

Heavy flavour tensions in the SM

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Outline – a little bit of sunshine on a rainy day ?

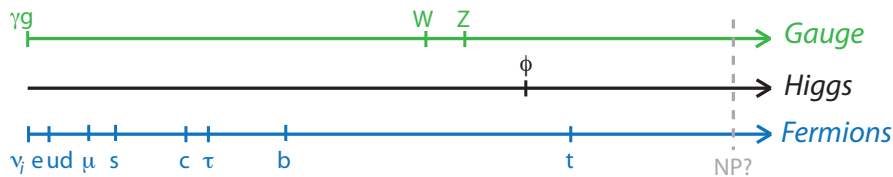


- 1 The power of flavour physics
- 2 Interesting deviations in $b \rightarrow c l \bar{\nu}_l$
- 3 Remarkable deviations in $b \rightarrow s l l$
- 4 Outlook

[See also talks by E. Smith, G. Wormser, W. Walkowiak in parallel sessions]

The power of flavour physics

Quark flavour physics



Important, unexplained hierarchy among 10 of 19 params of $SM_{m_\nu=0}$

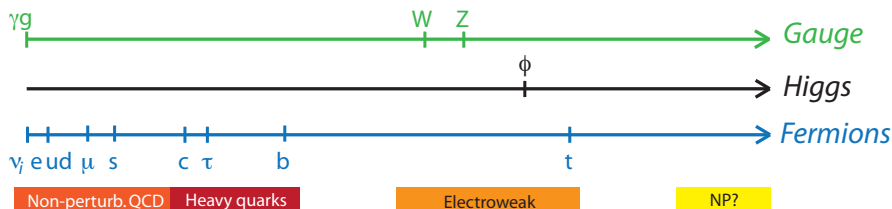
- Mass (6 params, a lot of small ratios of scales)
- CP violation (4 params, strong hierarchy between generations)
- Related to Yukawa couplings of the Higgs in SM

With phenomenological consequences for quark flavour dynamics

- Hierarchy of **CP asymmetries** according to generations
- **Quantum sensitivity** (via loops) to large range of scales
- GIM suppression of **Flavour-Changing Neutral Currents**

⇒ Interesting probe of the Standard Model and beyond...

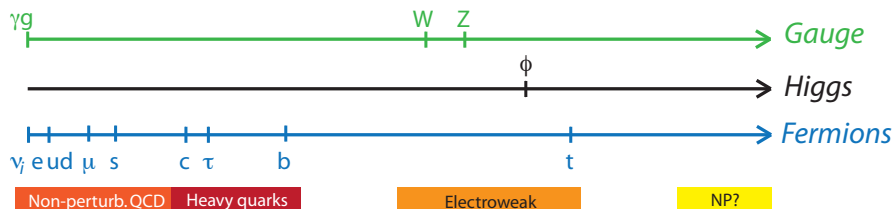
A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales

BSM \rightarrow SM+1/ Λ_{NP} ($\Lambda_{EW}/\Lambda_{NP}$) \rightarrow \mathcal{H}_{eff} (m_b/Λ_{EW}) \rightarrow *eff. theories* (Λ_{QCD}/m_b)

A multi-scale problem

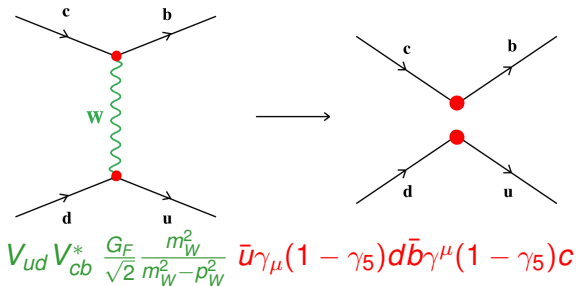


- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales
 $BSM \rightarrow SM+1/\Lambda_{NP} (\Lambda_{EW}/\Lambda_{NP}) \rightarrow \mathcal{H}_{eff} (m_b/\Lambda_{EW}) \rightarrow \text{eff. theories} (\Lambda_{QCD}/m_b)$
- Main theo problem from hadronisation of quarks into hadrons
description/parametrisation in terms of QCD quantities
decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties
lattice QCD simulations, sum rules, effective theories...

Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

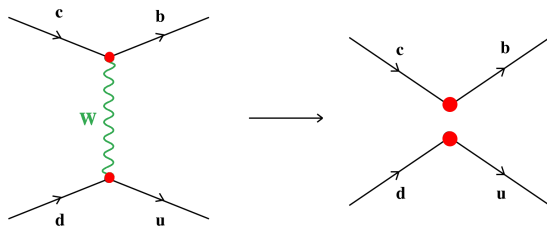
Short dist/Wilson coefficients and Long dist/local operator



Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

Short dist/Wilson coefficients and Long dist/local operator



$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u} \gamma_\mu (1 - \gamma_5) d \bar{b} \gamma^\mu (1 - \gamma_5) c + O(1/M_W^2)$$

Fermi theory carries some info on the underlying theory

- G_F : scale of NP physics
- \mathcal{O}_i : interaction with left-handed fermions, through charged spin 1
- Losing some info (gauge structure, Z^0 ...)
but a good start if no particle (=W) already seen

Looking for interesting processes

Starting from the SM
(or one of its extensions)

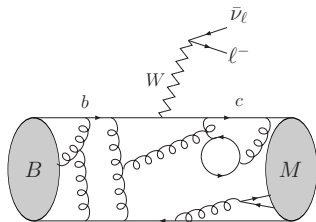
$$\mathcal{H}^{\text{eff}} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M | \mathcal{H}^{\text{eff}} | B \rangle = CKM \times \mathcal{C}_i \times \langle M | \mathcal{O}_i | B \rangle$$



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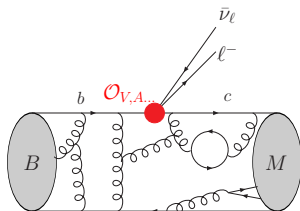
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involving hadronic quantities such as **form factors**

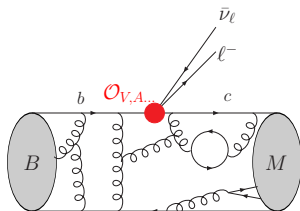
selecting processes for accurate predictions:

- semileptonic decays (form factors, not more complicated objects)
- ratios of branching ratios with different leptons
- ratios of observables with similar dependence on form factors
⇒ observables with limited sensitivity to (ratio of form) factors

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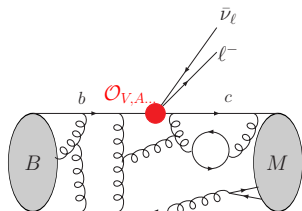
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Two possible uses of effective approaches

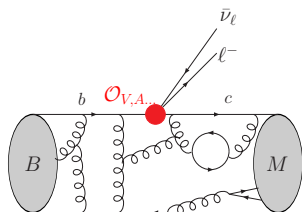
- fixing \mathcal{C}_i , computing SM and comparing with the data
- determining short-distance \mathcal{C}_i from the data and compare with SM

Handling B-meson form factors



For illustration, take $B \rightarrow V$ transitions, described in general by 7 form factors: V (vector), $A_{0,1,2}$ (axial) and $T_{1,2,3}$ (tensor), depending on $q^2 = (p_B - p_V)^2$

Handling B-meson form factors



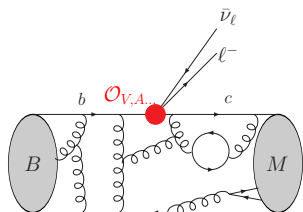
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Large recoil of the meson

$$(\Lambda \ll E_V \sim m_B)$$

- Light-cone sum rules (light V , parton language)
- Soft Collinear Effective Theory [Charles et al., Beneke, Feldmann]
 - in the limit $m_b \rightarrow \infty$, two soft form factors $\xi_{\perp}(q^2)$ and $\xi_{\parallel}(q^2)$
 - corrections: $O(\alpha_s)$ from hard gluons + nonperturbative $O(\Lambda/m_B)$

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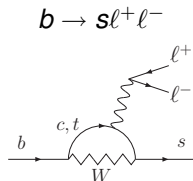
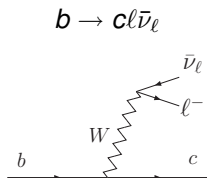
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Low recoil of the meson

$$(E_V \sim \Lambda_{QCD} \ll m_B)$$

- Lattice QCD simulations (discretised QCD)
- Heavy Quark Effective Theory [Neubert, Grinstein, Pirjol, Hiller, Bobeth, Van Dyk...]
 - in the limit $m_b \rightarrow \infty$, three soft form factors $f_{\perp}(q^2)$, $f_{\parallel}(q^2)$, $f_0(q^2)$
 - corrections: $O(\alpha_s)$ from hard gluons + nonperturbative $O(\Lambda/m_B)$

Two transitions of interest



SM
Spin 0
Spin 1
Observables
with
Tensions

tree (charged) ($V - A$)

$$\bar{B} \rightarrow D l \bar{\nu}_\ell$$

$$\bar{B} \rightarrow D^* l \bar{\nu}_\ell$$

Total Br

$$l = \tau, \mu, e$$

$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)} \tau \nu)}{Br(B \rightarrow D^{(*)} l \bar{\nu}_\ell)}$$

loop (neutral)

$$B \rightarrow K l l$$

$$B \rightarrow K^* l l, B_s \rightarrow \phi l l$$

$d\Gamma/dq^2 +$ Angular obs

$$l = \mu, e$$

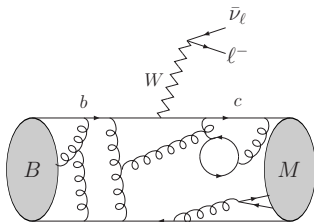
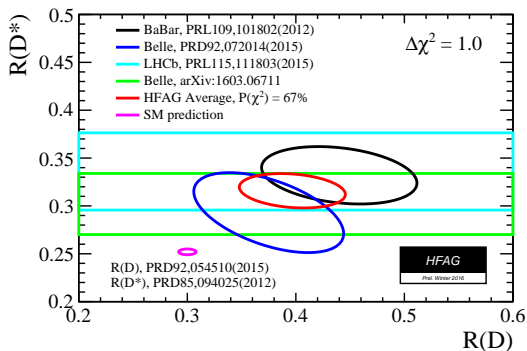
$$R_K = \frac{Br(B \rightarrow K \mu \mu)}{Br(B \rightarrow K e e)}$$

$Br(K, K^*, \phi + \mu \mu)$
angular obs (e.g., P'_5)

Two transitions exhibiting interesting patterns of deviations from SM

Interesting deviations in $b \rightarrow cl\bar{\nu}_\ell$

$b \rightarrow c\ell\bar{\nu}_\ell$: R_D and R_{D^*}



$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}\ell\bar{\nu}_\ell)}$$

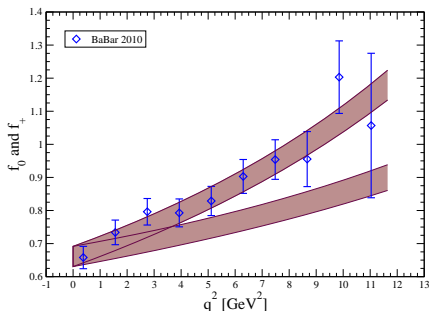
- different identification techniques of the τ for LHCb and B-factories
- $R(D)$ and $R(D^*)$ exceed SM predictions by 1.9σ and 3.3σ
- p-value = 5.2×10^{-5} , difference with SM preds at 4.0σ level
- consistent with 15% enhancement for $b \rightarrow c\tau\bar{\nu}_\tau$

What is the basis for these predictions ?

$B \rightarrow D\ell\bar{\nu}_\ell$ branching ratio

$$\frac{d\Gamma(B \rightarrow D\ell\bar{\nu}_\ell)}{dq^2} \propto |V_{cb}|^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{p}|^2 \left[\left(1 - \frac{m_\ell^2}{2q^2}\right)^2 M_B^2 |\vec{p}|^2 f_+^2(q^2) + \frac{3m_\ell^2}{8q^2} (M_B^2 + M_D^2)^2 f_0^2(q^2) \right]$$

- \vec{p} D -momentum in B -frame, $q^2 = (p_B - p_D)^2$ lepton invariant mass
- Two form factors $f_+(q^2)$ (vector) and $f_0(q^2)$ (scalar)
NP extension requires one more form factor f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range



[HPQCD collaboration]

$B \rightarrow D^* \ell \bar{\nu}_\ell$ branching ratio

$$\frac{d\Gamma(B \rightarrow D^* \ell \bar{\nu}_\ell)}{dq^2} \propto |V_{cb}|^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{q}| q^2 \left[\left(1 + \frac{m_\ell^2}{2q^2}\right)^2 (|H_+|^2 + |H_-|^2 + |H_0|^2) + \frac{3m_\ell^2}{2q^2} |H_t|^2 \right]$$

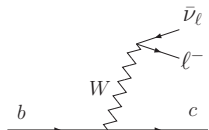
- H_λ describing $B \rightarrow D^*(\rightarrow D\pi)\ell\bar{\nu}_\ell$ with D^* helicity
- Interferences in principle accessible via angular analyses (but ν !)
- Four form factors $V, A_{0,1,2}$ (vector and axial)
NP extension requires 3 more form factors $T_{1,2,3}$ (tensor)

$B \rightarrow D^* \ell \bar{\nu}_\ell$ branching ratio

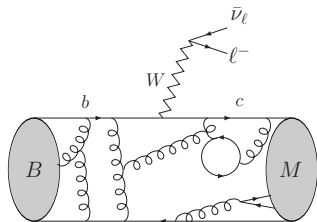
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NP extension requires 3 more form factors $T_{1,2,3}$ (tensor)
- No complete lattice determination, need other approaches !
 - HQET: Form factors related in the limit $m_b \rightarrow \infty$,
providing ratios of form factors up to $O(\Lambda/m_B)$ corrections
 - Normalisation from Belle on $B \rightarrow D^* \ell \bar{\nu}_\ell$ ($\ell = e, \mu$)
assuming no NP for light leptons

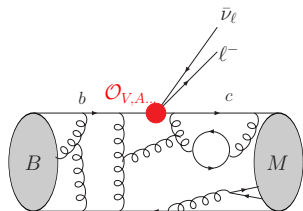
$b \rightarrow c l \bar{\nu}_l$: effective Hamiltonian



$b \rightarrow c l \bar{\nu}_l$: effective Hamiltonian



$b \rightarrow c \ell \bar{\nu}_\ell$: effective Hamiltonian

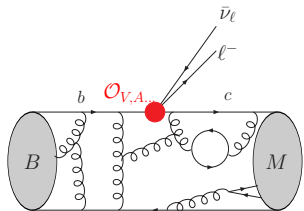


\mathcal{H}^{eff} to determine short-distance couplings
and **look for NP** model-independently

$$\mathcal{H}^{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_{\ell=e,\mu,\tau} (\bar{\ell} \gamma^\mu P_L \nu_\ell) \\ \times [\bar{c} \gamma^\mu P_L b + g_{SL} i \partial^\mu (\bar{c} P_L b) + g_{SR} i \partial^\mu (\bar{c} P_R b)]$$

$$[\text{with } P_{L,R} = (1 \mp \gamma_5)/2]$$

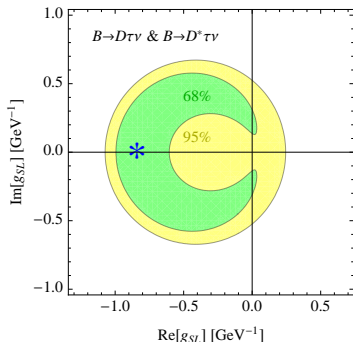
$b \rightarrow c \ell \bar{\nu}_\ell$: effective Hamiltonian



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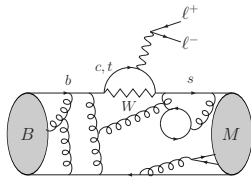
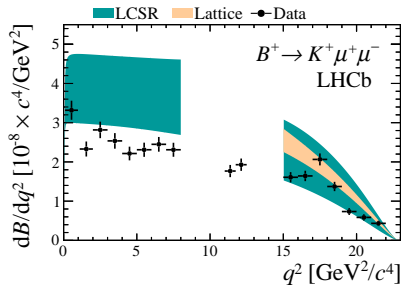
- Fit to R_D and R_{D^*} leading to viable explanation with scalar ops
- However only few observables measured (neutrino in final state)
- Improving on $B \rightarrow D^*$ form factors ?

[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov,

Pokorski, Crivellin, Freytsis, Ligeti, Ruderman...]

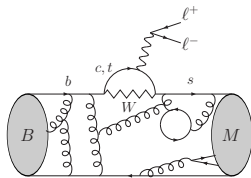
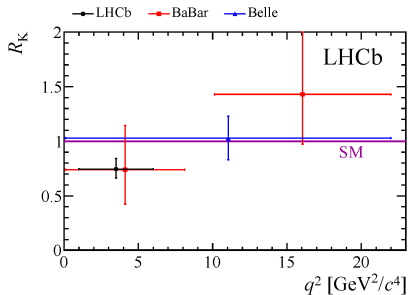
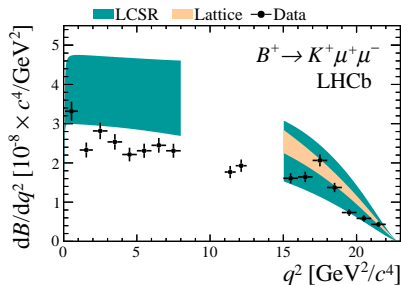
Remarkable deviations in $b \rightarrow sll$

$b \rightarrow sl^+l^-: B \rightarrow Kll$



- $Br(B \rightarrow K\mu\mu)$ too low compared to SM

$b \rightarrow sl^+l^-: B \rightarrow Kll$

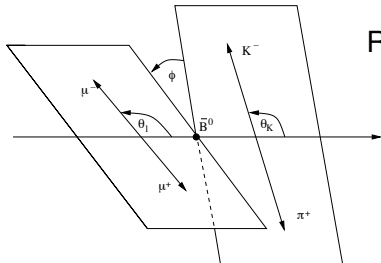


- $Br(B \rightarrow K\mu\mu)$ too low compared to SM

- $$R_K = \frac{Br(B \rightarrow K\mu\mu)}{Br(B \rightarrow Kee)} \Big|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- equals to 1 in SM (universality of lepton coupling), 2.6 σ dev
- would require NP coupling differently to μ and e

$$b \rightarrow sl^+l^-: B \rightarrow K^*(\rightarrow K\pi)\mu\mu \quad (1)$$

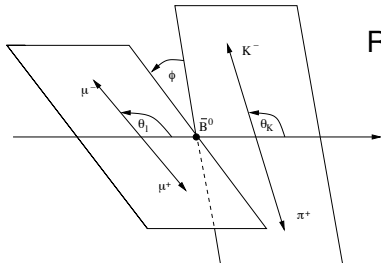


[Ali, Hiller, Matias, Krüger, Mescia, SDG, Virto, Hofer, Bobeth, van Dyck, Buras, Altmanshoffer, Straub, Bharucha, Zwicky, Gratrex, Hopfer, Becirevic, Sumensari, Zukanovic-Funchal ...]

Rich kinematics

- differential decay rate in terms of 12 **angular coeffs** $J_i(q^2)$
with $q^2 = (p_{\ell^+} + p_{\ell^-})^2$
- interferences between 8 **transversity amplitudes** for $B \rightarrow K^*(\rightarrow K\pi)V^*(\rightarrow \ell\ell)$

$$b \rightarrow sl^+l^-: B \rightarrow K^*(\rightarrow K\pi)\mu\mu \quad (1)$$



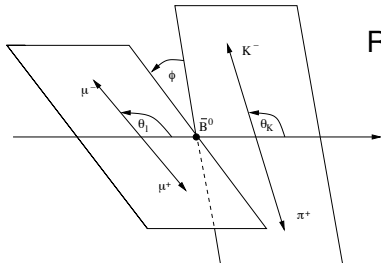
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- Transversity amplitudes in terms of 7 form factors $A_{0,1,2}$, V , $T_{1,2,3}$
- Relations between form factors in limit $m_B \rightarrow \infty$,
either when K^* very soft or very energetic (low/large-recoil)

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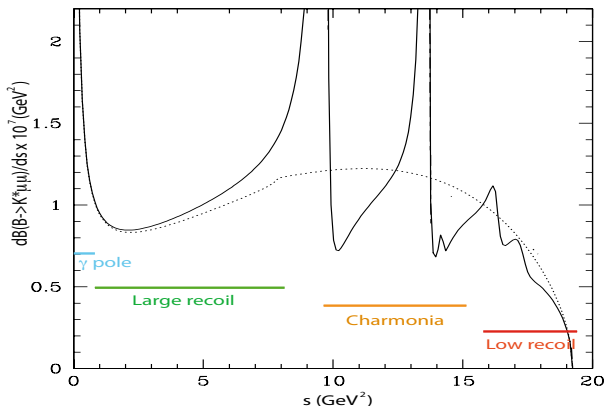
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- Relations between form factors in limit $m_B \rightarrow \infty$,
either when K^* very soft or very energetic (low/large-recoil)
- Build ratios of J_i where form factors cancel in these limits
(corrections by hard gluons $O(\alpha_s)$, power corr $O(\Lambda/m_B)$)
- Optimised observables P_i with **reduced hadronic uncertainties**

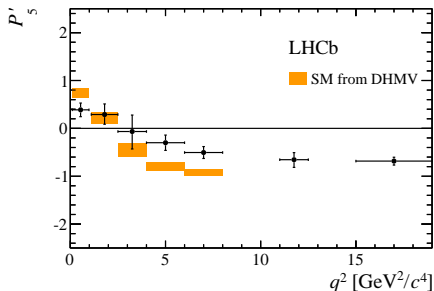
[Matias, Krüger, Becirevic, Schneider, Mescia, Virto, SDG, Ramon, Hurth; Hiller, Bobeth, Van Dyck]

$$b \rightarrow sl^+l^-: B \rightarrow K^*\mu\mu \quad (2)$$



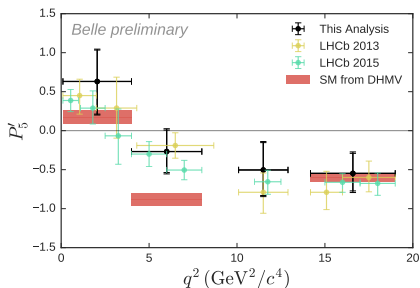
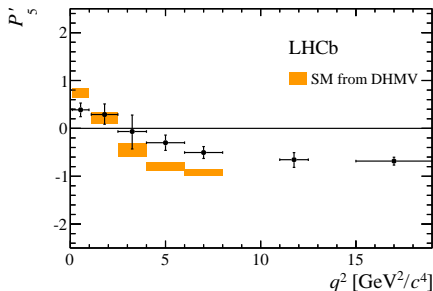
- Very large K^* -recoil ($4m_\ell^2 < q^2 < 1 \text{ GeV}^2$) γ almost real
- Large K^* -recoil ($q^2 < 9 \text{ GeV}^2$) energetic K^* ($E_{K^*} \gg \Lambda_{QCD}$)
- Charmonium region ($q^2 = m_{\psi, \psi', \dots}^2$ between 9 and 14 GeV^2)
- Low K^* -recoil ($q^2 > 14 \text{ GeV}^2$) soft K^* ($E_{K^*}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

$$b \rightarrow sl^+l^-: B \rightarrow K^*\mu\mu \quad (3)$$



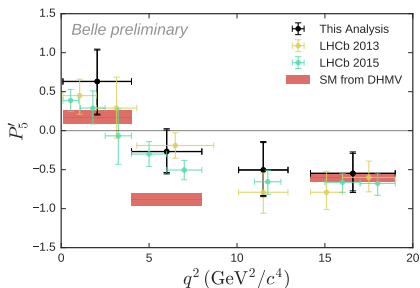
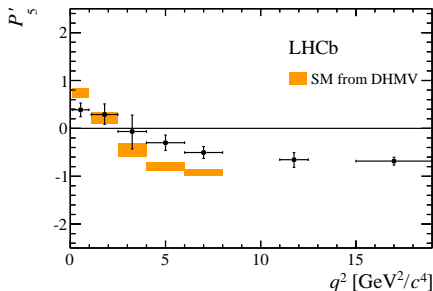
- Optimised observables P_i with **reduced hadronic uncertainties** at large recoil [Matias, Mescia, Virto, SDG, Ramon, Hurth, Hofer]
- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables, in particular two bins for P'_5 deviating from SM by **2.8σ** and **3.0σ**

$$b \rightarrow sl^+l^-: B \rightarrow K^* \mu\mu \quad (3)$$



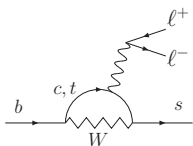
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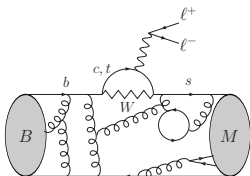
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- Also deviations in $BR(B \rightarrow K^*\mu\mu)$ and $BR(B_s \rightarrow \phi\mu\mu)$ at low recoil

$b \rightarrow s\mu\mu$ effective hamiltonian



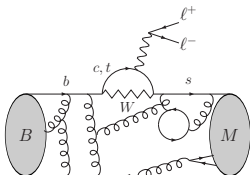
$$b \rightarrow s\gamma^* : \mathcal{H}_{\Delta F=1}^{SM} \propto \sum V_{ts}^* V_{tb} \mathcal{C}_i \mathcal{O}_i + \dots$$

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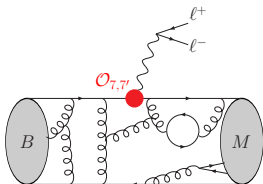
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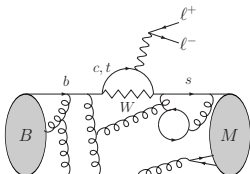


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- $\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s} \sigma^{\mu\nu} (1 + \gamma_5) F_{\mu\nu} b$ [real or soft photon]

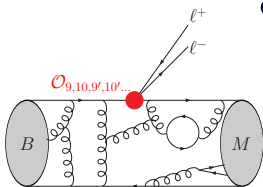


$b \rightarrow s\mu\mu$ effective hamiltonian

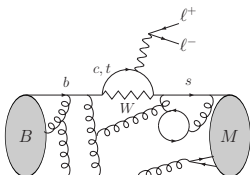


$$b \rightarrow s\gamma(^*) : \mathcal{H}_{\Delta F=1}^{SM} \propto \sum V_{ts}^* V_{tb} c_i \mathcal{O}_i + \dots$$

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- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s} \gamma_\mu (1 - \gamma_5) b \bar{\ell} \gamma^\mu \ell$ [$b \rightarrow s\mu\mu$ via Z /hard γ ...]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s} \gamma_\mu (1 - \gamma_5) b \bar{\ell} \gamma^\mu \gamma_5 \ell$ [$b \rightarrow s\mu\mu$ via Z]

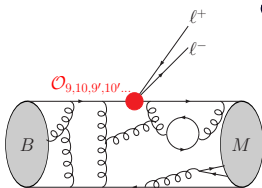


$b \rightarrow s\mu\mu$ effective hamiltonian



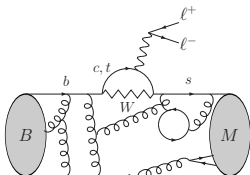
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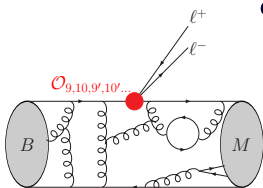
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$$C_7^{SM} = -0.29, \quad C_9^{SM} = 4.1, \quad C_{10}^{SM} = -4.3 \quad @ \quad \mu_b = m_b$$

NP changes short-distance C_i for SM or new long-distance ops \mathcal{O}_i

- Chirally flipped ($W \rightarrow W_R$) $\mathcal{O}_7 \rightarrow \mathcal{O}_{7'} \propto \bar{s} \sigma^{\mu\nu} (1 - \gamma_5) F_{\mu\nu} b$
- (Pseudo)scalar ($W \rightarrow H^+$) $\mathcal{O}_9, \mathcal{O}_{10} \rightarrow \mathcal{O}_S \propto \bar{s} (1 + \gamma_5) b \bar{\ell} \ell, \mathcal{O}_P$
- Tensor operators ($\gamma \rightarrow T$) $\mathcal{O}_9 \rightarrow \mathcal{O}_T \propto \bar{s} \sigma_{\mu\nu} (1 - \gamma_5) b \bar{\ell} \sigma_{\mu\nu} \ell$

Global analysis of $b \rightarrow s\mu\mu$ anomalies

[SDG, Hofer, Matias, Virto]

96 observables in total (LHCb for exclusive, no CP-violating obs)

- $B \rightarrow K^* \mu\mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)
- $B_s \rightarrow \phi \mu\mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \rightarrow K^+ \mu\mu, B^0 \rightarrow K^0 \mu\mu$ (BR)
- $B \rightarrow X_S \gamma, B \rightarrow X_S \mu\mu, B_s \rightarrow \mu\mu$ (BR), $B \rightarrow K^* \gamma$ (A_I and $S_{K^* \gamma}$)

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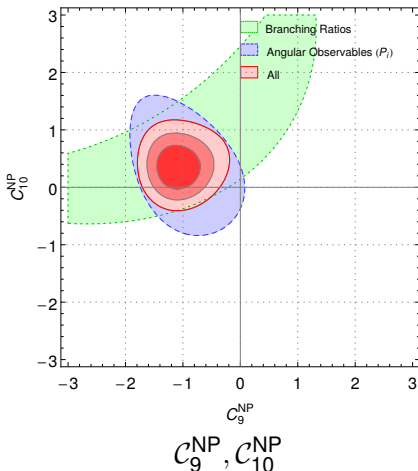
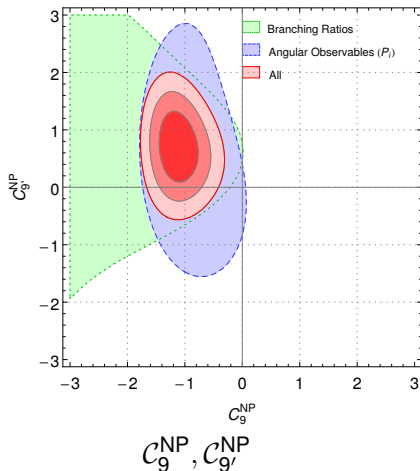
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Frequentist analysis

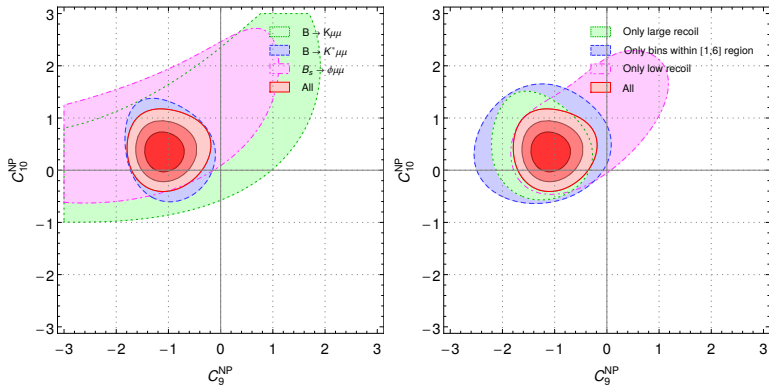
- $C_i(\mu_{ref}) = C_i^{SM} + C_i^{NP}$, with C_i^{NP} assumed to be real
- Experimental correlation matrix provided
- Theoretical correlation matrix treating all theo errors (form factors...) as Gaussian random variables
- Various hypotheses “NP in some C_i only” to be compared with SM

Some favoured scenarios (1)



- p-value=71% (goodness of fit), $\text{pull}_{SM} = 4.5\sigma$ (metrology)
- BRs and angular obs both favour $C_9^{\text{NP}} \simeq -1$ in all “good” scenarios
- results in agreement with [\[Altmanshoffer, Straub\]](#) and [\[Hurth, Mahmoudi, Neshatpour\]](#)

Some favoured scenarios (2)

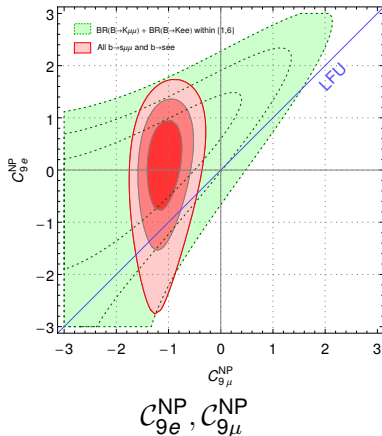


- Different processes and different kinematic ranges involving different theoretical tools
- $B \rightarrow K^*\mu\mu$ tighter than $B_s \rightarrow \phi\mu\mu$, tighter than $B \rightarrow K\mu\mu$
- Large recoil driving the discussion, but [1,6] bins already providing bulk of the effect, and low-recoil also in favour of $C_9^{\text{NP}} < 0$

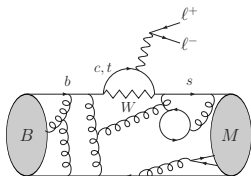
[Horgan et al., Bouchard et al., Altmannshofer and Straub]

Lepton-flavour (non) universality

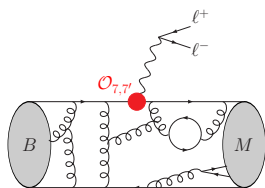
- Adding LHCb $BR(B \rightarrow Kee)$ and large-recoil obs for $B \rightarrow K^* ee$
- For several favoured scenarios, SM pull increases by $\sim 0.5\sigma$
- Favours violation of LFU, compatible with no NP in $b \rightarrow see$



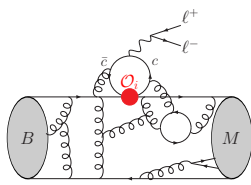
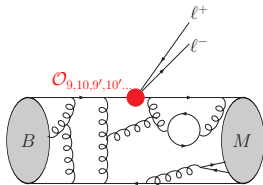
Controversies (1)



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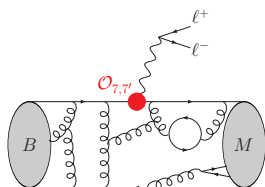


Form factors (local)

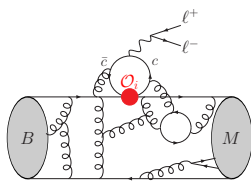
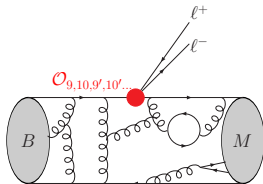


Charm loop (non-local)

Controversies (1)



Form factors (local)



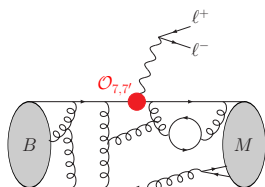
Charm loop (non-local)

Uncertainties in form factors

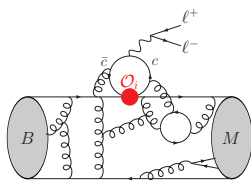
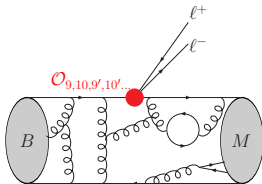
[Camalich, Jäger;Matias,Virto,Hofer,Capdevilla,SDG]

- EFT with limit $m_b \rightarrow \infty$ useful to correlate form factors with $O(\Lambda/m_b)$ **power corrections** to this limit
- Corrections with large impact on optimised observables ?

Controversies (1)



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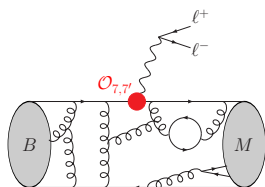
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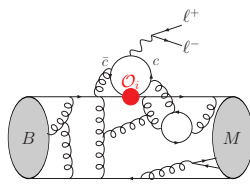
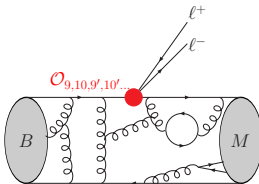
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- EFT with limit $m_b \rightarrow \infty$ useful to correlate form factors with $O(\Lambda/m_b)$ **power corrections** to this limit
- Corrections with large impact on optimised observables ?
- No, but accurate predictions require
 - appropriate definition of form factors in $m_b \rightarrow \infty$ limit
 - power corrections varied in agreement with info on form factors
 - proper propagation of correlations induced among form factors

Controversies (2)

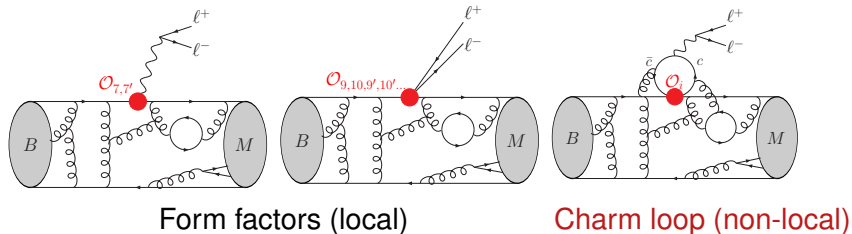


Form factors (local)



Charm loop (non-local)

Controversies (2)

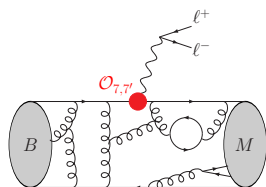


Uncertainties from charm loops

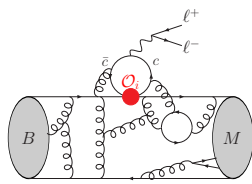
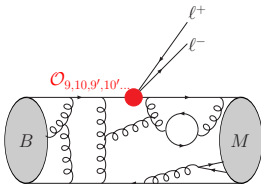
[Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Matias, Virto, Hofer, Capdevilla, SDG]

- Effect well-known (loop process, charmonium resonances)
- Yields q^2 - and hadron-dependent contrib with $O_{7,9}$ -like structures
 - order of magnitude from [Khodjamirian et al.] used in [SDG, Hofer, Matias, Virto]
 - other global fits use q^2 -dependent param. with $O(\Lambda/m_b)$ estimates

Controversies (2)



Form factors (local)



Charm loop (non-local)

Uncertainties from charm loops

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 - other global fits use q^2 -dependent param. with $O(\Lambda/m_b)$ estimates
- Bayesian extraction from data performed by [Ciuchini et al.]
 - q^2 -dependence present (as expected), apparently significant
 - actually not contradicting results of global fits, though less precise

Anomaly patterns

| | R_K | $\langle P'_5 \rangle_{[4,6],[6,8]}$ | $BR(B_s \rightarrow \phi\mu\mu)$ | low recoil BR | Best fit now |
|-----------------------|-------|--------------------------------------|----------------------------------|-----------------|--------------|
| C_9^{NP} | + | | | | |
| | - | ✓ | ✓ | ✓ | X |
| C_{10}^{NP} | + | ✓ | ✓ | ✓ | X |
| | - | | ✓ | | |
| $C_{9'}^{\text{NP}}$ | + | | ✓ | ✓ | X |
| | - | ✓ | ✓ | | |
| $C_{10'}^{\text{NP}}$ | + | ✓ | ✓ | | |
| | - | | ✓ | ✓ | X |

- assuming no NP in $b \rightarrow see$
- $C_9^{\text{NP}} < 0$ consistent with all anomalies
- lower sensitivity to other C_i (cannot be mimicked by long dist), with C_{10} most promising but no consistent picture yet
- global agreement with other fits performed by [\[Altmanshoffer, Straub\]](#) and [\[Hurth, Mahmoudi, Neshatpour\]](#)

Quo vadis ?

NP interpretations

No consistent global alternative from SM/long-dist. for $b \rightarrow sll$

- hadronic effects ($B \rightarrow K^* \mu\mu$, $B_s \rightarrow \phi \mu\mu$ at low and large recoils)
- statistical fluctuation (R_K)
- bad luck (\mathcal{C}_9 can accomodate all discrepancies by chance)

NP interpretations

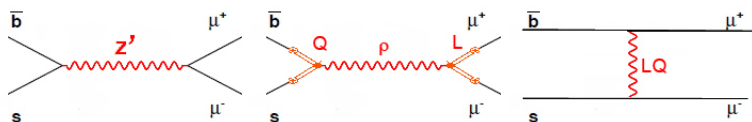
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NP models with new scale around TeV

often trying to connect $b \rightarrow sl^+l^-$ and $b \rightarrow cl\bar{\nu}_l$ (3rd vs 2nd gen)

- Z' boson (larger gauge group, e.g., $SU_C(3) \otimes SU_L(3) \otimes U_Y(1)$)
- Partial compositeness (mixing between known and extra fermions transforming under $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U_Y(1)$)
- Leptoquarks (coupling to a quark and a lepton, like $(3, 2, 1/6)$)
- MSSM susy definitely not favoured ...



[Buras, De Fazio, Girrbach, Blanke, Altmannshofer, Straub, Crivellin, D'Ambrosio, Becirevic, Sumensari, Isidori, Greljo...]

What next ?

$$b \rightarrow c l \bar{\nu}_l$$

[Freysis, Ligeti, Ruderman; Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov...]

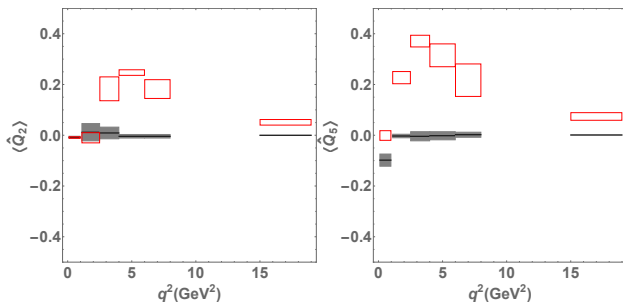
- Better control of form factors in $B \rightarrow D^* l \bar{\nu}_l$
- More measurements from angular analyses

What next ?

$b \rightarrow c \ell \bar{\nu}_\ell$

[Freysis, Ligeti, Ruderman; Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov...]

- Better control of form factors in $B \rightarrow D^* \ell \bar{\nu}_\ell$
- More measurements from angular analyses



$b \rightarrow s \ell^+ \ell^-$

[Matias, Virto, Hofer, Capdevilla, SDG...]

- Measurements (LHCb, Belle) of LFU-violating quantities R_{K^*} , but also cleaner quantities like $Q_i = P_i^\mu - P_i^e$ (null tests of the SM)
- $c\bar{c}$ dynamics from data (LFU ratios, non-res/resonant inters)
- Further lattice and LCSR determinations for the form factors

Outlook

$b \rightarrow s\ell^+\ell^-$ and $b \rightarrow c\ell\bar{\nu}_\ell$

- Many observables, more or less sensitive to hadronic unc.
- Interesting deviations from SM expectations
- Global fit to $b \rightarrow c\ell\bar{\nu}$ still only limited amount of information
- Global fit to $b \rightarrow s\ell^+\ell^-$ in favour of large deviation for C_9 in $b \rightarrow s\mu\mu$ and does not seem to favour hadronic explanations
- Many models proposed for either or both sets of deviations

Where to go ?

- Measurements of q^2 and angular dependence
- Other LFU violating observables
- Charm-loop for $b \rightarrow s\mu\mu$ (estimates, or clean observables)
- Provide lattice form factors over larger range (large recoil ?)
- Look for new observables (CP-violation, time-dependence, LFUV and LFV observables. . .)

A lot of (interesting) work on the way !

A few recent analyses

| Statistical approach | [SDG, Hofer Matias, Virto] Frequentist $\Delta\chi^2$ | [Straub & Altmannshofer] Frequentist $\Delta\chi^2$ | [Hurth, Mahmoudi, Neshatpour] Frequentist $\Delta\chi^2$ & χ^2 |
|---|--|---|--|
| Data | LHCb | Averages | LHCb |
| $B \rightarrow K^* \mu\mu$ data | P_i , Max likelihood | S_i , Max likelihood | S_i , Max l.& moments |
| Form factors | B-meson LCSR [Khodjamirian et al.] + lattice QCD | [Bharucha, Straub, Zwicky] fit light-meson LCSR + lattice QCD | [Bharucha, Straub, Zwicky] |
| Theo approach | soft and full ff | full ff | soft and full ff |
| $c\bar{c}$ large recoil | magnitude from [Khodjamirian et al.] | polynomial param | polynomial param |
| C_9^μ 1D 1 σ pull _{SM} | [-1.29,-0.87] 4.5 σ | [-1.54,-0.53] 3.7 σ | [-0.27,-0.13] 4.2 σ |
| “good scenarios” | see before | $C_9^{\text{NP}}, C_{9'}^{\text{NP}} = -C_{10}^{\text{NP}}$ $(C_9^{\text{NP}}, C_{9'}^{\text{NP}}), (C_9, C_{10}^{\text{NP}})$ | $(C_9^{\text{NP}}, C_{9'}^{\text{NP}}), (C_9^{\text{NP}}, C_{10}^{\text{NP}})$ |

⇒ Good overall agreement for the results of the three fits

$b \rightarrow s\mu\mu$: 1D hypotheses

- SM pull: $\chi^2(C_i = 0) - \chi_{\min}^2$ (metrology, how far best fit from SM ?)
- p-value: χ_{\min}^2 and N_{dof} (goodness of fit, how good is best fit ?)

| Coefficient | Best Fit Point | 3σ | Pull _{SM} | p-value (%) |
|--|----------------|----------------|--------------------|-------------|
| SM | — | — | — | 16.0 |
| C_7^{NP} | -0.02 | [-0.07, 0.03] | 1.2 | 17.0 |
| C_9^{NP} | -1.09 | [-1.67, -0.39] | 4.5 | 63.0 |
| C_{10}^{NP} | 0.56 | [-0.12, 1.36] | 2.5 | 25.0 |
| $C_9^{\text{NP}} = C_{10}^{\text{NP}}$ | -0.22 | [-0.74, 0.50] | 1.1 | 16.0 |
| $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ | -0.68 | [-1.22, -0.18] | 4.2 | 56.0 |
| $C_{9'}^{\text{NP}} = C_{10'}^{\text{NP}}$ | -0.07 | [-0.86, 0.68] | 0.3 | 14.0 |
| $C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$ | 0.19 | [-0.17, 0.55] | 1.6 | 18.0 |
| $C_9^{\text{NP}} = -C_{9'}^{\text{NP}}$ | -1.06 | [-1.60, -0.40] | 4.8 | 72.0 |
| $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ | -0.69 | [-1.37, -0.16] | 4.1 | 53.0 |
| $= -C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$ | | | | |
| $C_{9'}^{\text{NP}} = -C_{10}^{\text{NP}}$ | -0.19 | [-0.55, 0.15] | 1.7 | 19.0 |
| $= C_{9'}^{\text{NP}} = -C_{10'}^{\text{NP}}$ | | | | |

$b \rightarrow s\mu\mu$: 2D hypotheses

- Pull for the SM point in each scenario from $\chi_{\min}^2 - \chi^2(C_i = C_j = 0)$
- p -value from χ_{\min}^2 and N_{dof}
- several favoured scenarios, all with C_9^{NP} , hard to single out one

| Coefficient | Best Fit Point | Pull _{SM} | p-value (%) |
|--|------------------|--------------------|-------------|
| SM | — | — | 16.0 |
| $(C_7^{\text{NP}}, C_9^{\text{NP}})$ | $(-0.00, -1.07)$ | 4.1 | 61.0 |
| $(C_9^{\text{NP}}, C_{10}^{\text{NP}})$ | $(-1.08, 0.33)$ | 4.3 | 67.0 |
| $(C_9^{\text{NP}}, C_{7'}^{\text{NP}})$ | $(-1.09, 0.02)$ | 4.2 | 63.0 |
| $(C_9^{\text{NP}}, C_{9'}^{\text{NP}})$ | $(-1.12, 0.77)$ | 4.5 | 72.0 |
| $(C_9^{\text{NP}}, C_{10'}^{\text{NP}})$ | $(-1.17, -0.35)$ | 4.5 | 71.0 |
| $(C_9^{\text{NP}} = -C_{9'}^{\text{NP}}, C_{10}^{\text{NP}} = C_{10'}^{\text{NP}})$ | $(-1.15, 0.34)$ | 4.7 | 75.0 |
| $(C_9^{\text{NP}} = -C_{9'}^{\text{NP}}, C_{10}^{\text{NP}} = -C_{10'}^{\text{NP}})$ | $(-1.06, 0.06)$ | 4.4 | 70.0 |
| $(C_9^{\text{NP}} = C_{9'}^{\text{NP}}, C_{10}^{\text{NP}} = C_{10'}^{\text{NP}})$ | $(-0.64, -0.21)$ | 3.9 | 55.0 |
| $(C_9^{\text{NP}} = -C_{10}^{\text{NP}}, C_{9'}^{\text{NP}} = C_{10'}^{\text{NP}})$ | $(-0.72, 0.29)$ | 3.8 | 53.0 |

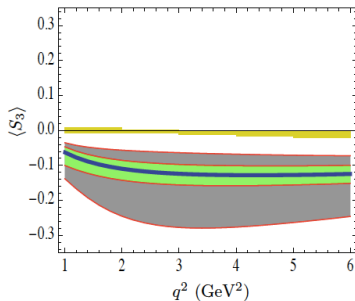
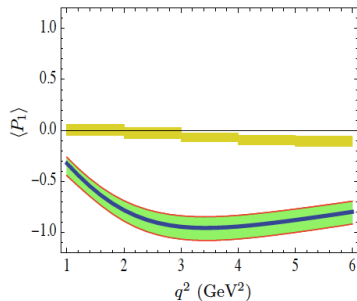
$b \rightarrow s\mu\mu$: 6D hypothesis

Letting all 6 Wilson coefficients vary (but only real)

| Coefficient | 1σ | 2σ | 3σ | Preference |
|-----------------------|-----------------|-----------------|-----------------|------------|
| C_7^{NP} | $[-0.02, 0.03]$ | $[-0.04, 0.04]$ | $[-0.05, 0.08]$ | no pref |
| C_9^{NP} | $[-1.4, -1.0]$ | $[-1.7, -0.7]$ | $[-2.2, -0.4]$ | negative |
| C_{10}^{NP} | $[-0.0, 0.9]$ | $[-0.3, 1.3]$ | $[-0.5, 2.0]$ | positive |
| $C_{7'}^{\text{NP}}$ | $[-0.02, 0.03]$ | $[-0.04, 0.06]$ | $[-0.06, 0.07]$ | no pref |
| $C_{9'}^{\text{NP}}$ | $[0.3, 1.8]$ | $[-0.5, 2.7]$ | $[-1.3, 3.7]$ | positive |
| $C_{10'}^{\text{NP}}$ | $[-0.3, 0.9]$ | $[-0.7, 1.3]$ | $[-1.0, 1.6]$ | no pref |

- C_9 is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $C_{9'}$ at 2σ
- Pull_{SM} for the 6D fit is 3.6σ

Sensitivity to form factors



- P_i designed to have limited sensitivity to form factors
- S_i CP-averaged version of J_i

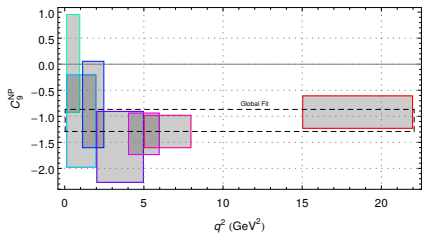
$$P_1 = \frac{2S_3}{1 - F_L} \quad F_L = \frac{J_{1c} + \bar{J}_{1c}}{\Gamma + \bar{\Gamma}} \quad S_3 = \frac{J_3 + \bar{J}_3}{\Gamma + \bar{\Gamma}}$$

Illustration for arbitrary NP point for two sets of LCSR form factors:

green [Ball, Zwicky] versus gray [Khodjamirian et al.]

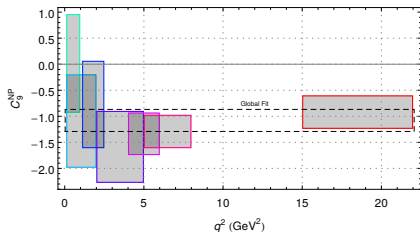
more or less easy to discriminate against yellow (SM prediction)

Cross-checks: q^2 -dependence of C_9



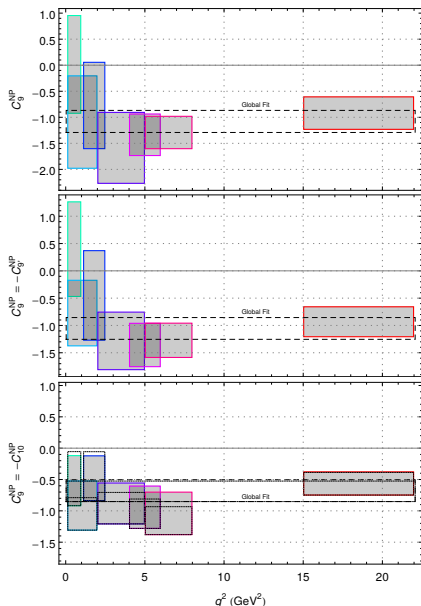
- C_9^{NP} bin by bin assuming NP in $C_9^{\text{NP}}, C_9^{\text{NP}} = -C_{9'}^{\text{NP}}$ or $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$

Cross-checks: q^2 -dependence of C_9



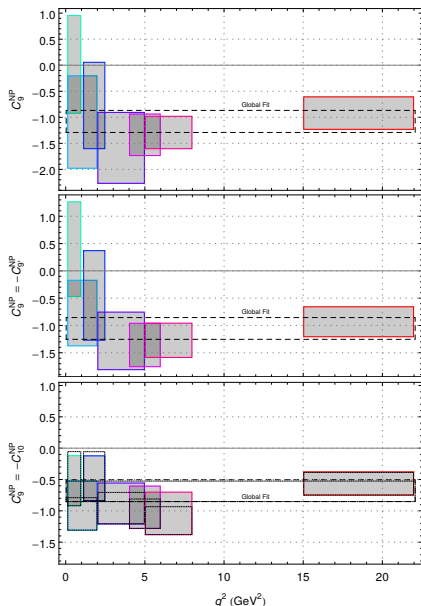
- C_9^{NP} bin by bin assuming NP in C_9^{NP} , $C_9^{\text{NP}} = -C_{9'}^{\text{NP}}$ or $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$
- Up: Assuming shift in C_9 only tests need for hadronic contrib:
 - NP in C_9 from short distances, q^2 -independent
 - Hadronic physics in C_9 is related to $c\bar{c}$ dynamics, (likely) q^2 -dependent

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Cross-checks: q^2 -dependence of C_9

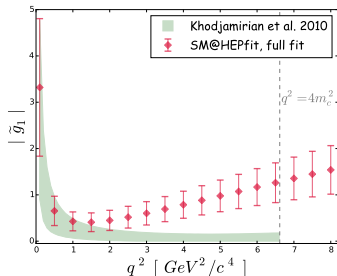


- C_9^{NP} bin by bin assuming NP in $C_9^{\text{NP}}, C_9^{\text{NP}} = -C_9'^{\text{NP}}$ or $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$
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 - Hadronic physics in C_9 is related to $c\bar{c}$ dynamics, (likely) q^2 -dependent
- Mid, down: correlated shift in C_9 and other C_i (never q^2 -depend: are NP scenarios consistent ?)
- No indication of q^2 -dependent contribution

Controversies: charm-loop contribution

$c\bar{c}$ contributions to helicity ampl g_i as q^2 -polynomial, extracting params from Bayesian to data “fit”

[Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli]

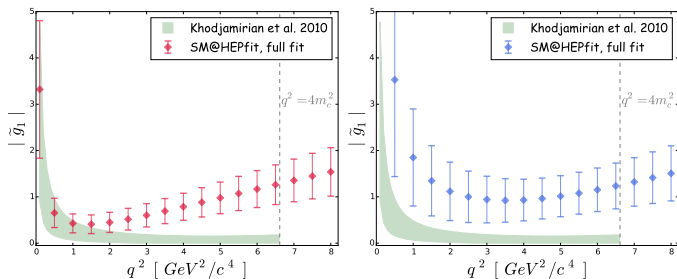


- constrained fit: imposing SM + $\Delta C_9^{BK(*)}$ [Khodjamirian et al.] at $q^2 < 1 \text{ GeV}^2$ yields q^2 -dep $c\bar{c}$ contribution, with “large” coefs for q^4

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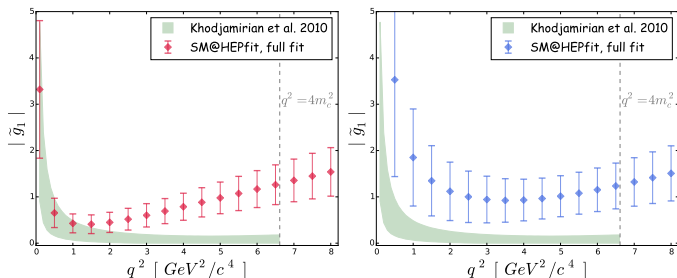


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- unconstrained fit: polynomial agrees with $\Delta C_9^{BK(*)}$ + large cst C_9^{NP} \implies constr. fit forced at low q^2 , compensation skewing high q^2
- no explanation for R_K or deviations in low-recoil BRs
- data on $B \rightarrow K^* \mu\mu$ to fix q^2 -polynomial before any prediction

More on very large power corrections (1)

- **Scheme:** choice of definition for the two soft form factors

$$\{\xi_{\perp}, \xi_{\parallel}\} = \{V, a_1 A_1 + a_2 A_2\}, \{T_1, A_0\}, \dots$$

- Power corrections for the other form factors from dimensional estimates or fit to other determinations (LCSR)

$$F(q^2) = F^{\text{soft}}(\xi_{\perp, \parallel}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \dots$$

- For some schemes, large(r) uncertainties found for some observables [Camalich, Jäger]

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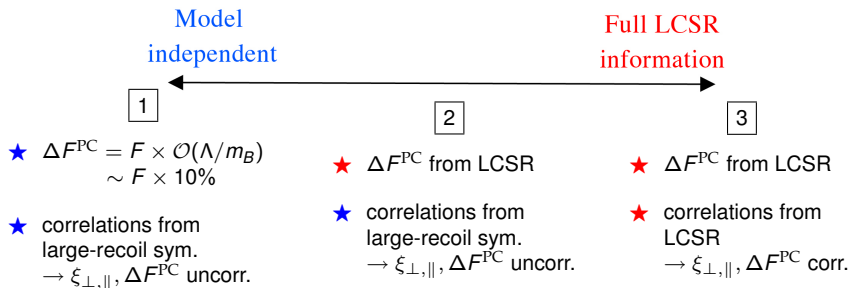
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Observables are scheme independent, but

procedure to compute them can be either **scheme dependent or not**

- Option 1: Include all correlations among error power corrections
- Option 2: Assign 10% uncorrelated uncertainties for pc
- 1 hinges on detail of ff determination, 2 depends on scheme ($a_i = b_i = 0$ for different form factors in each scheme)

More on very large power corrections (2)



More on very large power corrections (2)

Model
independent

Full LCSR
information

1

★ $\Delta F^{\text{PC}} = F \times \mathcal{O}(\Lambda/m_B)$
 $\sim F \times 10\%$

★ correlations from
large-recoil sym.
 $\rightarrow \xi_{\perp, \parallel}, \Delta F^{\text{PC}} \text{ uncorr.}$

2

★ ΔF^{PC} from LCSR

★ correlations from
large-recoil sym.
 $\rightarrow \xi_{\perp, \parallel}, \Delta F^{\text{PC}} \text{ uncorr.}$

3

★ ΔF^{PC} from LCSR

★ correlations from
LCSR
 $\rightarrow \xi_{\perp, \parallel}, \Delta F^{\text{PC}} \text{ corr.}$

| $P_5'[4.0, 6.0]$ | scheme 1 | scheme 2 |
|------------------|------------------|------------------|
| 1 | -0.72 ± 0.05 | -0.72 ± 0.12 |
| 2 | -0.72 ± 0.03 | -0.72 ± 0.03 |
| 3 | -0.72 ± 0.03 | -0.72 ± 0.03 |
| full BSZ | -0.72 ± 0.03 | |

- using [Bharucha, Straub, Zwicky] (correlations provided)
- 2 schemes defining $\xi_{\parallel, \perp}$
- expected magnitude for pc
- scheme indep. restored if ΔF^{PC} from LCSR
- ff in 1 at odds with LCSR