from Blake, Gershon, Hiller 1501.03309]

- $O^c_{1,2} \sim [\bar{s}\Gamma b]\ [\bar{c}\Gamma' c]$

- for $q^2 = M^2_{J/\psi}$ and $q^2 = M^2_{\psi(2S)}$, spectrum dominated by $H_b \to H_s \psi (\to \mu^+\mu^-)$
- experimental measurements provide additional information about non-local $\mathcal{H}_\lambda$ terms

$$\mathcal{H}_\lambda = P(\lambda)_\mu \, \langle H_s | \int d^4x \, e^{iq\cdot x} \, \mathcal{T}\{ J^\mu_{\text{em}}(x), [C_1 O_1^c + C_2 O_2^c](0) \} \, | H_b \rangle$$

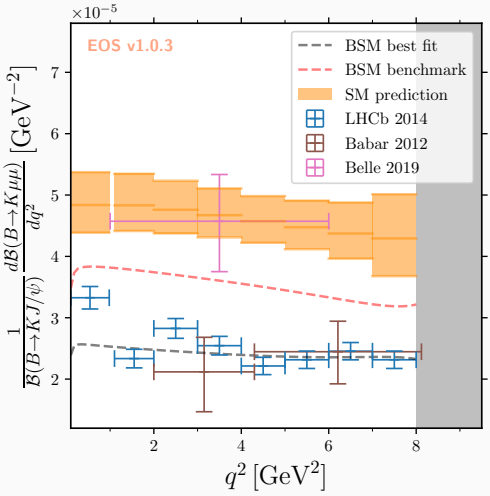


[sketch from Blake, Gershon, Hiller 1501.03309]

- $O^c_{1,2} \sim [\bar{s}\Gamma b]\,[\bar{c}\Gamma' c]$

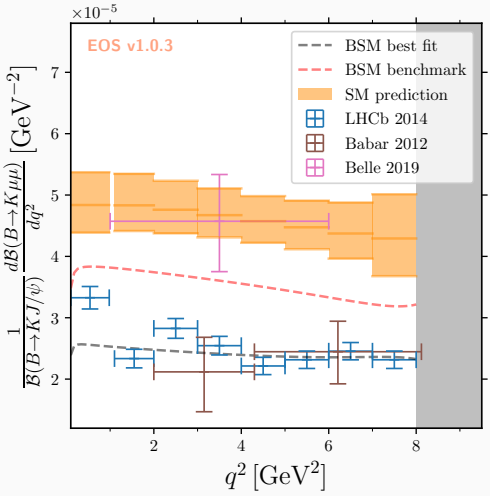
new strategy

- compute $\mathcal{H}_\lambda$ at spacelike q^2
- extrapolate to timelike $q^2 \leq 4M_D^2$ using suitable parametrization
- include information from decays to narrow charmonia J/ψ and $\psi(2S)$



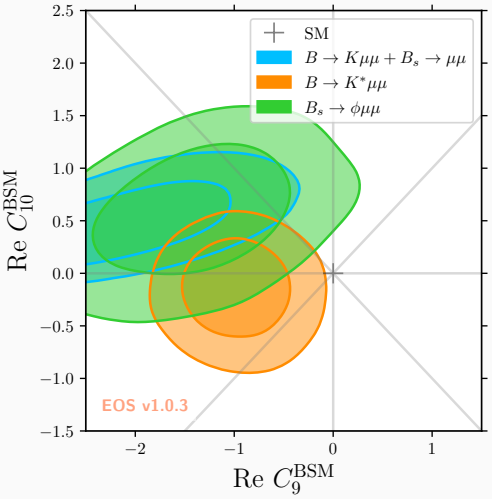
[Gubernari,Reboud,DvD,Virto 2206.03797]

- approach is systematically improvable



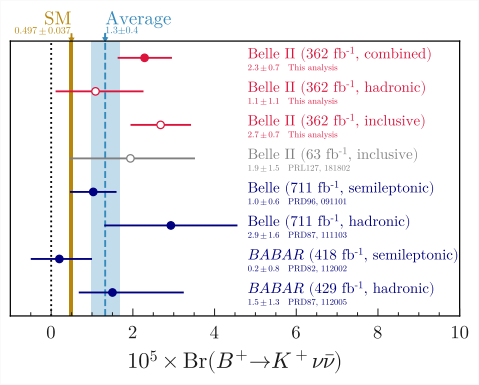
[Gubernari,Reboud,DvD,Virto 2206.03797]

- approach is systematically improvable
- benefits from both additional data and theory improvements



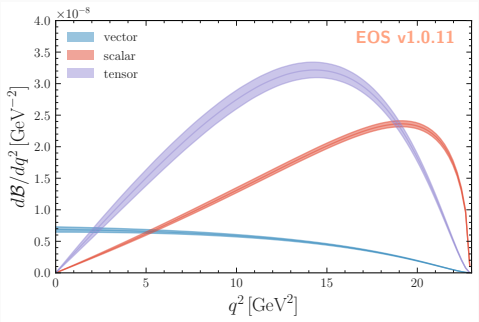
- approach is systematically improvable
- benefits from both additional data and theory improvements
- results are compatible with those in previous approaches albeit w/ still larger uncertainties

[Gubernari,Reboud,DvD,Virto 2206.03797]



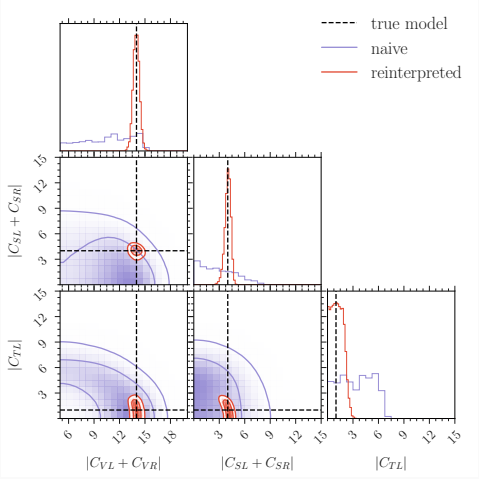
[Belle II 2311.14647]

- $b \to s\nu\bar{\nu}$: rare loop-mediated processes, theoretically similar to $b \to s\ell^+\ell^-$
- Belle II: first evidence of $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$, using two different tagging methods
- branching ratio is $\sim 2.7\sigma$ larger than SM prediction suggests



[Gärtner et al. 2402.08417]

- rate measurement delicately depends on SM prediction for the kinematic distribution (here: q^2)
- EFT interpretation difficult, since BSM can change the shape significantly



- rate measurement delicately depends on SM prediction for the kinematic distribution (here: q^2)
- EFT interpretation difficult, since BSM can change the shape significantly
- Belle II aim to provide shape information through likelihood in `HistFactory` format
- full likelihood seems crucial to accurate pheno interpretation (when scalar/tensor sources are considered)

[Gärtner et al. 2402.08417]

- current experiments cover semileptonic b & c decays, including rare decays
  - caveat: measurement of absolute $\mathcal{B}$ only realistic at Belle II, and only for B mesons

- a Z pole experiment would change this picture qualitatively
  - seeing 10^{11} $\bar{b}b$ pairs from 4 years running FCC-ee on the Z pole
    - Belle II w/ $5 \cdot 10^{10}$ B meson pairs over next 11 years
    - LHCb Upgrade II w/ 10^{15} $\bar{b}b$ pairs in 6 years
  - providing access to absolute $\mathcal{B}$s for B, B_s, B_c, Λ_b decays
  - Λ_b: increasing BSM sensitivity due to substantial polarisation in $Z \to \Lambda_b \overline{\Lambda}_b$
  - $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$: opening complementary decays compared to current experiments
    see talk by M. Kenzie on Monday [Amhis,Kenzie,Reboud,Wiederhold 2309.11353]

- puzzle in charm: large amounts of precise BESIII data seem to yield too small $|V_{cs}|$

  [Bolognani,Reboud,DvD,Vos 2407.06145]

  - opens significant deficit in CKM unitarity tests for 2nd row and 2nd column

- going forward: need to define interface between heavy-flavour analyses and global HEFT/SMEFT fits
  - how to transfer results from low-energy fits to HEFT/SMEFT fits accurately and efficiently?

- only heavy flavour: did not discuss kaons, see talk by M. Gorbahn on Wednesday

Conclusion

- very rich ongoing and planned heavy flavour programme at the (HL-)LHC, SuperKEKB, and BEPC II
- theory/pheno needs to catch up with projected experimental sensitivities, in particular in regard to ongoing puzzles/anomalies
  - tackling issues beyond “higher order loop calculations”
- future collider run on the Z pole would provide substantial amount of qualitatively different data