Data-driven Approaches to Exclusive $b \to s\ell\ell$

Andrea Mauri & Javier Virto

Beyond the Flavor Anomalies II – April 21st, 2021

Anomalies in $b \to s\ell\ell$ occur across the spectrum of decay observables:

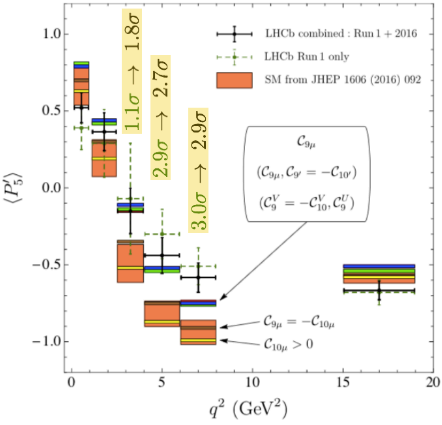
NP "clean" (*e.g.* R_K) $\longleftarrow - - - - - \longrightarrow$ QCD-sensitive observables (*e.g.* $\mathcal{B}$)

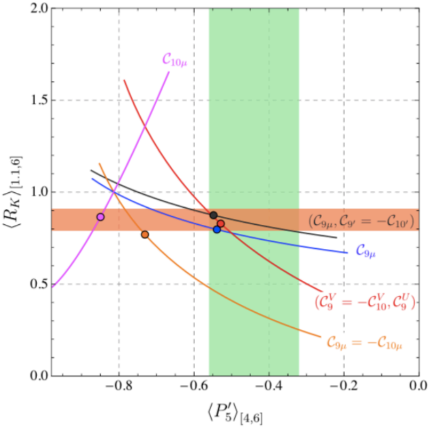
Opportunity to study **BOTH** *New Physics* and *QCD* in "rare" decays.

A point that can be hopefully made is that:

> The intensive experimental flavor physics program in the next decade is such that **experimental data** will be used to improve *SM (QCD) predictions*, allowing for finer and very reliable *New Physics analyses*.

Fits to $b \to s\ell\ell$ (R_K and P_5' measurements from LHCb 2019, 2020)





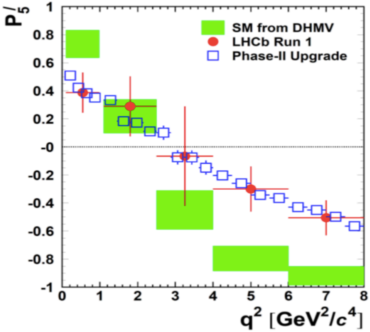
Algeró et al. Addendum to Eur.Phys.J.C 79 (2019)

Future expectations

☐ 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

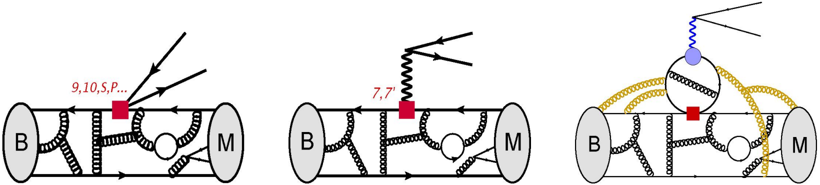
$$\mathrm{Pull}(P_5'^{[2.5,4.0]}) = 3.5\sigma \xrightarrow{2020} 2.8\sigma$$

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

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

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

Anatomy of $B \to M_\lambda \ell^+ \ell^-$ EFT Amplitudes

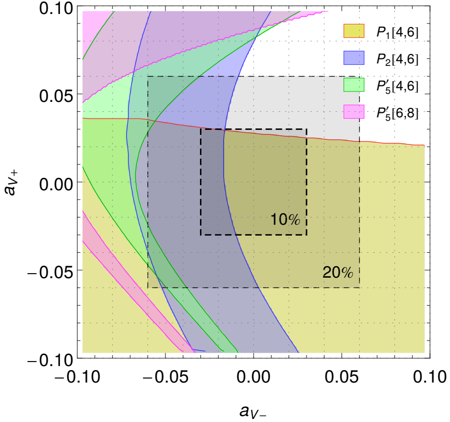


$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]\right\} + \mathcal{O}(\alpha_{\rm em}^2)$$

- Local (Form Factors) : $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k)|\, \bar{s}\, \Gamma_\lambda^{(T)}\, b\, |\bar{B}(k+q)\rangle$
- Non-Local : $\mathcal{H}_\lambda(q^2) = i\,\mathcal{P}_\mu^\lambda \int d^4x\, e^{iq\cdot x} \langle \bar{M}_\lambda(k)|T\{\mathcal{J}_{\rm em}^\mu(x), \mathcal{C}_i\, \mathcal{O}_i(0)\}|\bar{B}(q+k)\rangle$

Experimental Tests: Redundancy provides form factor info

Descotes-Genon, Hofer, Matias, Virto 2016

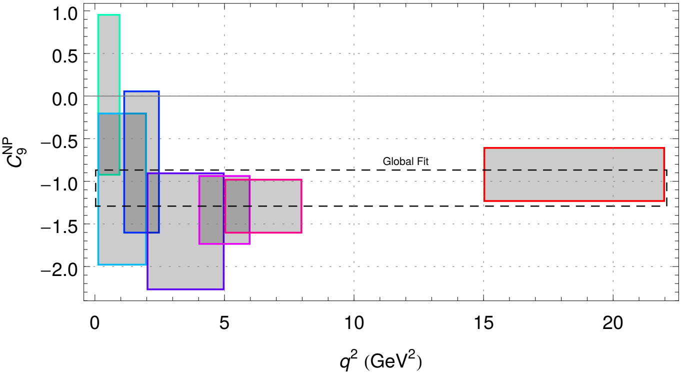


Data will only be consistent with certain form factor values....

.... and may need NP for that!

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

Descotes-Genon, Hofer, Matias, Virto 2016

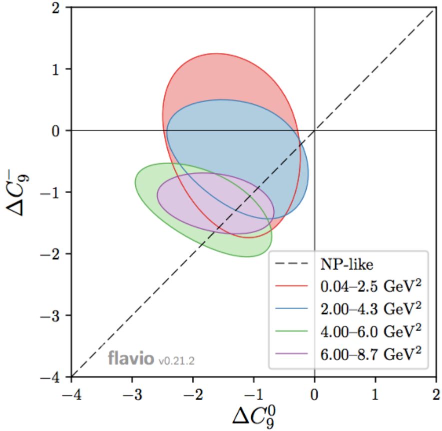


Fits provide a-posteriori tests that q^2-dependence of non-local effects is correct

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

Experimental Tests: NP contributions to WCs are helicity-independent

Altmannshofer, Niehoff, Stangl, Straub 1703.09189

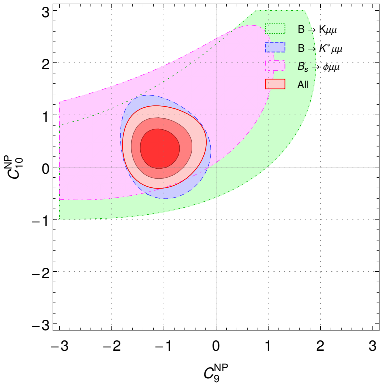


Fits provide a-posteriori tests that λ-dependence of non-local effects is correct

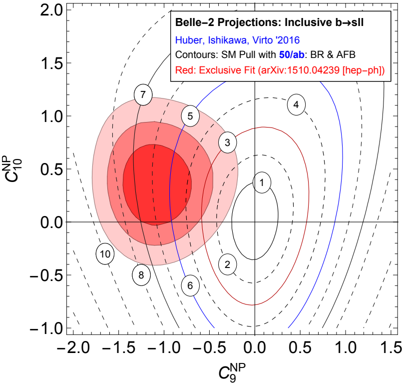
.... and passing this test will be increasingly harder!

Experimental Tests: Same with mode-independence

Descotes-Genon, Hofer, Matias, Virto 2016



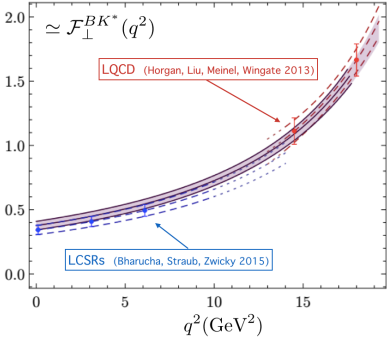
Huber, Ishikawa, Virto, Belle-II Physics Book

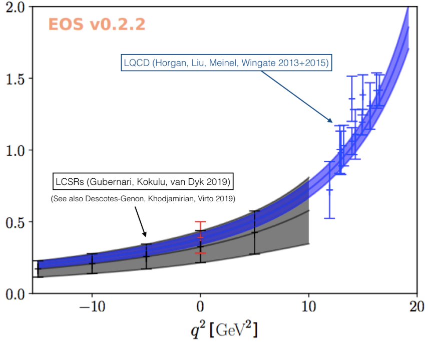


Consistency at EFT-level is Model-Indep. and a data-driven test of Theory (QCD).

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

Local form factors





- Two main approaches: (1) Lattice QCD (large q^2) (2) LCSRs (low q^2)
- Two approaches to LCSRs, in terms of (1) K^* LCDAs (2) B LCDAs
- q^2 dependence can be parametrized model-independently

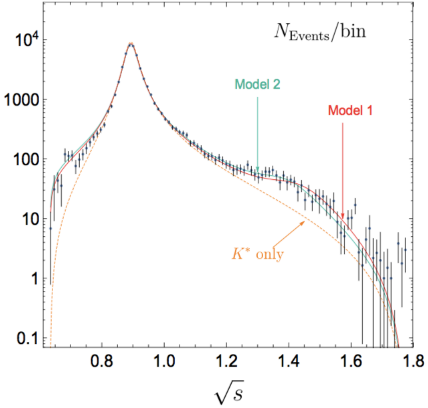
Form factors for unstable mesons (e.g., K^*)

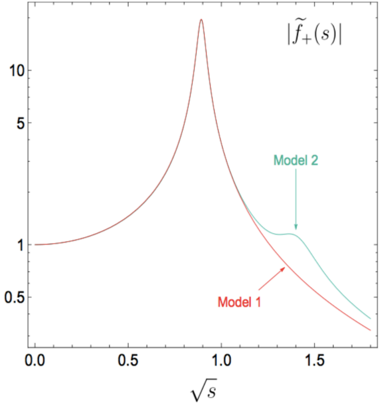
Descotes-Genon, Khodjamirian, Virto 2019

$$\boxed{\int_{s_{\rm th}}^{s_0} ds\, e^{-s/M^2}\ \omega_i(s,q^2)\ f_+^\star(s)\ \ F_i^{(T)(\ell=1)}(s,q^2) = \mathcal{P}_i^{(T),\rm OPE}(q^2,\sigma_0,M^2)}$$

$K\pi$ form factor $f_+(s)$ from $\tau \to K\pi\nu_\tau$

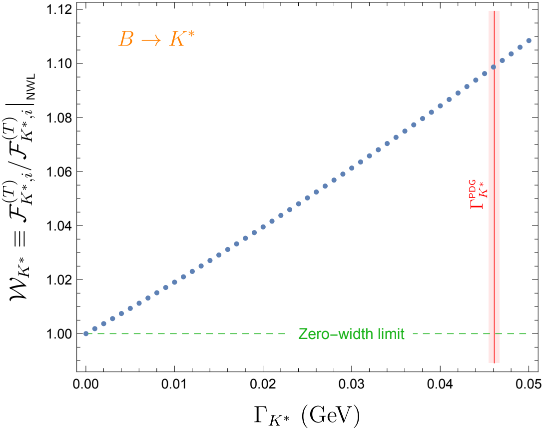
Data from Belle, arXiv:0706.2231 [hep-ex]





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

Descotes-Genon, Khodjamirian, Virto 2019



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

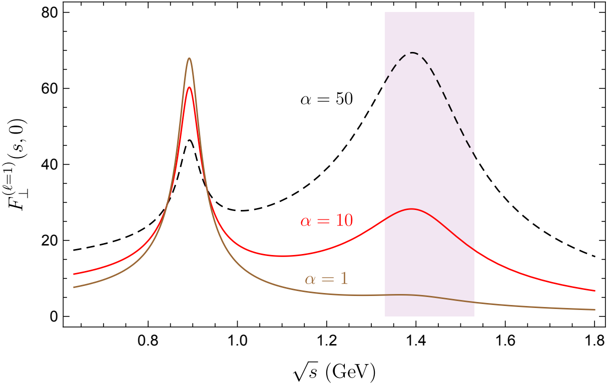
$$\mathcal{W}_{K^*} \simeq 1 + 1.9\,\frac{\Gamma_{K^*}}{m_{K^*}}$$

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

$\Rightarrow$ **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 $B \to K\pi\ell\ell$

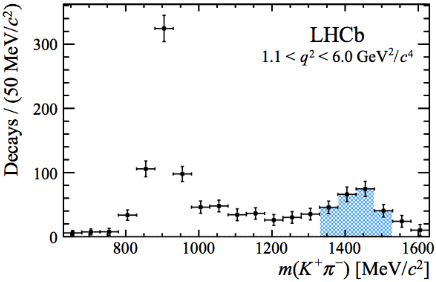
Descotes-Genon, Khodjamirian, Virto 2019

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

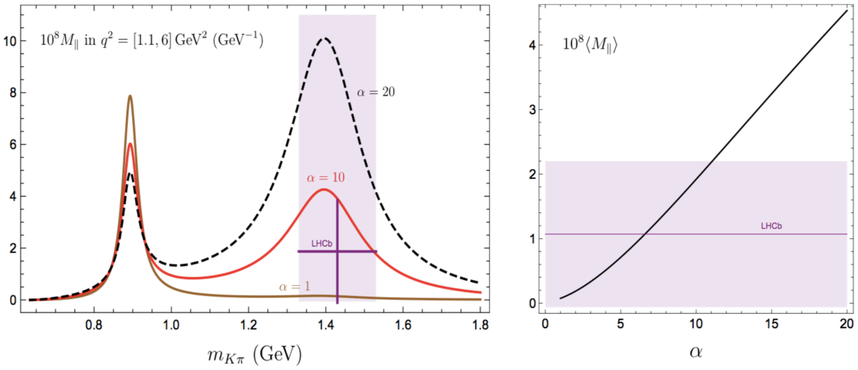
$$\frac{d\Gamma}{dq^2 dk^2 d\Omega} = \frac{1}{4\pi} \sum_{i=1}^{41} f_i(\Omega) \, \tilde{\Gamma}_i(q^2, k^2)$$

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

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



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; Gubernari, van Dyk, Virto 2020

- $\rho_{\lambda,c}(t)$: $B \to K^{(*)} J/\psi$, $B \to K^{(*)}\psi(2S)$, $B \to K^{(*)} D\bar{D}$, ...

- $\rho_{\lambda,sb}(t)$: $B \to K^{(*)}\phi$, $B \to K^{(*)}\bar{K}K$, ...

- $\rho_{\lambda,ud}(t)$: $B \to K^{(*)}\rho$, $B \to K^{(*)}\omega$, $B \to K^{(*)}\pi\pi$, $B \to K^{(*)}\pi\pi\pi$, ...

Charm contribution $\longrightarrow$ numerically leading

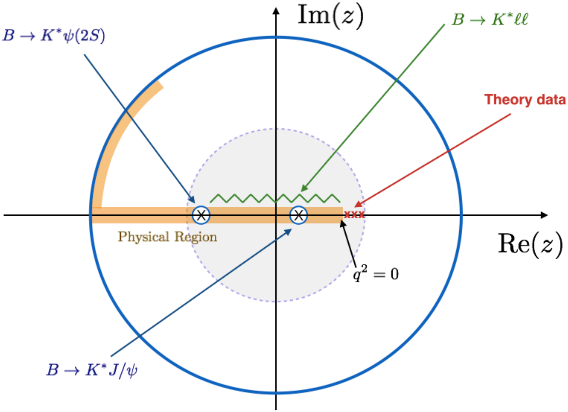
From OPE region to physical region requires DATA ($B \to K^{(*)} X_{1--}$)

Non-local Form Factors: analyticity

Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305

Gubernari, van Dyk, Virto 2011.09813

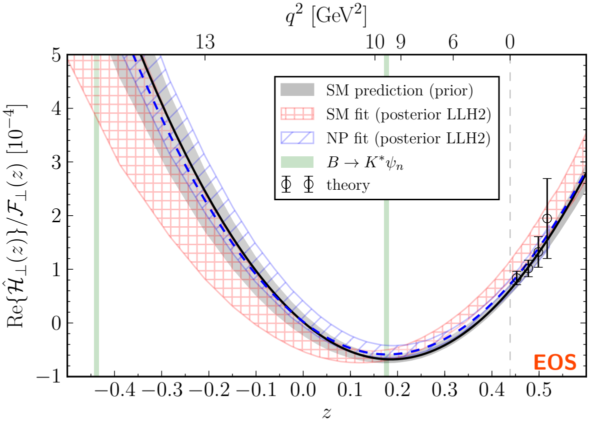
$\hat{\mathcal{H}}_\lambda^{B\to M}(z) = \sum_{n=0}^{\infty} a_{\lambda,n}^{B\to M} p_n^{B\to M}(z)$



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



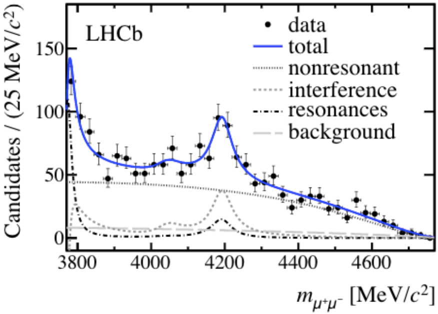
PRIOR $\Rightarrow$ SM prediction for $B \to K^* \mu\mu$

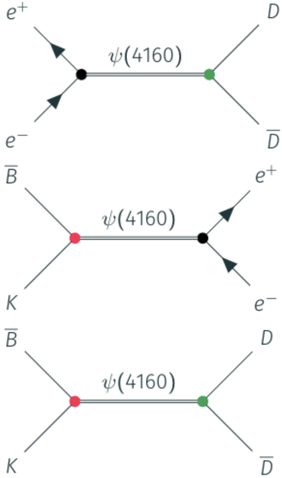
POSTERIOR $\Rightarrow$ SM prediction for $B \to K^* e^+ e^-$ $\Rightarrow$ LFU tests!

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

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

Amplitude analysis of $B^0 \to K^* \mu^+ \mu^-$

☐ Nice interplay between theory and experiments

☐ State-of-the-art inputs from theory to extract best info from data

☐ Vice-versa: possible determination (validation) of theoretical assumptions from data

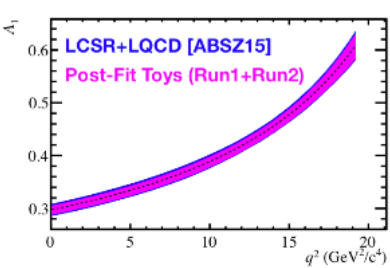
Need to parametrize the decay amplitudes:

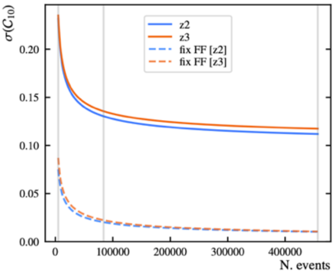
$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Form factor treatment in $B^0 \to K^* \mu^+ \mu^-$ amplitude analysis

☐ Constrained to Bharucha, Straub, Zwicky '15

☐ Form factor uncertainties will limit the experimental sensitivity on the Wilson coefficients after LHCb Upgrade I [50 fb^{-1}]





Q1: What is the impact of the K^{*0} narrow width approximation in the treatment of the Form Factors in the analysis?

☐ Naively parametrized as $FF(q^2) \times BW(m_{K\pi})$

- $BW(m_{K\pi})$ contains phase-space factor $\Rightarrow$ q^2-dependent

$\Rightarrow$ Fit posterior can give good indication about the preferred FF values in data

$\Rightarrow$ Plus, residual (q^2-dependent) difference can be absorbed by $\mathcal{H}_\lambda(q^2)$

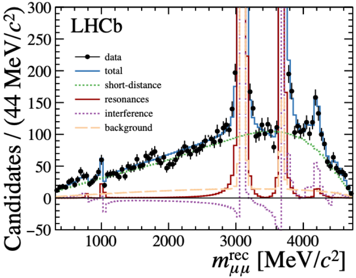
- However, we risk to bias the interpretation of $\mathcal{H}(q^2)$...

Non-local terms $\mathcal{H}(q^2)$ in $B^0 \to K^*\mu^+\mu^-$ amplitude analysis

☐ Two complementary approaches considered at LHCb: `Isobar-like` Blake et al, 1709.03921; Cornella et al, 2001.04470 and `z-expansion` Bobeth et al, 1707.07305; Chrzaszcz et al, 1805.06378; Gubernari et al, 2011.09813

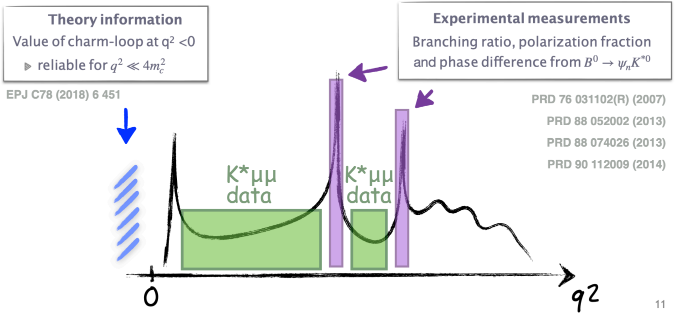
☐ Level of compatibility between the two can give useful hint on our understanding of non-local hadronic contributions

$\Rightarrow$ Run-I $B^+ \to K^+\mu^+\mu^-$ result suggests non-local terms have little impact outside resonant regions LHCb, EPJ C (2017) 77, 161

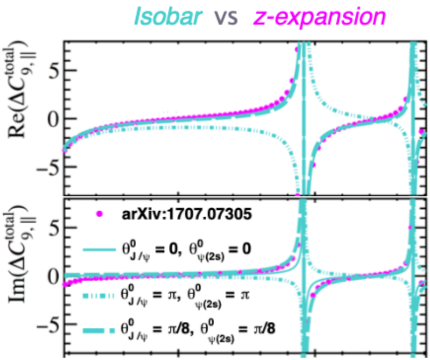


Non-local hadronic: z-expansion

- Attempt to be as much model-independent as possible
  - $\hat{\mathcal{H}}_\lambda(q^2) \equiv \sum_k \alpha_k^{(\lambda)} z^k$
- Goal: detect q^2-dependent non-local contribution
- Constrained from theory ($q^2 < 0$) and $B^0 \to \psi_n K^*$ measurements
  - $\mathrm{Res}_{q^2 \to m_\psi} \mathcal{H}_\lambda = \frac{m_\psi f_\psi^* \mathcal{A}_\lambda^\psi}{m_B^2}$
- **Interesting test: remove theory constraints and check compatibility**



Q2: What kind of information can we provide to the theory community?



Blake et al, **EPJ C78 (2018) 6, 453**

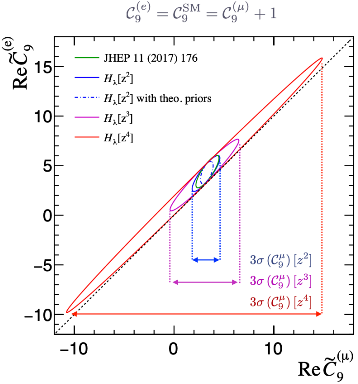
Unbinned LFU amplitude analysis AM, Serra, Coutinho, 1805.06401

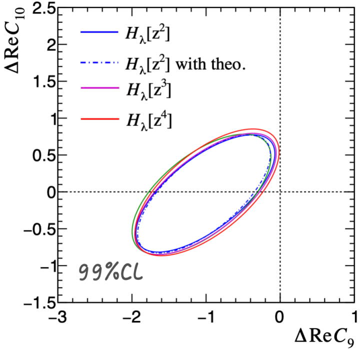
☐ Simultaneous analysis of $B^0 \to K^* \mu^+ \mu^-$ and $B^0 \to K^* e^+ e^-$

$\Rightarrow$ All (nuisance) hadronic parameter are shared

Define $\Delta C_i = C_i^{(\mu)} - C_i^{(e)} \Rightarrow$ model-independent

$\Rightarrow$ Include (unbinned) information from R_{K^*}, $\Delta P_5'$, ...





Q3: How to preserve the use of available data in the future?

Release nothing and proceed anyway.	Release background-subtracted data.	Allow for reinterpretation behind an API.
No risk of data mis-use.	Not much work.	Hide experimental details.
No extra work.	Full flexibility given.	Flexibility can be defined.
Cannot update when hadronic information improves	Difficult to use, big risk of mis-use.	A lot of work.
Ultimate sensitivity is lost.	Will people accept this before data is fully exhausted?	Relies on some level of consistency between analyses.

By. P. Owen