Phenomenology of $B_q \to D_q\{K, \pi\}$ decays

Matthew Kirk, Stefan Meiser

based on work with Oliver Atkinson, Christoph Englert, Gilberto Tetlalmatzi-Xolocotzi; Danny van Dyk, Javier Virto

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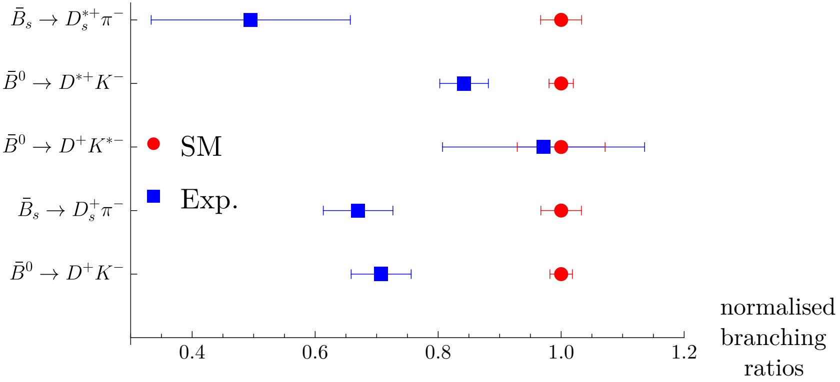
Beyond the Flavour Anomalies VI, 10 April 2025

Motivation



- How should we interpret these deviations?

Possible Explanations for the discrepancy

1. Experiment: problems with measurements?
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2. Underestimated theoretical uncertainties?
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3. Beyond the Standard Model physics?
   - Can think about this using a low energy EFT (WET) – work by Stefan
   - Or in terms of a high energy EFT (SMEFT) – work by Matthew

Understanding non-leptonic decays

Overview of collinear factorisation

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- In the heavy-quark limit, heavy meson decays factorise into form factors, LCDAs and perturbative scattering kernels:

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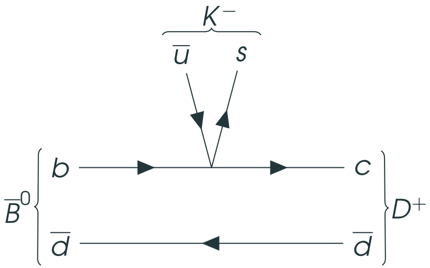
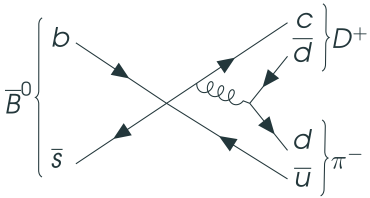
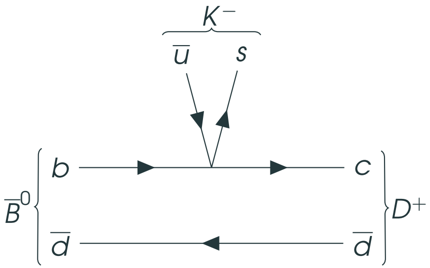
- Non-factorisable corrections are major source of uncertainties, which can come from e.g. annihilation, penguin and dipole topologies

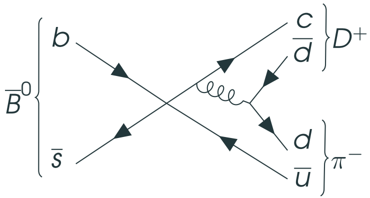




- Look at meson decays where the underlying quark decay involves four different flavours in the final state $\Rightarrow$ no annihilation topologies

Annihilation free decays





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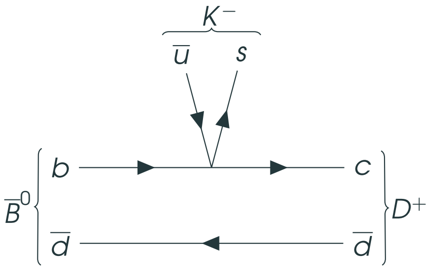

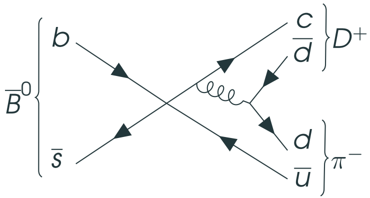

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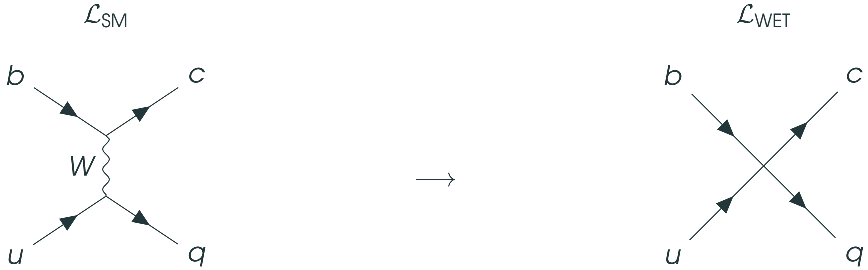
- LCSR estimate of matrix elements agrees with data, but large uncertainties [Piscopo, Rusov 2307.07594]

Interpretation within the Weak Effective Theory

- Integrate out all the particles above the W mass from the SM (matching)



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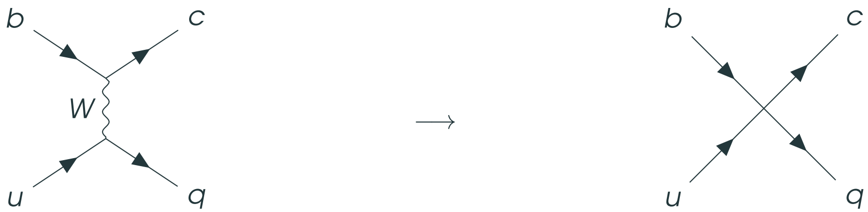
$\mathcal{L}_{\text{SM}}$ $\mathcal{L}_{\text{WET}}$



- Add all the operators invariant under the broken symmetry group $SU(3)_c \otimes U(1)_{em}$

$$\mathcal{L}_{\text{WET}} = \mathcal{L}_{QCD+QED} + \mathcal{L}^{qbcu}$$

- Effective Lagrangian for $b \to c\bar{u}q$ decays ($q = d, s$):

$$\mathcal{L}^{qbcu} = -\frac{4G_F}{\sqrt{2}} V_{cb} V_{uq}^* \sum_{i=1}^{10} \left(C_1^i \, \mathcal{Q}_1^i + C_2^i \mathcal{Q}_2^i \right) ,$$

with

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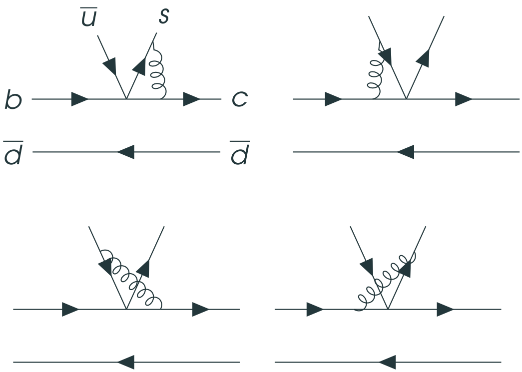
- Here: WC flavour universal and real

Hard-scattering kernels

$$\langle L^- D_q^+ |\, \mathcal{O}_i \,| \overline{B}_q^0 \rangle = \sum_j F_j^{B\to D}(m_L^2) \int_0^1 du\, T_{ij}^{\mathrm{I}}(u)\, \Phi_L(u) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$$



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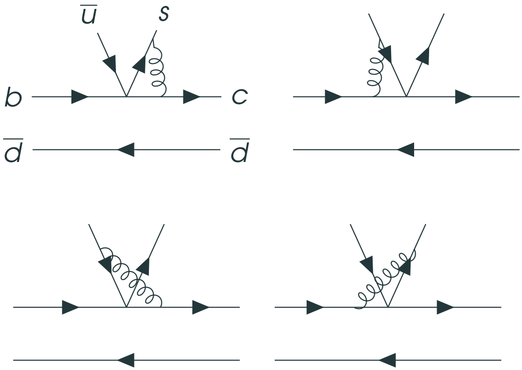

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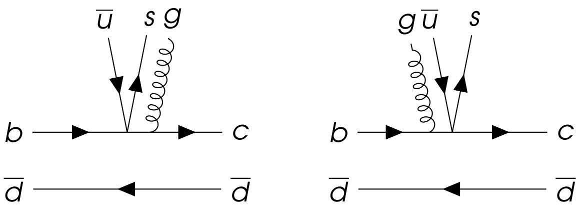
- Checked $m_c \to 0$ limit [Beneke, Neubert 0308039], [Beneke, Buchalla, Neubert, Sachrajda 0104110]

Contribution from three-particle light meson state :



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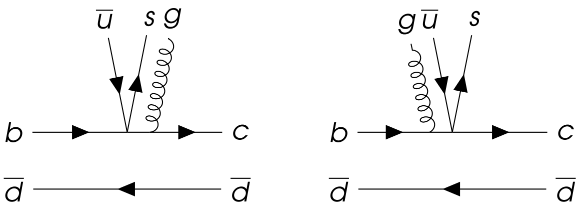

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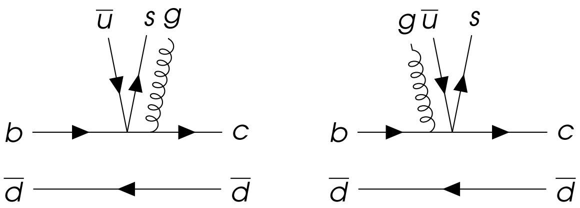

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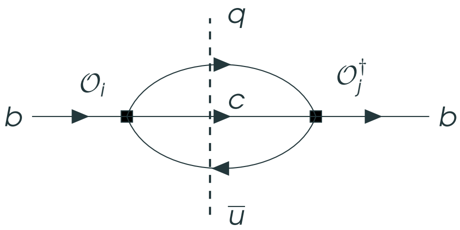
- Tensor: contributions are highly suppressed

Experimental data and lifetime constraint



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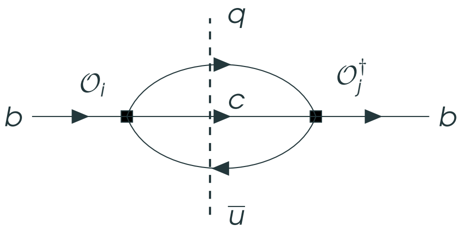

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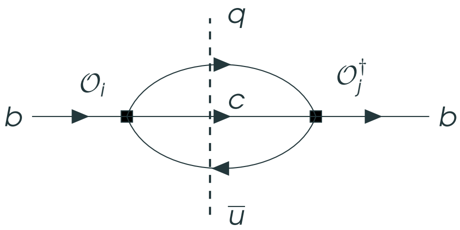

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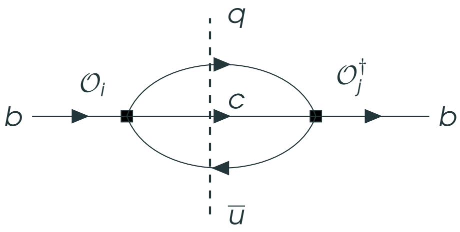

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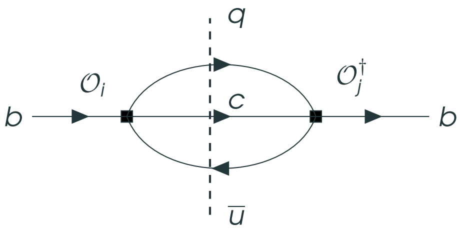

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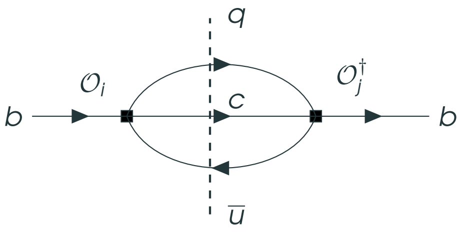

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  - WET-1: Vary $\mathcal{C}^{qbcu}_{1,\ldots,4}$ (SM coefficients)
  - WET-2: Vary $\mathcal{C}^{qbcu}_{5,\ldots,10}$ while keeping SM coefficients fixed to their SM values
  - WET-3: Vary $\mathcal{C}^{qbcu}_{1',\ldots,4'}$ while keeping SM coefficients fixed to their SM values
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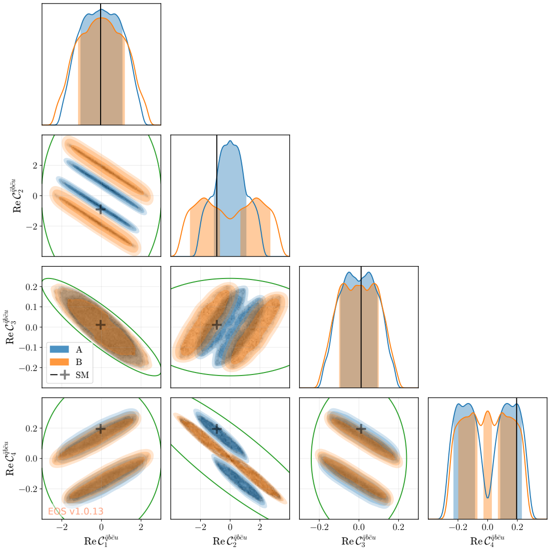
- Scenarios with four WCs preferred, but chiralities are indistinguishable

Bounds on WC



- Bounds on WC in terms of posterior distribution

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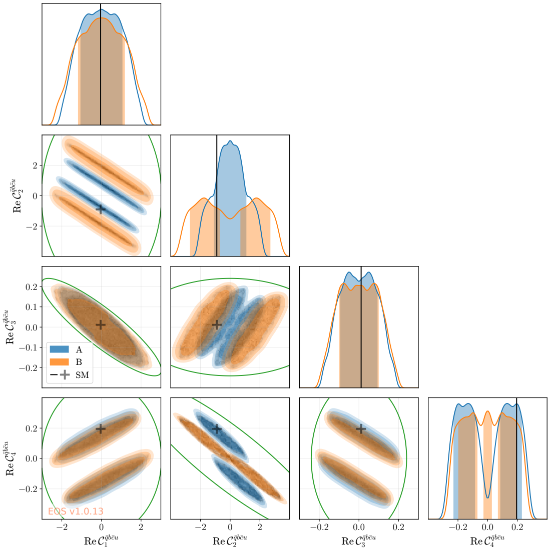

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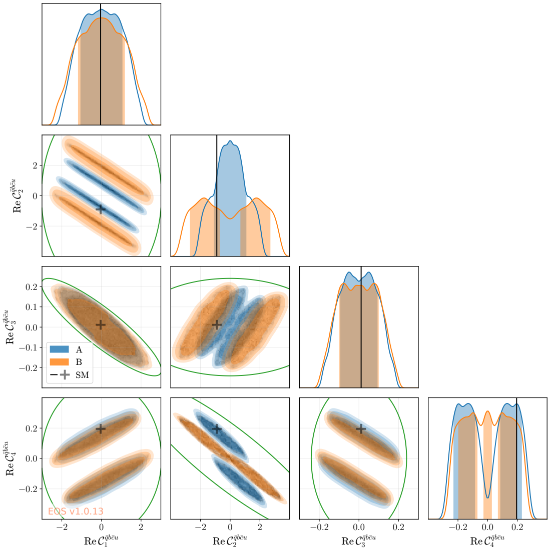

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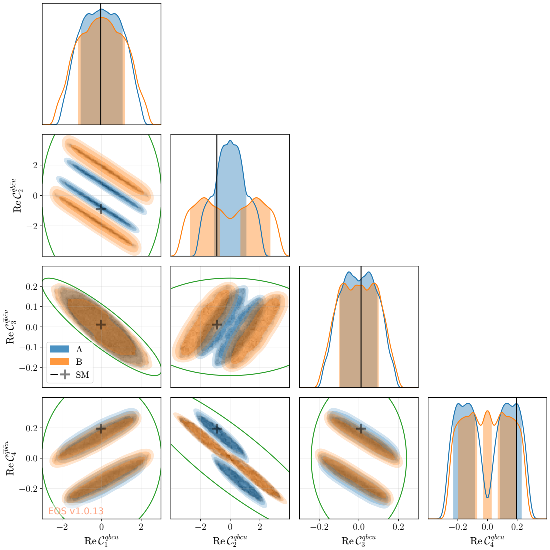

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- SM point seems to be included, but it is not (hollow shell)
- Lifetime constraints very important for some combinations of WCs $\Rightarrow$ directions are poorly constrained by exclusive BRs

Interpretation within the SMEFT

SMEFT summary

- We add to the SM all operators consistent with the SM gauge group $(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$ and field content (Q, u, d, L, e, H)

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- Connects different observables together, partly through RG running, partly through structure of SMEFT . . .

Top-bottom connection

- Since the SMEFT is written in terms of the $SU(2)$ quark doublet $Q_i = (u_i, d_i)$, any NP involving LH bottom quarks will necessarily bring in effects in top physics

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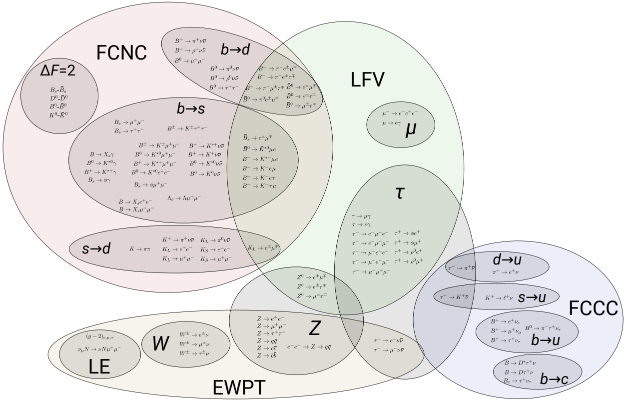
  - ATLAS 2023 measured $\sigma(t\bar{t})$ to 1.8 % precision [2303.15340]
  - CMS 2014 measured the top width to 10 % [1404.2292]

Collider vs flavour

- Is this good enough to be competitive with other low energy flavour measurements?
- Use `SMEFTsim` and `MadGraph` to simulate effect of BSM in top production, and place limits on our WCs

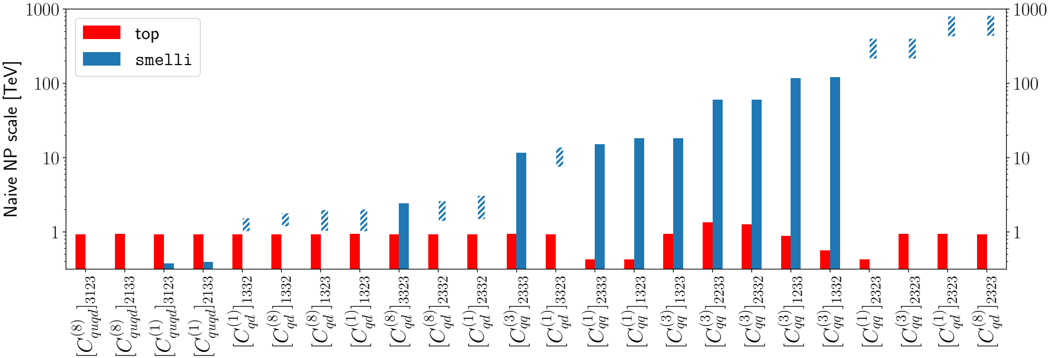
Collider vs *flavour*



[Figure courtesy of David Straub & Peter Stangl]

- After LHC, the other main component of our study is the global likelihood from `smelli`
- Now more than 500 observables are included across many sectors

Constraints on SMEFT WCs

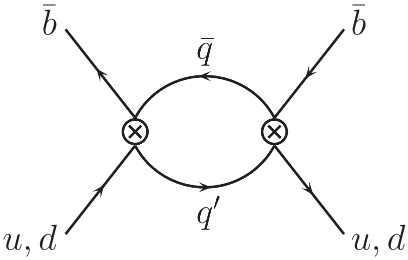


- Top bounds are (roughly) flavour blind
- A handful where these top collider measurements are the leading constraint!

Can the non-leptonic anomalies be explained in SMEFT?

- Take one WC at a time, and see if
  1. a non-zero value can explain the discrepancy in the non-leptonic decays, while also
  2. not being ruled out by other constraints

Lifetime ratio



- As mentioned earlier, B meson lifetimes are sensitive to our four-quark operators
- In the SMEFT study, we use $\tau(B^+)/\tau(B_d)$
- Contributions are known for the full set of BSM operators in the case of
  - $(\bar{s}b)(\bar{c}c)$ [Jäger, Kirk, Lenz, Leslie 1701.01983, 1910.12924]
  - $(\bar{s}b)(\bar{c}u)$ and $(\bar{d}b)(\bar{c}u)$ [Lenz, Müller, Piscopo, Rusov 2211.02724]

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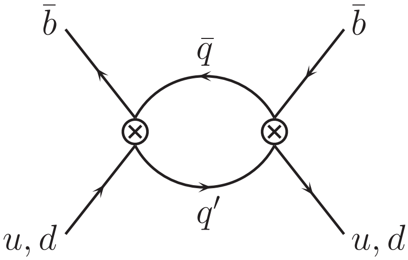

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- This observable turns out to be very important in a few cases (but negligible in others)

Potential SMEFT explanations

- Our initial study identified 9 SMEFT coefficients which lead to a large reduction of the total χ^2
  - By large I mean a pull of more than $3\,\sigma$ relative to our SM predictions

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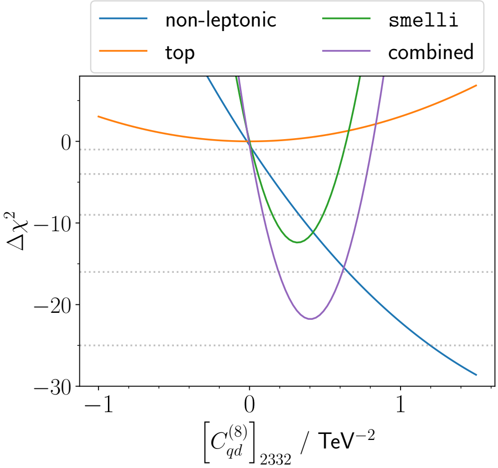
- Showcase three: $[C_{qd}^{(8)}]_{2332}$, $[C_{quqd}^{(1)}]_{3123}$, $[C_{ud}^{(1)}]_{1232}$

Potential SMEFT explanations: $[C_{qd}^{(8)}]_{2332}$

$$\mathcal{O}_{qd}^{(8)} = (\overline{q}\gamma_\mu t^a q)(\overline{d}\gamma^\mu t^a d)$$



- Some weak constraints from top
- Non-leptonic tension can be highly reduced
- Quark flavour improvement enters via 1-loop matching

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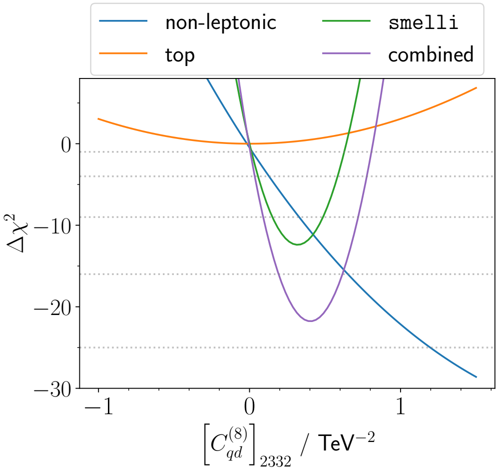
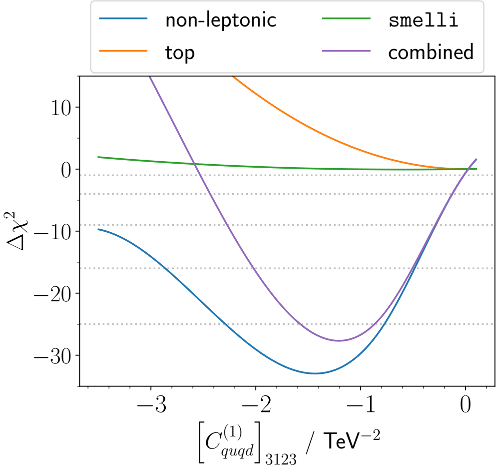


- Some weak constraints from top
- Non-leptonic tension can be highly reduced
- Quark flavour improvement enters via 1-loop matching
  - Correlations between $\Delta F = 2$ and $b \to s\ell\ell$ are crucial here, demonstrating importance of doing a global fit!

Potential SMEFT explanations: $[C_{quqd}^{(1)}]_{3123}$

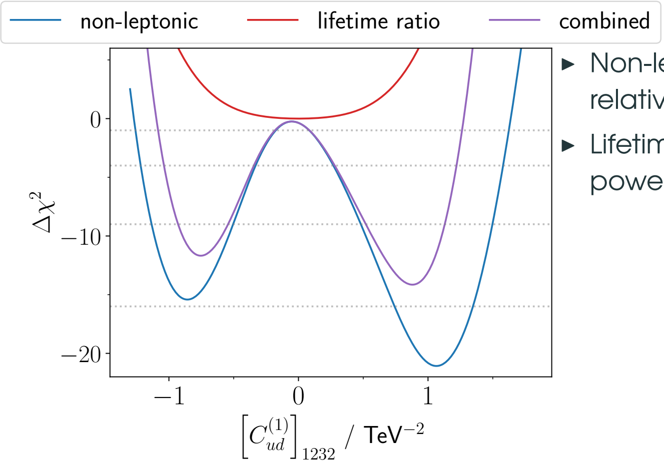
$$\mathcal{O}_{quqd}^{(1)} = (\overline{q}\gamma_\mu u)\varepsilon(\overline{q}\gamma^\mu d)$$



- No flavour (i.e. `smelli`) constraints
- Top measurements are the main constraint on NP in the non-leptonics

Potential SMEFT explanations: $[C_{ud}^{(1)}]_{1232}$

$$\mathcal{O}_{ud}^{(1)} = (\overline{u}\gamma_\mu u)(\overline{d}\gamma^\mu d)$$



- Non-leptonic favours a relatively large coupling
- Lifetime ratio becomes powerful in this case

Summary

Summary and Outlook

- In supposedly well understood non-leptonic decays, large discrepancies exist

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- In supposedly well understood non-leptonic decays, large discrepancies exist
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  - Can we understand power corrections in a more systematic way?
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Summary and Outlook

- In supposedly well understood non-leptonic decays, large discrepancies exist
  - What needs to be done to convinced ourselves (and others!) that these discrepancies are signs of BSM physics?
- WET analysis favours NP
  - Can we simultaneously constrain all WCs by using more observables?
  - Can we understand power corrections in a more systematic way?
- SMEFT analysis shows promising directions, and LHC bounds are becoming important
  - What future precision is available, from both theory and experiment?
  - What flavour assumptions should we be making?

Backup Slides

Choice of WET bases: BMU basis

$$\mathcal{Q}_1^{VLL} = [\overline{c}_\alpha \gamma_\mu P_L b_\beta] \left[\overline{q}_\beta \gamma^\mu P_L u_\alpha\right] \,, \qquad \mathcal{Q}_2^{VLL} = [\overline{c}_\alpha \gamma_\mu P_L b_\alpha] \left[\overline{q}_\beta \gamma^\mu P_L u_\beta\right] \,,$$

$$\mathcal{Q}_1^{SLR} = [\overline{c}_\alpha P_L b_\beta] \left[\overline{q}_\beta P_R u_\alpha\right] \,, \qquad \mathcal{Q}_2^{SLR} = [\overline{c}_\alpha P_L b_\alpha] \left[\overline{q}_\beta P_R u_\beta\right] \,,$$

$$\mathcal{Q}_1^{VRL} = [\overline{c}_\alpha \gamma_\mu P_R b_\beta] \left[\overline{q}_\beta \gamma^\mu P_L u_\alpha\right] \,, \qquad \mathcal{Q}_2^{VRL} = [\overline{c}_\alpha \gamma_\mu P_R b_\alpha] \left[\overline{q}_\beta \gamma^\mu P_L u_\beta\right] \,,$$

$$\mathcal{Q}_1^{SRR} = [\overline{c}_\alpha P_R b_\beta] \left[\overline{q}_\beta P_R u_\alpha\right] \,, \qquad \mathcal{Q}_2^{SRR} = [\overline{c}_\alpha P_R b_\alpha] \left[\overline{q}_\beta P_R u_\beta\right] \,,$$

$$\mathcal{Q}_3^{SRR} = [\overline{c}_\alpha \sigma_{\mu\nu} P_R b_\beta] \left[\overline{q}_\beta \sigma^{\mu\nu} P_R u_\alpha\right] \,, \qquad \mathcal{Q}_4^{SRR} = [\overline{c}_\alpha \sigma_{\mu\nu} P_R b_\alpha] \left[\overline{q}_\beta \sigma^{\mu\nu} P_R u_\beta\right]$$

Choice of WET bases: Bern basis

$$\mathcal{O}_1^{qbcu} = [\overline{q} P_R \gamma_\mu b]\,[\overline{c}\gamma^\mu u]\,, \qquad \mathcal{O}_2^{qbcu} = \left[\overline{q} P_R \gamma_\mu T^A b\right]\left[\overline{c}\gamma^\mu T^A u\right]\,,$$

$$\mathcal{O}_3^{qbcu} = [\overline{q} P_R \gamma_{\mu\nu\rho} b]\,[\overline{c}\gamma^{\mu\nu\rho} u]\,, \qquad \mathcal{O}_4^{qbcu} = \left[\overline{q} P_R \gamma_{\mu\nu\rho} T^A b\right]\left[\overline{c}\gamma^{\mu\nu\rho} T^A u\right]\,,$$

$$\mathcal{O}_5^{qbcu} = [\overline{q} P_R b]\,[\overline{c} u]\,, \qquad \mathcal{O}_6^{qbcu} = \left[\overline{q} P_R T^A b\right]\left[\overline{c} T^A u\right]\,,$$

$$\mathcal{O}_7^{qbcu} = [\overline{q} P_R \sigma_{\mu\nu} b]\,[\overline{c}\sigma^{\mu\nu} u]\,, \qquad \mathcal{O}_8^{qbcu} = \left[\overline{q} P_R \sigma_{\mu\nu} T^A b\right]\left[\overline{c}\sigma^{\mu\nu} T^A u\right]\,,$$

$$\mathcal{O}_9^{qbcu} = [\overline{q} P_R \gamma_{\mu\nu\rho\sigma} b]\,[\overline{c}\gamma^{\mu\nu\rho\sigma} u]\,, \qquad \mathcal{O}_{10}^{qbcu} = \left[\overline{q} P_R \gamma_{\mu\nu\rho\sigma} T^A b\right]\left[\overline{c}\gamma^{\mu\nu\rho\sigma} T^A u\right]$$

Bayesian framework

- Object of interest is the posterior distribution:

$$P(\vec{x}\,|\,D,M) \propto P(D\,|\,\vec{x},M)\,P_0(\vec{x}\,|\,M)\,,$$

  with likelihood $P(D\,|\,\vec{x},M)$ and prior $P_0(\vec{x}\,|\,M)$
- Model comparison using evidences:

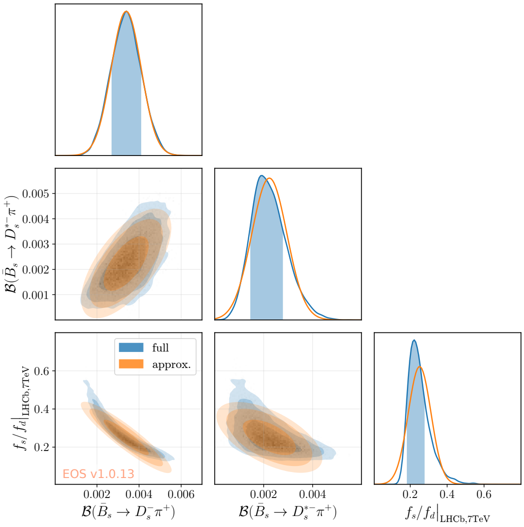
$$Z \equiv P(D\,|\,M_i) = \int d\vec{x}\,P(D\,|\,\vec{x},M_i)\,P_0(\vec{x}\,|\,M_i)\,.$$

- Ratio of evidences of two models gives the Bayes' factor

$$K(M_1,M_2) \equiv P(D\,|\,M_1)/P(D\,|\,M_2)$$

- If $K(M_1,M_2) > (<) 1$ $M1$ ($M2$) is preferred
- $1 < K \leq 3$: barely worth mentioning, $3 < K \leq 10$: substantial, $10 < K \leq 100$: strong, $100 < K$: decisive

Likelihood



- Using PDG values is inconsistent
  $\Rightarrow$ construct likelihood from auxiliary observables [Bordone, Gubernari, Huber, Jung, van Dyk 2007.10338]

- Complicated likelihood
  $\Rightarrow$ Gaussian approximation with a total of four observations

Form factor prior

Parameter	Value ± uncertainty	Comments
$f_0^{B_s\to D_s}(m_\pi^2)$	0.669 ± 0.011	Gaussian
$f_0^{B\to D}(m_K^2)$	0.675 ± 0.011	Gaussian
$A_0^{B_s\to D_s^*}(m_\pi^2)$	0.688 ± 0.056	Gaussian
$A_0^{B\to D^*}(m_K^2)$	0.704 ± 0.035	Gaussian

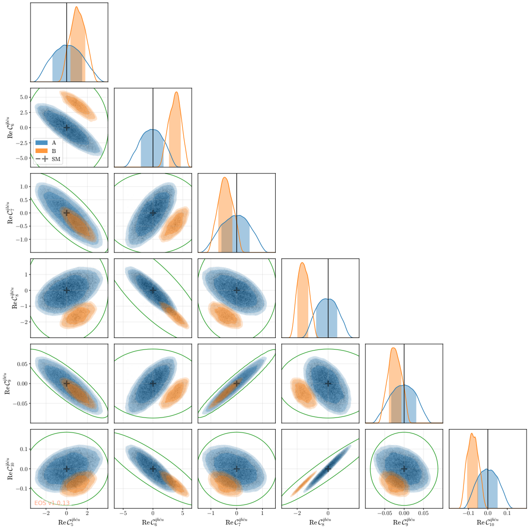
Full FF prior including correlations can be found in `EOS` under

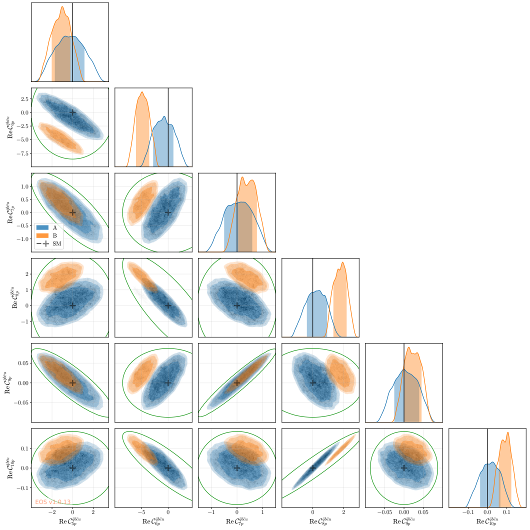
```
B_(s)->D_(s)^(*)::FormFactors[f_0(Mpi2),f_0(MK2),A_0(Mpi2),A_0(MK2)]@BGJvD:2019A
```

Model comparison

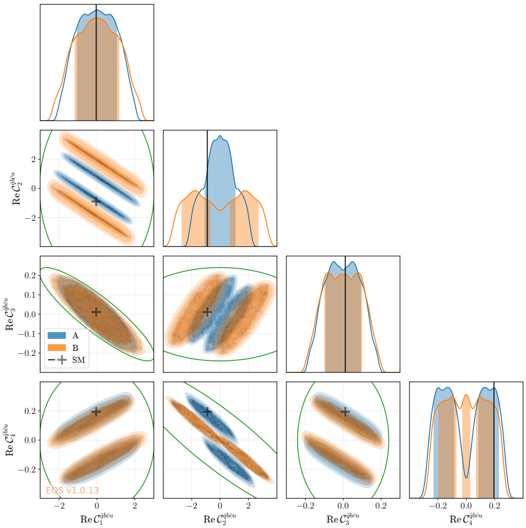
Fit model M	Labelled mode	χ^2	$\log P(D, M)$
SM	—	26.69	9.04 ± 0.03
SM+PC	—	25.18	9.71 ± 0.10
SM+PC′	—	1.58	29.12 ± 0.04
WET-1	A	1.61	21.75 ± 0.03
WET-1	B	1.67	21.77 ± 0.03
WET-2	A	1.57	18.40 ± 0.03
WET-2	B	1.34	16.35 ± 0.03
WET-3	A	1.62	21.60 ± 0.03
WET-3	B	1.32	21.50 ± 0.03
WET-4	A	1.54	18.48 ± 0.03
WET-4	B	1.69	16.62 ± 0.03

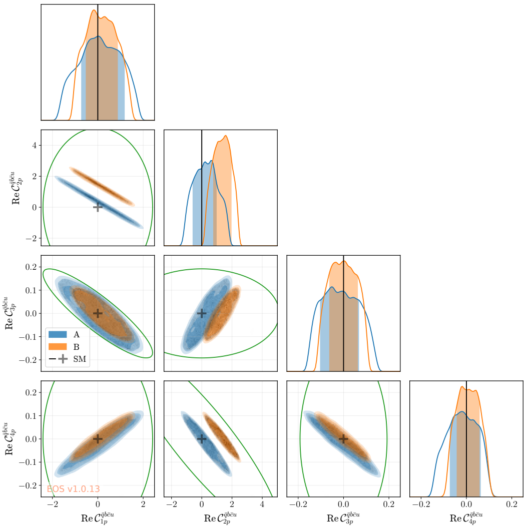
Corner plots: WET-2 and WET-4





Corner plots: WET-1 and WET-3





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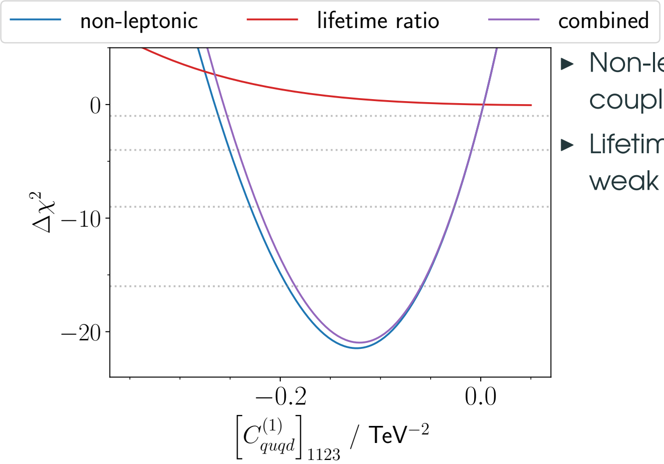
$$\mathcal{O}^{(1)}_{quqd} = (\overline{q}\gamma_\mu u)\varepsilon(\overline{q}\gamma^\mu d)$$



- Non-leptonic favours a large coupling
- Lifetime ratio present but weak

SM predictions by AEKT-X

	Channel	Experiment	SM	Pull
R_K	$\overline{B}^0 \to D^+ K^-$	0.058 ± 0.004	$0.082^{+0.002}_{-0.001}$	$\approx 5.6\,\sigma$
$R_{s\pi}$	$\overline{B}_s \to D_s^+ \pi^-$	0.71 ± 0.06	$1.06^{+0.04}_{-0.03}$	$\approx 5\,\sigma$
R_{K^*}	$\overline{B}^0 \to D^+ K^{*-}$	0.136 ± 0.023	$0.14^{+0.01}_{-0.01}$	$\approx 0.16\,\sigma$
R_K^*	$\overline{B}^0 \to D^{*+} K^-$	0.064 ± 0.003	$0.076^{+0.002}_{-0.001}$	$\approx 3.6\,\sigma$
$R_{s\pi}^*$	$\overline{B}_s \to D^{*+} \pi^-$	$0.52^{+0.18}_{-0.16}$	$1.05^{+0.04}_{-0.03}$	$\approx 3.1\,\sigma$

with

$$R_{(s)L}^{(*)} \equiv \Gamma(\overline{B}^0_{(s)} \to D_{(s)}^{(*)+} L^-) \Big/ \left.\frac{d\Gamma(\overline{B}^0_{(s)} \to D_{(s)}^{(*)+} \ell^- \overline{\nu}_\ell)}{dq^2}\right|_{q^2=m_L^2}$$

Experimental data

- ATLAS is full run 2 data sample (140 fb^{-1})
- CMS is run 1, only 19.7 fb^{-1}

Naive NP scale

Given an allowed range for a WC $-a < C < b$, where $a, b > 0$, and a, b, C all have dimension of inverse mass squared, convert to a naive scale as

$$\Lambda_{\rm NP} = 1/\sqrt{\max(a,b)}$$

NP favoured by SMEFT?

- Some of our SMEFT coefficients run into operators that affect ΔM_s (and some other $\Delta F = 2$
- Correlation between $b \to s\ell\ell$ (via V_{cb}) is crucial!
- Without correlations, overall the fit gets worse!
- But with correlations, actually improvement!

NP favoured by SMEFT? Rough numerical example

- Consider two observables $O_{1,2}$ which have deviations $P_{1,2}$ relative to experiment (deviation = (theory - exp) / error)
- One ("$bs\ell\ell$") has a deviation of around 4σ in both the SM and a given NP point: $P_1^{\mathrm{SM}} = P_1^{\mathrm{NP}} = 4$
- The other ("ΔM_s") is slightly below experiment in the SM, quite a bit above at the same NP point: $P_1^{\mathrm{SM}} = -0.5, P_1^{\mathrm{NP}} = 2$
- Assuming no correlation, the χ^2 for this NP point is slightly worse than the SM: $\Delta\chi^2 \sim 4$
- But if the two observables have a 50% correlation, $\Delta\chi^2 \sim -10$! NP point is favoured!