Rare B Decays at LHCb Upgrade II

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Rare B Decays:

- FCNCs (leptonic, rare semileptonic, rare hadronic)
- Lepton-Universality-Violating observables
- Lepton-Flavor-Violating modes
- Lepton-Number-Violating modes

Strong suppression of these decays in the SM $\Rightarrow$ Smoking guns of NP

BUT: FCNCs are no longer "rare" for LHCb!

e.g. $N_{events}(Run\,1) = 2398$; $N_{events}(2016) = 2187$ for $B \to K^* \mu\mu$

And will become "quite-common" decays at **Upgrade II**.

Considerations about *rare* vs. *clean*

- Generically "rare" implies "clean" because theory (QCD) uncertainties are proportional to the observable quantity (thus irrelevant).
- Only useful if allowed NP is **large** compared to SM "prediction"/"bound". (i.e., if observable $\simeq$ "smoking gun")
- This is t-dependent, and situation changes as: (**Exp. driven!**)
    1. Pheno bounds restrict NP space (scale and/or eff. couplings)
    2. Experimental analyses improve
- As soon as we start probing SM predictions with 10-20% (experimental) precision, the "rare"-"clean" ideology breaks down

  Note: but "Rare" still means we are probing very high NP scales!!
  But improvement is harder...

Conclusion: Opportunity to study BOTH *New Physics* and *QCD* in “rare” decays.

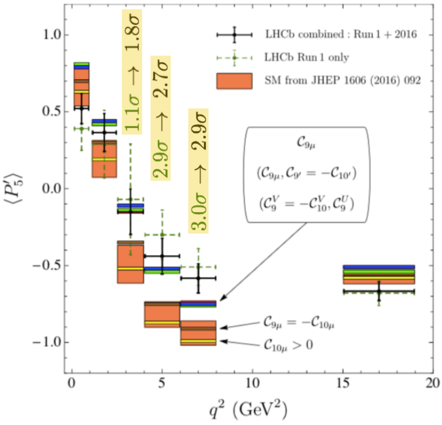
The point I want to discuss in this talk is that:

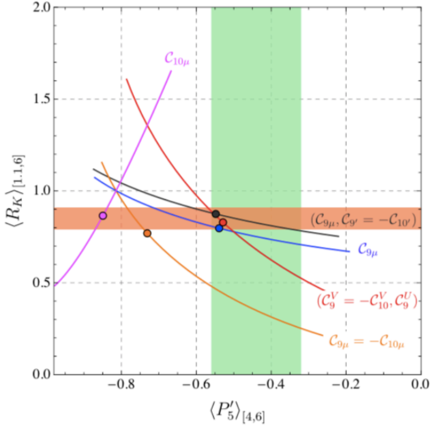
> the intensive physics program at LHCb Upgrade II is such that experimental data can be used to improve *SM (QCD) predictions*, allowing for finer and more reliable *New Physics analyses*.

Topics to be discussed :

- Current fits to $b \to s\ell\ell$ (including 2020) and future
- Tests: correlations in form factors
- Tests: momentum and helicity dependence of Non-local effects.
- Local form factors: sum rules and width effects
- Non-local form factors: analyticity
- Non-local form factors @ high-q^2: K-matrix
- (Time dependence)
- (Non-local form factors: $SU(3)$ connection $b \to s$ and $b \to d$)

Current fits to $b \to s\ell\ell$ (New R_K and P_5' measurements (LHCb 2019, 2020))





More details: Algeró et al. Addendum to Eur.Phys.J.C 79 (2019)

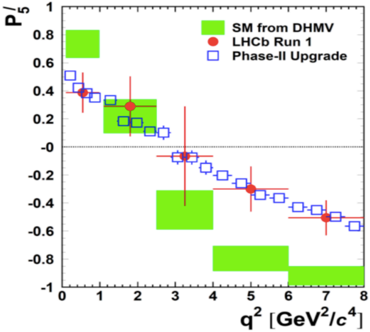
S.Descotes Genon, Talk at "Beyond the flavour anomalies", WED April 1st, 14:00 CEST (https://zoom.us/j/325145602)

About the future

☐ By 2030, the (LFUV) anomalies will be either confirmed or ruled-out independently by LHCb Phase-1 and Belle II. Albrecht et al, 1709.10308

☐ Phase-2 will put some experimental errors to negligible levels

CERN-LHCC-2017-003, LHCb EoI



P_5' defined in

Descotes-Genon, Matias, Ramon, Virto 1207.2753

☐ Bottleneck is SM uncertainties:

Assuming vanishing exp uncertainties

$$\text{Pull}(P_5'^{[2.5,4.0]}) = 3.5\sigma \xrightarrow{2020} 2.8\sigma$$

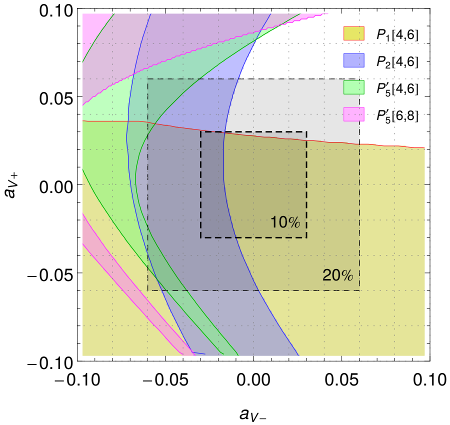
$$\text{Pull}(P_5'^{[4.0,6.0]}) = 6.5\sigma \xrightarrow{2020} 4.8\sigma$$

$$\text{Pull}(P_5'^{[6.0,8.0]}) = 5.4\sigma \xrightarrow{2020} 4.5\sigma$$

$\Rightarrow$ Need to improve theory uncertainties ("Local" and "Non-local" Form Factors)

Tests: Redundancy provides form factor info

Descotes-Genon, Hofer, Matias, Virto 2016

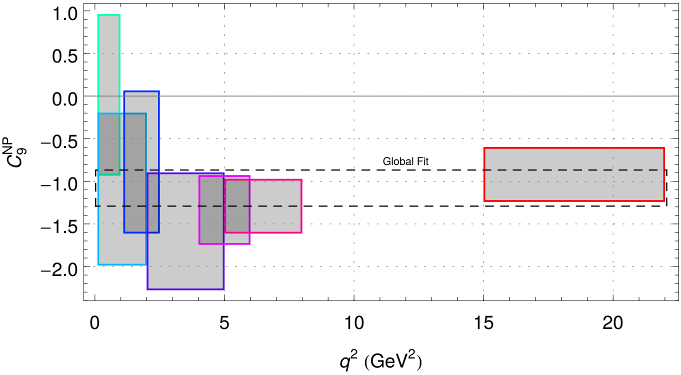


Data will only be consistent with certain form factor values....

.... and may need NP for that!

Tests: NP contributions to WCs are q^2-independent

Descotes-Genon, Hofer, Matias, Virto 2016

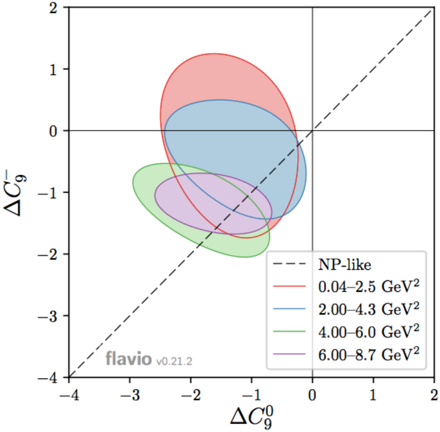


Fits provide a-posteriori tests that q^2-dependence of non-local effects is correct

.... and passing this test (with finer binning) will be increasingly harder!

Tests: NP contributions to WCs are helicity-independent

Altmannshofer, Niehoff, Stangl, Straub 1703.09189

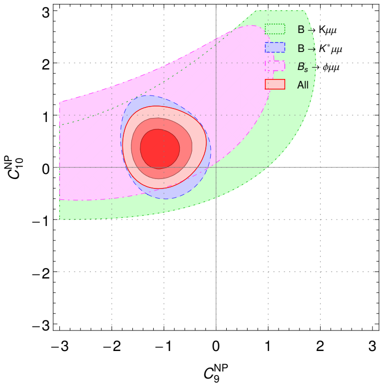


Fits provide a-posteriori tests that λ-dependence of non-local effects is correct

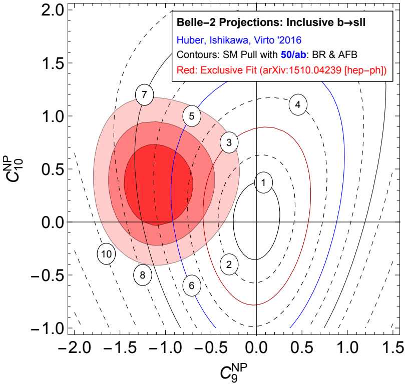
.... and passing this test will be increasingly harder!

Tests: Same with mode-independence

Descotes-Genon, Hofer, Matias, Virto 2016



Huber, Ishikawa, Virto, Belle-II Physics Book

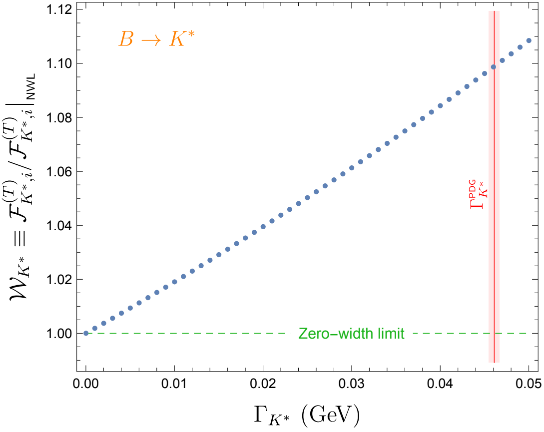


Consistency at EFT-level is Model-Indep. and a data-driven test of Theory (QCD).

[Note: Inclusive mode has its own non-local effect]

Form factors for unstable mesons (e.g., K^*): width effects

Descotes-Genon, Khodjamirian, Virto 2019



Crucial input: $\tau \to K\pi\nu$

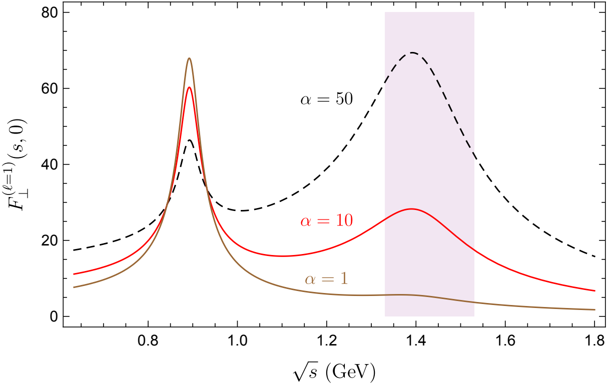
$$\mathcal{W}_{K^*} \simeq 1 + 1.9\,\frac{\Gamma_{K^*}}{m_{K^*}}$$

$$\mathcal{W}_{K^*} = 1.09 \pm 0.01$$

$\Rightarrow$ **BRs are corrected by a factor** $|\mathcal{W}_{K^*}|^2 \simeq 1.2$ (increasing anomalies)

Form factors for unstable mesons (e.g., K^*)

Descotes-Genon, Khodjamirian, Virto 2019



$$\alpha = 1: \ \mathcal{F}_{K^*,\perp}(0) = 0.28\ ; \quad \alpha = 10: \ \mathcal{F}_{K^*,\perp}(0) = 0.22\ ; \quad \alpha = 50: \ \mathcal{F}_{K^*,\perp}(0) = 0.11\ .$$

High $K\pi$-Mass Moments in $B \to K\pi\ell\ell$

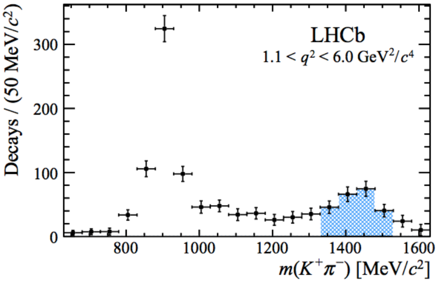
Descotes-Genon, Khodjamirian, Virto 2019

Differential decay rate including S,P,D waves – – [$d\Omega = d\cos\theta_\ell \, d\cos\theta_K \, d\phi$]

$$\frac{d\Gamma}{dq^2 dk^2 d\Omega} = \frac{1}{4\pi} \sum_{i=1}^{41} f_i(\Omega)\, \tilde{\Gamma}_i(q^2, k^2)$$

The 41 moments $\tilde{\Gamma}_i(q^2, k^2)$ have been measured by LHCb (arXiv:1609.04736) in the bins

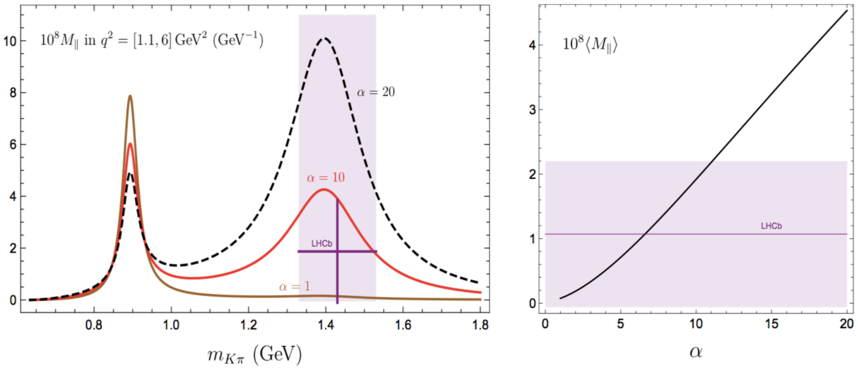
$$\sqrt{k^2} \in [1.33, 1.53]\mathrm{GeV}\ , \quad q^2 \in [1.1, 6]\mathrm{GeV}^2$$



High $K\pi$-Mass Moments in $B \to K\pi\ell\ell$

Descotes-Genon, Khodjamirian, Virto 2019

Example: $\langle M_\| \rangle$ (= some smart combination of moments) :



Bounds: From $\langle M_\| \rangle$: $\alpha \lesssim 11$; From $\langle M_\perp \rangle$: $\alpha \lesssim 17$; From $\langle M_{\rm re} \rangle$: $\alpha \lesssim 18$.

So far bounds from *dBR* are stronger (something like $\alpha \lesssim 3$).

Non-local Form Factors: OPE + dispersion relations

$$\mathcal{H}_{\lambda,x}(q^2) = \mathcal{H}^{\rm OPE}_{\lambda,x}(q_0^2 < 0) + (q^2 - q_0^2) \int_{s_{\rm th}}^{\infty} dt\, \frac{\rho_{\lambda,x}(t)}{(t - q^2 - i\epsilon)(t - q_0^2)}$$

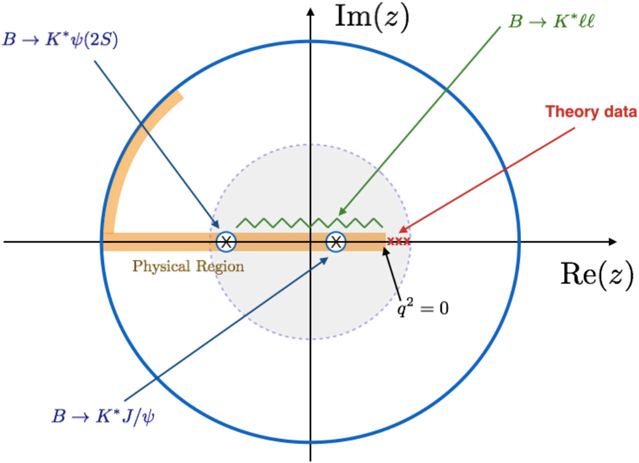
- $\mathcal{H}^{\rm OPE}_{\lambda,x}(q_0^2)$: Theory   e.g. Khodjamirian et al 2010, 2012; Asatrian, Greub, Virto 2019
- $\rho_{\lambda,c}(t)$: $B \to K^{(*)} J/\psi$, $B \to K^{(*)}\psi(2S)$, $B \to K^{(*)} D\bar{D}$, ...
- $\rho_{\lambda,sb}(t)$: $B \to K^{(*)}\phi$, $B \to K^{(*)}\bar{K}K$, ...
- $\rho_{\lambda,ud}(t)$: $B \to K^{(*)}\rho$, $B \to K^{(*)}\omega$, $B \to K^{(*)}\pi\pi$, $B \to K^{(*)}\pi\pi\pi$, ...

Charm contribution $\longrightarrow$ numerically leading

From OPE region to physical region requires DATA ($B \to K^{(*)} X_{1--}$)

Non-local Form Factors: analyticity

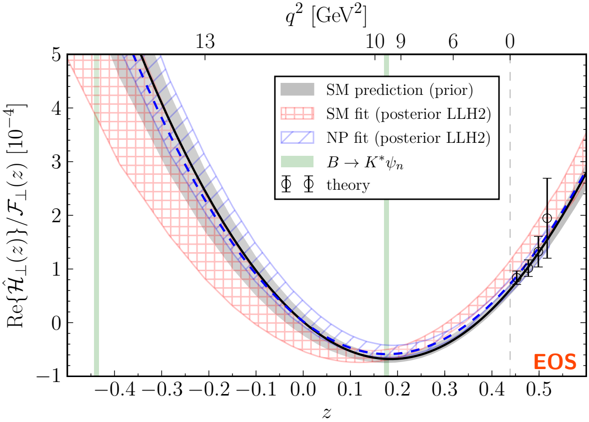
Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305



Constrain non-local effect with $B \to K^* \psi_n$ | Use interresonance $B \to K^* \ell\ell$ DATA

Non-local Form Factors: analyticity

Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305



PRIOR $\Rightarrow$ SM prediction for $B \to K^* \mu\mu$

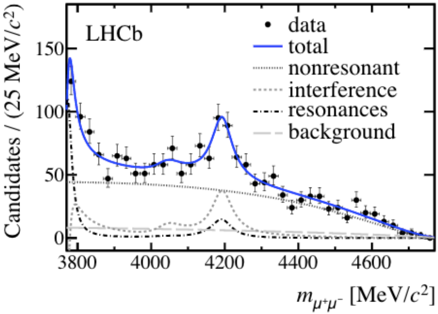
POSTERIOR $\Rightarrow$ SM prediction for $B \to K^* e^+ e^-$ $\Rightarrow$ LFU tests!

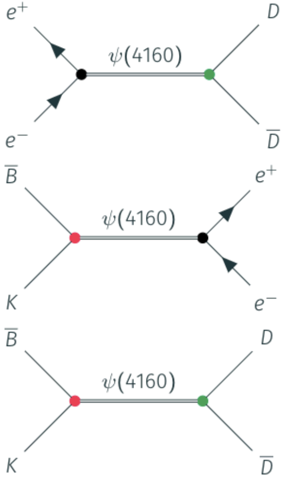
$\Rightarrow$ $SU(3)$ prediction for $b \to d\ell\ell$ —- (requires more discussion)

For prospects from LHCb see A.Mauri et al

P-vector (K-matrix) approach to $B \to K^* \ell\ell$ @ high-q^2

Kürten, van Dyk, et al, w.i.p





$\psi(4160)$:

- expectation: ● small!
- empirically: ● > ●
- prediction: $\psi(4160)$ should be more even more visible in $B \to KD\bar{D}$!

P-vector (K-matrix) approach to $B \to K^* \ell\ell$ @ high-q^2

Kürten, van Dyk, et al, w.i.p

Channels: Only $J^{PC} = 1^{--}$ $\bar{c}c$ states, plus an "eff. channel" associated to the ratio R_c.

	e^+e^-	$D^0\bar{D}^0$	$D^+_{(s)}D^-_{(s)}$	$D^0\bar{D}^{*0}$	$D^+_{(s)}D^{*-}_{(s)}$	$D^{*0}\bar{D}^{*0}$	$D^{*+}_{(s)}D^{*-}_{(s)}$	$B\bar{K}^{(*)}$
e^+e^-								♡
$D^0\bar{D}^0$	♣							♣
$D^+_{(s)}D^-_{(s)}$	♣							○
$D^0\bar{D}^{*0}$	♣							○
$D^+_{(s)}D^{*-}_{(s)}$	♣							○
$D^{*0}\bar{D}^{*0}$	♣							○
$D^{*+}_{(s)}D^{*-}_{(s)}$	♣							○

Resonances: $\psi(3770, 4040, 4160, 4415)$, $X(3940, 4230, 4260, 4360, 4660)$

Highly non-trivial fit to all $c\bar{c}$ $\Rightarrow$ LOCAL prediction for $B \to K^{(*)}\ell\ell$

Summary

The wealth of data collected at Upgrade II will allow to **test, improve and produce precise SM predictions** for rare decays. This will force us to push the limits of our theoretical approaches to QCD effects.

In particular,

- Global fits will challenge our theoretical input independently of New Physics
- Data-driven approaches to local and non-local form factors will dominate
- A "hyper-global" approach to rare decays will be implemented, addressing simultaneously New Physics and QCD by the interplay of many different modes and observables.

I have shown that this has already started, but data is not yet precise enough.

Everything applies to **BARYONIC decays**, too, and including these is part of the Upgrade II program and the "hyper-global" approach.