Angular Distributions in Rare *b* Decays

(from a theoretical perspective – including baryons)

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particle **p**hysics **p**henomenology after the **H**iggs discovery

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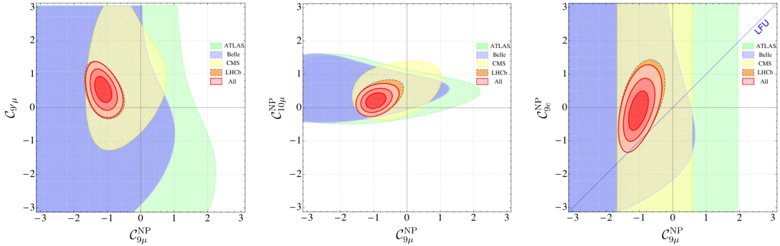
Disclaimer:

- A comprehensive review on angular observables and *B*-decay anomalies has been presented by Sébastien Descotes-Genon at BEAUTY 2019: [PoS (Beauty2019) 015]
  - benefits of optimized angluar observables for NP fits
  - global fits for SM vs. NP (including LFU-violating observables)
  - Wilson coefficients, form factors and all that
  - ...
- This talk will thus focus on:
  - theoretical subtleties (mostly concerning hadronic uncertainties)
  - recent developments (in particular for baryonic modes)
  - what to expect from theory in the future (sometimes speculative)

Preliminaries

What we are after . . .

Experimental constraints on Wilson coefficients $C_{9,10,9',10',\ldots}$
describing $b \to s\ell^+\ell^-$ — in the Standard Model or with "New Physics"



[Descotes-Genon @Beauty2019]

- "optimized" angular observables give detailed information on decay dynamics, where experimental and theoretical systematics cancel to some extent
- careful statistical analysis:
  - → take into account parametric and systematic hadronic uncertainties
  - → discrimate between SM vs. NP interpretation in global fits

→ plenary talk by Javier Virto from monday

Theoretical Toolbox

- Weak effective Hamiltonian:
  - short-distance dynamics from flavour transitions in the SM or in NP models or in SM-EFT encoded in Wilson coefficients $C_i(\mu)$ ✓
  - scale-dependence controlled by RG running ✓

precise predictions for: $\boxed{C_i(\mu_b)}$ (where $\mu_b \sim \mathcal{O}(m_b)$)

- Factorization Approximation ("naive factorization")
  - hadronic matrix elements reduced to transition form factors
  - (light-cone) sum-rules constrain FFs at large recoil energy ✓
  - lattice QCD simulations constrain FFs at low recoil energy ✓
  - μ_b-dependence of Wilson coefficients not matched ✗
- Effective Wilson coefficients incorporate LO quark-loop effects

$$\boxed{C_7 \to C_7^{\rm eff}\,, \qquad C_9 \to C_9^{\rm eff}(q^2)}$$

  - Match LO scale dependence ✓
  - not applicable near hadronic sub-structures (resonances,. . .) ✗

Theoretical Toolbox

Beyond naive factorization:

"factorizable" and "non-factorizable" corrections from radiative QCD effects or power-suppressed terms of relative order $\Lambda_{\rm QCD}/m_b$

- low hadronic recoil ($q^2 \gtrsim 16$ GeV^2):
  - expansion in $1/m_b \oplus$ expansion in α_s
    $\to$ Heavy-quark effective theory
- large hadronic recoil ($q^2 \lesssim 6$ GeV^2):
  - expansion in $1/m_b \sim 1/2E_K \oplus$ expansion in α_s
    $\to$ "QCD (improved) factorization" / Soft-collinear effective theory

Non-perturbative analyses using analyticity / unitarity / dispersion relations

- correlation functions as complex functions of complex arguments
- find parametrizations consistent with analytic properties in QFT
- use experimental and theoretical information to constrain parameters

Decays of B Mesons

- benefit of optimized angular observables for NP searches

  [1202.4266, 1212.2321, 1303.5794, ...]

- angular observables combined with LFU violation in $b \to s\ell^+\ell^-$:
  deviations from SM in C_9 as large as 25%
- advanced theoretical and phenomenological studies for
  "golden decay channels", $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$

  [see e.g. Belle II Physics Book and refs. therein]

- phenomenological studies for many further decay modes, recent studies:
  - time-dependent angular analysis in $B_d \to K_S\ell\ell$ [2008.08000]
  - angular analysis of $B_s \to f_2'(\to K^+K^-)\mu^+\mu^-$ [2009.06213]

(for experimental aspects, see talk by Adlène Hicheur from monday)

Bobeth et al. [arXiv:1707.07305]
(see also talk by Javier Virto from monday)

General decomposition of SM $B \to K^*$ transversity amplitudes ($\lambda = \perp, \|, 0$)

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

- short-distance effects in $C_{7,9,10}$
- factorizable hadronic effects in (generalized) form-factor functions $\mathcal{F}_\lambda^{(T)}(q^2)$
- non-factorizable hadronic effects in helicity- and q^2-dependent functions

$$\mathcal{H}_\lambda(q^2) \equiv \text{(LO quark loops + perturbative and non-perturbative corrections)}$$

- QCDF/SCET theoretical calculations constrain $\mathcal{H}_\lambda$ for $q^2 \ll 4m_c^2$ (preferably $q^2 < 0$)
- $B \to J/\psi K^*$ and $B \to \psi(2S) K^*$ measurements constrain $\mathcal{H}_\lambda$ around $q^2 \simeq M^2_{J/\psi,\psi'}$

Bobeth et al. [arXiv:1707.07305]
(see also talk by Javier Virto from monday)

conformal mapping:

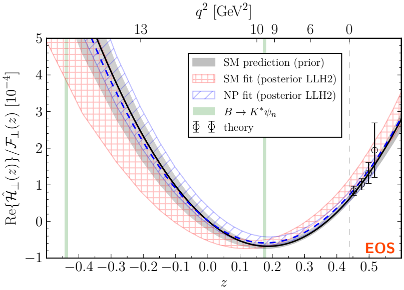
$$q^2 \mapsto z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

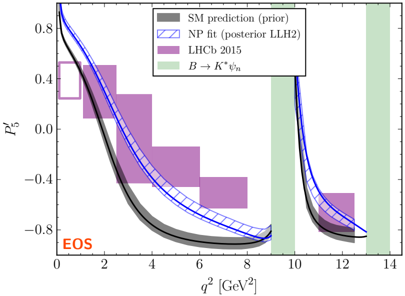
- with open-charm threshold $t_+ = 4M_D^2$
- optimized value for $t_0 = t_+ - \sqrt{t_+ \left(t_+ - M^2_{\psi(2S)}\right)}$ (to make $|z|$ small)

z-expansion: (here: only charmful operators $O_{1,2}^{(c)}$ taken into account)

$$\mathcal{H}_\lambda(z) = \underbrace{\frac{1 - z\, z^*_{J/\psi}}{1 - z_{J/\psi}}}_{J/\psi\text{-pole}} \underbrace{\frac{1 - z\, z^*_{\psi(2S)}}{z - z_{\psi(2S)}}}_{\psi'\text{-pole}} \mathcal{F}_\lambda(z) \sum_{k=0}^{K} \underbrace{\alpha_k^{(\lambda)}}_{\text{fit parameters}} z^k$$

Bobeth et al. [arXiv:1707.07305]
(see also talk by Javier Virto from monday)





SM prediction (prior):

- residues at $q^2 = M^2_{J/\psi,\psi(2S)}$ from exp.
- theory input at $q^2 = \{-7, -5, -3, -1\}$ GeV^2 as pseudo-data

SM or NP fit (posterior)

- include angular observables in $B \to K^* \mu^+ \mu^-$

Hurth/Mahmoudi/Neshatpour [arXiv:2006.04213]

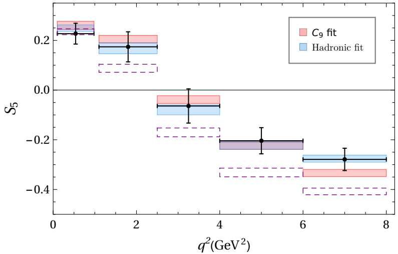
for earlier work, see also [Ciuchini et al. 2015] [Arbey et al. 2018] [Chrzaszsz et al. 2019] . . .

"How to disentangle NP Effects from non-factorizable hadronic effects?"

- Any NP fit for Wilson coefficients $C_{7,9}^{(\prime)}$ from angular observables *alone* is embedded in a more general hadronic fit with open parameters in $\mathcal{N}_\lambda(q^2)$

Example: Fit with real δC_9 vs. hadronic fit with 9 complex coefficients

(simplified approach: expansion of $\mathcal{N}_\lambda$ around QCDF to second order in q^2)



- by construction: hadronic fit yields better description of angular observable S_5

$B \to K^* \bar{\mu}\mu/\gamma$ observables	($\chi^2_{\rm SM} = 85.1$)		
	best-fit value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-1.11 ± 0.15	49.7	6.0σ
h_λ	(see below)	26.0	4.7σ

Hurth/Mahmoudi/Neshatpour [arXiv:2006.04213]

Details of hadronic fit:

$B \to K^* \bar{\mu}\mu/\gamma$ observables ($\chi^2_{\rm SM} = 85.1$, $\chi^2_{\rm min} = 25.96$; ${\rm Pull}_{\rm SM} = 4.7\sigma$)		
	Real	Imaginary
$h_+^{(0)}$	$(-2.37 \pm 13.50) \times 10^{-5}$	$(7.86 \pm 13.79) \times 10^{-5}$
$h_+^{(1)}$	$(1.09 \pm 1.81) \times 10^{-4}$	$(1.58 \pm 1.69) \times 10^{-4}$
$h_+^{(2)}$	$(-1.10 \pm 2.66) \times 10^{-5}$	$(-2.45 \pm 2.51) \times 10^{-5}$
$h_-^{(0)}$	$(1.43 \pm 12.85) \times 10^{-5}$	$(-2.34 \pm 3.09) \times 10^{-4}$
$h_-^{(1)}$	$(-3.99 \pm 8.11) \times 10^{-5}$	$(1.44 \pm 2.82) \times 10^{-4}$
$h_-^{(2)}$	$(2.04 \pm 1.16) \times 10^{-5}$	$(-3.25 \pm 3.98) \times 10^{-5}$
$h_0^{(0)}$	$(2.38 \pm 2.43) \times 10^{-4}$	$(5.10 \pm 3.18) \times 10^{-4}$
$h_0^{(1)}$	$(1.40 \pm 1.98) \times 10^{-4}$	$(-1.66 \pm 2.41) \times 10^{-4}$
$h_0^{(2)}$	$(-1.57 \pm 2.43) \times 10^{-5}$	$(3.04 \pm 29.87) \times 10^{-6}$

- each individual hadronic parameter still consistent with zero (!)

Hurth/Mahmoudi/Neshatpour [arXiv:2006.04213]

Applying Wilks' Theorem:

$B \to K^* \bar{\mu}\mu/\gamma$ observables; low-q^2 bins up to 8 GeV^2								
nr. of free parameters	1 (Real δC_9)	2 (Real $\delta C_7, \delta C_9$)	2 (Comp. δC_9)	4 (Comp. $\delta C_7, \delta C_9$)	3 (Real $\Delta C_9^{\lambda,\text{PC}}$)	6 (Comp. $\Delta C_9^{\lambda,\text{PC}}$)	9 (Real $h^{(0,1,2)}_{+,-,0}$)	18 (Comp. $h^{(0,1,2)}_{+,-,0}$)
0 (plain SM)	6.0σ	5.6σ	5.8σ	5.4σ	5.4σ	5.5σ	5.0σ	4.7σ
1 (Real δC_9)	—	0.5σ	1.5σ	1.2σ	0.6σ	1.8σ	1.1σ	1.5σ
2 (Real $\delta C_7, \delta C_9$)	—	—	—	1.4σ	—	—	1.3σ	1.6σ
2 (Comp. δC_9)	—	—	—	0.8σ	—	1.7σ	—	1.4σ
4 (Comp. $\delta C_7, \delta C_9$)	—	—	—	—	—	—	—	1.5σ
3 (Real $\Delta C_9^{\lambda,\text{PC}}$)	—	—	—	—	—	2.2σ	1.4σ	1.7σ
6 (Comp. $\Delta C_9^{\lambda,\text{PC}}$)	—	—	—	—	—	—	—	0.1σ
9 (Real $h^{(0,1,2)}_{+,-,0}$)	—	—	—	—	—	—	—	1.5σ

- any preference among the various fit scenarios is $\lesssim 2\sigma$

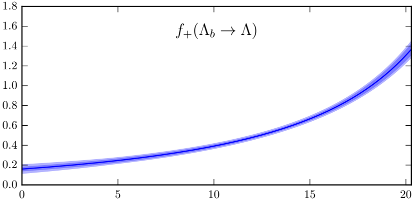
$\rightarrow$ situation concerning "NP or hadronic effects?" still inconclusive (?)

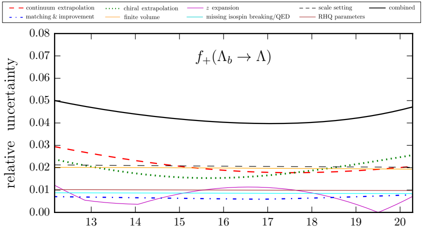
Decays of Λ_b Baryons

- large # of angular observables
  $\to$ sensitive to all Dirac structures in H_{eff} $\surd$
  $\to$ expect similar deviations from SM as in $B \to K^{(*)}\ell^+\ell^-$ **!**
- Λ_b could be produced polarised $(\surd)$
  (can be tested in angular distributions)
- Λ_b spectator system is a diquark
  $\to$ different hadronic uncertainties compared to B-meson decays (!)
  $\to$ $\Lambda_b \to \Lambda$ form factors available from lattice QCD $\surd$
  $\to$ current understanding of spectator-dependent effects poor **X**

Böer/TF/van Dyk [arXiv:1410.2115]
see also: **Gutsche et al. [arXiv:1301.3737]**

- $\Lambda_b \to \Lambda$ described by 10 independent form factors conveniently defined in helicity basis [e.g. TF/Yip 2012]
- reduction $10 \to 2$ at low recoil energy ($m_\Lambda \sim E_\Lambda \ll m_b$) [HQET]
- reduction $10 \to 1$ at large recoil energy ($m_\Lambda \ll E_\Lambda \sim m_b$) [SCET]
- FFs accessible with lattice QCD [Detmold/Meinel 2016]
  - $\to$ simulation in low-recoil region
  - $\to$ extrapolation to large recoil by "z-expansion"





Böer/TF/van Dyk [arXiv:1410.2115]

- unpolarized Λ_b decay in terms of 10 angular observables
- depend on Wilson coefficients, form factors, and parity-violating decay parameter α in weak $\Lambda \to N\pi$ decay
  - $\to$ additional forward-backward asymmetries (as compared to $B \to K^*$ mode)
  - $\to$ sensitive to independent combinations of Wilson coefficients
- construct optimized angular observables that (in factorization approx.)
  - only depend on combinations of Wilson coefficients
  - only depend on ratios of form factors
  - only depend on Wilson coefficients and one form-factor ratio

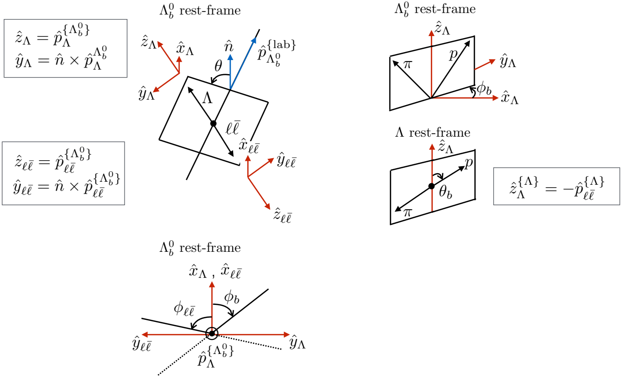
$\Lambda_b \to \Lambda$ provides complementary information on $b \to s\ell^+\ell^-$

(for related studies see also:

... [1111,1849], [1301.3737], [1410.2115], [1710.01335], [1802.09404], [1804.08527] ...)

Blake/Kreps [arXiv:1710.00746]

- angular distributions for polarized Λ_b described by five angles
  $\to$ 24 *additional* angular observables



Blake/Meinel/van Dyk [arXiv:1912.05811]

(for earlier works, see also [Meinel/van Dyk 2016, Das 2018])

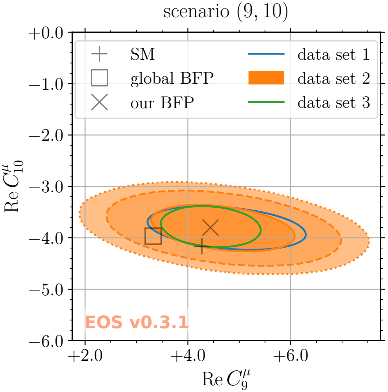
Updated Bayesian analysis:

- New Results (!) for parity-violating parameter α in $\Lambda \to p\pi^-$ [BESIII]
- complete set of angular observables from LHCb [JHEP 09 (2018) 146]
- constraints from time-integrated $\mathcal{B}(B_s \to \mu_+\mu_-)$ [ATLAS,CMS,LHCb]
- updated value for the Λ_b fragmentation function
  $\to$ updated value for $\mathcal{B}(\Lambda_b \to J/\psi\Lambda)$,
  (used as a normalization in LHCb measurement of $\Lambda_b \to \Lambda\mu^+\mu^-$)

Results:

- Λ_b polarization compatible with zero, $|P_{\Lambda_b}| \leq 11\%$ (@95%)
- angular distributions compatible with SM
- similarly good fit with NP in C_9 only: $C_9 = 4.8 \pm 0.8$
- slightly better fit for NP in $C_{9,10}$: $C_9 = 4.4 \pm 0.8$ $C_{10} = -3.8 \pm 0.3$
  (compatible with global fit for B-meson decays and with SM)

Blake/Meinel/van Dyk [arXiv:1912.05811]



global best-fit-point refers to [1704.05340]

Model comparison:

- The two scenarios with [SM only] or [NP in C_9 only] are almost equally efficient in describing the data.
- Scenario with [NP in $C_{9,10}$] "*strongly disfavored*"
- Scenario with [NP in $C_{9,10,9',10'}$] "*decisively disfavored*"

Yan [arXiv:1911.11568]

- include full set of operators in $H_{\rm eff}$
  (scalar, pseudo-scalar, vector, axial-vector, tensor)
- lepton mass kept finite $\to$ applicable for decays into τ leptons
- Comparison with SM and scalar-leptoquark model (S_1+S_3)

updated LHCb data not yet included . . .

Das [arXiv:1909.08676]

(for earlier work, see also [Sahoo/Mohanta 2016])

- Models that explain LFU violation in B decays often also lead to LFV
- study $b \to s \ell_1^+ \ell_2^-$ decays in $\Lambda_b \to \Lambda$ transitions
- non-factorizable long-distance QCD effects are absent $\surd$
- LFV tiny in the SM $\to$ clear sign of NP (!)

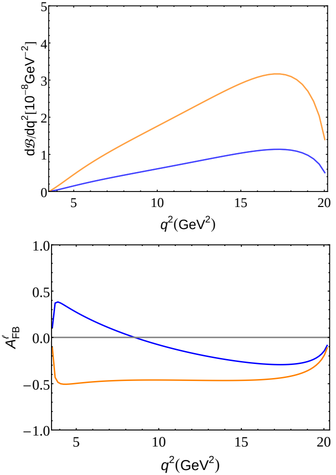
Results

- all vector, axial-vector, scalar and pseudo-scalar operators included
- branching ratio and leptonic FB asymmetry in terms of angular coefficients

$$\frac{d\mathcal{B}}{dq^2} = 2K_{1ss} + K_{1cc}\,, \qquad A_{FB}^{\ell} = \frac{3}{2}\,\frac{K_{1c}}{K_{1ss} + K_{1cc}}$$

- benchmark model with vector leptoquark $U_1 = (3,1)_{3/2}$
  parameter space constrained by other low-energy observables

Das [arXiv:1909.08676]



- q^2 distribution of differential branching ratio and lepton-side forward-backward asymmetry,

  shown for one set of benchmark values of the U_1 model parameters allowed by low-energy observables.

  The blue and orange lines correspond to $\Lambda_b \to \Lambda\tau^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\tau^-$.

- predictions from allowed parameter space:

$$\langle\mathcal{B}(\Lambda_b \to \Lambda\tau^+\mu^-)\rangle \in [1.55 \times 10^{-9}, 7.83 \times 10^{-6}]$$

$$\langle\mathcal{B}(\Lambda_b \to \Lambda\mu^+\tau^-)\rangle \in [5.01 \times 10^{-9}, 1.78 \times 10^{-5}]$$

$$\langle A_{\rm FB}^{\ell}(\Lambda_b \to \Lambda\tau^+\mu^-)\rangle \in [-0.2504, -0.003]$$

$$\langle A_{\rm FB}^{\ell}(\Lambda_b \to \Lambda\mu^+\tau^-)\rangle = -0.4040$$

Large ranges due to poor experimental bounds on $B_s \to \tau^+\tau^-$, $B^+ \to K\tau^+\tau^-$.

$\Rightarrow$ LFV branching ratios are accessible in LHCb !

Decays of Λ_b Baryons to excited $\Lambda(1520)$

- $\Lambda(1520)$ decays through strong interaction into pK or nK,
  appears to dominate $\Lambda_b \to pK^- J/\psi$ around $m_{pK} \sim 1.5$ GeV
- $\Lambda(1520)$ has spin-parity $J^P = 3/2^-$

- complementary information on NP in $b \to s\ell^+\ell^-$ $\surd$
- $\Lambda_b \to \Lambda^*$ form factors more involved on the lattice,
  preliminary studies [Meinel/Rendon 2016], very recent results [Meinel/Rendon, today] $\surd$

- poor theoretical knowledge on $\Lambda(1520)$ hadronic structure X
- recoil energy not particularly large, and m_{Λ^*} not very small
  $\to$ potentially large corrections to HQET/SCET relations (X)

Descotes-Genon/Novoa-Brunet [1903.00448]
Das/Das [2003.08366]

Modifications compared to $\Lambda_b \to \Lambda(J/P = 1/2^+)$:

- theoretical subtleties with quantization of spin-3/2 fields, irrelevant in narrow-width approx. (tree-level propagation of on-shell state)
- $\Lambda(1520)$ state described by Rarita-Schwinger spinor $u_\alpha(k, s_\Lambda)$
  $\to$ additional form-factor structures $(10 \to 14)$
  $\to$ conveniently described in helicity basis
  $\to$ additional form factors vanish in HQET/SCET limit (conjecture)
- differential decay rate for unpolarized $\Lambda_b \to \Lambda^*$ now described in terms of 12 angular coefficients (instead of 10 for $\Lambda_b \to \Lambda$)

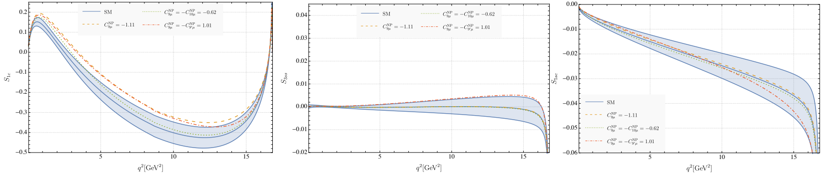
Theoretical improvements (so far):

- QCD corrections of $\mathcal{O}(\alpha_s)$ to HQET form-factor relations at low recoil

[Das/Das 2020]

Descotes-Genon/Novoa-Brunet [1903.00448]

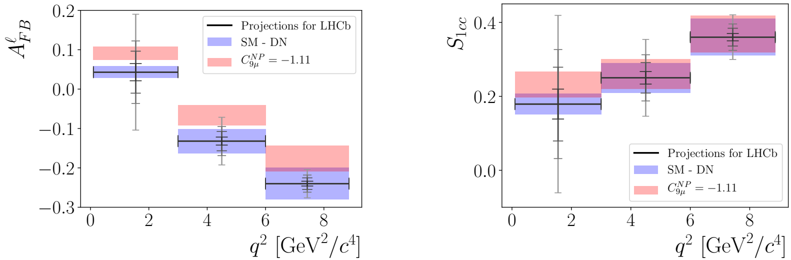
Preliminary numerical studies:
(using form factors from quark model, and approximate error estimates)



- angular coefficients show some sensitivity to right-handed NP in C_9' √
- also estimates for leptonic forward-backward asymmetry (zero crossing) √
- hadronic forward-backward asymmetries vanish (strong decay of $\Lambda(1520)$), can be exploited in experimental identification of $\Lambda(1520)$ candidates (!)

Amhis et al. [2005.09602]
Descotes-Genon/Novoa-Brunet [1903.00448]

LHCb sensitivity studies (for SM vs. NP scenario with $C_{9\mu}^{\mathrm{NP}} = -1.11$):



grey-scale markers: Run-2, Run-3, Run-4, Upgrade-2

Summary / Outlook

Angular observables in exclusive $b \to s\ell^+\ell^-$ decays provide crucial information on short- and long-distance dynamics in *b*-hadron decays:

- very good interface between experimental measurements, phenomenological analyses, and theoretical interpretation
- hadronic uncertainties from non-factorizable contributions can be reduced by data-driven methods
- model-independent global fits in different SM or NP scenarios
- interplay with LFU-violating observables

$\rightarrow$ include more decay modes/observables as cross-check

$\rightarrow$ more sophisticated theory analyses, in particular for baryonic modes

$\rightarrow$ at some stage also non-trivial QED corrections become important

[see e.g. recent preprint 2009.00929]

ご清聴　ありがとうございました。

Thanks for your (digital) attention!