Rare b decays: BSM fits and angular distributions

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Beauty 2019, Ljubljana, 1/10/19

Rare b decays: $b \to s\ell\ell$, anomalies, $\mathcal{C}_{9\mu}^{NP}$, P_5' and all that

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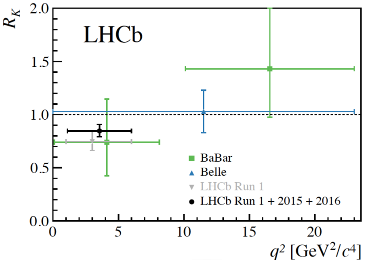
LPT Orsay

$b \to s\ell\ell$: a bird's-eye view

2019 updates on LFU violation in $b \to s\ell\ell$



- LHCb update

$$R_K^{[1.1,6]} = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$$
$$= 0.846^{+0.060+0.016}_{-0.054-0.014}$$

- Belle at low and large K recoils, 1 ± 0.2, but 20% isospin asymmetry
- From 2.6 to 2.5σ wrt SM

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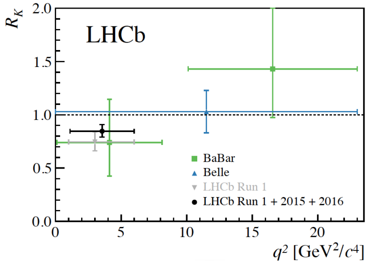

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- Belle at low and large K recoils, 1 ± 0.2, but 20% isospin asymmetry
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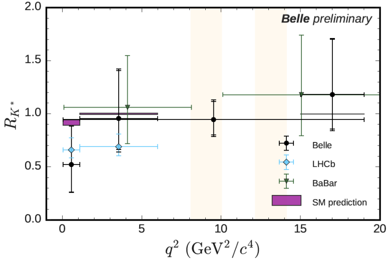
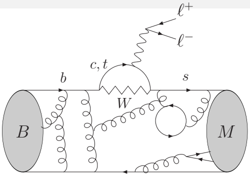
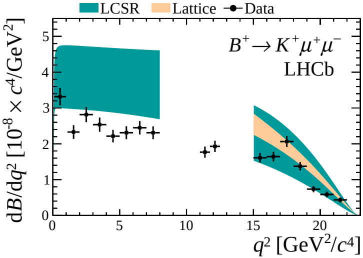
- Belle: $R_{K^*} = \frac{B(B \to K^*\mu\mu)}{B(B \to K^*ee)}$ in 3 bins (large/low-K^* recoil)
- OK with SM, but also LHCb [2.3 (2.6) σ from SM for $R_{K^*}^{[0.045,1.1]}$ ([1.1,6])]

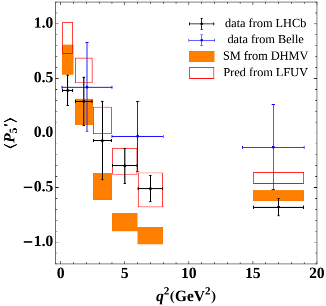


Beyond R_K, R_{K^*}, more deviations in $b \to s\ell\ell$



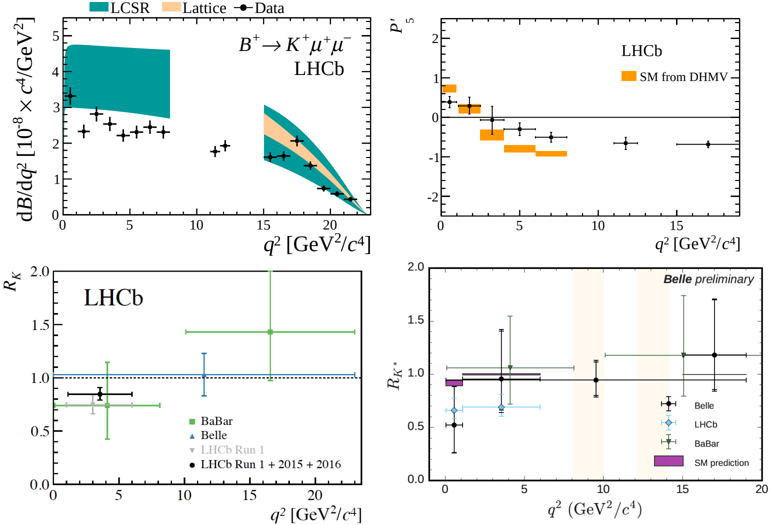
- Many observables for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$
- 2-3σ deviations observed w.r.t. SM
  - BR for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (require knowledge of hadronic uncertainties)
  - Angular distr of $B \to K^*\mu\mu$ with optimised obs (eg P_5'), where part of hadronic uncertainties cancel
  - Hints of lepton flavour universality violation: $b \to see$ vs $b \to s\mu\mu$ angular distributions





[LHCb, Belle, ATLAS, CMS]

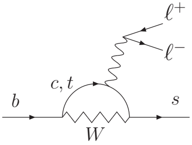
Looking for a consistent picture



Many data, a few deviations on the way, rare decay sensitive to NP
Do these results form a consistent New Physics picture ?

Computing the observables

Weak effective theory



$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

to separate short and long distances ($\mu_b = m_b$)

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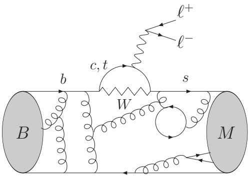

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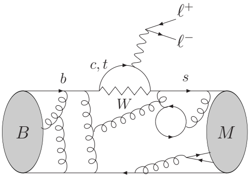

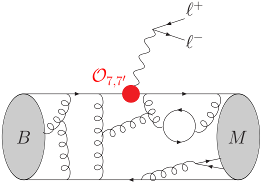

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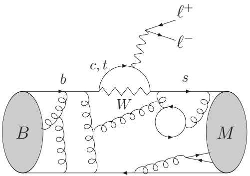

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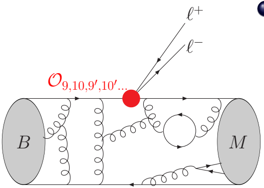
- $\mathcal{O}_{10\ell} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]



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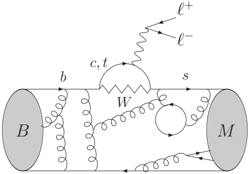

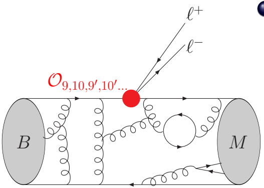

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$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

$A = \mathcal{C}_i$ (short dist) $\times$ Hadronic qties (long dist)

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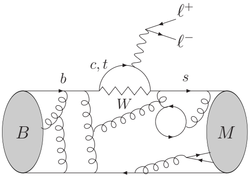

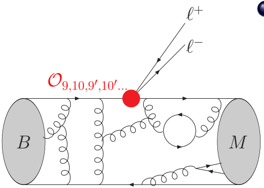

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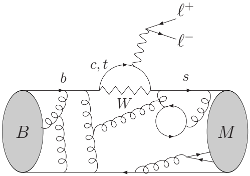
NP changes short-distance $\mathcal{C}_i$ or adds new operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_7 \to \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) $\mathcal{O}_{9\ell}, \mathcal{O}_{10\ell} \to \mathcal{O}_{S\ell} \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, \mathcal{O}_{P\ell}$
- Tensor operators ($Z \to T$) $\mathcal{O}_{9\ell} \to \mathcal{O}_{T\ell} \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\ \bar{\ell}\sigma_{\mu\nu}\ell$

Two sources of hadronic uncertainties

$$A(B \to K^*\ell\ell) = \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^*[(A_\mu + T_\mu)\bar{u}_\ell\gamma^\mu v_\ell + B_\mu \bar{u}_\ell\gamma^\mu\gamma_5 v_\ell]$$



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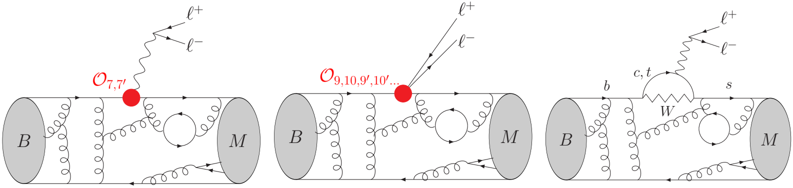

Form factors (local)

- Local contributions (here with SM $\mathcal{C}_i$): 7 form factors

$$\begin{aligned} A_\mu &= -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s} \sigma_{\mu\nu} P_R b | B \rangle + \mathcal{C}_9 \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle \\ B_\mu &= \mathcal{C}_{10} \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle \qquad \lambda : \ K^* \text{ helicity} \end{aligned}$$

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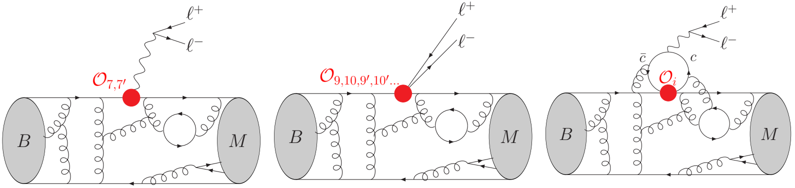

Form factors (local) Charm loop (non-local)

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- Non-local contributions (charm loops): hadronic contribs.

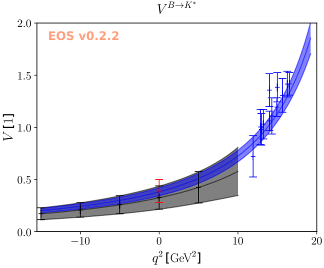
T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

Hadronic uncertainties: form factors

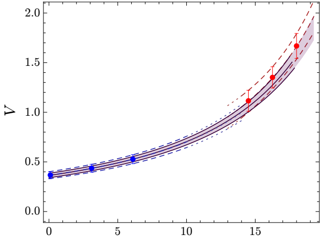
3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice QCD [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: Light-Cone Sum Rules (B-meson or light-meson DAs)

[Khodjamirian, Mannel, Pivovarov, Wang; Bharucha, Straub, Zwicky; Gubernari, Kokulu, van Dyk]



B-meson LCSR + lattice



Light-meson LCSR + lattice

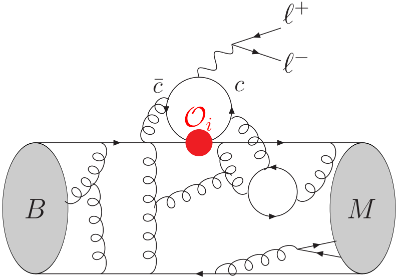
- correlations among the form factors needed
  - known from direct determination
  - recovered from EFT with $m_b \to \infty$ + $O(\alpha_s)$ + $O(1/m_b)$

[Jäger, Camalich; Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]

Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- should depend on q^2 and hadrons, but lepton universal
- high q^2: quark-hadron duality

[Beylich, Buchalla, Feldmann]



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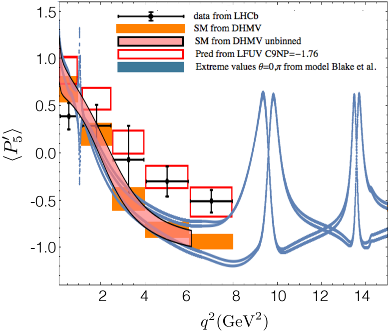

Several approaches at low q^2 agree

- LCSR estimates [Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, van Dyk]
- order of magnitude estimate for the fits (LCSR or Λ/m_b), checked with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]

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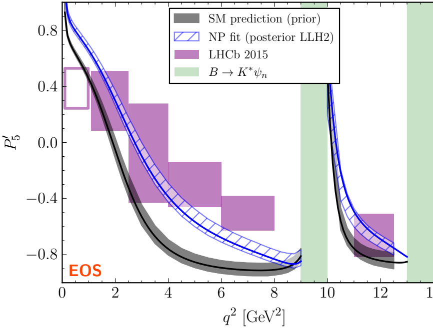

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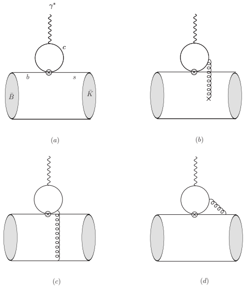
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- fit of q^2-parametrisation to the data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Capdevila, SDG, Hofer, Matias]
- dispersive representation + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

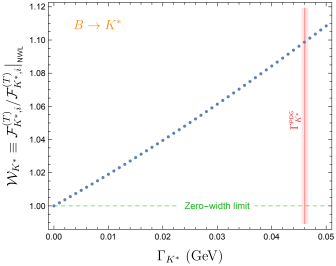
Pending questions



- Estimate of soft-gluon $c\bar{c}$ contribution from Light-Cone Sum Rules
  - Several $c\bar{c}$ contributions, with hard and soft gluons (hard to estimate)
  - Soft-gluon correction from LCSR smaller than thought ? [Gubernari, Van Dyk]
  - Impact on contribution to be worked out (not used at face value in fits)

- Narrow-width approx for form factors
  - Not problem for K or ϕ, but for K^* ?
  - Lattice QCD : other collaborations ?
  - K^*-meson LCSR: not able to catch the effect (need to use $K\pi$ DAs)
  - B-meson LCSR: universal 10% effect, increasing SM discrepancy

[Khodjamirian, SDG, Virto]



Fitting the observables

Observables

	Inclusive	Exclusive
$b \to s\gamma$	$B \to X_s\gamma$	$B_s \to \phi\gamma$, $B \to K^*\gamma$
$b \to s\mu\mu$	$B \to X_s\mu\mu$	$B_s \to \mu\mu$, $B \to K(^*)\mu\mu$, $B_s \to \phi\mu\mu$, $\Lambda_b \to \Lambda\mu\mu$
LFU (e vs μ)		R_{K^*}, R_K, $Q'_{i=4,5} = P'_{i\mu} - P'_{ie}$

- Mostly Br, but also angular observables for $B \to 4$ bodies
- Anomalies in
  - Br for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ ($B_s \to \mu\mu$, $\Lambda_b \to \Lambda\mu\mu$)
  - Angular observables P_i for $B \to K^*\mu\mu$ at large K^* recoil
  - LFUV quantities: R_K, R_{K^*}
- Combine all these observables in a statistical framework to overconstrain short-distance physics $\mathcal{C}_i$ and compare with SM

Many groups contributed over the last few years.
My apologies for this incomplete sampling for lack of time

A few general comments on the fits

Recent global analyses with LFUV + a subset of other observables:

- fit to hypothesis with some $\mathcal{C}_i^{NP}$, with χ^2 involving th. and exp. unc.
- *p*-value : $\chi^2_{\rm min}$ considering N_{dof} [does hyp. yield overall good fit ?]
- $\mathrm{Pull}_{\rm SM}$: $\chi^2_{min}(\mathcal{C}_i = 0) - \chi^2_{min}$ [does hyp. solve SM deviations ?]

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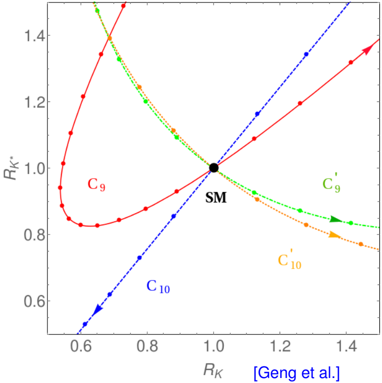

[Geng et al.]

- LFUV obs with reduced hadronic unc. but degeneracy between shifts in $\mathcal{C}_{ie}^{NP}$ and $\mathcal{C}_{i\mu}^{NP}$
- other observables lift degeneracy, favour NP in $b \to s\mu\mu$, but more sensitive to hadronic unc.
- Scalar and tensor often ignored : SM + chirality flipped enough
- CP conservation generally assumed (hence real $\mathcal{C}_i^{NP}$)

(Algueró et al., 1903.09578)

- Obs:excl $b \to s\ell\ell$ (BR,P_i),$B \to K^*\gamma$,$B \to X_s\ell\ell$,$B \to X_s\gamma$, $R_{K^{(*)}}$, Q_i
- Approach: Frequentist, private code
- Form factors: B-meson LCSR with EFT correlations + lattice
- LD charm: order of magnitude from KMPW, but sign left arbitrary

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- Subset: 22 obs (LFUV,$b \to s\gamma$,$B_s \to \mu\mu$,$B \to X_s\mu\mu$) (SM p-val 8%)

2019		Best fit	1 σ CL	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$L_q \otimes V_\ell$	-0.89	$[-1.23, -0.59]$	3.3σ	52 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$L_q \otimes L_\ell$	-0.46	$[-0.53, -0.29]$	4.0σ	74 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.61	$[-2.13, -0.96]$	3.0σ	42 %

(Algueró et al., 1903.09578)

- Obs:excl $b \to s\ell\ell$ (BR,P_i),$B \to K^*\gamma$,$B \to X_s\ell\ell$,$B \to X_s\gamma$, $R_{K^{(*)}}$, Q_i
- Approach: Frequentist, private code
- Form factors: B-meson LCSR with EFT correlations + lattice
- LD charm: order of magnitude from KMPW, but sign left arbitrary

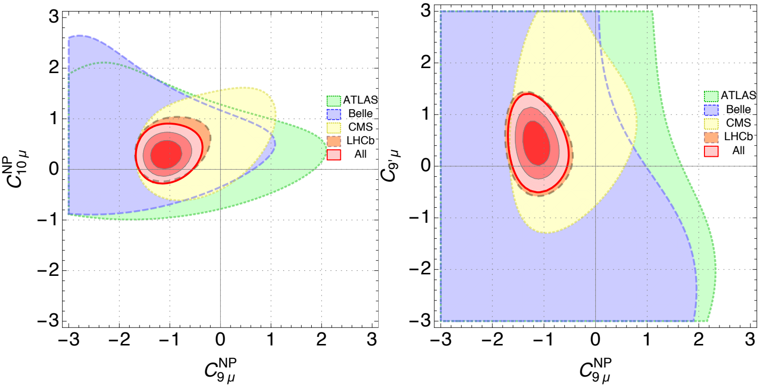
- Subset: 22 obs (LFUV,$b \to s\gamma$,$B_s \to \mu\mu$,$B \to X_s\mu\mu$) (SM p-val 8%)

2019		Best fit	1 σ CL	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$L_q \otimes V_\ell$	-0.89	$[-1.23, -0.59]$	3.3σ	52 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$L_q \otimes L_\ell$	-0.46	$[-0.53, -0.29]$	4.0σ	74 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-1.61	$[-2.13, -0.96]$	3.0σ	42 %

- All: fit to 180 obs (SM p-value 11%)

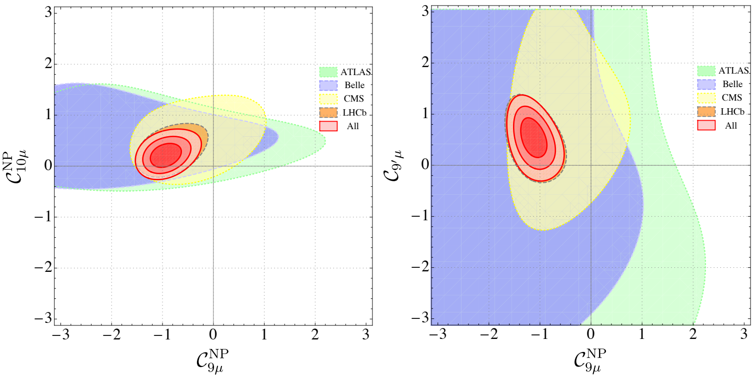
2019		Best fit	1 σ CL	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$L_q \otimes V_\ell$	-0.98	$[-1.15, -0.81]$	5.6σ	65 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$L_q \otimes L_\ell$	-0.46	$[-0.56, -0.37]$	5.2σ	56 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}$	$A_q \otimes V_\ell$	-0.99	$[-1.15, -0.82]$	5.5σ	63 %

- Right-handed currents are back in favour due to R_K closer to 1



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$: 5.6$\sigma$ (2017) (left-handed, SM-like)
- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$: 5.7$\sigma$ (2017) (right-handed currents)

(Algueró et al., 1903.09578)



- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$: 5.6$\sigma$ (2017) $\to$ 5.4σ (2019) (left-handed, SM-like)
- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$: 5.7$\sigma$ (2017) $\to$ 5.7σ (2019) (right-handed currents)

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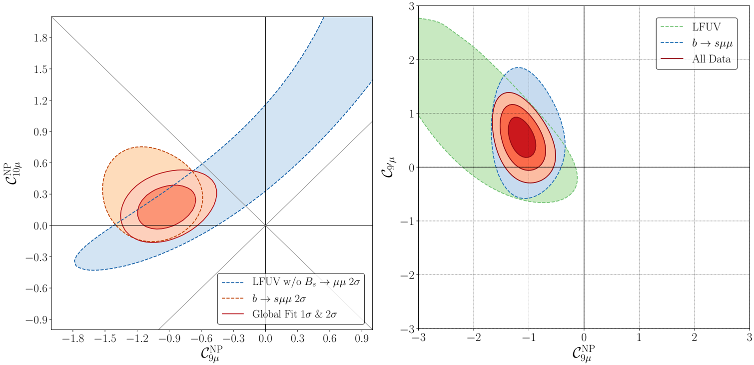
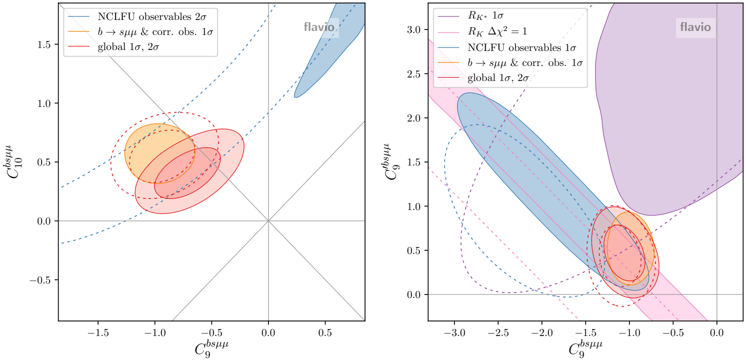


- $(\mathcal{C}^{\rm NP}_{9\mu}, \mathcal{C}^{\rm NP}_{10\mu})$: 5.6$\sigma$ (2017) $\to$ 5.4σ (2019) (left-handed, SM-like)
- $(\mathcal{C}^{\rm NP}_{9\mu}, \mathcal{C}_{9'\mu})$: 5.7$\sigma$ (2017) $\to$ 5.7σ (2019) (right-handed currents)
- Separating 3 σ regions for $b \to s\mu\mu$ and purely LFUV
  - LFUV favours $\mathcal{C}^{\rm NP}_{10\mu} > 0$ and $\mathcal{C}^{\rm NP}_{9'\mu} > 0$
  - $b \to s\mu\mu$ essentially in favour of $\mathcal{C}^{\rm NP}_{9\mu} < 0$

(Aebischer et al., 1903.10434)

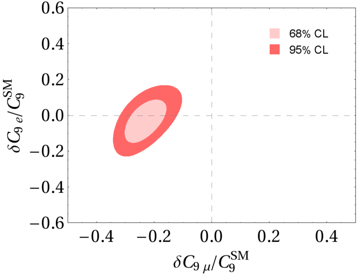
- Obs: same + $\Lambda_b \to \Lambda\mu\mu$ [BR,A_{FB}]
- Stat approach: Frequentist, flavio code
- Form factors: global fit to K^*-meson LCSR + lattice
- LD charm: q^2-polynomial with 10% from amplitude

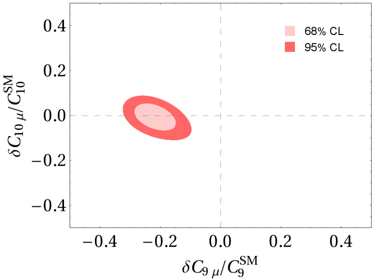


- Higher p-values: 6.3σ and 6.0σ
- 1D hyps: preference for $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$ with tensions among obs.

(Arbey et al., 1904.08399)

- Obs: similar to Algueró et al
- Stat approach: Frequentist, SuperIso code
- Form factors: global fit to K^*-meson LCSR + lattice
- LD charm: q^2-polynomial with 10% size of QCD fact





- decreased tension between $R_{K^{(*)}}$ and others concerning $\mathcal{C}_{10\mu}^{\rm NP}$
- 1D hyps: preference for $\mathcal{C}_{9\mu}^{\rm NP}$
- No need for NP in electrons (in agreement with other groups)

Other works and favoured NP scenarios

Other works from [Alok et al. 1903.09617] [Kowalska et al. 1903.10932] [D'amico et al. 1704.05438 updated] [Ciuchini et al. 1903.09632] with different settings, similar favoured NP scenarios

1D hyp	Algueró	Aebischer	Alok	Arbey	D'amico	Kowalska
$\mathcal{C}_{9\mu}^{\rm NP}$	5.6σ	5.9σ	6.2σ	5.3σ	6.5σ	4.7σ
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	5.2σ	6.6σ	6.4σ	4.5σ	5.9σ	4.8σ
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP}$	5.5σ	-	6.4σ	-	-	-

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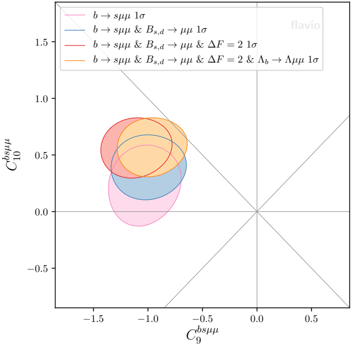
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}^{\rm NP}$	5.5σ	-	6.4σ	-	-	-

- NP hyps with significant pulls
- Right-handed currents interesting (due to R_K closer to 1)
- $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$ favoured by [Aebischer et al.] as a combined effect of
  - $BR(B_s \to \mu\mu)$
  - $\Lambda_b \to \Lambda\mu\mu$ inputs
  - $\Delta m_{d,s}$ assuming no NP in $\Delta B = 2$ (not done in other fits)



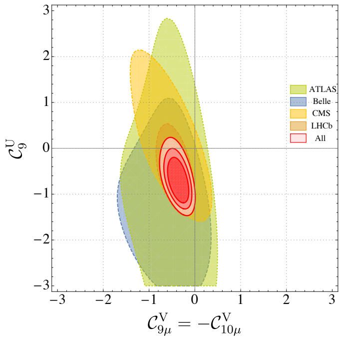
Lepton Flavour Universal NP ?

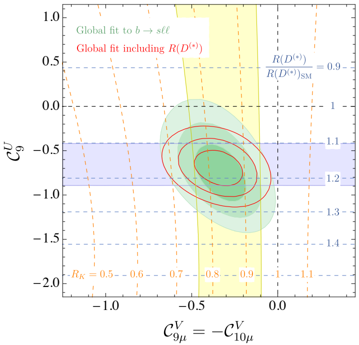
R_K and R_{K^*} support LFUV NP, but there could also be a LFU piece

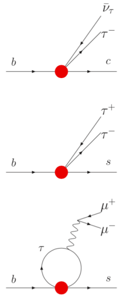
$$\mathcal{C}_{ie} = \mathcal{C}_i^{\rm U} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\rm U} + \mathcal{C}_{i\mu}^{\rm V} \qquad \mathcal{C}_{i\tau} = \mathcal{C}_i^{\rm U} + \mathcal{C}_{i\tau}^{\rm V}$$

[Algueró et al, Aebischer et al.]

- Favoured hyps (5.6-6.5σ) with similar LF**U** and LFU**V** contribs
- Natural in models explaining $b \to c\tau\nu$ with $V - A$ operators...
- ...imply large $b \to s\tau\tau$ through $SU(2)_L$, small universal $b \to s\ell\ell$ radiative corrs. in $\mathcal{C}_9^{\rm U}$ (SMEFT, leptoquarks...) [Crivellin et al., Capdevila et al.]







How to go forward ?

How to disentangle/confirm NP scenarios

Hadronic uncertainties

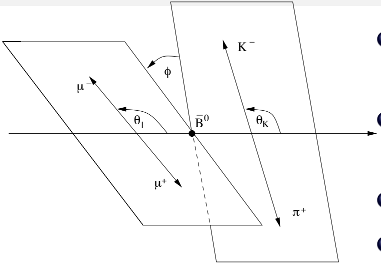
- Different hadronic environments
- Optimised observables designed to cancel hadronic uncertainties

Sensitivity to different NP scenarios

- Separate and probe different polarisation/helicity states
- Translated into different geometries of decays

Exploit angular distributions, if possible with new hadronic states using a few lessons learned from $B \to K^* \mu\mu$

$B \to K^* \ell\ell$: angular analysis



- θ_l: angle of emission between $K^{\star 0}$ and μ^- in di-lepton rest frame
- θ_{K^*}: angle of emission between $K^{\star 0}$ and K^- in di-meson rest frame
- ϕ: angle between the two planes
- q^2: dilepton invariant mass

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \sum_i f_i(\theta_{K^*}, \phi, \theta_l) \times I_i$$

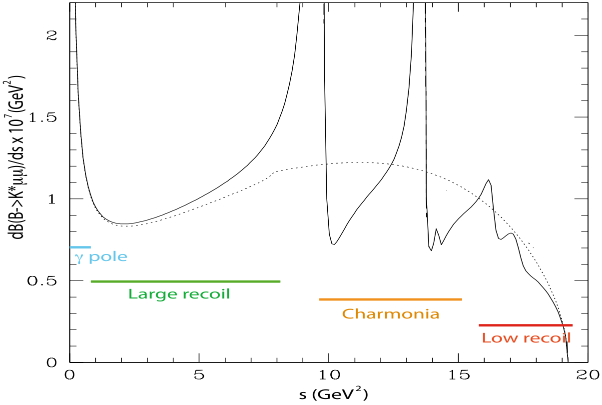
with 12 angular coeffs I_i, interferences between 8 transversity ampl.

- $\perp, ||, 0$ (+ virtual t) polaris. of (real) $K^* \to K\pi$, (virtual) $V^* \to \mu\mu$
- L, R chirality of $\mu\mu$ pair

$A_{\perp,L/R}$, $A_{||,L/R}$, $A_{0,L/R}$, A_t + scalar A_s depend on

- q^2 (lepton pair invariant mass)
- Wilson coefficients $C_7, C_9, C_{10}, C_S, C_P$ (and flipped chiralities)
- $B \to K^*$ form factors $A_{0,1,2}$, V, $T_{1,2,3}$ from $\langle K^* | \mathcal{O}_i | B \rangle$

Kinematic regions for $B \to K^* \mu\mu$



- Very large K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2) γ almost real
- Large K^*-recoil ($q^2 < 9$ GeV^2) energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)
- Charmonium region ($q^2 = m^2_{\psi,\psi'\ldots}$ between 9 and 14 GeV^2)
- Low K^*-recoil ($q^2 > 14$ GeV^2) soft K^* ($E_{K^*} \simeq \Lambda_{QCD}$)

Form factors and optimised observables

7 independent form factors $A_{0,1,2}$, V ($O_{9,10}$) and $T_{1,2,3}$ (O_7), where scales Λ and m_B can be separated in limits of low and large K^* recoil

- Large-recoil limit ($\sqrt{q^2} \sim \Lambda_{QCD} \ll m_B$) [LEET/SCET, QCDF]
  - two soft form factors $\xi_\perp(q^2)$ and $\xi_{||}(q^2)$
  - $O(\alpha_s)$ corr. from hard gluons [computable], $O(\Lambda/m_B)$ [nonpert]

[Charles et al., Beneke, Feldmann]

- Low-recoil limit ($E_{K^*} \sim \Lambda_{QCD} \ll m_B$) [HQET]
  - three soft form factors $f_\perp(q^2), f_{||}(q^2), f_0(q^2)$
  - $O(\alpha_s)$ corr. from hard gluons [computable] and $O(\Lambda/m_B)$ [nonpert]

[Grinstein, Pirjol; Hiller, Bobeth, Van Dyk...]

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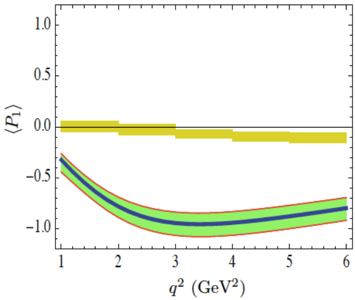
[Grinstein, Pirjol; Hiller, Bobeth, Van Dyk...]

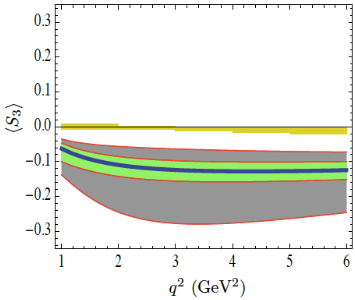
Optimised observables = Obs. where soft form factors cancel at LO

- Large recoil: 6 optimised obs. ($P_1, P_2, P_3, P_4', P_5', P_6'$)
  + 2 form-factor dependent obs. (Γ, A_{FB}, F_L...)
  exhausting information in (partially redundant) angular coeffs I_i
- Low-recoil: similar game with 5 optimised observables

[Matias, Krüger, Mescia, SDG, Virto, Hiller, Bobeth, Dyck, Buras, Altmanshoffer, Straub...]

Sensitivity to form factors





- P_i optimised to have limited sensitivity to form factors
- S_i CP-averaged version of I_i

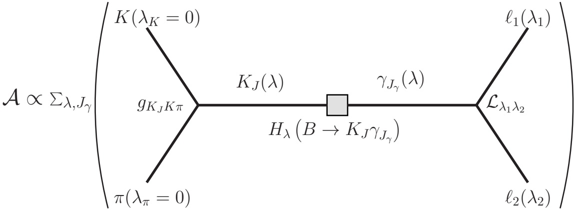
$$P_1 = 2S_3/(1-F_L) \qquad\qquad S_3 = (I_3+\bar{I}_3)/(\Gamma+\bar{\Gamma})$$

different sensivity to form factors for given NP scenario
(form factors from LCSR: green [Ball, Zwicky] vs gray [Khodjamirian et al.])

- P_i exploited with great success in $B \to K^* \mu\mu$ [First part of this talk]
  ...and it can also be used as LFUV probe $Q_i = P_{i\mu} - P_{ie}$

Extending the discussion to other modes

Generalised helicity amplitude analysis



General decay $B_{J_B} \to K_{J_K}(\to K\pi)\gamma_{J_\gamma}(\to \bar{\ell}_1 \ell_2)$ [Gratrex, Hopfer, Zwicky; Dey]

- Linking helicities and angular dependence (D-Wigner fns)

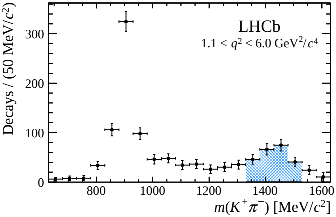
$$\mathcal{A}(A \to B_1 B_2) = \langle \theta, \phi, \lambda_1 \lambda_2 | J_A, M_A \rangle \propto D^{J_A}_{M_A, \lambda_1 - \lambda_2}(\phi, \theta, -\phi) \times \mathcal{A}^{J_A}_{M_A, \lambda_1, \lambda_2}$$

- Decomposition over all helicities (real and virtual) using

$$g^{\mu\nu} = \sum_{\lambda, \lambda' \in \{t, +1, -1, 0\}} \epsilon^\mu(\lambda) \epsilon^{\nu *}(\lambda') G_{\lambda\lambda'} \qquad G_{\lambda\lambda'} = \mathrm{diag}(1, -1, -1, -1)$$

- Helicity conservation in the decay chain, parity arguments. . .
- General expressions recovering eg angular dep for $B \to K(^*)\mu\mu$

$B \to K_J^*(\to K\pi)\ell\ell$ at high $K\pi$ mass

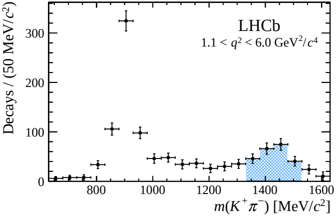


Several resonances at higher $K\pi$ mass and sometimes higher spin

- $K^*(1410), K_0^*(1430), K_2^*(1430)$
- $K^*(1680), K_3^*(1780), K_4^*(2045)$

LHCb measurements around 1430 MeV

$B \to K_J^*(\to K\pi)\ell\ell$ at high $K\pi$ mass

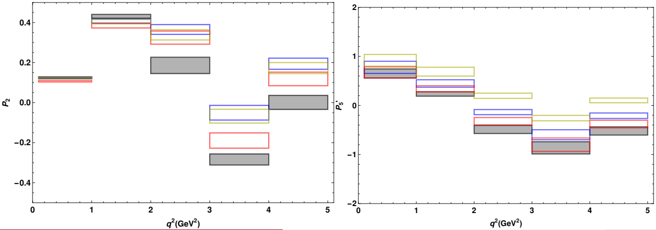


Several resonances at higher $K\pi$ mass and sometimes higher spin

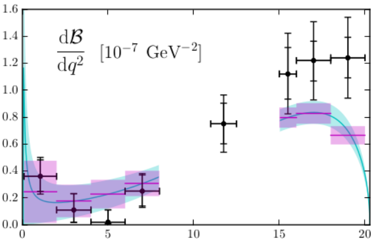
- $K^*(1410), K_0^*(1430), K_2^*(1430)$
- $K^*(1680), K_3^*(1780), K_4^*(2045)$

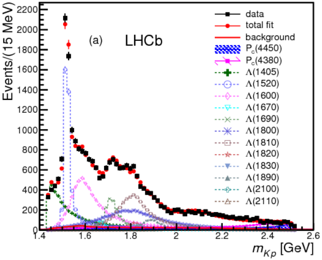
LHCb measurements around 1430 MeV

- Form factors: general, in HQET, in SCET, but few inputs
- $c\bar{c}$ loops: quark-had dual (low recoil), LCSR (large recoil, not yet)
- $B \to K_J\mu\mu$ (BR, F_L, A_{FB}) analysed in [Lü, Wang;Dey]
- $B \to K_2^*\mu\mu$ considered in more detail in [Das, Kindra, Kumar, Mahajan]



- quite similar to $B \to K^*\mu\mu$ if no tensor op
- identification of optim. obs. at large recoil

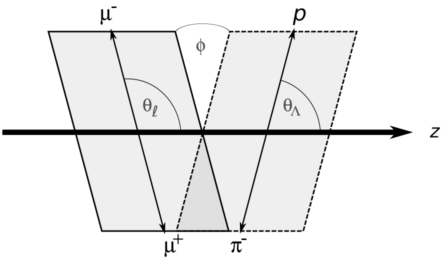




$\Lambda(1115)$
$J^P = 1/2^+$
decays weakly into $p\pi$
BR and low-recoil angular obs
measured by LHCb

$\Lambda^*(1520)$
$J^P = 3/2^-$
decays strongly into pK
not measured by LHCb
peak well seen at $q^2 = m^2_{J/\psi}$

- Form factors: lattice (low recoil) or LCSR (large recoil, not yet)
- $c\bar{c}$ loops: quark-hadron dual (low rec) or LCSR (large rec, not yet)



[Böer, Feldmann, van Dyk; Das]

- 10 form factors from lattice QCD [Detmold et al]
- 8 helicity amplitudes
- 10 angular coefficients
- Weak decay of $\Lambda \to p\pi$, parametrised by asymmetry $\alpha \sim 0.7$
- Polarized Λ_b case in [Blake, Kreps]

$$\frac{d^4\Gamma(\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} K(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

$$\begin{aligned} K = &\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\ &+ \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda \\ &+ \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi \\ &+ \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\cos\phi\,. \end{aligned}$$

$$K_{1cc} = \frac{1}{2}\left[|A^R_{\perp 1}|^2 + |A^R_{||1}|^2 + (R \leftrightarrow L)\right],$$

$$K_{2cc} = +\alpha\mathrm{Re}(A^R_{\perp 1} A^{*R}_{||1}) + (R \leftrightarrow L),$$

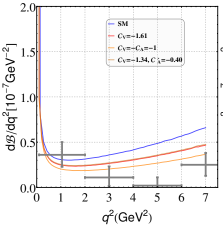
$$\ldots$$

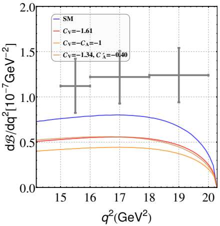
Large recoil (SCET) [Böer, Feldmann, van Dyk; Das]

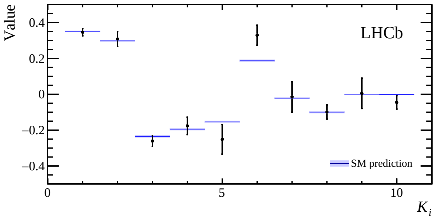
- all form factors are equal or vanish
- any ratio of K is optimised

Low recoil (HQET)

- form factors linear combination of 2 form factors ξ_1 and ξ_2
- one optimised observable $X_1 \equiv K_{1c}/K_{2cc}$
- angular moments available from LHCb
  - largest discrepancy for K_{2c}, 2.6 σ from SM (too large, not physical)
  - for the moment, limited sensitivity to favoured NP scenarios

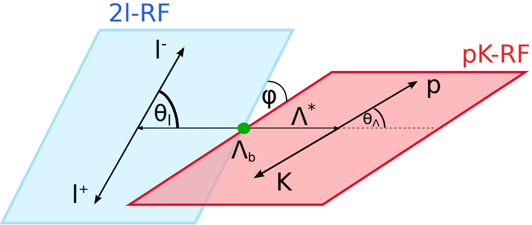






$\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-$

[SDG, Novoa Brunet]



$$\frac{d^4\Gamma(\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} L(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

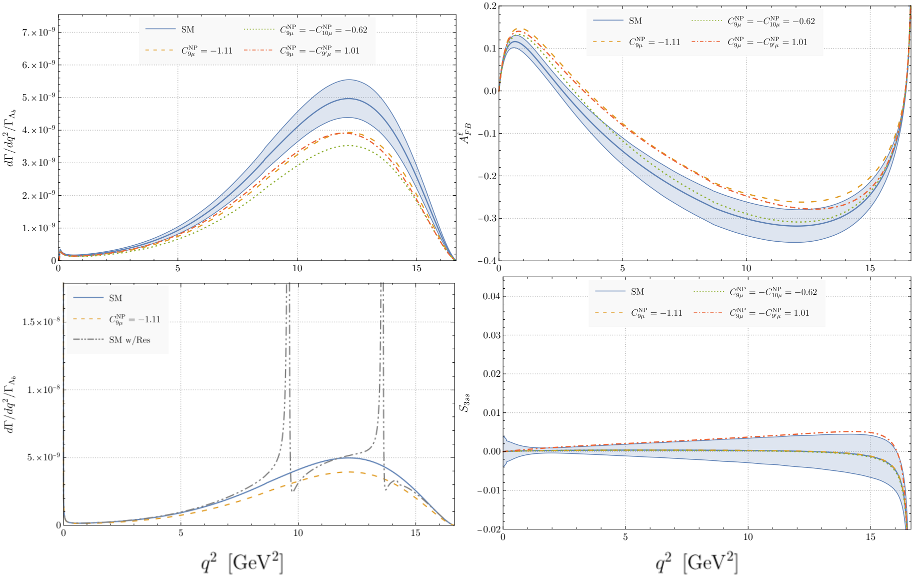
$$\begin{aligned} L = &\cos^2\theta_\Lambda \left(L_{1c}\cos\theta_\ell + L_{1cc}\cos^2\theta_\ell + L_{1ss}\sin^2\theta_\ell\right) \\ &+ \sin^2\theta_\Lambda \left(L_{2c}\cos\theta_\ell + L_{2cc}\cos^2\theta_\ell + L_{2ss}\sin^2\theta_\ell\right) \\ &+ \sin^2\theta_\Lambda \left(L_{3ss}\sin^2\theta_\ell\cos^2\phi + L_{4ss}\sin^2\theta_\ell\sin\phi\cos\phi\right) \\ &+ \sin\theta_\Lambda\cos\theta_\Lambda\cos\phi(L_{5s}\sin\theta_\ell + L_{5sc}\sin\theta_\ell\cos\theta_\ell) \\ &+ \sin\theta_\Lambda\cos\theta_\Lambda\sin\phi(L_{6s}\sin\theta_\ell + L_{6sc}\sin\theta_\ell\cos\theta_\ell) \end{aligned}$$

- 14 form factors (prelim lattice results [Meinel et al])
- 12 helicity amplitudes
- 12 angular coefficients
- SCET: single form factor, any ratio of L optimised
- HQET: two form factors, no non-trivial optim. obs.
- relationships among L's in both limits

$$L_{1c} \propto \left(\mathrm{Re}(A^L_{\perp 1} A^{L*}_{\parallel 1}) - (L \leftrightarrow R)\right),$$

$$L_{3ss} \propto \left(\mathrm{Re}(B^L_{\parallel 1} A^{L*}_{\parallel 1}) - \mathrm{Re}(B^L_{\perp 1} A^{L*}_{\perp 1}) + (L \leftrightarrow R)\right),$$

$\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-$ angular observables



Uncertainties (over)guesstimated, sensitivity to right-handed currents

Outlook

Outlook

Global fits to $b \to s\ell\ell$

- updates on LFUV R_K and R_{K^*}
- many groups, with significant pulls wrt SM for a few scenarios like $\mathcal{C}_9^{\rm NP}$, $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$, $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$
- differences in hierarchies of preferences, related to inputs used
- fit outcome recast in LFUV and LFU NP contributions

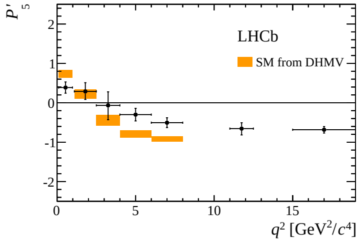
Angular analysis

- additional way to tame hadronic uncertainties and probe NP
- general helicity amplitude analysis + HQET/SCET
- $B \to K_J(\to K\pi)\ell\ell$ at higher mass with many resonances involved
- $\Lambda_b \to \Lambda(\to p\pi)\ell\ell$ and $\Lambda_b \to \Lambda^*(\to pK)\ell\ell$ with different ang distrib

More theoretical and experimental work needed to use these modes and thus sharpen our understanding of the current $b \to s\ell\ell$ anomalies

Focus on P_5'

[SDG, Matias, Ramon, Virto]



$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2+|A_{||}|^2)}}$$

LHCb measurements (crosses) significantly away from SM (boxes) in the large-recoil region

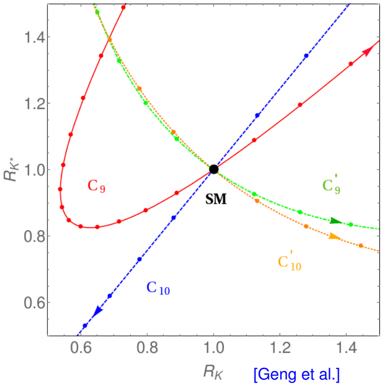
In large recoil limit with no right-handed current, with $\xi_{\perp,||}$ form factors

$$A^L_{\perp,||} \propto \pm\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s) \qquad A^R_{\perp,||} \propto \pm\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{s}\mathcal{C}_7\right]\xi_\perp(s)$$

$$A^L_0 \propto -\left[\mathcal{C}_9 - \mathcal{C}_{10} + 2\frac{m_b}{m_B}\mathcal{C}_7\right]\xi_{||}(s) \qquad A^R_0 \propto -\left[\mathcal{C}_9 + \mathcal{C}_{10} + 2\frac{m_b}{m_B}\mathcal{C}_7\right]\xi_{||}(s)$$

- In SM, $\mathcal{C}_9 \simeq -\mathcal{C}_{10}$ leading to $|A^R_{\perp,||}| \ll |A^L_{\perp,||}|$
- If $\mathcal{C}_9^{\mathrm{NP}} < 0$, $|A^R_{0,||,\perp}|$ increases, $|A^L_{0,||,\perp}|$ decreases, $|P_5'|$ gets lower
- For P_4', sum with $A_{0,||}$, so not sensitive to $\mathcal{C}_9$ in the same way

R_K and R_{K^*} in EFT

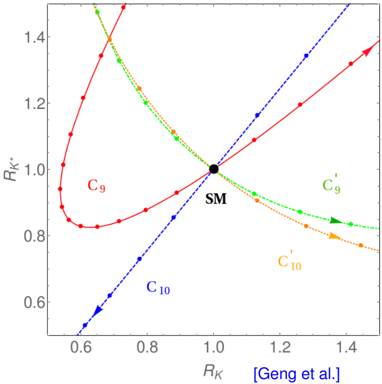


[Geng et al.]

- R_K: $Br(B \to K\ell\ell)$ involves one amplitude depending on
  - 3 $B \to K$ form factors (one suppr by m_ℓ^2/q^2, one by $\mathcal{C}_7$)
  - charmonium contributions (process-dependent but LFU)
  - $\mathcal{C}_9 + \mathcal{C}_{9'}$ and $\mathcal{C}_{10} + \mathcal{C}_{10'}$

$\Longrightarrow$hadronic contrib cancel for R_K, very accurate for all q^2 and $\mathcal{C}_i$

R_K and R_{K^*} in EFT



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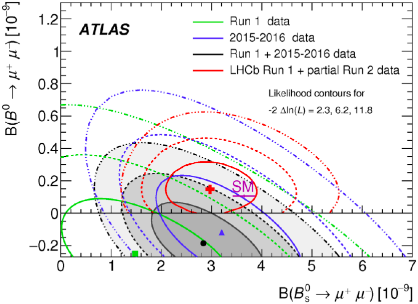
$\Longrightarrow$hadronic contrib cancel for R_K, very accurate for all q^2 and $\mathcal{C}_i$

- R_{K^*}: $Br(B \to K^*\ell\ell)$ involve several helicity ampl depending on
  - 7 $B \to K^*$ form factors (one suppressed by m_ℓ^2/q^2)
  - charmonium contributions (process-dependent but LFU)
  - depending on helicity amplitude: $\mathcal{C}_9 \pm \mathcal{C}_{9'}$ and $\mathcal{C}_{10} \pm \mathcal{C}_{10'}$

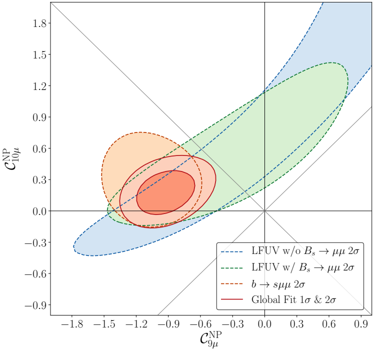
$\Longrightarrow$hadronic contrib cancel for R_{K^*} in SM because right-handed helicities suppressed but less efficient with NP (slightly larger unc)

$B_s \to \mu\mu$ (1)

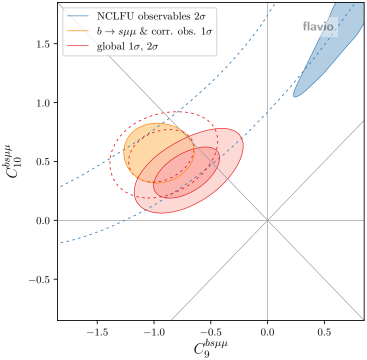


- Recent results increasing a bit the discrepancy between SM and (a tad too low) exp average
  - ATLAS 2018 $Br(B_s \to \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$
  - LHCb 2017 $Br(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
  - CMS 2013 $Br(B_s \to \mu\mu) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
- Depending on the fit group
  - Different methods of averaging
  - Different inputs for f_{B_s} and higher-order (EW, QCD) corrections
  - Discrepancy wrt SM from 1.5 σ ot 2 σ

$B_s \to \mu\mu$ (2)



[Algueró et al.]



[Aebischer et al.]

- [Arbey et al.] $B_s \to \mu\mu$ no major role in incoherence of the observables
- [Algueró et al.] Using 1D or 2D exp average for $B_s \to \mu\mu$ does not change significantly the hierarchy of NP scenarios

Other interesting NP scenarios

2017	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.03	-1.12	+0.31	+0.03	+0.38	+0.02
1 σ	$[-0.01, +0.05]$	$[-1.34, -0.88]$	$[+0.10, +0.57]$	$[+0.00, +0.06]$	$[-0.17, +1.04]$	$[-0.28, +0.36]$
2 σ	$[-0.03, +0.07]$	$[-1.54, -0.63]$	$[-0.08, +0.84]$	$[-0.02, +0.08]$	$[-0.59, +1.58]$	$[-0.54, +0.68]$

- 6D scenario (SM + chirally flipped in $b \to s\mu\mu$) in 2017

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Bfp	+0.01	-1.10	+0.15	+0.02	+0.36	-0.16
1 σ	$[-0.01, +0.05]$	$[-1.28, -0.90]$	$[-0.00, +0.36]$	$[-0.00, +0.05]$	$[-0.14, +0.87]$	$[-0.39, +0.13]$
2 σ	$[-0.03, +0.06]$	$[-1.44, -0.68]$	$[-0.12, +0.56]$	$[-0.02, +0.06]$	$[-0.49, +1.23]$	$[-0.58, +0.33]$

- 6D scenario (SM + chirally flipped in $b \to s\mu\mu$) in 2017 and 2019
  - $\mathcal{C}_{9\mu}^{\rm NP} < 0$ needed, $\mathcal{C}_{9'\mu}^{\rm NP} > 0$, $\mathcal{C}_{10\mu}^{\rm NP} > 0$, $\mathcal{C}_{10'\mu}^{\rm NP} < 0$ favoured
  - SM pull 5.1 σ (5.0 σ in 2017)

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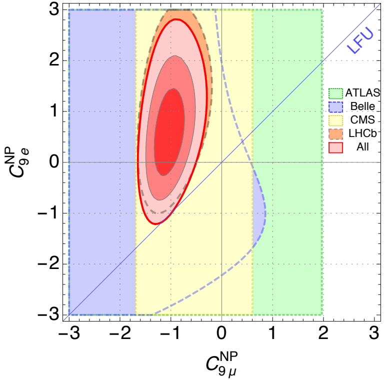

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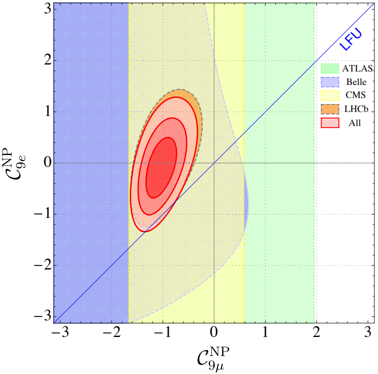

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  - Less need for NP in $b \to see$
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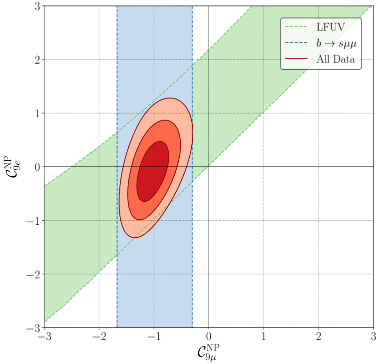

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An EFT connection

Connect $b \to c\tau\nu$ and $b \to s\ell\ell$ within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

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- Two operators with left-handed doublets (*ijkl* generation indices)

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i \gamma_\mu Q_j][\bar{L}_k \gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i \gamma_\mu \vec{\sigma} Q_j][\bar{L}_k \gamma^\mu \vec{\sigma} L_l]$$

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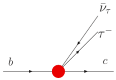

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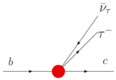
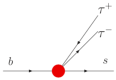
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K(^*)\nu\nu$, Z decays, direct production in $\tau\tau$





An EFT connection

Connect $b \to c\tau\nu$ and $b \to s\ell\ell$ within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

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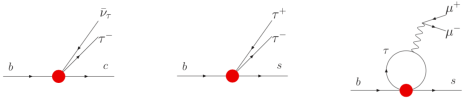
  - Avoids bounds from $B \to K(^*)\nu\nu$, Z decays, direct production in $\tau\tau$
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$



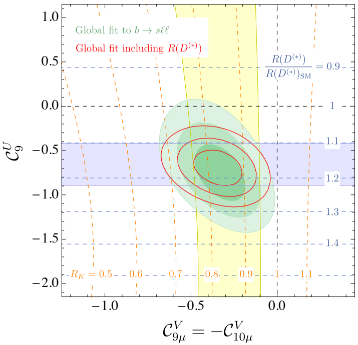
An EFT connection: anomaly constraints

Scenario LFU + LFUV NP

- $\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$ from small $\mathcal{O}_{2322}$ $[b \to s\mu\mu]$
- $\mathcal{C}^{\rm U}_{9}$ from radiative corr from large $\mathcal{O}_{2333}$ $[b \to c\tau\nu$ and $b \to s\mu\mu]$

Generic flavour structure and NP at the scale Λ yields

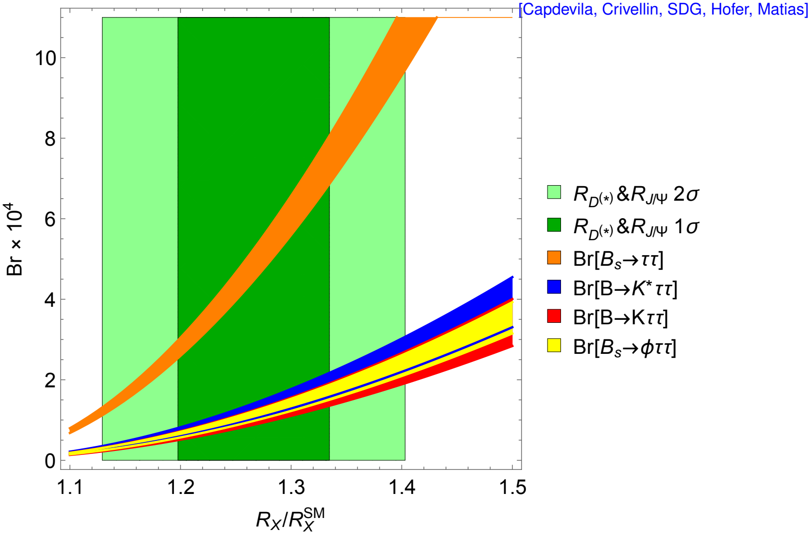
$$\mathcal{C}^{\rm U}_{9} \approx 7.5 \left(1 - \sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)};\rm SM}}}\right) \times \left(1 + \frac{\log(\Lambda^2/(1\,\mathrm{TeV}^2))}{10.5}\right)$$



$\Longrightarrow$ Agreement with (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV

An EFT connection: enhancement of $b \to s\tau\tau$

[Capdevila, Crivellin, SDG, Hofer, Matias]

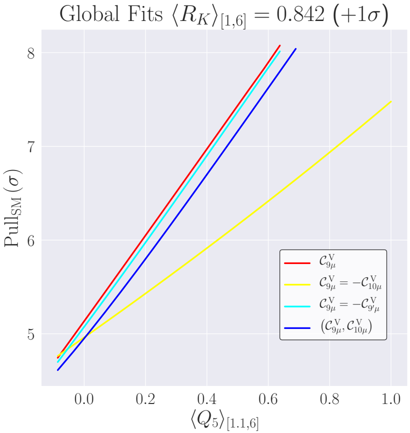


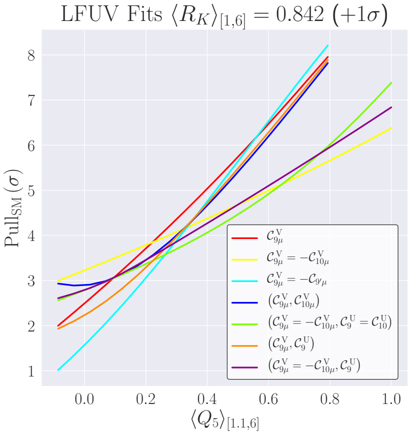
$$\mathrm{Br}(B_s \to \tau^+\tau^-)_{\mathrm{LHCb}} \leq 6.8\times 10^{-3}, \quad \mathrm{Br}(B \to K\tau^+\tau^-)_{\mathrm{Babar}} \leq 2.25\times 10^{-3}$$

Disentangling scenarios: Q_5'

- $Q_5 = P_5^{\mu\prime} - P_5^{e\prime}$ interesting observable to disentangle
  - $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$ from others NP scenarios in $b \to s\mu\mu$
  - classes of scenarios allowing for LFU contributions

[Alguero, Capdevila, SDG, Masjuan, Matias]





Endpoint behaviours

When $q^2 \to 0$

- Never reached in $b \to s\ell\ell$ as $q^2 \geq 4m_\ell^2$, but in $b \to s\gamma$ decay
$$BR(B_{J_B} \to K_{J_K}\gamma) \propto \lim_{q^2 \to 0} \left(q^2 \times \frac{d\Gamma(B_{J_B} \to K_{J_K}\ell\ell)}{dq^2} \right)$$
- Only ± 1 photon polarisations contribute + helicity conservation
- Constraints on behaviour of helicity amplitudes at $q^2 \to 0$ (pole for transverse amplitudes in $B \to K^*\ell\ell$, no pole for $B \to K\ell\ell$)

When $q^2 \to (m_{B_{J_B}} - m_{K_{J_K}})^2$ [Hiller, Zwicky]

- 3-momenta are zero or opposite leading to isotropy in obs.
- manifest by additional syms. among helicity amplitudes
- $B \to K^*\ell\ell$: $H = 0$ for scalar ops, $H_+ = H_- = -H_0$ and $H_t = 0$ for vector ops... leading to relations among I_i, $F_L = 1/3$, $A_{FB} = 0$...
- possible generalisations for K and for higher-spin K-resonances