Recent developments in rare and semileptonic B meson decays

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Outline:

1. Motivation
2. $b \to s\ell^+\ell^-$ decays
3. $b \to c\ell\bar{\nu}$ decays
4. The new physics solution

Introduction

The Standard Model: theory that better describes interactions among elementary particles.

Is the SM complete?

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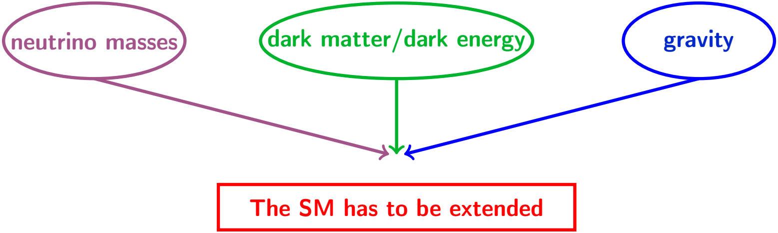

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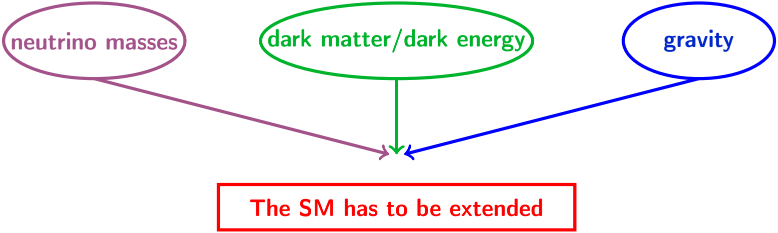

- The SM can be regarded as a low energy realisation of a more complete theory living above the electroweak scale
- Is there any part of the SM that can be affected by NP?

The flavour structure

- Strong hierarchy among the Yukawa couplings
- Many free parameters

$Y_q \sim$ 

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1) Why is the flavour sector so special?

2) Is there space for NP?

The flavour problem

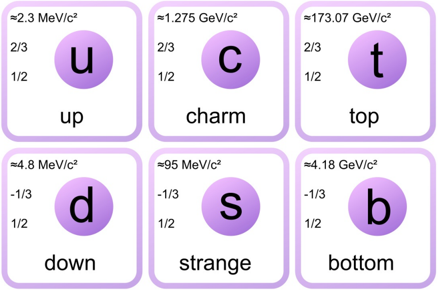
1) The SM flavour problem

- The study of a deeper reason behind the peculiar structure of Yukawa couplings.

2) The NP flavour problem

- Why don't we observe any NP in flavour processes yet?
- What is the flavour structure of the physics beyond the SM?
- What energy scales?
  No absolute energy scale, strongly dependent on the NP couplings.

How do we study the flavour structure?



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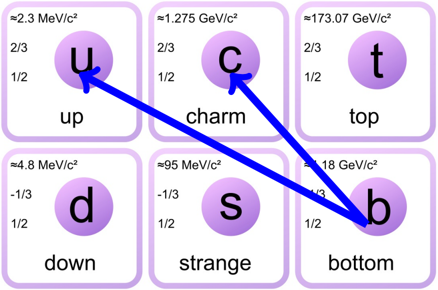

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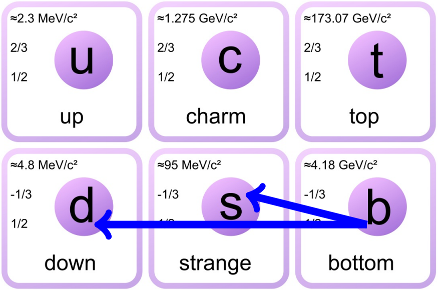

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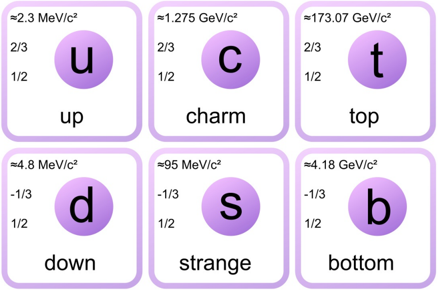

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- $u^j \to u^i \ell^+ \ell^-$: top decays or D physics

From parton to hadrons

The scale characterising hadron dynamics is Λ_{QCD}

Non perturbative techniques are needed

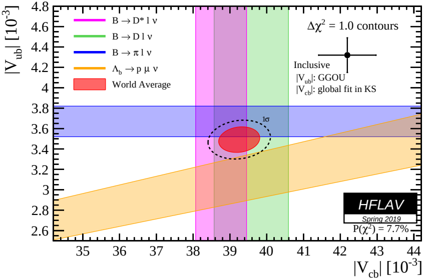
$$\langle H_f | J_i | H_i \rangle \propto \mathcal{F}_i$$

$\mathcal{F}_i$: is a form factor, a scalar function encoding the non perturbative dynamics

- Lattice QCD
- Sum rules

Usually uncertainties are sizeable....

A puzzle in the CKM elements



- Inclusive: $B \to X_c \ell \bar{\nu}$

  [P. Gambino, K. J. Healey, S. Turczyk, '16]

$$V_{cb}^{\text{incl}} = (42 \pm 0.65) \times 10^{-3}$$

- Exclusive: $B \to D \ell \bar{\nu}$ and $B \to D^* \ell \bar{\nu}$

No general consensus yet, depends highly on the data set used and the assumptions for the hadronic decays

Violation of Lepton Flavour Universality

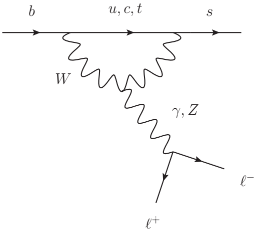
Babar, Belle and LHCb saw a hints of **L**epton **F**lavour **U**niversality **V**iolation: channels with different lepton species in the final state behave differently

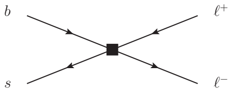
The channels explored so far are semileptonic decays of B-meson

- Flavour changing neutral currents $\boldsymbol{b \to s}$: $\boldsymbol{\mu}$ vs $\boldsymbol{e}$
- Charged currents $\boldsymbol{b \to c}$: $\boldsymbol{\tau}$ vs $\boldsymbol{\mu/e}$

Rare decays

$b \to s\ell\ell$





$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[-C_1\mathcal{O}_1 - C_2\mathcal{O}_2 + C_9\mathcal{O}_9 + C_{10}\mathcal{O}_{10}\right]$$

$$\mathcal{O}_1 = (\bar{s}\gamma^\mu P_L b)(\bar{c}\gamma_\mu c) \qquad \mathcal{O}_2 = (\bar{s}\gamma^\mu T^a P_L b)(\bar{c}\gamma_\mu T^a c)$$
$$\mathcal{O}_9 = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell) \qquad \mathcal{O}_{10} = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$
$$\mathcal{O}_7 = (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$$

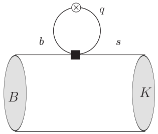
- Wilson coefficients are calculated at NNLO **[M.Gorbahn, U. Haish, '04]**

$B \to K^{(*)}\ell^+\ell^-$

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- Local: $\mathcal{F}_\lambda^{(T)} = \langle K^{(*)}(k)|\bar{s}\Gamma_\lambda^{(T)} b|\bar{B}(k+q)\rangle$
  - form factors calculated on lattice and LCSR [HPQCD, '13, N. Gubernari, A. Kokulu, D. van Dyk, '18]

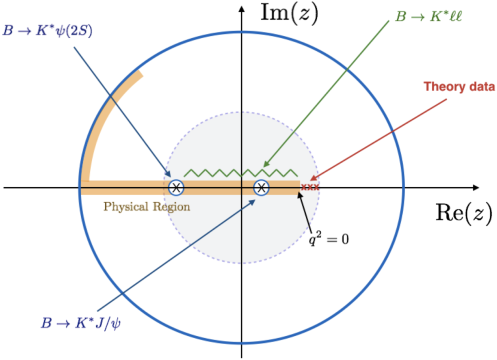
- Non-local: $\mathcal{H}_\lambda(q^2) = iP_\mu^\lambda \int d^4x\, e^{iqx} \langle K^{(*)}(k)|T\left\{\mathcal{J}^\mu_{\text{em}}, C_i\mathcal{O}_i(0)\right\}|\bar{B}(k+q)\rangle$



- Theory side: OPE at negative q^2 [Khodjamirian et al, '10]
- Data are needed to match the OPE with the physical region

Non-local form factor

[C. Bobeth, M. Chrzaszcz, D. van Dyk, J. Virto, '17]



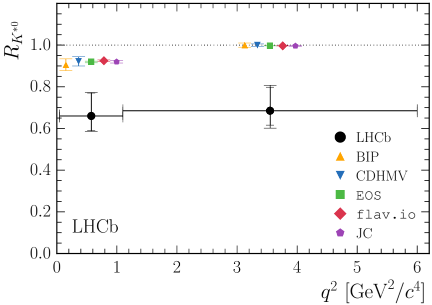
- Conformal transformation $q^2 \mapsto z(q^2)$, with $|z| < 1$
- $\mathcal{H}_\lambda \propto \sum \alpha_k z^k$
- Does the series converge?

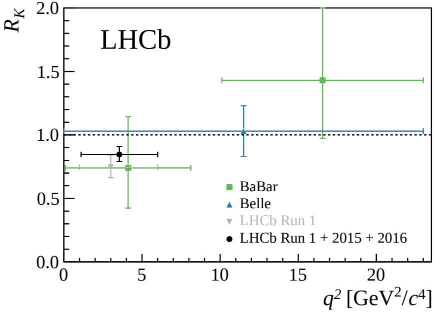
[N. Gubernari, D. van Dyk, J. Virto, 20xx.xxxx]

QED Effects

- Comparison with PHOTOS [MB, Isidori, Pattori, '16]
  - Effects on $\mathcal{B}$ large, smaller in the LFU ratios
  - Estimation of residual theory error for LFU ratios $\sim 1\%$
- Analytical calculation of virtual and real emission [Isidori, Nabeebaqccus, Zwicky, '20]
  - Confirms the previous results
  - Potential sizeable effect on differential distributions
- In the case of $B_s \to \mu\mu$ [Beneke, Bobeth, Szafron, '17,'19]
  - SCET techniques used to evaluate the corrections
  - power enhanced contributions found

$R_{K^{(*)}}$



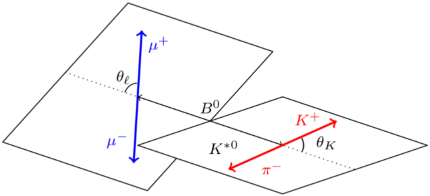


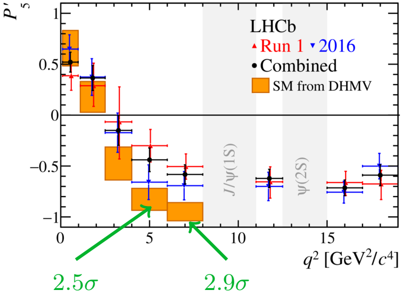
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- reduction of hadronic uncertainties
- charm loop effect cancel

- R_K: 2.5σ tension
- R_{K^*}: 2.1σ tension at low q^2
- R_{K^*}: 2.5σ tension in the central q^2 bin

Angular observables in $B \to K^* \mu\mu$

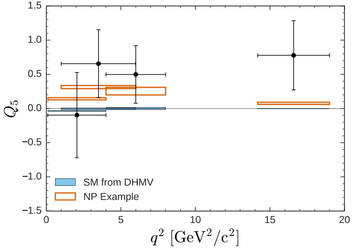




Is there charm loop pollution?

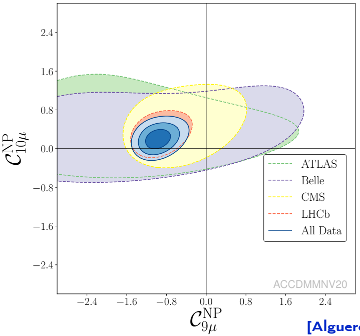
$$Q_5 = P_5'^{\mu} - P_5'^{e}$$

[Capdevila et a. '16]



How do we interpret these deviations?

- Global fit to $b \to s\ell\ell$ data
- $\mathcal{C}_i \mapsto \mathcal{C}_i^{\mathsf{SM}} + \mathcal{C}_i^{\mathsf{NP}}$
- $\mathcal{C}_9^{\mu}$ must deviate from the SM



[Alguerò et al., '19]

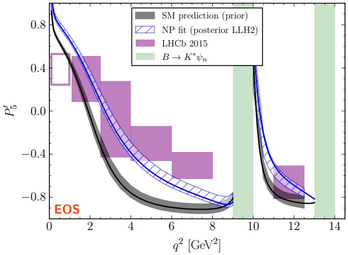
- LHCb drives the fit
- Model building requires $C_9^{\mu} = -C_{10}^{\mu} \sim -0.5$ with a pull of 5.8

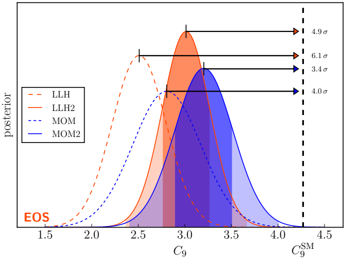
$\Rightarrow$ see the talk by S.Nehatpour

Other fits: Ciuchini et al, Aebischer at al, ...

The charm loop impact

[C. Bobeth, M. Chrzaszcz, D. van Dyk, J. Virto, '17]



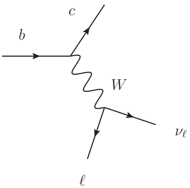


Even with the inclusion of the charm loop effect, there is a clear indication for NP!

Semileptonic decays

$b \to c$ semileptonic transitions

Tree-level process within the SM



Effective hamiltonian description

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left(\bar{c}_L \gamma_\mu b_L\right) \left(\bar{\tau}_L \gamma_\mu \nu_L\right)$$

- $B \to D$: SM form factors available from lattice calculations
- $B \to D^*$: only few points available from lattice

Additional shape information are needed

BGL vs CLN parametrisations

BGL [Boyd, Grinstein, Lebed, '95]

- Based on analyticity of the form factors
- Expansion of FFs using the conformal variable z
- Large number of free parameters

CLN [Caprini, Lellouch, Neubert, '97]

- Expansion of FFs using HQET
- Reduction of free parameters
- FFs are not indepentent

The BGL fit

[Bernlochner et al, Nandi et al,..]
[Gambino, Jung, Schacht, '19]

- Belle data from 2017 and 2018 are available
- Lattice data (when available)
- Expansion in the z variable

$$F_i = \frac{1}{P_i(z)\phi_i(z)} \sum_{k=0}^{n_i} a_k^i z^k$$

P_i: Blaschke factors, ϕ_i outer functions

- Unitarity constraints

$$\sum_k (a_k)^2 < 1$$

- Expansion up to z^2

$$|V_{cb}^{D^*}| = 39.6^{+1.1}_{-1.0} \times 10^{-3}$$

The HQE parametrisation

- Expansion of QCD Lagrangian in $1/m_{b,c}$
- At leading order in $1/m_{b,c}$: all $B \to D^{(*)}$ form factors are given by a single Isgur-Wise function
- Systematic expansion in $1/m_{b,c}$ and α_s
- at higher orders the form factors are still related $\Rightarrow$ reduction of free parameters

Problem: contradiction with lattice data!

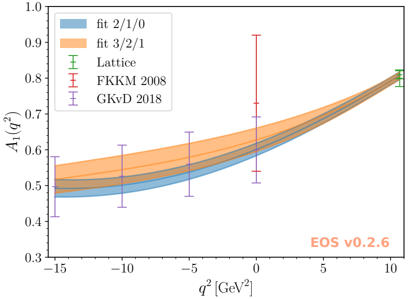
- $1/m_c^2$ corrections have to be systematically included [Jung, Straub, '18, MB, M.Jung, D.van Dyk, '19]

The HQE results

[MB, M.Jung, D.van Dyk, '19,
MB, N. Gubernari, M.Jung, D.van Dyk, '19]

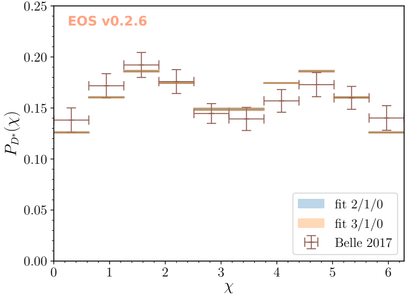
- Unitarity bounds
- Lattice for $B \to D^{(*)}$
- LCSR for all form factors (except tensor)
- Consistent expansion to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$

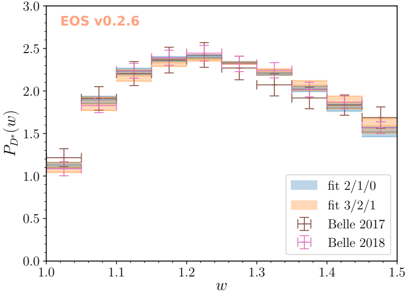
Theory inputs only

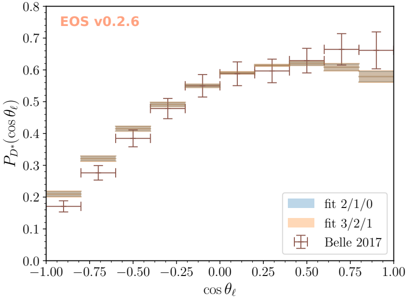


Errors are well under control

Challenging data

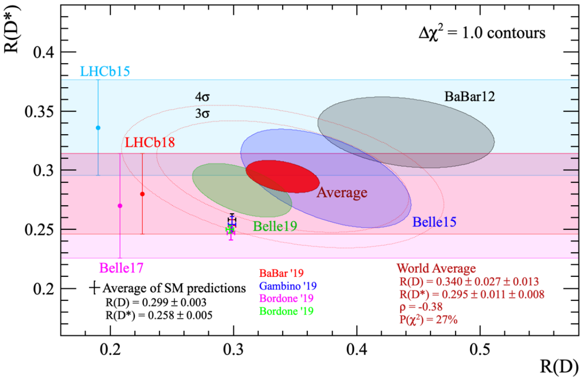






$$V_{cb} = (39.3 \pm 1.7) \times 10^{-3}$$

$R_{D^{(*)}}$



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})}$$

- The combination of all data and theory inputs shows a deviation of $3 - 4\sigma$

$$R_{D^*} = 0.247 \pm 0.006$$

$R_{J/\psi}$

- J/ψ is a $\bar{c}c$ state $\Rightarrow$ heavy quark techniques are not applicable right away
- LCSR+ NRQCD **[Leljak, Melic, Patra, '19]**

$$R_{J/\psi} = 0.23 \pm 0.1$$

- Lattice calculation (SM form factors only) **[HPQCD, '20]**

$$R_{J/\psi} = 0.2601 \pm 0.0036$$

- LHCb measurement

$$R^{\text{exp}}_{J/\psi} = 0.71 \pm 0.17(stat) \pm 0.18(syst)$$

2σ tension

The New Physics solution

New physics for the anomalies

Are this signals first signs of New Physics? We don't know yet.

- The significance we have so far is not enough to claim a discovery.
- The pattern seems very convincing, but only new measurements can give us the final answer.
- However, given this strong indication for NP, it is worth to investigate this hypothesis.

How should NP look like?

- NP physics has to couple strongly to the third generation of fermions
- A mechanism needs to suppress the couplings with the light generations
  $\Rightarrow$ possible link to an explanation of the Yukawa couplings

What are the possible mediators?

1) Colourless Mediators

- $W' + Z'$: tension with high-p_T searches with $\tau_L \tau_L$ or $b_L b_L$ final states

  [Greljo,Isidori,Marzocca,'15]

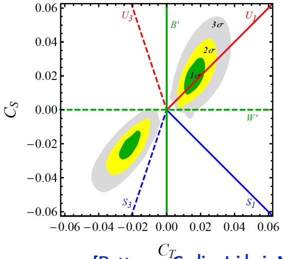
- Solutions with right-handed neutrino are motivated and help to ease the tension with $b \to c\tau\nu$ data but they are most likely to be excluded from high-p_T

  [Greljo, Camalich,Ruiz-Álvarez,'18]

2) Leptoquark Mediators

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

[Angelescu, Bečirević, Faroughy , Sumensari, '18]



[Buttazzo, Greljo, Isidori, Marzocca, '17]

- U_1 vector leptoquark is the favoured single particle solution
- As a vector particle, it needs a UV completion

The Pati-Salam U_1

[MB, C. Cornella, J.Fuentes-Martin, G. Isidori, '17/'18]

- Extension of the SM gauge group to the Pati-Salam group
- Leptoquark is flavour blind
- Strong constraints from LFV processes like $K_L \to \mu e$

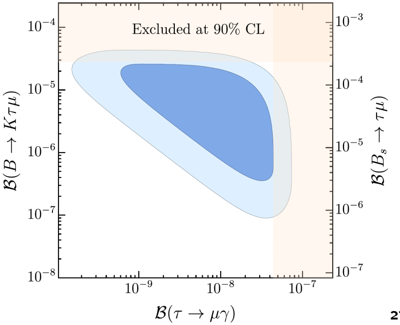
Way-out:

$$\mathsf{PS}^3 = [\mathsf{SU}(4) \times \mathsf{SU}(2)_\mathsf{L} \times \mathsf{SU}(2)_\mathsf{R}]^3$$

- In the UV the 3 families are charged under 3 independent gauge groups

- Light LQ coupled mainly to 3rd gen
- Accidental U(2) flavor symmetry
- Natural structure of SM Yukawa

Other references: Di Luzio et al, Crivellin et al, Grinstein et al, ...



The Frogatt-Nielsen power counting

- EFT approach: no hypothesis on how flavour is broken
- Classification of all the possible spurions corresponding to a specific gauge representation
- We assign a FN like power counting: new U(1) charges determine the strength of the NP interactions

The U_1 case: [MB, O.Cata, T. Feldmann, '19]

- good fit to low energy data
- LFV processes with τ are enhanced
- UV completion needed for complete 1 loop analysis

The S_1+S_3 case: [MB, O.Cata, T. Feldmann, R. Mandal, 20xx.xxxx]

- complete 1 loop analysis
- strong constraints from $K^+ \to \pi^+ \nu\bar{\nu}$
- smoking gun: $\tau \to \mu\gamma$
- other recent analysis in 2008.09548 has equivalent results

Conclusions

- Flavour constitutes an interesting place where to look for NP
- An intriguing patterns of deviations in rare and semileptonic decays B decays hint to LFUV
- Concerning SM predictions, progresses have been made in the last years and they seem overall under control
- The U_1 leptoquark seems a good candidate to fit the anomalies but a UV completion is needed
- The FN power counting has potential in explaining low energy data for both the U_1 and the S_1+S_3 scenario

Appendix

HQET in a nutshell

- $b \to c$: the partonic transition involves only heavy quarks

- in the limit $m_{b,c} \to \infty$ but $m_c/m_b = \text{finite}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_\infty + \mathcal{O}(1/m_Q)$$

  and $\mathcal{L}_\infty$ is independent of the heavy quark masses

- HQET's spin-flavour symmetry relates the various form factors, with breaking between symmetry relations suppressed by powers of $1/m_Q$

To leading power the form factors are all proportional to a single Isgur-Wise function $\xi(w)$

- $\xi(w)$ is the same for any $b \to c$ transitions involving $B^{(*)}$ and $D^{(*)}$.

The $B \to D^*$ case

How do we get information on the $B \to D^*$ form factors?

- HQET + α_s and $1/m_{b,c}$ corrections + data inputs from Belle

  [Fajfer, Kamenik, Nisandzic, 2012]

- We can also use dispersive bounds to set contraints on the form factors (only $J^P = 1^{\pm}$)

  [Boyd, Grinstein,Lebed, '95
  Caprini, Lellouch, Neubert, '97]

- HQET + dispersive bounds + data

  [Bigi, Gambino, Schacht, 2017
  Bernlochner, Ligeti, Papucci, Robinson, 2017]

Open issues:

- Are the expansions used so far enough?
- Is there a way to parametrise form factors without using data?

Our approach

Working assumptions 1:

- We expand the FFs using HQET
- We introduce a **consistent** power counting: $\epsilon^2 \sim \frac{\alpha_s}{\pi} \sim \frac{\bar{\Lambda}}{2m_b} \sim \frac{\bar{\Lambda}^2}{4m_c^2}$
  - full $1/m_c^2$ terms **must** be introduced
  - available only partially **[Jung, Straub,'18]**
  - The order at which we expand leading, subleading and sub-subleading IW functions is determined by comparing different fits
- We use the **full set** of unitary bounds for all the decays $B^{(*)} \to D^{(*)}$

[MB, Jung, van Dyk, Eur. Phys. J. C 80, 74 (2020)]

Working assumptions 2:

- How to properly introduce $B_s \to D_s^{(*)}$ decays?
- How large is the breaking of $SU(3)_F$?

[MB, Gubernari, Jung, van Dyk, 2019]

Inputs

Inputs:

- Lattice points for $B \to D$ and $B_s \to D_s$

  [HPQCD 2015, Fermilab/MILC 2015, FLAG 2016, HPQCD 2019]

- Zero-recoil lattice points for $B \to D^*$ and $B_s \to D_s^*$

  [Fermilab/MILC 2014, HPQCD 2017, HPQCD 2019]

- The ratios $f_T^{(s)}/f_+^{(s)}$ and f_T/f_+

  [M.Atoui, V.Morénas, D. Bečiveric, F. Sanfilippo, '13]

- The ratio $f_0^{(s)}(q^2 = m_\pi^2)/f_0(q^2 = m_\pi^2)$

  [Fermilab/MILC 2015]

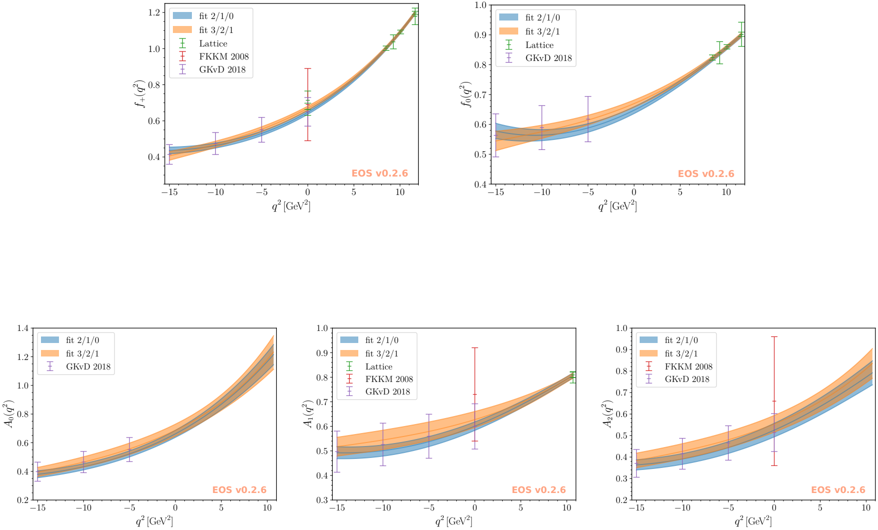
- QCD sum rules for subleading Isgur-Wise Functions
  - update of the results for light quarks and consistent treatment of uncertainties
  - recast of the sum rules for s quark

  [MB, Gubernari, Jung, van Dyk, 2019]

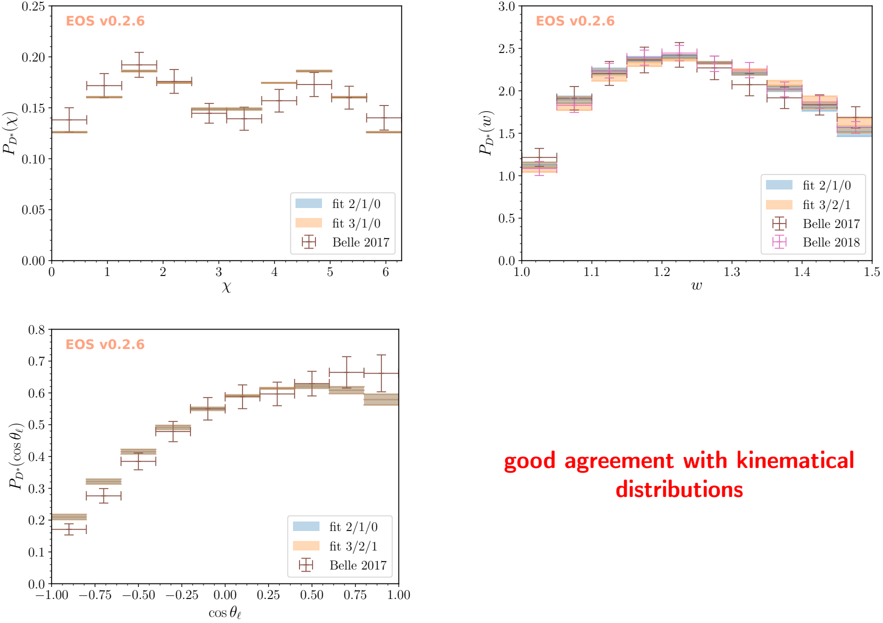
- Introduce new LCSR results [Gubernari, Kokulu, van Dyk, 2018 MB, Gubernari, Jung, van Dyk, 2019]

Fit results

[MB, Jung, van Dyk, Eur. Phys. J. C 80, 74 (2020)]



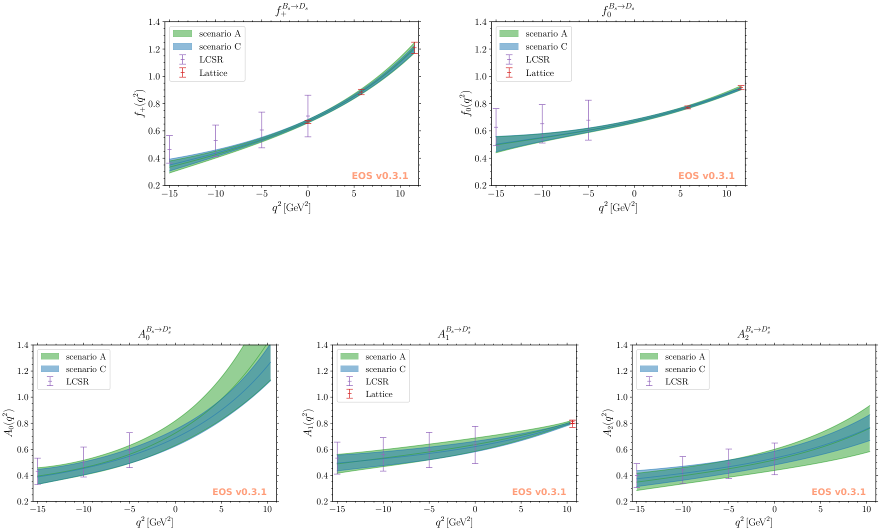
Comparison with kinematical distributions



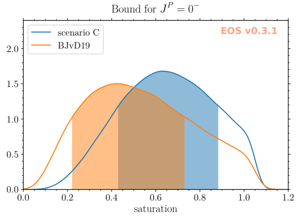
good agreement with kinematical distributions

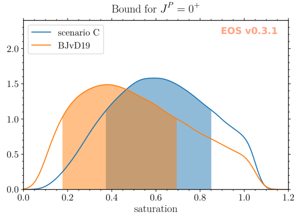
Fit for $B_s \to D_s^{(*)}$

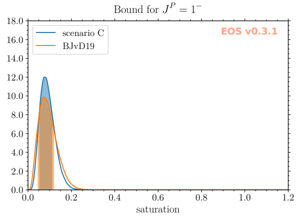
[MB, Gubernari, Jung, van Dyk, 1912.09335]

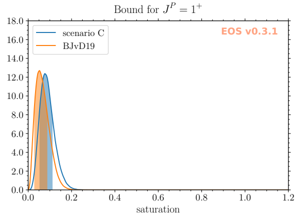


Results: unitary bounds





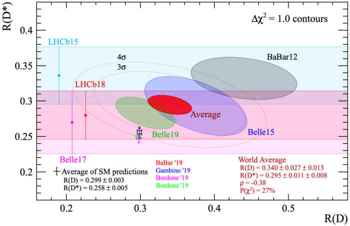




Predictions

Universality Ratios:

$$R(D) = 0.2989 \pm 0.0032$$
$$R(D^*) = 0.2472 \pm 0.0050$$
$$R(D_s) = 0.2970 \pm 0.0034$$
$$R(D_s^*) = 0.2450 \pm 0.0082$$



V_{cb} extraction:

$$V_{cb}|_{BD} = (40.7 \pm 1.1) \times 10^{-3} \longleftarrow 1.5\sigma$$

$$V_{cb}|_{BD*} = (38.8 \pm 1.4) \times 10^{-3} \longleftarrow 2\sigma$$

Compatibility with LHCb analysis of $B_s \to D_s^{(*)}$ **[2001.03225]**

- Compatibility with $R^{(*)} = \mathcal{B}(B_s \to D_s^{(*)} \mu\bar{\nu}) / \mathcal{B}(B \to D^{(*)} \mu\bar{\nu})$ and $\mathcal{B}(B_s \to D_s^* \mu\bar{\nu}) / \mathcal{B}(B_s \to D_s \mu\bar{\nu})$ at less than 1σ

HQET in a nutshell

- In HQET it is convenient to work with **velocities** instead of momenta
- Instead of q^2 we use the dimensionless variable $w = v_B \cdot v_{D^*}$
- When the $B(b)$ decays such that the $D^*(c)$ is at rest in the $B(b)$ frame

$$v_B = v_{D^*} \qquad \Rightarrow \qquad w = 1$$

- The brown muck doesn't realise that anything changed
- At zero recoil, the leading IW function is **normalized**

$$\xi(w = 1) = 1$$

V_{cb} and NP

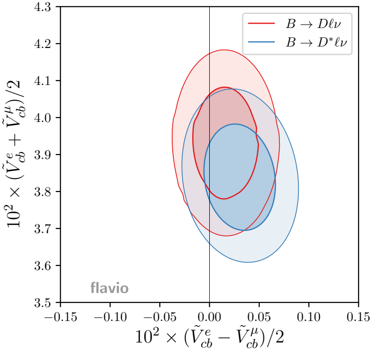
[Jung, Straub 2018]

- If we allow LFUV between μ and electrons

$$\tilde{V}_{cb}^{\ell} = V_{cb}(1 + C_{V_L}^{\ell})$$

- Fitting data from Babar and Belle

$$\frac{\tilde{V}_{cb}^{e}}{\tilde{V}_{cb}^{\mu}} = 1.011 \pm 0.012$$



$$\frac{1}{2}(\tilde{V}_{cb}^{e} + \tilde{V}_{cb}^{\mu}) = (3.87 \pm 0.09)\%$$
$$\frac{1}{2}(\tilde{V}_{cb}^{e} + \tilde{V}_{cb}^{\mu}) = (0.022 \pm 0.023)\%$$

Motivation

Anatomy of the ratios

$$\frac{\mathrm{d}\Gamma_\tau}{\mathrm{d}q^2} = \frac{\mathrm{d}\Gamma_{\tau,1}}{\mathrm{d}q^2} + \frac{\mathrm{d}\Gamma_{\tau,2}}{\mathrm{d}q^2}$$

$$\frac{\mathrm{d}\Gamma_{\tau,1}}{\mathrm{d}q^2} = \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2\left(1 + \frac{m_\tau^2}{2q^2}\right) \qquad R_{D^{(*)}}^{\tau,1} = \frac{\int_{m_\tau^2}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma_{\tau,1}}{\mathrm{d}q^2}}{\int_0^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}}$$

$$\frac{\mathrm{d}\Gamma_{\tau,2}}{\mathrm{d}q^2} = \Gamma_0 \, \frac{m_\tau^2}{q^2} c_0 \qquad R_{D^{(*)}}^{\tau,2} = \frac{\int_{m_\tau^2}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma_{\tau,2}}{\mathrm{d}q^2}}{\int_0^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \, \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}}$$

$$R_D^{\tau,1} = 0.176 \qquad R_D^{\tau,2} = 0.123$$

$$R_{D^*}^{\tau,1} = 0.232 \qquad R_{D^*}^{\tau,2} = 0.028$$

The contribution of $R_{D^*}^{\tau,2}$ in the error budget is small

The z-expansion

We can map the variable w into the conformal variable z:

$$z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} - \sqrt{2}}$$

- Easier implementation of unitarity and analiticity
- The value of $|z|$ is expected to be small $\Rightarrow$ better convergence of the expansion
- We can also combine HQET and dispersive bounds

The effect on $R_{D^{(*)}}$

R_D	0.299 ± 0.011	1503.07237 (FNAL/MILC)
	0.300 ± 0.008	1505.03925 (HPQCD)
	0.299 ± 0.003	1703.05330
	0.299 ± 0.004	1703.09977
$R_{D^{(*)}}$	0.252 ± 0.003	1203.2654
	0.257 ± 0.003	1703.05330
	$0.258^{0.010}_{-0.009}$	1707.09509
	0.257 ± 0.005	1703.09977

BGL vs CLN

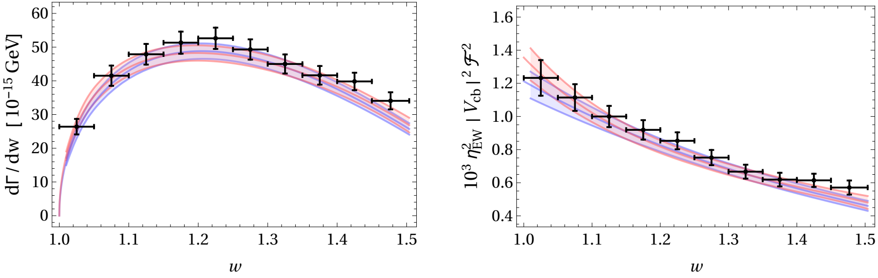
- Both BGL and CLN parametrisation of form factors rely on using unitarity arguments.

[Boyd, Grinstein, Lebed, '95

Caprini, Neubert, Lellouch, '98]

- CLN relies on HQET.

- Unfolded distributions from Belle allowed to repeat an independent fit.



BGL has a more conservative error

Provides better agreement with inclusive V_{cb}

Motivation

If I assume $\Lambda_{\mathsf{NP}} >> v$: the SM gauge group is not broken up to Λ_{NP}

I can use SMEFT and match it to the WET

$$C_{V_L}^{\ell\ell'} = -\,v^2\frac{V_{ci}}{V_{cb}}C_{lq}^{(3)\ell\ell' i3} + v^2\frac{V_{ci}}{V_{cb}}C_{\phi q}^{(3)i3}\delta_{\ell\ell'} \qquad C_{V_R}^{\ell\ell'} = +\,\frac{v^2}{2}C_{\phi ud}^{23}\delta_{\ell\ell'}$$

$$C_{S_R}^{\ell\ell'} = -\,\frac{v^2}{2}\frac{V_{ci}}{V_{cb}}C_{ledq}^{\ell\ell' 3i} \qquad C_{T}^{\ell\ell'} = -\,\frac{v^2}{2}\frac{V_{ci}}{V_{cb}}C_{lequ}^{(3)\ell\ell' 3i}$$

$$C_{S_L}^{\ell\ell'} = -\,\frac{v^2}{2}\frac{V_{ci}}{V_{cb}}C_{lequ}^{(1)\ell\ell' 3i}$$

The WC $C_{V_R}^{\ell\ell'}$ must be flavour universal and diagonal

The coefficients might be constrained by different flavour processes

Scalar solutions

With scalars LQ, we need at least **two** mediators

- Composite scenario: $S_1 + S_3$ **[D.Marzocca]**
  - Strong dynamics not known
  - B_s mixing + EWPT create tension with $R_{D^{(*)}}$
  - Need to enforce some couplings to be zero to avoid proton decay
- GUT inspired scenarios: $S_3 + R_2$ **[Bečiveríc, Doršner, Fajfer, Faroughy,Košnik,Sumensari]**
  - Predicts interesting LFV signals
  - No explicit realisation so far which avoids proton decay

What is still to be done?

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

- Colourless solution $W' + Z'$: tension with high-p_T searches with $\tau_L \tau_L$ or $b_L b_L$ final states [Greljo,Isidori,Marzocca,'15]
- Solutions with right-handed neutrino are motivated and help to ease the tension with $b \to c\tau\nu$ data but they are most likely to be excluded from high-p_T [Greljo, Camalich,Ruiz-Álvarez,'18]

It seems like there is not much space left...

What are we looking for?

...but data can help us!

If the anomalies are trues, NP **must** appear somewhere else.

A full dedicated flavour physics program run by LHCb, Belle II but also experiments like NA62 is needed to

- determine the flavour structure of the NP sector;
- different correlations among low energy observable can help to distinguish the possible models.

Only with such programs will we be able to determine what type of NP is realised in nature.

BGL vs CLN parametrisations

CLN

[Caprini, Lellouch, Neubert, '97]

- Expansion of FFs using HQET
- $1/m_{b,c}$ corrections included
- Expansion of leading IW function up to 2nd order in $(w-1)$

BGL

[Boyd, Grinstein, Lebed, '95]

- Based on analyticity of the form factors
- Expansion of FFs using the conformal variable z
- Large number of free parameters

Hadronic Matrix Elements

$$\langle D|\bar{c}\,\Gamma_{\mu_1\mu_2} b|\bar{B}\rangle = \sum_i S^i_{\mu_1\mu_2} F_i(q^2)$$

$$\langle D^*(\lambda)|\bar{c}\,\Gamma_\mu b|\bar{B}\rangle = \sum_\lambda \sum_i \epsilon^\alpha(\lambda) S^i_{\alpha\mu} F_i(q^2)$$

Form Factor: scalar function which encodes the non-perturbative dynamics

- $B \to D$: 2FF + 1 tensor for NP
  - vector current: 2 FF
  - tensor current: 1 FF
- $B \to D^*$: 4FF + 3 tensor for NP
  - vector current: 1 FF
  - axial-vector current: 3 FF
  - tensor current: 3 FF