Theoretical perspectives

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Beyond Flavour Anomalies, 26/4/22

An interpretation of the organisers' request

First of all, regrets for not being in Durham
(I missed my flight due to the dreadful chaos that is called Orly)

- Long-standing $b \to s\ell\ell$ anomalies (10 years next year !)
- Different approaches for the fits yields a very consistent picture
- More data awaited from LHCb, Belle II, CMS, ATLAS...
- Starting discussions for the workshop

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Unlikely : "perspectives"

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Unlikely : "perspectives"

Likely : "ramblings"

Recent additions to $b \to s\ell\ell$

2019-2020

- LHCb : $R_K^{[1,1.6]}$ and angular analysis of $B \to K^* \mu\mu$
- Belle
  - R_K in [1,6] and above 14.18
  - R_{K*} in [0.015,1.1], [1,1.6], [15,19]

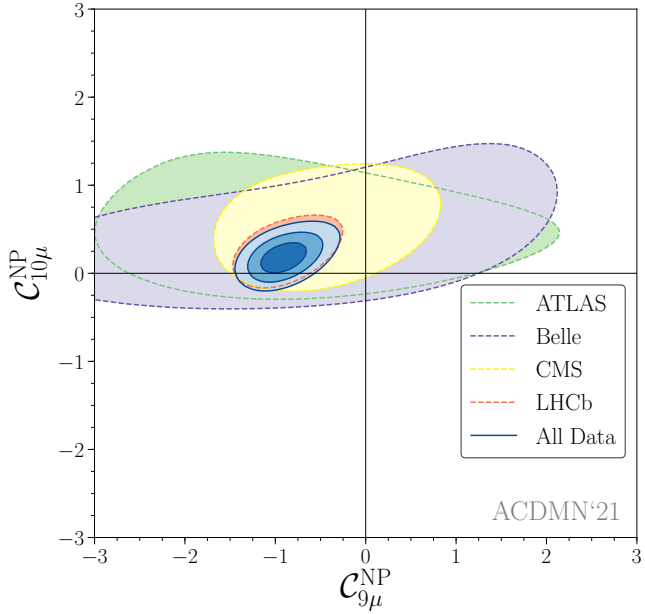
2021-2022

- LHCb
  - $R_K^{[1.1,6]}$ with deviation from SM above 3 σ
  - $R_{K_S}^{[1.1,6]}$ and $R_{K^{*+}}^{[0.045,6]}$ consistent with SM at 2σ but below 1
  - $Br(B_s \to \mu\mu)$ SM-like
  - angular analysis and Br for $B_s \to \phi\mu\mu$
  - angular analysis for $B \to K^* ee$ at low q^2
  - angular analysis for $B^+ \to K^{*+}\mu\mu$
- CMS
  - A_{FB} and F_L for $B^+ \to K^{*+}\mu\mu$
  - angular analysis for $B^+ \to K^+\mu\mu$
- Belle: R_K in bins and Br for $B \to K\mu\mu$ (isospin asymmetry ?)
- Belle II: R_{K^*} in [1.1,6.0] (below 1) and Br for $B \to K^*\mu\mu$

Some favoured scenarios

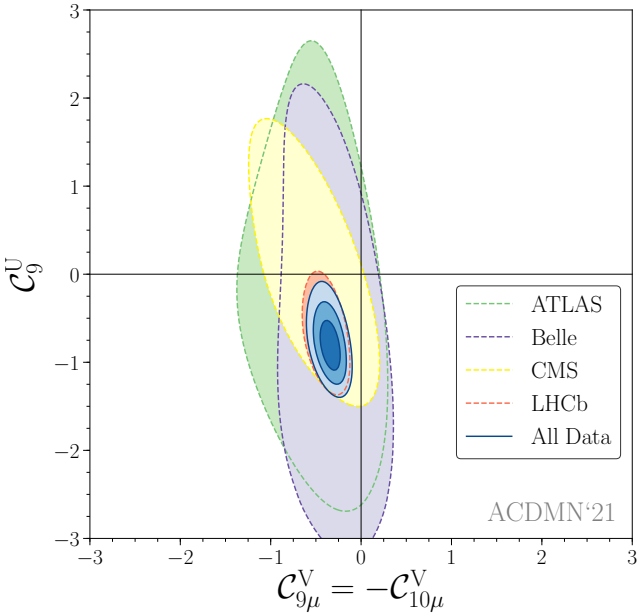
NP in $b \to s\mu\mu$ only

- $\mathcal{C}_{9\mu}^{NP}$
- $\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10\mu}^{NP}$
- and in particular $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$
- $\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9'\mu}^{NP} = -\mathcal{C}_{10'\mu}^{NP}$



NP in $b \to see$ and $b \to s\mu\mu$:
$\mathcal{C}_{ie}^{NP} = \mathcal{C}_i^U \qquad \mathcal{C}_{i\mu}^{NP} = \mathcal{C}_i^U + \mathcal{C}_i^V$

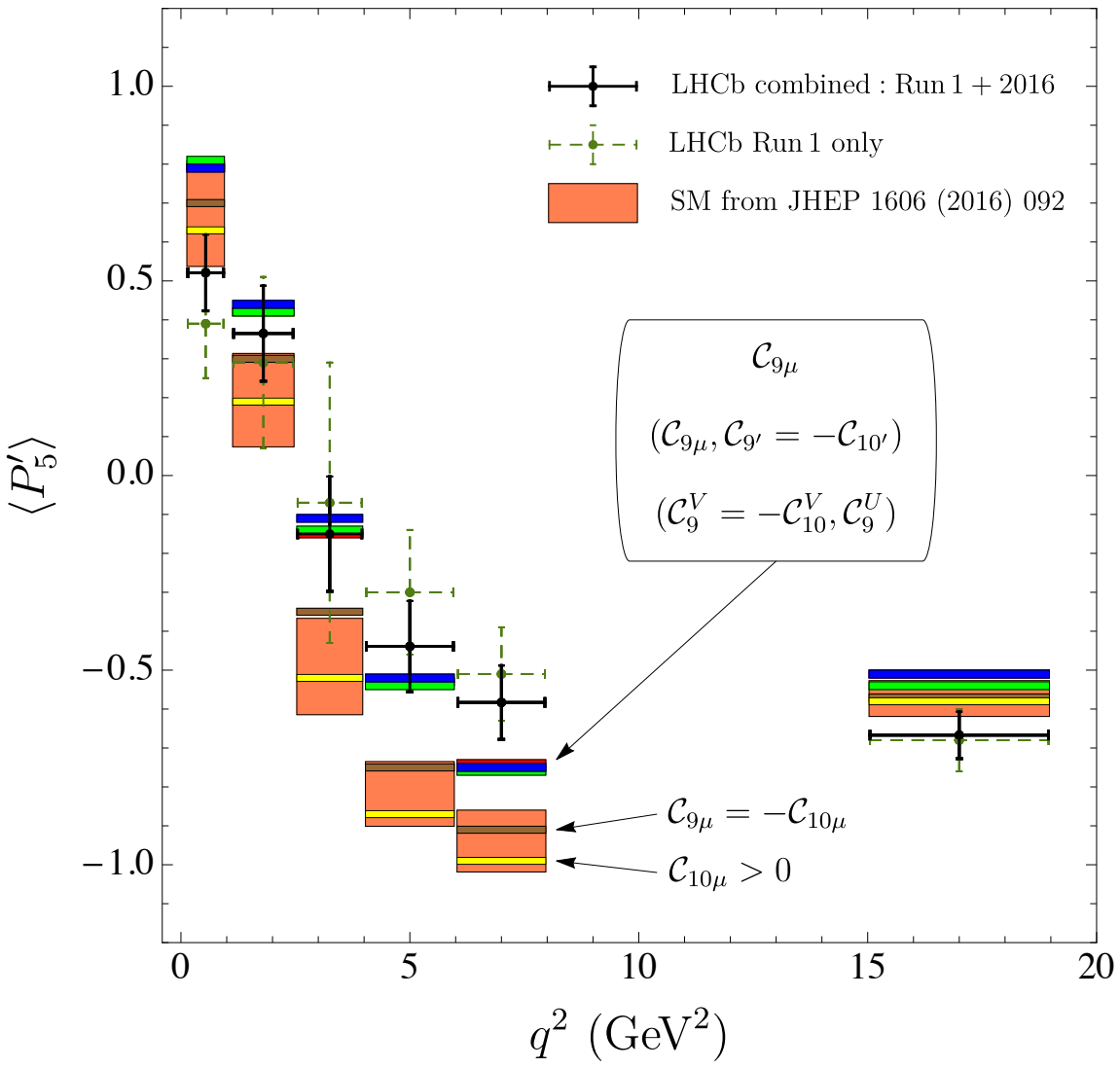
- $\mathcal{C}_9^V = -\mathcal{C}_{10}^V, \mathcal{C}_9^U$
- $\mathcal{C}_9^V = -\mathcal{C}_{10}^V, \mathcal{C}_9^U = \mathcal{C}_{10}^U$
- $\mathcal{C}_9^V, \mathcal{C}_{10}^U$
- $\mathcal{C}_9^V, \mathcal{C}_{10'}^U$



Consistency of scenarios

- Increase of significance for some scenarios, but same hierarchies

Consistency of scenarios



- Increase of significance for some scenarios, but same hierarchies
- Reduction of the internal tensions of the fit
  - for P_5'

for some of the scenarios

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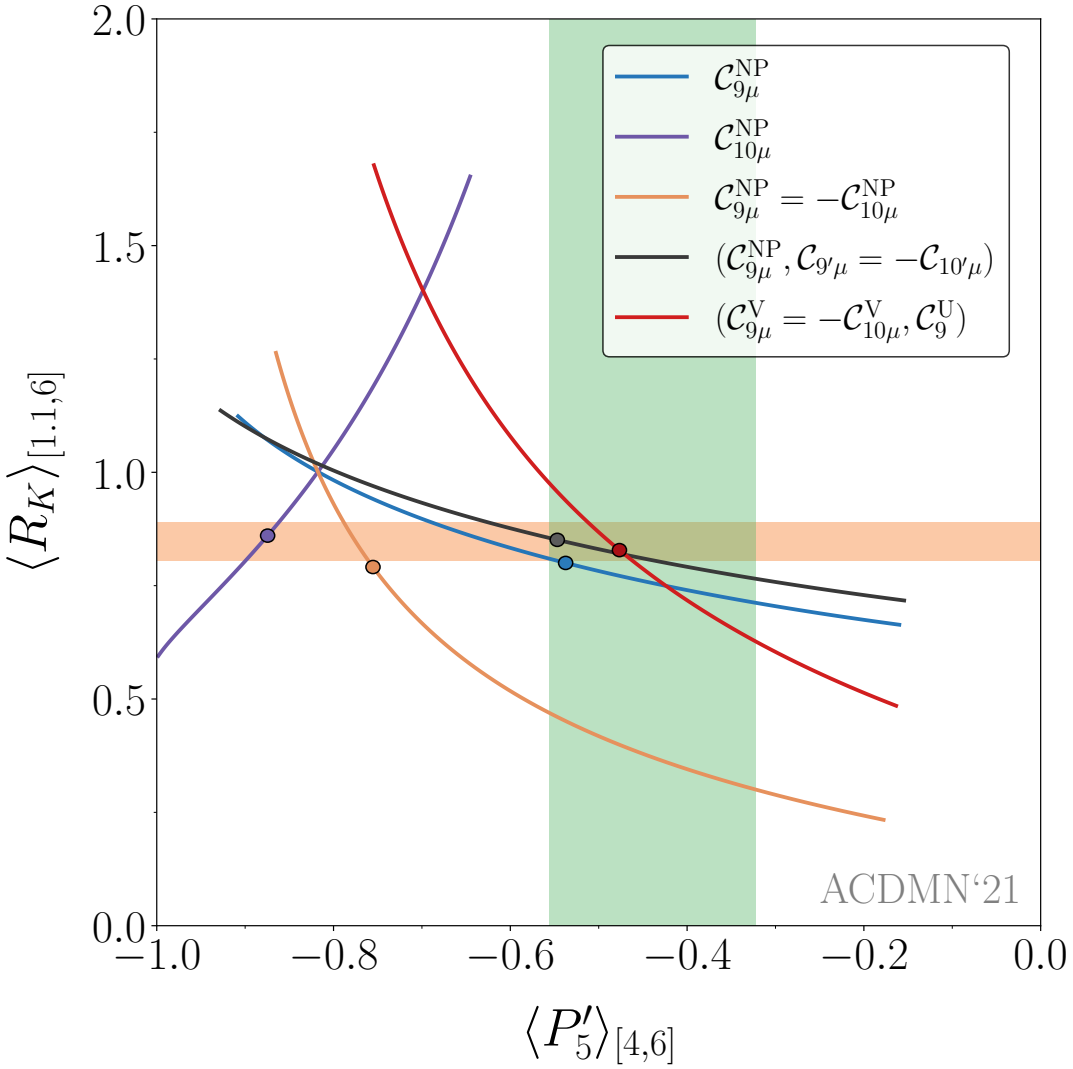

- Increase of significance for some scenarios, but same hierarchies
- Reduction of the internal tensions of the fit
  - for P_5'
  - between P_5' and R_K

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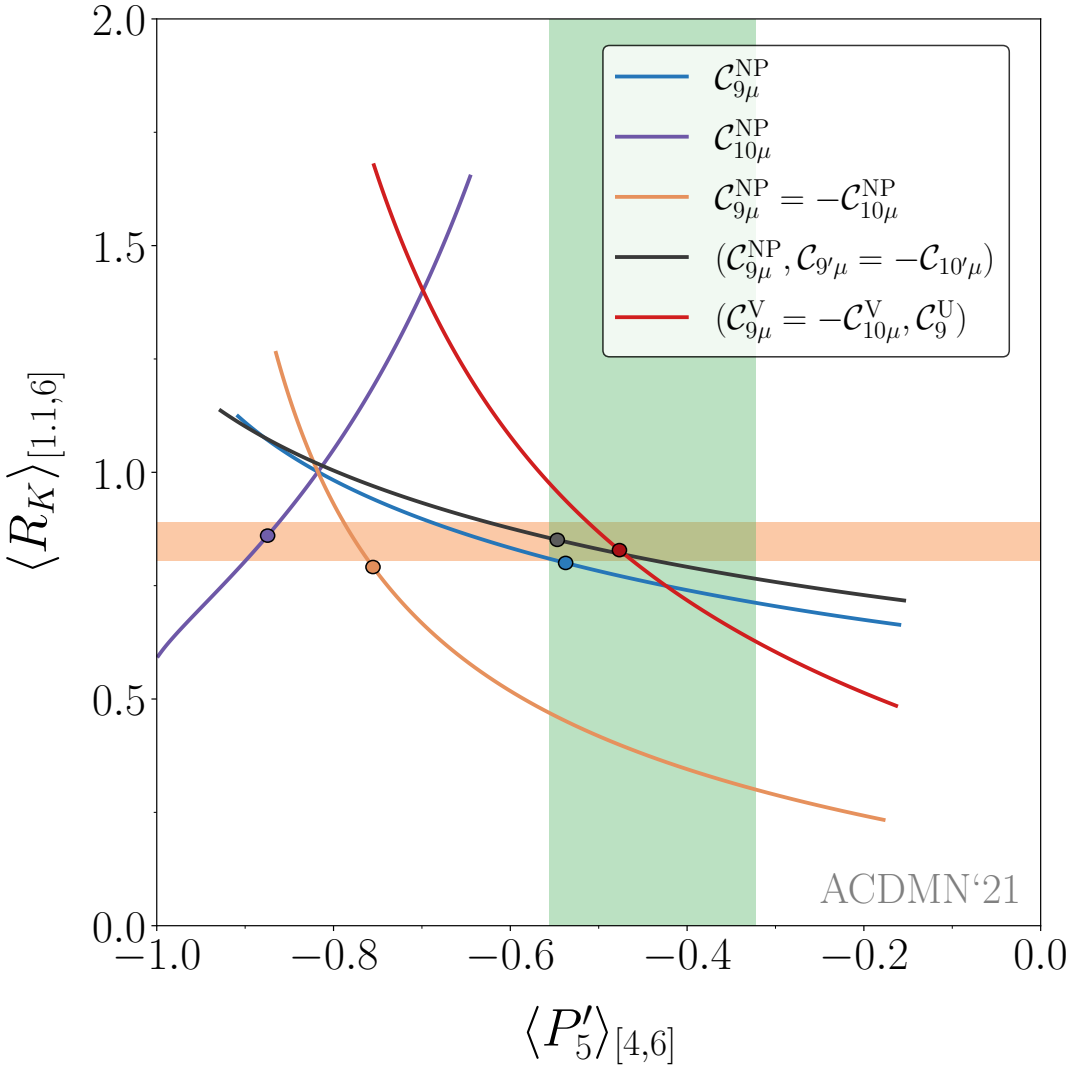

- Increase of significance for some scenarios, but same hierarchies
- Reduction of the internal tensions of the fit
  - for P_5'
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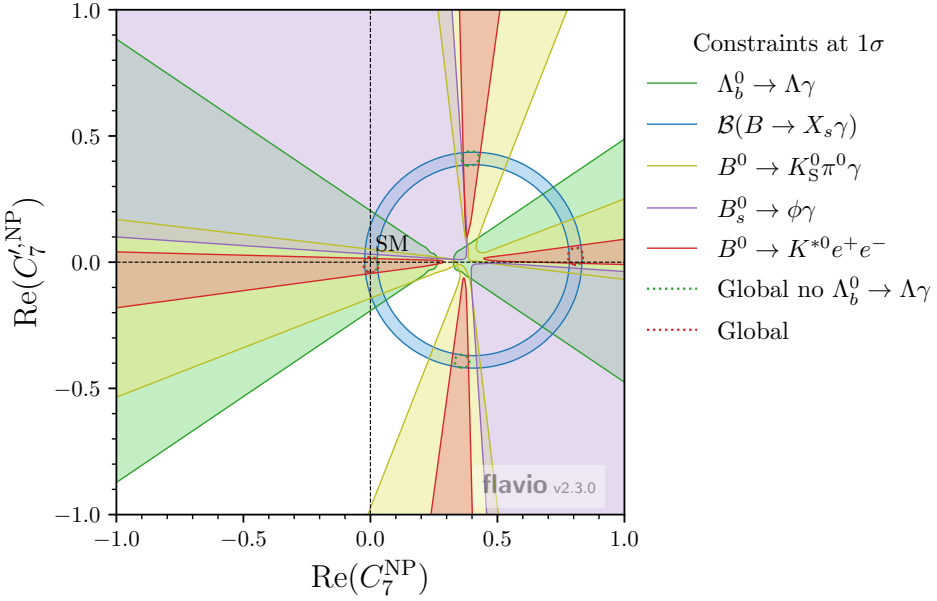
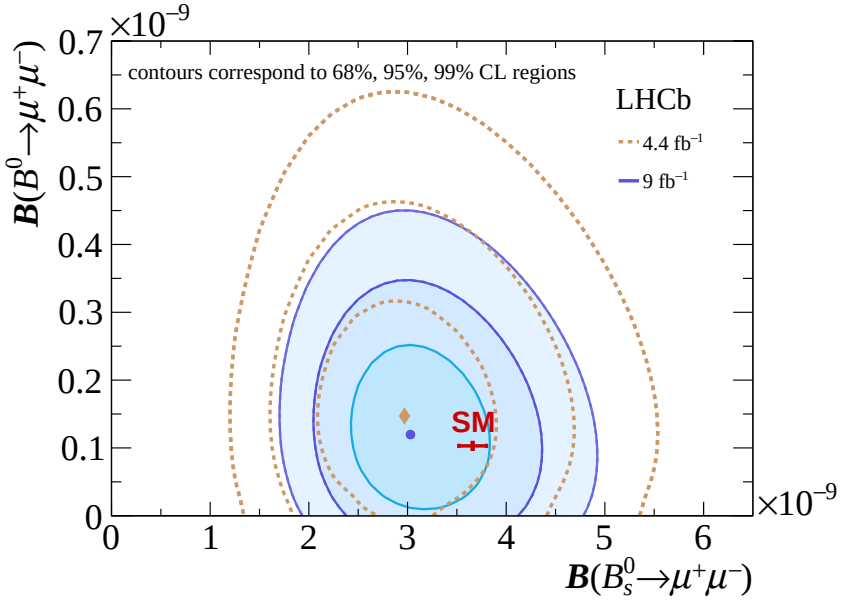
  for some of the scenarios
- p-value of SM decreased

Non-SM operators





Most of the scenarios involve the operators already present in the SM

- Right-handed currents
  - Possibility of $\mathcal{C}_{9'}$ or $\mathcal{C}_{10'}$ in some of the fits (but subleading)
  - But no need for significant $\mathcal{C}_{7'}$: most recently from γ pol in $\Lambda_b \to \Lambda\gamma$
- Scalar/pseudoscalar contributions
  - $B_s \to \mu\mu$ (and $B_d \to \mu\mu$) rather SM-like according to LHCb
  - Effective lifetime not measured precisely enough to give more info
  - $\mathcal{C}_{S,P}$ and $\mathcal{C}_{S',P'}$ if compensation, but not needed

Two sources of hadronic uncertainties

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

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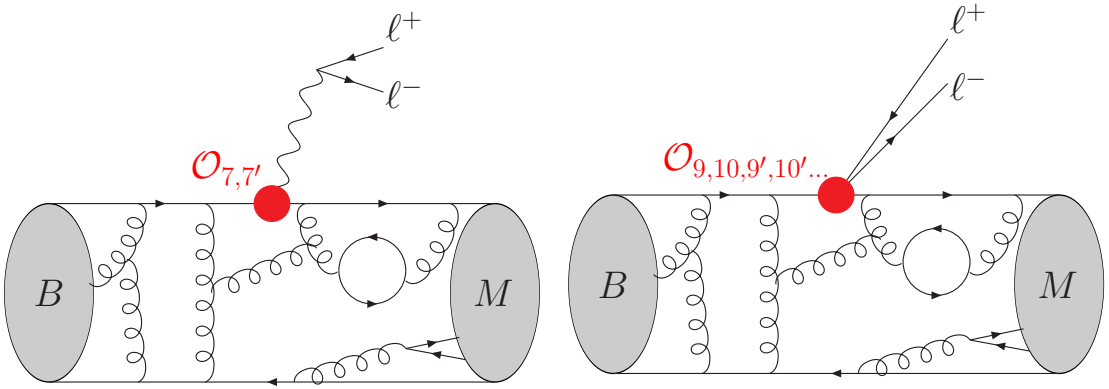

Form factors (local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

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

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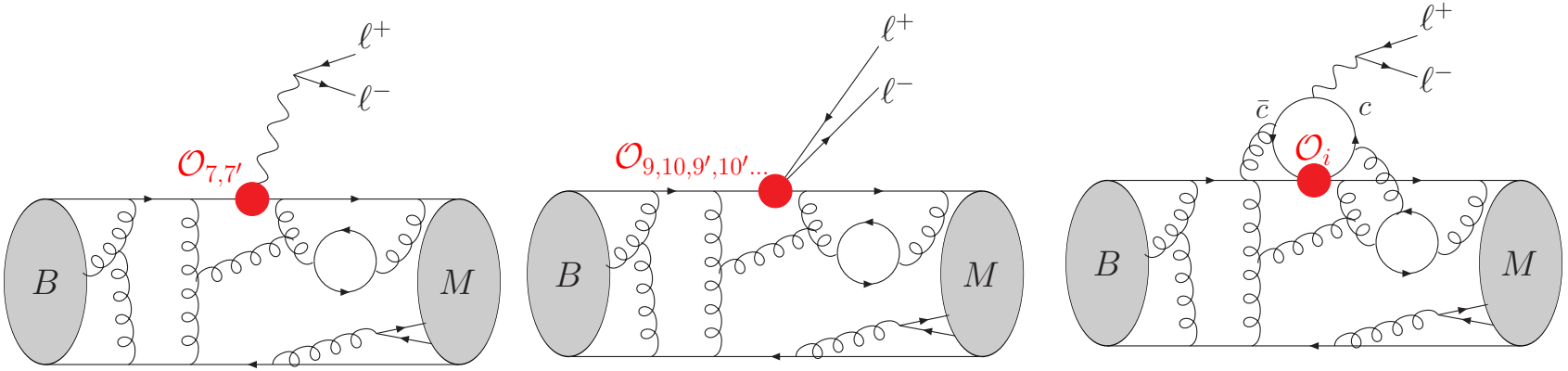

Form factors (local) Charm loop (non-local)

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

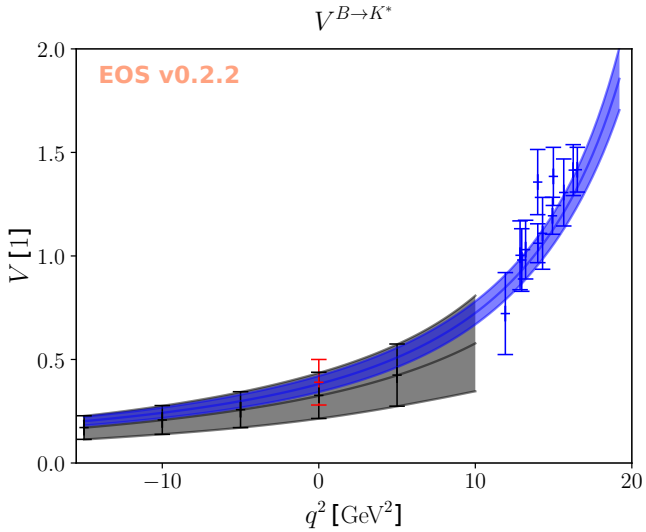
T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

Hadronic uncertainties: form factors

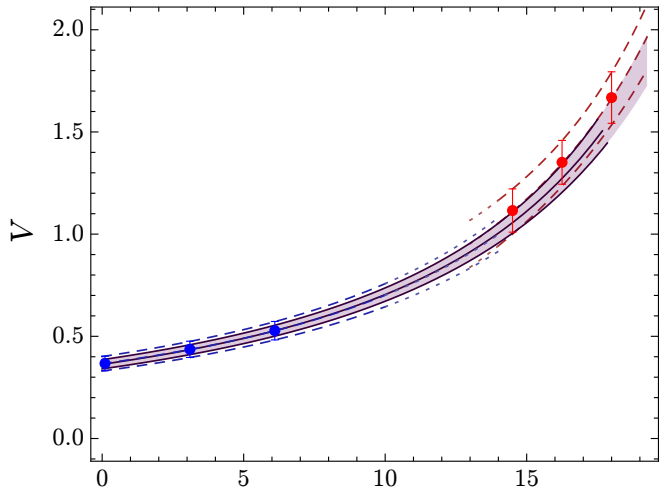
3 form factors for K, 7 form factors for K^* and ϕ

- 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 from
  - direct determination and/or combined fit to low and large recoils
  - EFT with $m_b \to \infty$ + $O(\alpha_s)$ + $O(1/m_b)$

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

- optimised observables P_i to reduce impact of form factor unc

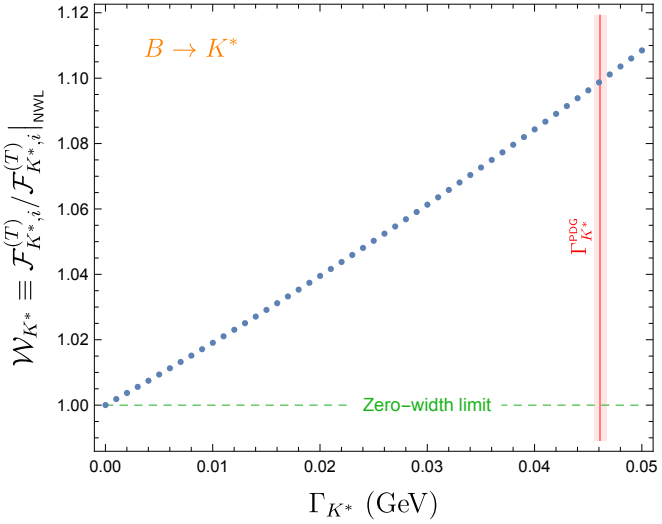
Questions on form factors

Systematics of the methods

- Uncertainty B-meson LCSR 3 times larger than light-meson LCSR
- One lattice result for $B \to K^*$, $B_s \to \phi$, two for $B \to K$ (2013-15), only for a limited large-q^2 region, any update ?
- Combination with lattice QCD data: statistical combination decreasing the uncertainties + systematics correlation ?
- Lattice for the normalisation and LCSR for the q^2 dependence ?

Narrow-width approx for form factors

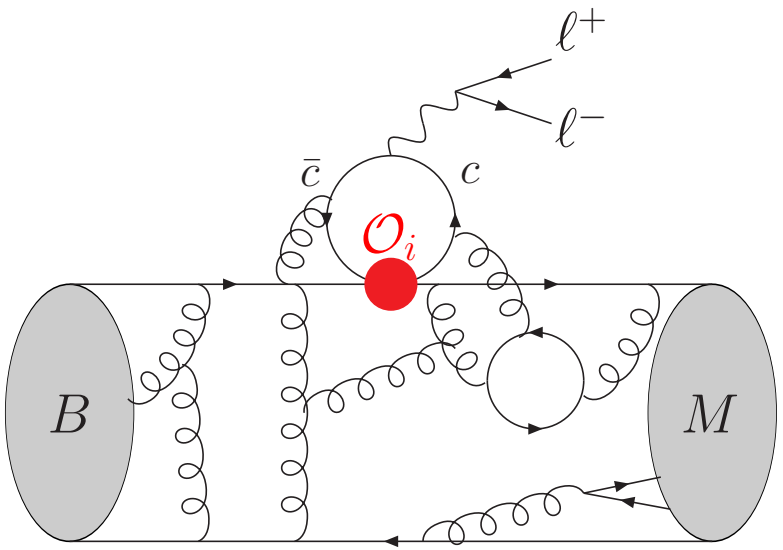
- Not problem for K or ϕ, but for K^* ?
- Lattice : Not much known (a few % ?)
- K^*-meson LCSR: not able to catch the effect (need to use $K\pi$ DAs)
- B-meson LCSR: universal 10% effect, increasing SM discrepancy



[Khodjamirian, SDG, Virto]

Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.
- quark-hadron duality approx at large q^2 (syst of few %)



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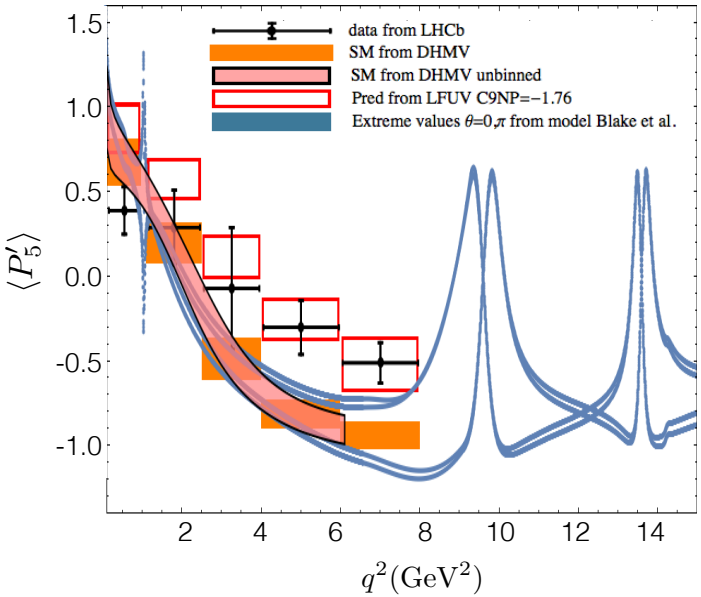

Several approaches agree at low-q^2

- LCSR estimates [Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, Van Dyk]
- order of magnitude estimate for the fits (LCSR or Λ/m_b)

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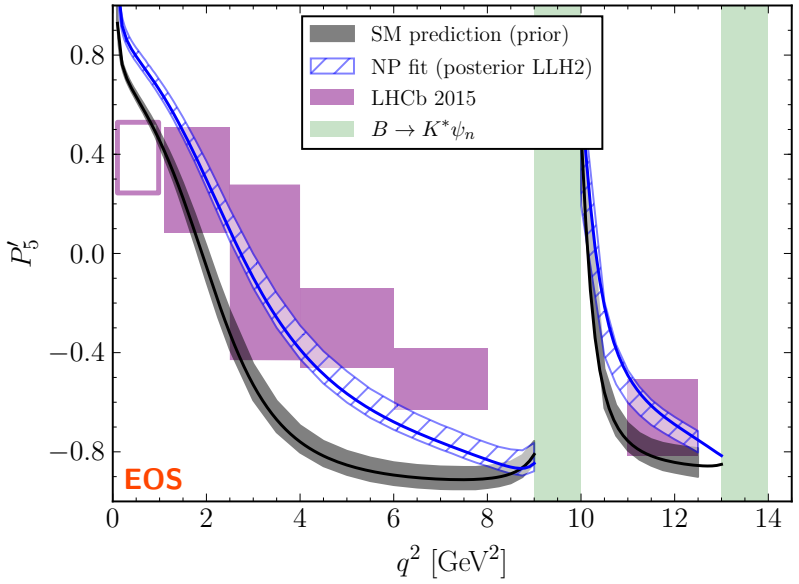

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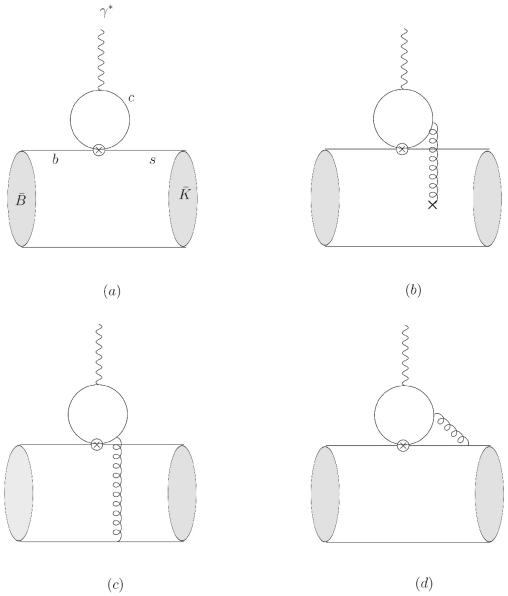
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- fit of q^2-parametrisation to the data

  [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Capdevila, SDG, Hofer, Matias]
- dispersive repr/z-exp + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

Questions on charm loops



Estimate of $c\bar{c}$ contribution at $q^2 < 0$

- Several $c\bar{c}$ contributions, with hard (QCD fact) and soft gluons (LCSR)
- Soft-gluon correction from LCSR smaller than thought, due to cancellations among three-particle contribs and model inputs

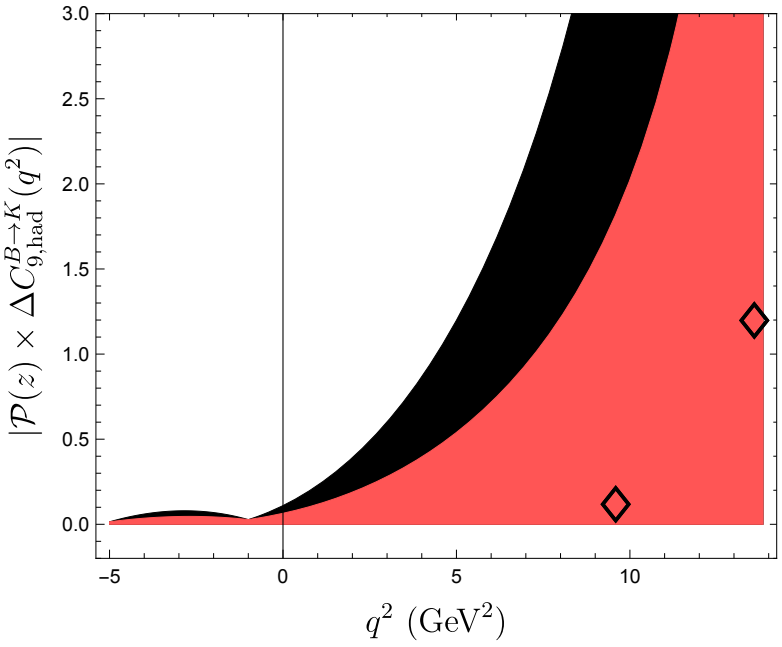
[Khodjamirian et al; Gubernari, Van Dyk, Virto]

Extrapolate at higher q^2 or interpolate up to charmonium ?

- polynomial in q^2
- dispersion relation [Khodjarmiran et al]
- z-exp with bounds on coeffs

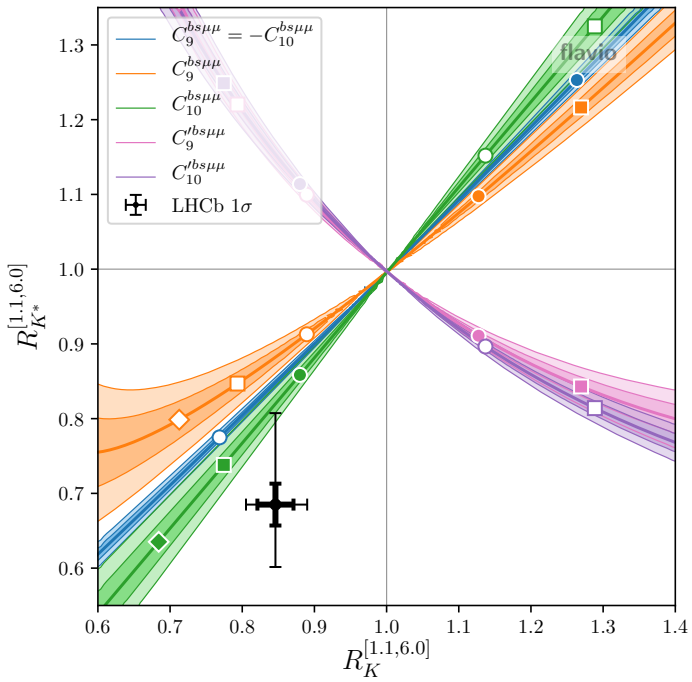
[Bobeth, Chrzaszcz, van Dyk, Virto, Gubernari, Reboud]

$\Longrightarrow$Impact of parametrisations with fewer theoretical inputs ?



LFU fits: $R_X + B_s \to \mu\mu + b \to s\gamma$

[Altmanshoffer, Stangl]



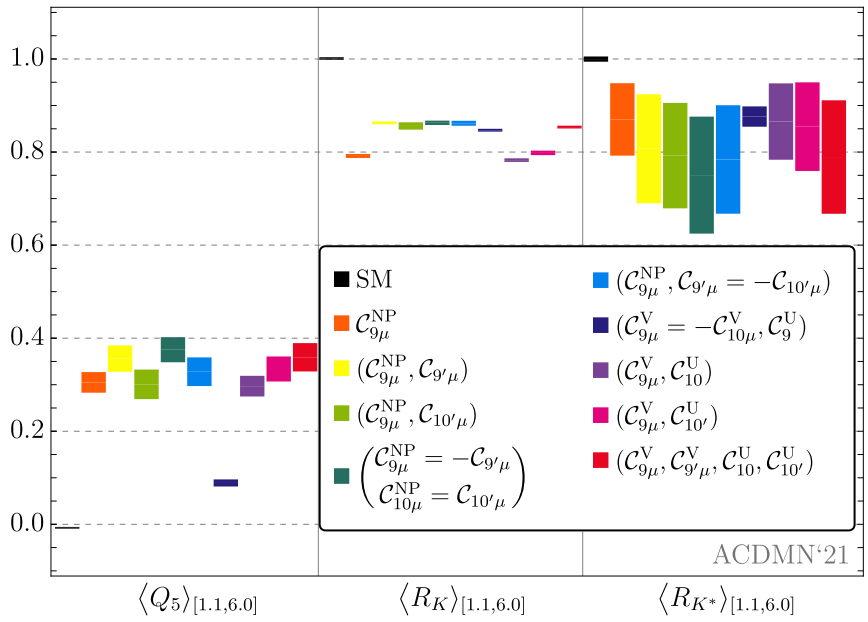
- Still some residual sensitivity to hadronic uncertainties, especially modes with several helicity amplitudes ($B \to K^* \ell\ell$, $B_s \to \phi\ell\ell$)
- $c\bar{c}$ loops do not cancel in R_X, entering NP interpretation: bin- and process-dep addition to $\mathcal{C}_9$, e.g. in $\mathcal{C}_L^{SM}$ in linearised $O(m_\ell, \mathcal{C}_7, \mathcal{C}_{NP})$ expression

$$R_X \simeq 1 + \mathrm{Re}\left[2\frac{\mathcal{C}_L^\mu - \mathcal{C}_L^e}{\mathcal{C}_L^{SM}} + \eta_X \frac{\mathcal{C}_{L'}^\mu - \mathcal{C}_{L'}^e}{\mathcal{C}_L^{SM}}\right] \text{ with } \mathcal{C}_{L(')} = \mathcal{C}_{9(')} - \mathcal{C}_{10(')}$$

[Hiller, Schmaltz; Isidori, Lancierini, Mathad, Owen, Serra, Coutinho]

- Models for these contributions: effective ndof for LFU fits lower than naive number (echo of global CKM fits) [Isidori et al]
- Interpretation of $\chi^2_{\min}$ with naive ndof actually conservative

Well-trodden paths ?



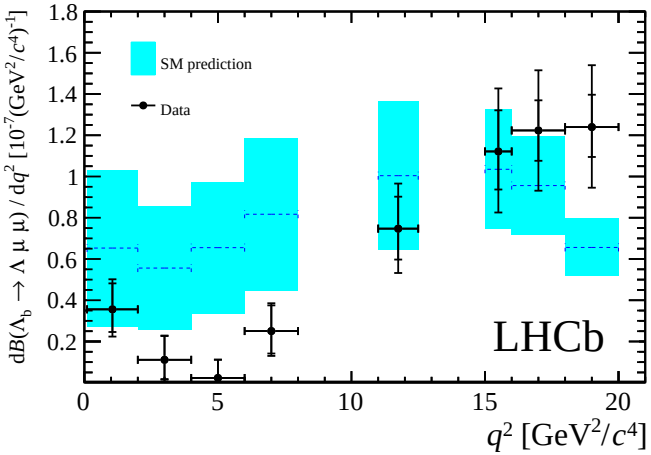
- R_K, R_{K^*} at high q^2: completely different systematics, similar predictions for all scenarios (around 0.75)
- R_ϕ: no issue with final state width, consistency check
- Q_5: distinguish $\mathcal{C}_9^V = -\mathcal{C}_{10}^V, \mathcal{C}_9^U$ from other scenarios

- Anything LFU ratio with several intermediate states (like R_{pK}) complicated : interferences, form factors, or sum rule analysis...
- S-wave: data available from the differential decay rate
  - if info on scalar form factors obtained
  - or reexpressed in terms of P-wave observables

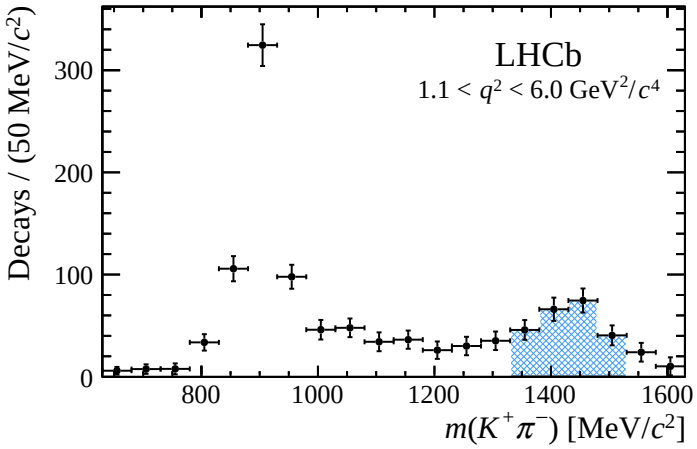
[Algueró, Alvarez-Cartelle, Matias, Patel, Petridis; Khodjamirian, SDG, Vos, Virto]

More modes

$d\Gamma(\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-)/dq^2$



$B \to K\pi\mu\mu$ around $K^*(1430)$



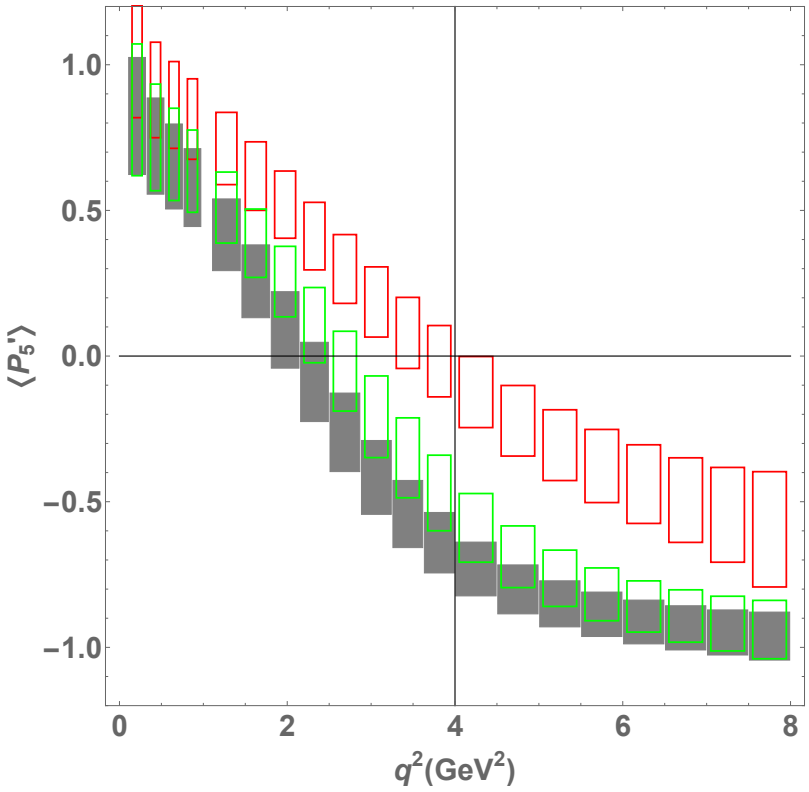
Different info and systematics in angular distributions known for

- $B \to K^{*J}(\to K\pi)\ell^+\ell^-$ [Lu, Wang; Gratrex, Hopfer, Zwicky; Dey; Das, Kindra, Kumar, Mahajan]
- $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ [Böer, Feldmann, van Dyk; Detmold, Meinel; Das; Blake, Kreps]
- $\Lambda_b \to \Lambda(1520)(\to NK)\ell^+\ell^-$ [Amhis, SDG, Marin Benito, Novoa Brunet, Schune; Das, Das]

- Form factors poorly known [Detmold, Lin, Meinel, Wingate, Rendon; SDG, Khodjamirian, Virto]
- Large recoil: factorisation, $c\bar{c}$ contributions
- Low recoil: estimate of quark-hadron duality violation
- Pending issue of $b \to \Lambda_b$ fragmentation fraction

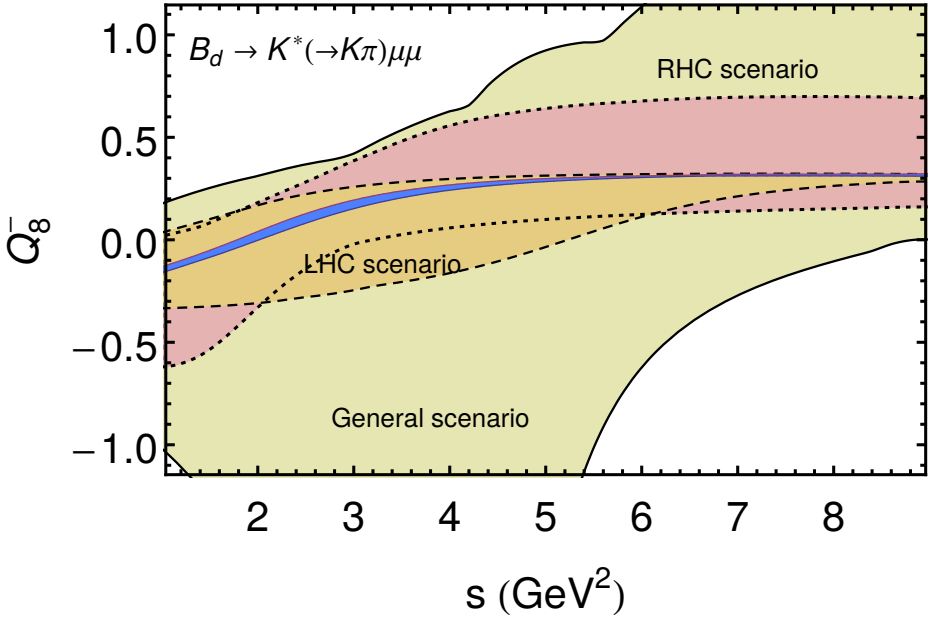
[T. Blake, S. Meinel, D. van Dyk]

More observables



Smaller bins to probe q^2 dependence better

(green $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$, red $\mathcal{C}_{9\mu}^{\rm NP}$)



Time-dependent observables in

$B_d \to K^*(\to K_S\pi^0)\ell^+\ell^-$,

$B_s \to \phi(\to K^+K^-)\ell^+\ell^-$,

$B_d \to K_S\ell\ell$

[SDG, Virto; Novoa Brunet, Vos]

Effective connections

SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$) $\quad \mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$
with higher-dim ops involving only SM fields and SM gauge sym

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

- provides constraints between scalar/pseudoscalar coefficients and rules out tensor contributions
- if only left-handed vector NP, two ops. with left-handed doublets

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

  so natural connection with other processes from the quark and lepton doublets, in particular $b \to c\tau\nu$, $b \to s\tau\tau$, $b \to s\nu\nu$
- but requires a flavour model to connect the different lepton families
- obviously, connections to other flavour anomalies/processes if we enter model building in a more elaborate manner

$b \to c\tau\nu$

- 10-15% enhancement compared to SM in LFU R_D, R_{D^*} (mainly driven by Babar) + enhancement for $R_{J/\psi}$ (LHCb)
- no clear sign of NP in angular obs (but large uncertainties)
- LHCb: LFU in $\Lambda_b \to \Lambda_c$ compatible with SM but central value 25% lower, in disagreement with model-indep expectations [Blanke et al]

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- If we focus on SMEFT vector ops. with left-handed doublets

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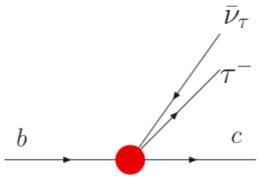

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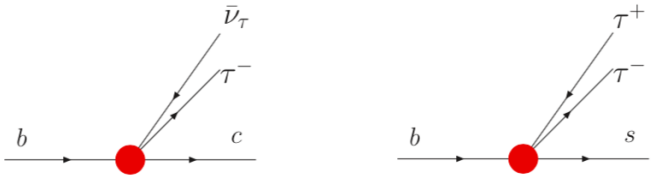
  - Avoids bounds from $B \to K^{(*)}\nu\nu$, Z decays, direct production in $\tau\tau$



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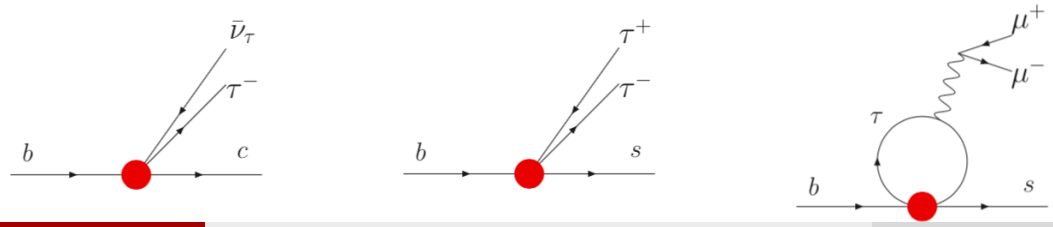
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$



$b \to c\tau\nu$, $b \to s\mu\mu$, $b \to s\tau\tau$

Interesting combined NP scenario

- $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ from small $\mathcal{O}_{2322}$ [$b \to s\mu\mu$]
- $\mathcal{C}_{9}^{\rm U}$ from rad corr to large $\mathcal{O}_{2333}$ [$b \to c\tau\nu$, $b \to s\mu\mu$]
- No contrib from $\mathcal{O}_{3333}$ [EWPO, direct LHC searches in $\tau^+\tau^-$]

Generic flavour struct, NP scale Λ

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

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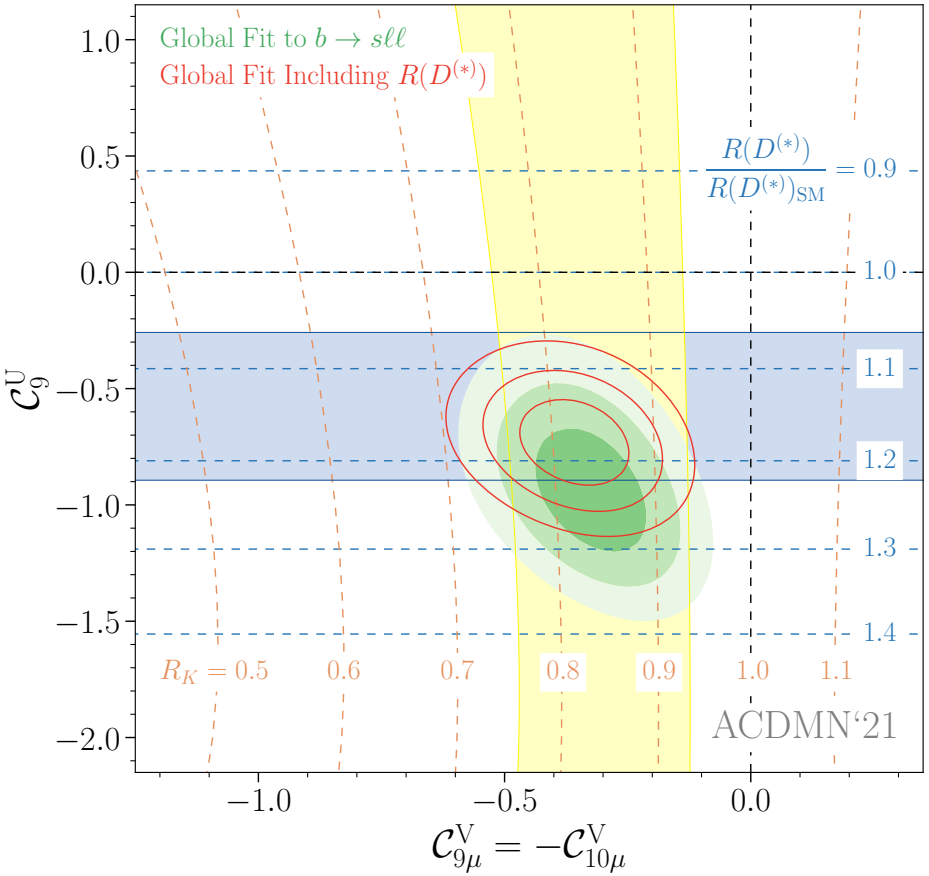

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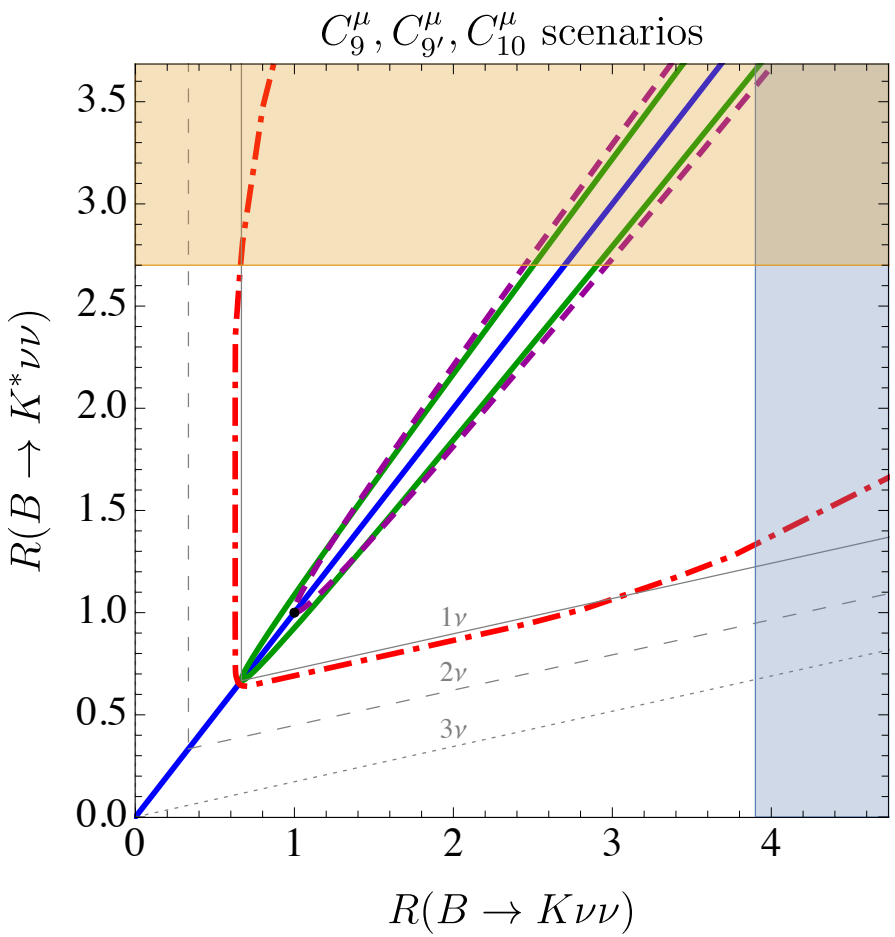
- $\text{Pull}_{\rm SM}$ up to 8.0 σ once $R_{D^{(*)}}$ included
- Huge enhancement of $b \to s\tau\tau$ modes $O(10^{-4})$, also distorting $b \to s\mu\mu$ spectrum in charmonia region

[Capdevila et al, Cornella et al]

$b \to s\nu\nu$

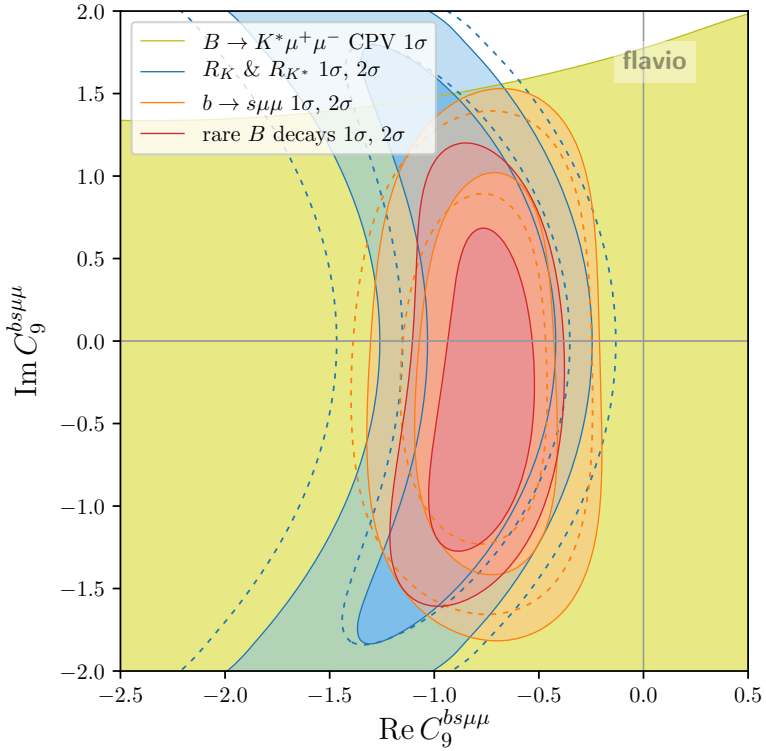
SMEFT with vector left- and right-handed ops. [SDG, Fajfer, Kamenik, Novoa-Brunet]

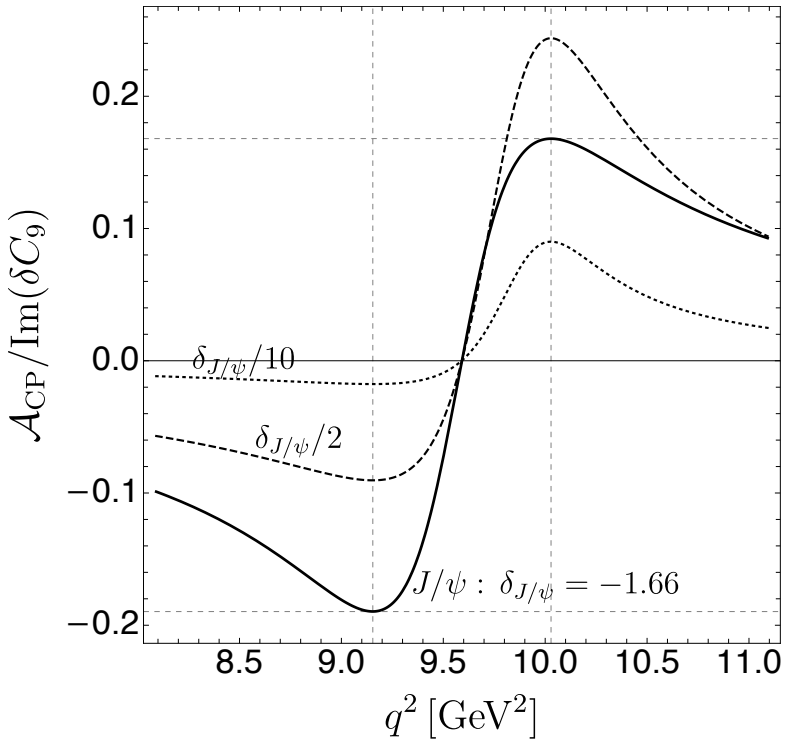


$$R(i \to f) \equiv \frac{\mathcal{B}(i \to f)}{\mathcal{B}(i \to f)_{\rm SM}}$$

- Blue: (G)MFV case [Kagan, Volansky, Zupan]
- 1 σ region allowed by $b \to s\mu\mu$ transitions
  - Green: NP only in muons
  - Purple: Opposite NP effects in μ and τ
  - Red: Hierarchical NP effects according to the generation, proportional to m_ℓ
- Grey: no information on $b \to s\mu\mu$ and significant NP couplings to 1, 2, 3 ν

CP-violation





[Biswas, Nandi, Ray, Kumar Patra; Altmannshoffer, Stangl]

- Complex Wilson coefficients (NP weak phases)
- CP-asymmetries available for $B \to K^* \mu\mu$, $B_s \to \phi\mu\mu$...
- Favoured scenarios with real and imaginary parts in $\mathcal{C}_{9\mu,9'\mu,10\mu}$
- Large imaginary parts are allowed (Im $\mathcal{C}_9$ enhances rates)
- Interplay with strong phases (provided by $c\bar{c}$ contributions), enhanced near charmonium peak

[Bečirević, Fajfer, Košnik, Smolkovič]

Thanks for your attention