Flavour anomalies

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Louvain-La-Neuve, 17/6/16

Outline

1. The power of flavour physics
2. Interesting deviations in $b \to c\ell\bar{\nu}_\ell$
3. Remarkable deviations in $b \to s\ell\ell$
4. Outlook

The power of flavour physics

Particle physics

Central question of QFT-based particle physics

$$\mathcal{L} =?$$

Particle physics

Central question of QFT-based particle physics

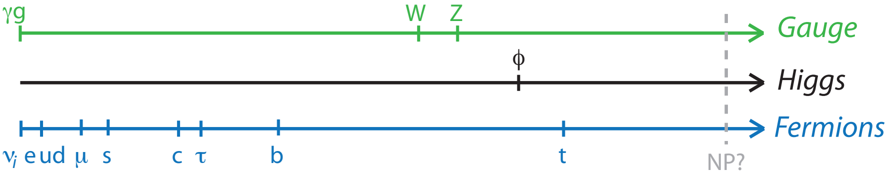
$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?

SM best answer up to now, but

- neutrino masses
- dark matter
- dark energy
- baryon asymmetry of the universe
- hierarchy problem

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

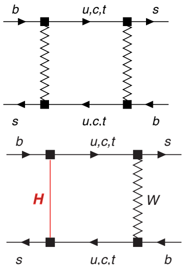
- Hierarchy of CP asymmetries according to generations
- Quantum sensitivity (via loops) to large range of scales
- GIM suppression of Flavour-Changing Neutral Currents

$\Longrightarrow$ Interesting probe of the Standard Model and beyond...

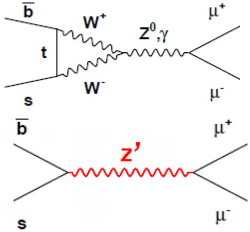
Flavour-Changing Neutral Currents

Forbidden in SM at tree level, and suppressed by GIM at one loop
so good place for NP to show up (tree or loops)

$\Delta F = 2$: B_s mixing

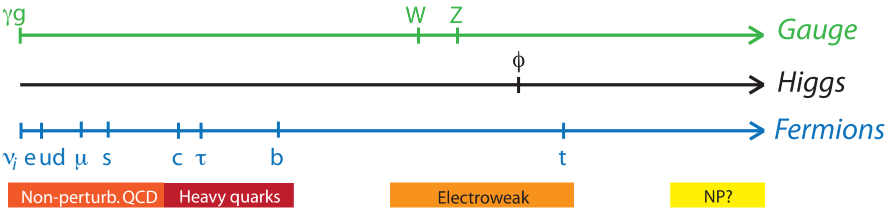


$\Delta F = 1$: $B_s \to \mu\mu$



Experimental and theoretical effort
on interesting FCNC transitions

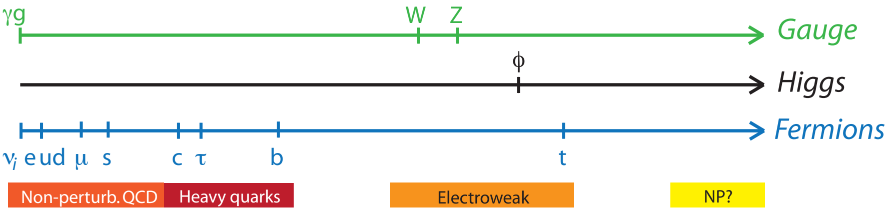
A multi-scale problem



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

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

A multi-scale problem



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- Main theo problem from hadronisation of quarks into hadrons

  description/parametrisation in terms of QCD quantities

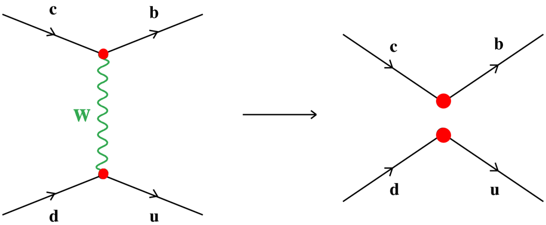
  decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties

  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



$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \; \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

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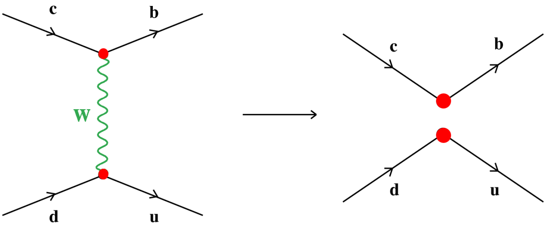


$$V_{ud} V^*_{cb} \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5) d \bar{b}\gamma^\mu(1-\gamma_5) c + O(1/M_W^2)$$

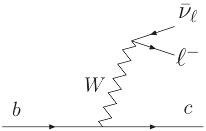
Fermi theory carries some info on the underlying theory

- G_F: scale of underlying 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)



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

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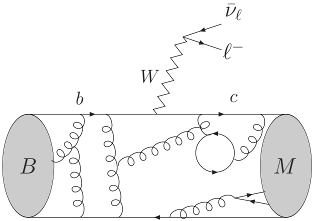

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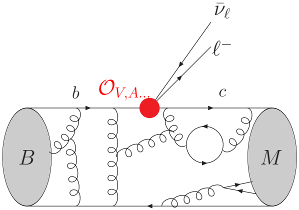

involving hadronic quantities such as form factors

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

$\Longrightarrow$observables with limited sensitivity to (ratio of form) factors

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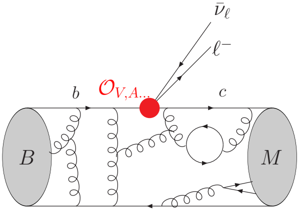

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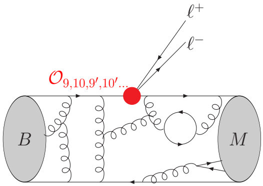
Two possible uses of effective approaches

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

B-meson form factors



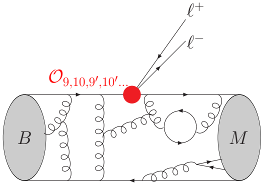
For illustration, take $B \to V$ transitions, described in general by 7 form factors: V (vector), $A_{0,1,2}$ (axial) and $T_{1,2,3}$ (tensor), depending on $q^2 = (p-k)^2$

$$
\begin{aligned}
\langle V(k)|\bar{s}\gamma_\mu(1-\gamma_5)|B(\epsilon,p)\rangle &= -i\epsilon_\mu(m_B+m_V)A_1(q^2) + i(p+k)_\mu(\epsilon^*\cdot q)\frac{A_2(q^2)}{m_B+m_V} \\
&\quad + iq_\mu(\epsilon^*\cdot q)\frac{2m_V}{q^2}\tilde{A}_0(q^2) + \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma\frac{2V(q^2)}{m_B+m_V} \\
\langle V(k)|\bar{s}\sigma_{\mu\nu}q^\nu(1+\gamma_5)|B(\epsilon,p)\rangle &= i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma 2T_1(q^2) + \epsilon^*_\mu(m_B^2-m_V^2)T_2(q^2) \\
&\quad -(p+k)_\mu(\epsilon^*\cdot q)\tilde{T}_3(q^2) + q_\mu(\epsilon^*\cdot q)T_3(q^2)
\end{aligned}
$$

with $\tilde{A}_0$ linear combination of $A_{0,1,2}$ and $\tilde{T}_3$ of $T_{2,3}$

Can these form factors be further simplified/factorised using $\Lambda \ll m_B$?

The last step of factorisation



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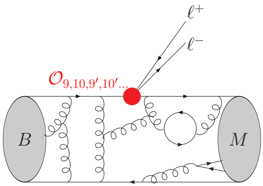

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Large recoil of the meson $(\Lambda \ll E_V \sim m_B)$

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

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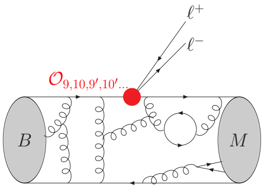

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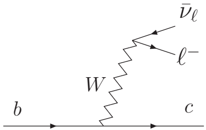
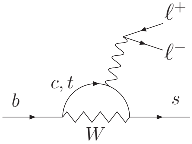
Low recoil of the meson $(E_V \sim \Lambda_{QCD} \ll m_B)$

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

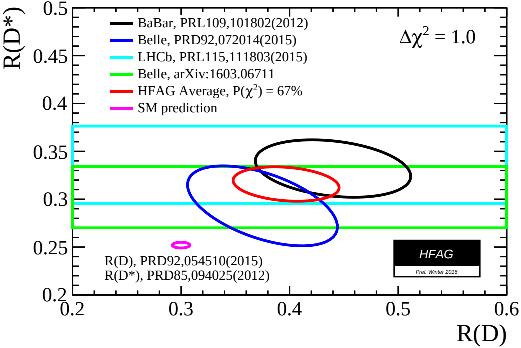
Two transitions of interest

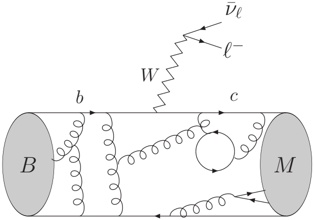
	$b \to c\ell\bar{\nu}_\ell$	$b \to s\ell^+\ell^-$
		
SM	tree (charged) ($V - A$)	loop (neutral)
Spin 0	$\overline{B} \to D\ell\bar{\nu}_\ell$	$B \to K\ell\ell$
Spin 1	$\overline{B} \to D^*\ell\bar{\nu}_\ell$	$B \to K^*\ell\ell$, $B_s \to \phi\ell\ell$
Observables	Total Br	$d\Gamma/dq^2$ + Angular obs
with	$\ell = \tau, \mu, e$	$\ell = \mu, e$
Tensions	$R_{D(*)} = \frac{Br(B \to D(^*)\tau\nu)}{Br(B \to D(^*)\ell\bar{\nu}_\ell)}$	$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$ $Br\ (K, K^*, \phi + \mu\mu)$ angular obs (e.g., P_5')

Two transitions exhibiting interesting patterns of deviations from SM

Interesting deviations in $b \to c\ell\bar{\nu}_\ell$

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





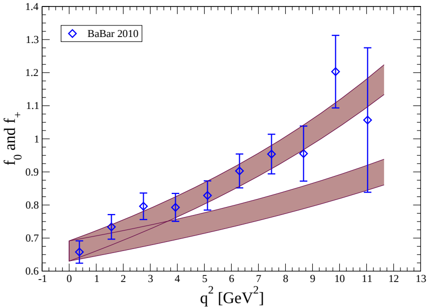
$$R_{D(*)} = \frac{Br(B \to D(^*)\tau\nu)}{Br(B \to D(^*)\ell\bar{\nu}_\ell)}$$

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

What is the basis for these predictions ?

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

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



- $\vec{p}$ 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]

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

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

- H_λ describing $B \to D^*(\to D\pi)\ell\bar{\nu}_\ell$ 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)

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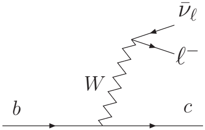
- No complete lattice determination, need other approaches !
  - HQET: Form factors related in the limit $m_b \to \infty$,
    providing ratios of form factors up to $O(\Lambda/m_B)$ corrections
  - Normalisation from Belle on $B \to D^* \ell \bar{\nu}_\ell$ ($\ell = e, \mu$)
    assuming no NP for light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

[Fajfer, Kamenik, Nisandzic]

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



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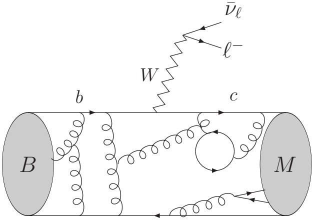

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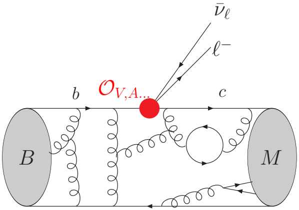

$\mathcal{H}^{\rm eff}$ to determine short-distance couplings and look for NP model-independently

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

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

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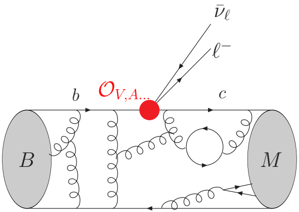

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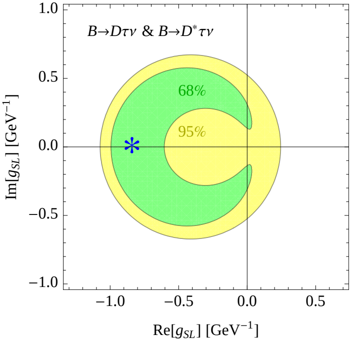
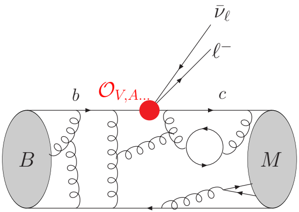
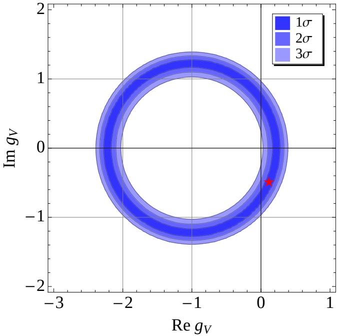


- Fit to R_D and R_{D^*} leading to viable explanation
- Scalar operators

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





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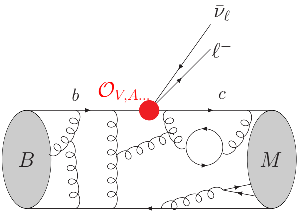
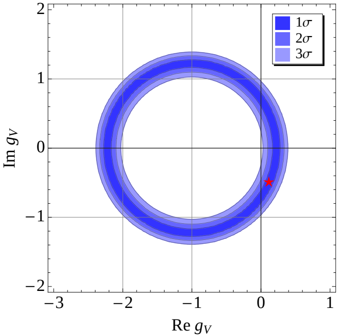
[with $P_{L,R} = (1 \mp \gamma_5)/2$]

- Fit to R_D and R_{D^*} leading to viable explanation
- Scalar operators or vector operators

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





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$$\times[\bar{c}\gamma^\mu P_L b + g_V \bar{c}\gamma^\mu b + g_{SL} i\partial^\mu(\bar{c}P_L b) + \ldots]$$

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

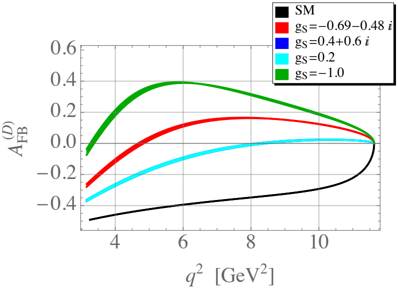
- Fit to R_D and R_{D^*} leading to viable explanation
- Scalar operators or vector operators
- However only few observables measured (neutrino in final state)
- Improving on $B \to D^*$ form factors ?

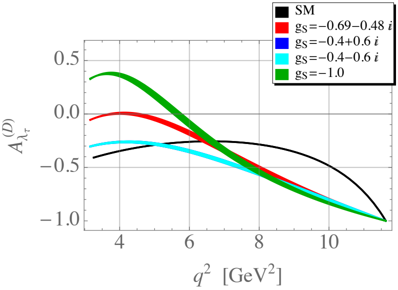
[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov, Pokorski, Crivellin, Freytsis, Ligeti, Ruderman. . .]

$b \to c\ell\bar{\nu}_\ell$: more observables on the way

3 observables for $B \to D\ell\nu$

- differential decay rate $d\Gamma/dq^2$
- forward-backward asymmetry
- lepton-polarisation asymmetry



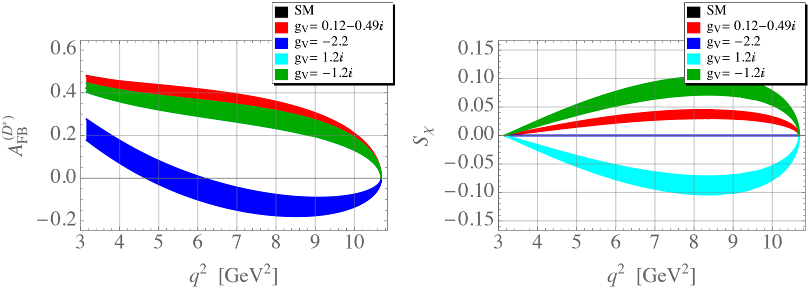


[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov. . .]

$b \to c\ell\bar{\nu}_\ell$: more observables on the way

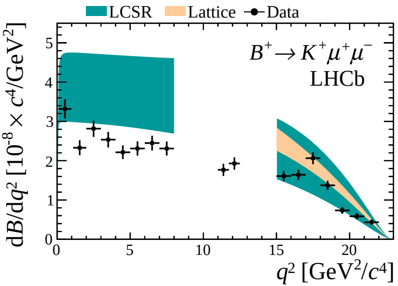
11 observables for $B \to D^*(\to D\pi)\ell\nu$

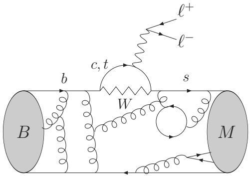
- differential decay rate $d\Gamma/dq^2$
- forward-backward asymmetry
- lepton-polarisation asymmetry
- partial decay rate according to D^* polar $(d\Gamma_L/dq^2)/(d\Gamma_T/dq^2)$
- angular observables (asymmetries with respect to two angles)



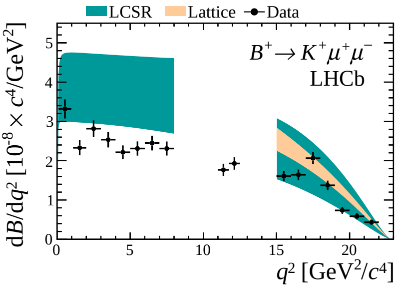
[Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov. . .]

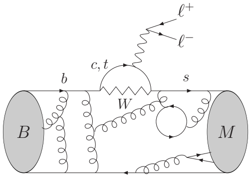
Remarkable deviations in $b \to s\ell\ell$

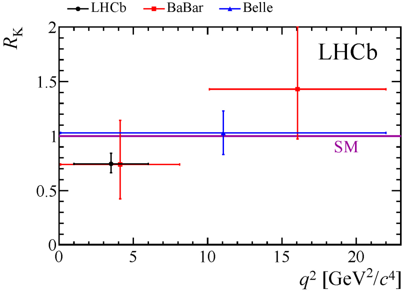




- $Br(B \to K\mu\mu)$ too low compared to SM

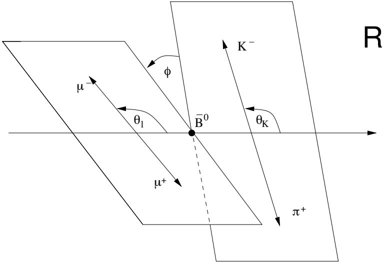






- $Br(B \to K\mu\mu)$ too low compared to SM
- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
- equals to 1 in SM (universality of lepton coupling), 2.6 σ dev
- would require NP coupling differently to μ and e

$b \to s\ell^+\ell^-$: $B \to K^*(\to K\pi)\mu\mu$ (1)



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 $B \to K^*(\to K\pi) V^*(\to \ell\ell)$

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

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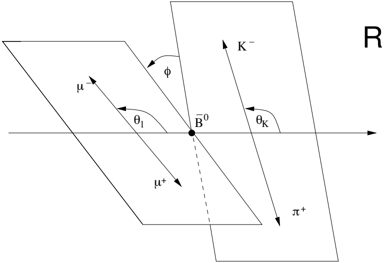

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- Transversity amplitudes in terms of 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- Relations between form factors in limit $m_B \to \infty$, either when K^* very soft or very energetic (low/large-recoil)

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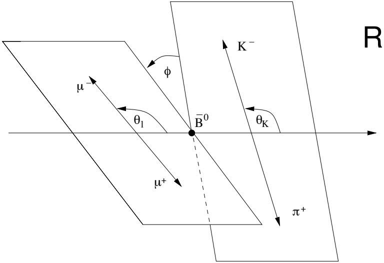

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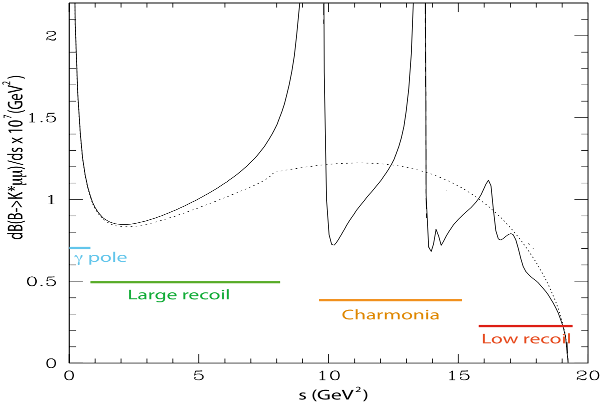
- Transversity amplitudes in terms of 7 form factors $A_{0,1,2}$, V, $T_{1,2,3}$
- Relations between form factors in limit $m_B \to \infty$,
  either when K^* very soft or very energetic (low/large-recoil)
- Build ratios of J_i where form factors cancel in these limits
  (corrections by hard gluons $O(\alpha_s)$, power corrs $O(\Lambda/m_B)$)
- Optimised observables P_i with reduced hadronic uncertainties

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

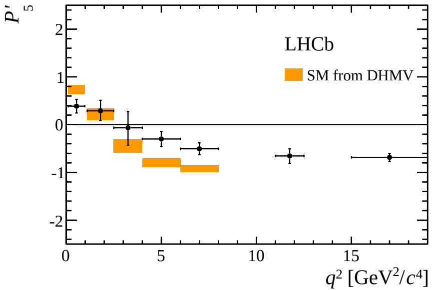
$b \to s\ell^+\ell^-$: $B \to K^*\mu\mu$ (2)



- 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^* ($E_{K^*} \gg \Lambda_{QCD}$)

  LCSR, SCET, QCD factorisation
- 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^* ($E_{K^*} \simeq \Lambda_{QCD}$)

$b \to s\ell^+\ell^-$: $B \to K^*\mu\mu$ (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 2.8 σ and 3.0 σ

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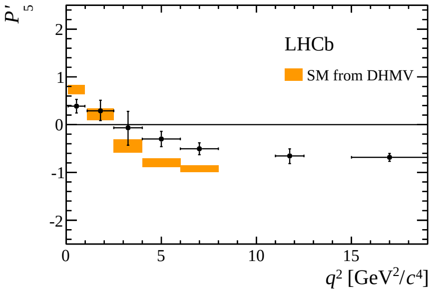

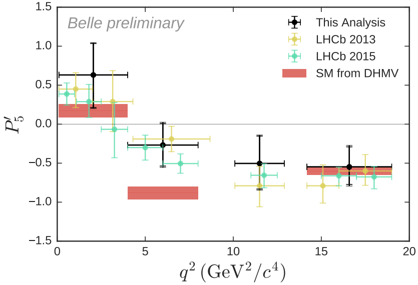

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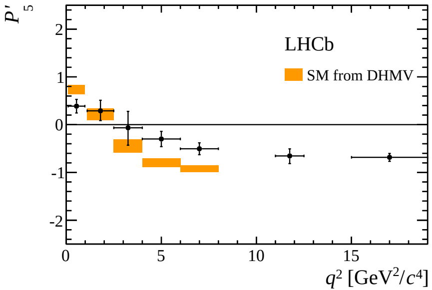

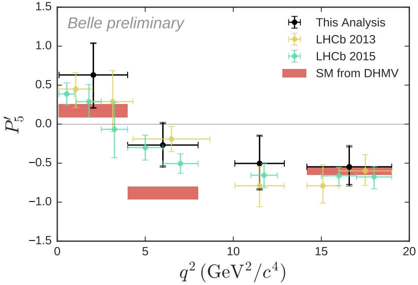

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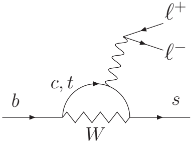
- Discrepancies for some (but not all) observables,
  in particular two bins for P'_5 deviating from SM by 2.8 σ and 3.0 σ
- ...confirmed by Belle last month
- Also deviations in $BR(B \to K^*\mu\mu)$ and $BR(B_s \to \phi\mu\mu)$ at low recoil

$b \to s\mu\mu$ effective hamiltonian



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

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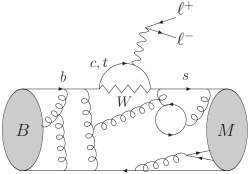

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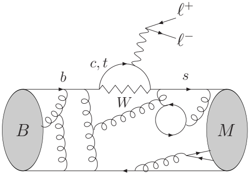

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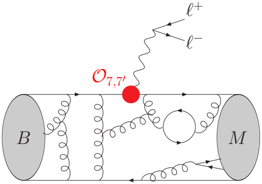

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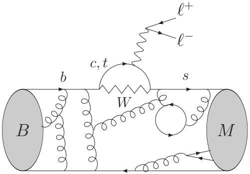

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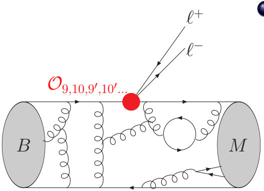
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]



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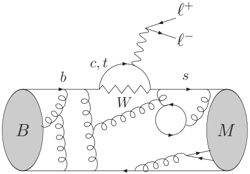

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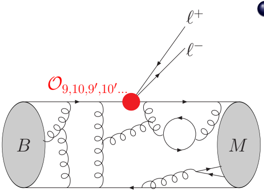

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3 \ @\ \mu_b = m_b$$

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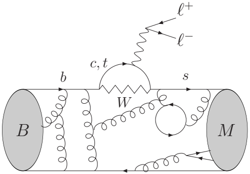

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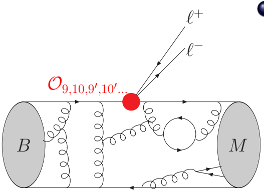

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3 \text{ @ } \mu_b = m_b$$

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

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

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

[SDG, Hofer, Matias, Virto]

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

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

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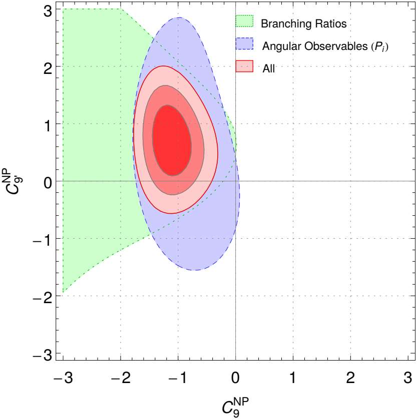
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\mu\mu$ (BR)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR), $B \to K^*\gamma$ (A_I and $S_{K^*\gamma}$)

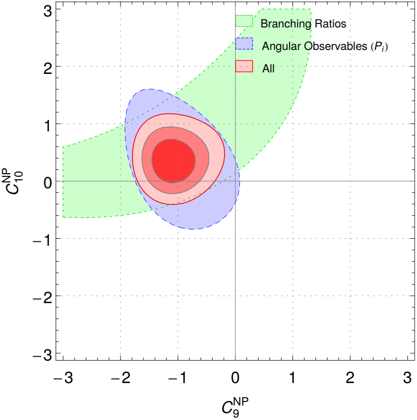
Frequentist analysis

- $\mathcal{C}_i(\mu_{ref}) = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ 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 $\mathcal{C}_i$ only" to be compared with SM

Some favoured scenarios (1)



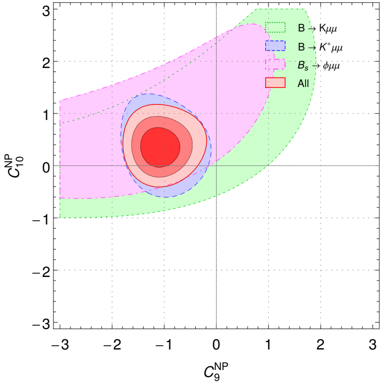
$\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}$

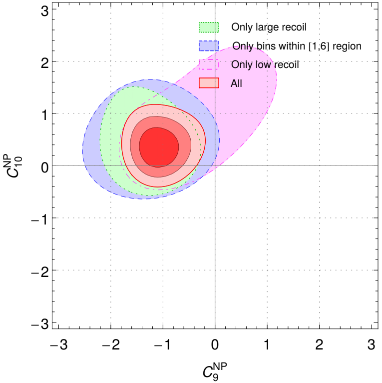


$\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP}$

- p-value=71% (goodness of fit), $\text{pull}_{SM} = 4.5\sigma$ (metrology)
- BRs and angular obs both favour $\mathcal{C}_9^{NP} \simeq -1$ in all “good” scenarios
- results in agreement with [Altmanshoffer, Straub] and [Hurth, Mahmoudi, Neshatpour]

Some favoured scenarios (2)



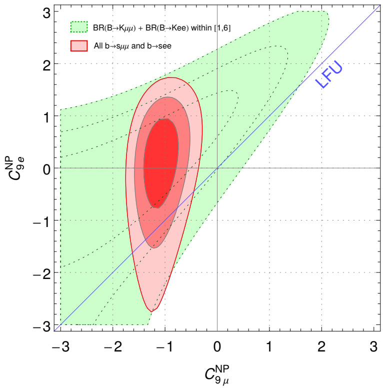


- Different processes and different kinematic ranges involving different theoretical tools
- $B \to K^*\mu\mu$ tighter than $B_s \to \phi\mu\mu$, tighter than $B \to K\mu\mu$
- Large recoil driving the discussion, but [1,6] bins already providing bulk of the effect, and low-recoil also in favour of $\mathcal{C}_9^{NP} < 0$

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

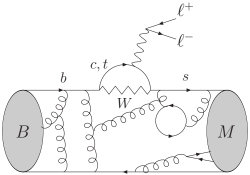
Lepton-flavour (non) universality

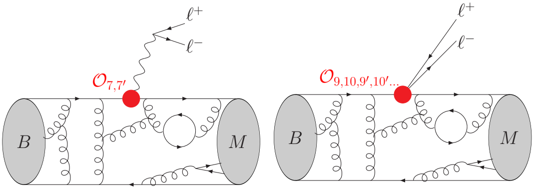
- Adding LHCb $BR(B \to Kee)$ and large-recoil obs for $B \to K^* ee$
- For several favoured scenarios, SM pull increases by $\sim 0.5\sigma$
- Favours violation of LFU, compatible with no NP in $b \to see$



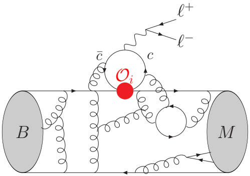
$\mathcal{C}_{9e}^{\rm NP}, \mathcal{C}_{9\mu}^{\rm NP}$

Controversies (1)



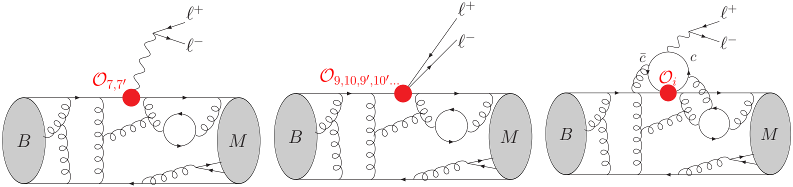


Form factors (local)



Charm loop (non-local)

Controversies (1)

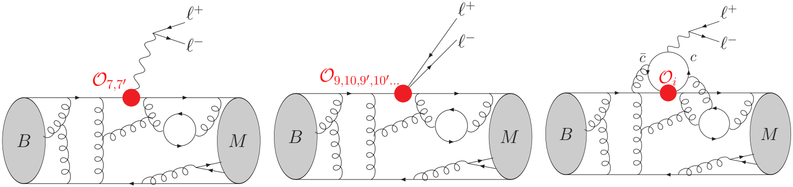


Form factors (local) Charm loop (non-local)

Uncertainties in form factors [Camalich, Jäger;Matias,Virto,Hofer,Capdevilla,SDG]

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

Controversies (1)

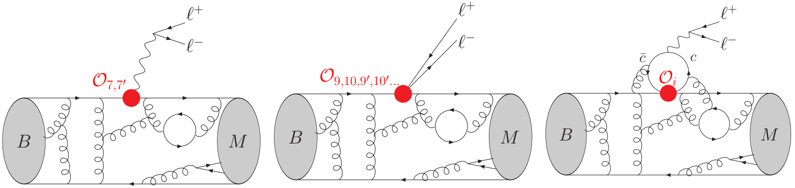


Form factors (local) Charm loop (non-local)

Uncertainties in form factors [Camalich, Jäger;Matias,Virto,Hofer,Capdevilla,SDG]

- EFT with limit $m_b \to \infty$ 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 $m_b \to \infty$ limit
  - power corrections varied in agreement with info on form factors
  - proper propagation of correlations induced among form factors

Controversies (2)



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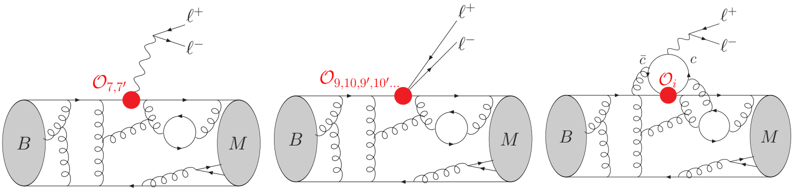

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Uncertainties from charm loops

[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 $\mathcal{O}_{7,9}$-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

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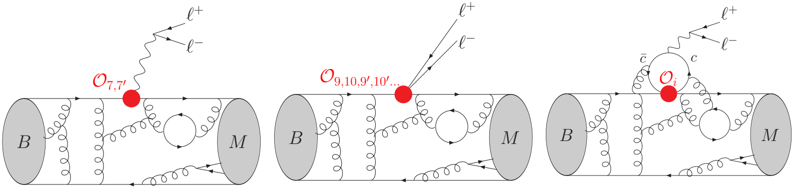

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  - other global fits use q^2-dependent param. with $O(\Lambda/m_b)$ estimates
- Bayesian extraction from data performed by [Ciuchini et al.]
  - q^2-dependence present, significant, following [Khodjamirian et al.]
  - actually not contradicting results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

Anomaly patterns

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR	Best fit now
$\mathcal{C}_9^{NP}$	$+$					
	$-$	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{NP}$	$+$	✓		✓	✓	X
	$-$		✓			
$\mathcal{C}_{9'}^{NP}$	$+$			✓	✓	X
	$-$	✓	✓			
$\mathcal{C}_{10'}^{NP}$	$+$	✓	✓			
	$-$			✓	✓	X

- assuming no NP in $b \to see$
- $\mathcal{C}_9^{NP} < 0$ consistent with all anomalies
- lower sensitivity to other $\mathcal{C}_i$ (cannot be mimicked by long dist), with $\mathcal{C}_{10}$ most promising but no consistent picture yet
- global agreement with other fits performed by [Altmanshoffer, Straub] and [Hurth, Mahmoudi, Neshatpour]

Quo vadis ?

NP interpretations

Improvement needed for form factors in $b \to c\ell\nu$,

but no consistent global alternative from SM/long-dist. for $b \to s\ell\ell$

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

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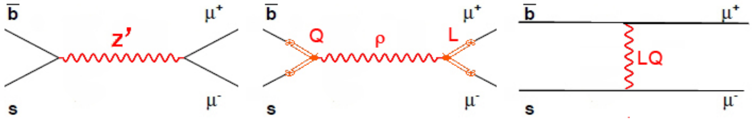
NP models with new scale around TeV
often trying to connect $b \to s\ell^+\ell^-$ and $b \to c\ell\bar{\nu}_\ell$ (3rd vs 2nd gen)

- Z', W' bosons (larger gauge group)
- Partial compositeness (mixing between known and extra fermions)
- Leptoquarks (coupling to a quark and a lepton)
- MSSM susy definitely not favoured . . .



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

What next ?

$b \to c\ell\bar{\nu}_\ell$ [Freytsis, Ligeti,Ruderman; Fajfer, Kamenik, Nisandzic, Becirevic, Tayduganov. . .]

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

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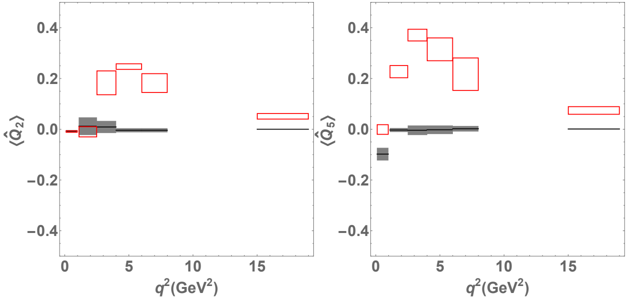


$b \to s\ell^+\ell^-$ [Matias,Virto,Hofer,Capdevilla,SDG. . .]

- 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

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

- Many observables, more or less sensitive to hadronic unc.
- Interesting deviations from SM expectations
- Global fit to $b \to c\ell\bar{\nu}$ still only limited amount of information
- Global fit to $b \to s\ell^+\ell^-$ in favour of large deviation for $\mathcal{C}_9$ in $b \to s\mu\mu$ 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 $b \to s\mu\mu$ (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 !

International Workshop on

Flavor Physics and New Physics Searches

26-30 September 2016, Fréjus, France

Information and Registration on http://indico.in2p3.fr/e/FlavorNewPhys

A few recent analyses

	[SDG, Hofer Matias, Virto]	[Straub & Altmannshofer]	[Hurth, Mahmoudi, Neshatpour]
Statistical approach	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$	Frequentist $\Delta\chi^2$ & χ^2
Data	LHCb	Averages	LHCb
$B \to K^*\mu\mu$ 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
$\mathcal{C}_9^\mu$ 1D 1σ	[-1.29,-0.87]	[-1.54,-0.53]	[-0.27,-0.13]
pull$_{SM}$	4.5 σ	3.7 σ	4.2σ
"good scenarios"	see before	$\mathcal{C}_9^{NP}, \mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$ $(\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}), (\mathcal{C}_9, \mathcal{C}_{10}^{NP})$	$(\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}), (\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP})$

$\Longrightarrow$Good overall agreement for the results of the three fits

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

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

Coefficient	Best Fit Point	3σ	Pull_{SM}	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
$\mathcal{C}_9^{\text{NP}}$	-1.09	$[-1.67, -0.39]$	4.5	63.0
$\mathcal{C}_{10}^{\text{NP}}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.22	$[-0.74, 0.50]$	1.1	16.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.68	$[-1.22, -0.18]$	4.2	56.0
$\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$	-0.07	$[-0.86, 0.68]$	0.3	14.0
$\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	0.19	$[-0.17, 0.55]$	1.6	18.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.06	$[-1.60, -0.40]$	4.8	72.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.69	$[-1.37, -0.16]$	4.1	53.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.19	$[-0.55, 0.15]$	1.7	19.0

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

- Pull for the SM point in each scenario from $\chi^2_{\rm min} - \chi^2(\mathcal{C}_i = \mathcal{C}_j = 0)$
- p-value from $\chi^2_{\rm min}$ and N_{dof}
- several favoured scenarios, all with $\mathcal{C}_9^{\rm NP}$, hard to single out one

Coefficient	Best Fit Point	$\mathrm{Pull}_{\rm SM}$	p-value (%)
SM	–	–	16.0
$(\mathcal{C}_7^{\rm NP}, \mathcal{C}_9^{\rm NP})$	$(-0.00, -1.07)$	4.1	61.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10}^{\rm NP})$	$(-1.08, 0.33)$	4.3	67.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{7'}^{\rm NP})$	$(-1.09, 0.02)$	4.2	63.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{9'}^{\rm NP})$	$(-1.12, 0.77)$	4.5	72.0
$(\mathcal{C}_9^{\rm NP}, \mathcal{C}_{10'}^{\rm NP})$	$(-1.17, -0.35)$	4.5	71.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-1.15, 0.34)$	4.7	75.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP})$	$(-1.06, 0.06)$	4.4	70.0
$(\mathcal{C}_9^{\rm NP} = \mathcal{C}_{9'}^{\rm NP}, \mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-0.64, -0.21)$	3.9	55.0
$(\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}, \mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP})$	$(-0.72, 0.29)$	3.8	53.0

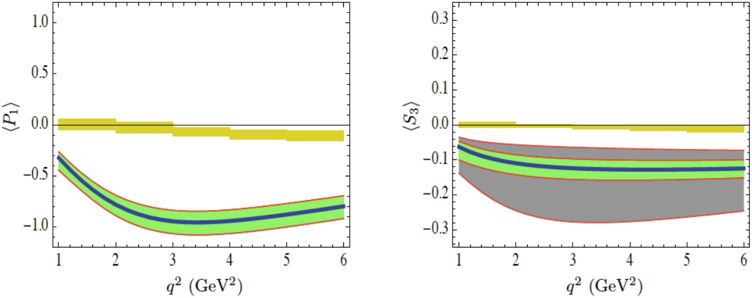
$b \to s\mu\mu$: 6D hypothesis

Letting all 6 Wilson coefficients vary (but only real)

Coefficient	1σ	2σ	3σ	Preference
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$	no pref
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$	negative
$\mathcal{C}_{10}^{\rm NP}$	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$	positive
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.06]$	$[-0.06, 0.07]$	no pref
$\mathcal{C}_{9'}^{\rm NP}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$	positive
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$	no pref

- $\mathcal{C}_9$ is consistent with SM only above 3σ
- All others are consistent with zero at 1σ except for $\mathcal{C}_{9'}$ at 2 σ
- $\text{Pull}_{\rm SM}$ 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

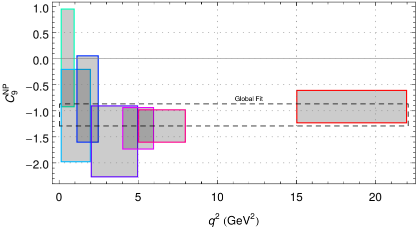
$$P_1 = \frac{2S_3}{1-F_L} \qquad F_L = \frac{J_{1c}+\bar{J}_{1c}}{\Gamma+\bar{\Gamma}} \qquad S_3 = \frac{J_3+\bar{J}_3}{\Gamma+\bar{\Gamma}}$$

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 $\mathcal{C}_9$



- $\mathcal{C}_9^{\rm NP}$ bin by bin assuming NP in $\mathcal{C}_9^{\rm NP}$, $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$ or $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$

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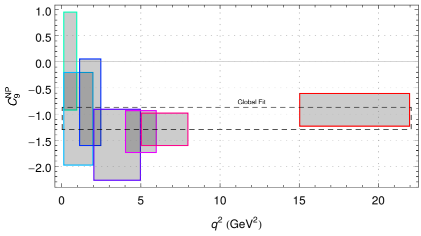

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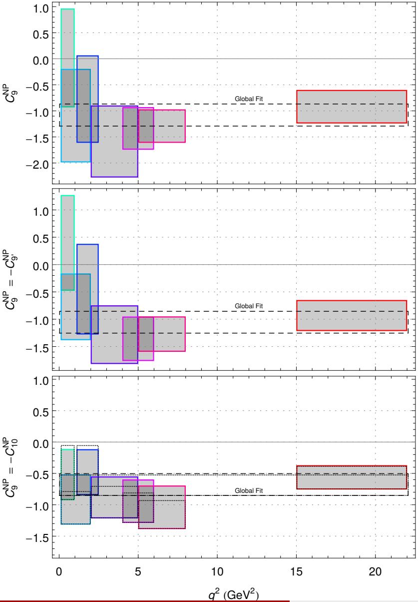
- Up: Assuming shift in $\mathcal{C}_9$ only tests need for hadronic contrib:
  - NP in $\mathcal{C}_9$ from short distances, q^2-independent
  - Hadronic physics in $\mathcal{C}_9$ is related to $c\bar{c}$ dynamics, (likely) q^2-dependent

Cross-checks: q^2-dependence of $\mathcal{C}_9$



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- Mid, down: correlated shift in $\mathcal{C}_9$ and other $\mathcal{C}_i$ (never q^2-depend: are NP scenarios consistent ?)

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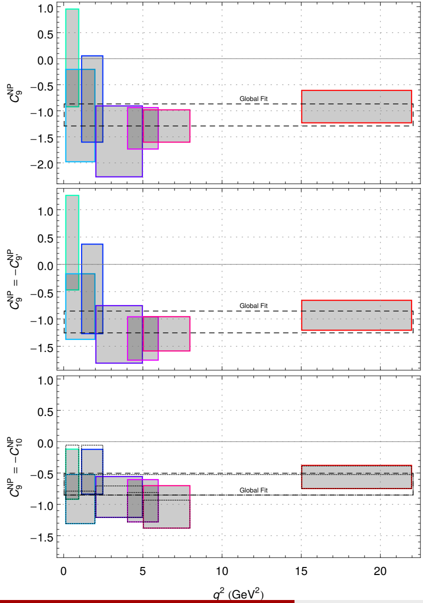

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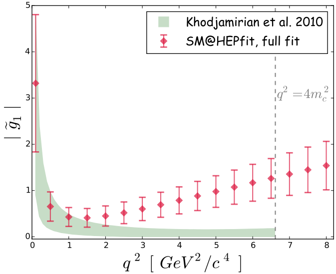
- Mid, down: correlated shift in $\mathcal{C}_9$ and other $\mathcal{C}_i$ (never q^2-depend: are NP scenarios consistent ?)
- No indication of q^2-dependent contribution

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 + $\Delta\mathcal{C}_9^{BK^{(*)}}$ [Khodjamirian et al.] at $q^2 < 1$ GeV^2 yields q^2-dep $c\bar{c}$ contribution, with "large" coefs for q^4

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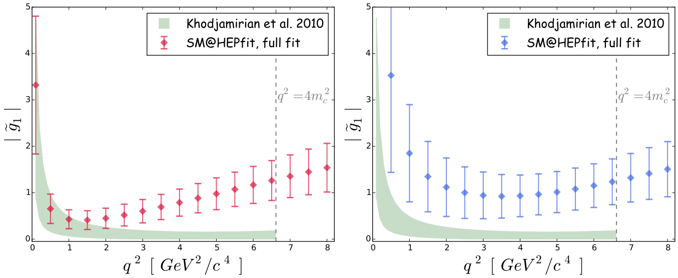

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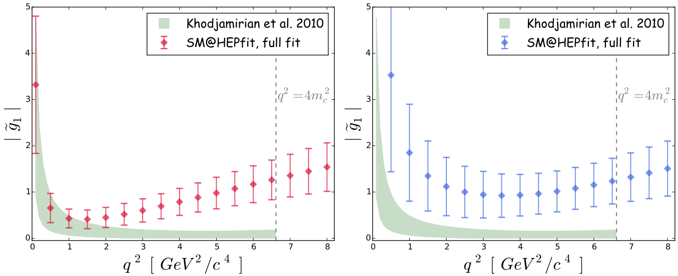

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- no explanation for R_K or deviations in low-recoil BRs
- data on $B \to K^*\mu\mu$ to fix q^2-polynomial before any prediction

More on very large power corrections (1)

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

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

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

$$F(q^2) = F^{\rm soft}(\xi_{\perp,||}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

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

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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)

Model independent ⟵⟶ Full LCSR information

1

- ★ $\Delta F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B)$
  $\sim F \times 10\%$
- ★ correlations from large-recoil sym.
  $\rightarrow \xi_{\perp,\parallel}, \Delta F^{\rm PC}$ uncorr.

2

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

3

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

More on very large power corrections (2)

Model independent ⟵⟶ Full LCSR information

1

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

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

2

★ $\Delta F^{\rm PC}$ from LCSR

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

3

★ $\Delta F^{\rm PC}$ from LCSR

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

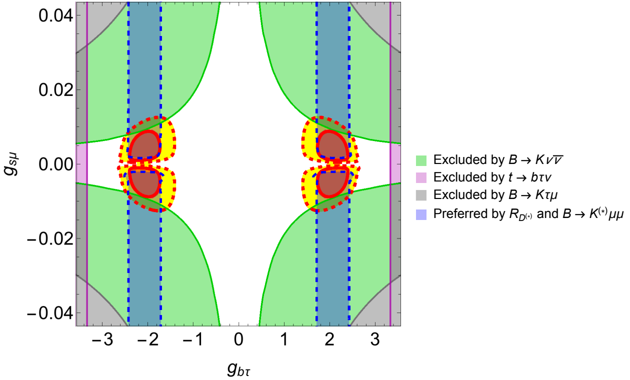
$P_5'[4.0,6.0]$	scheme 1	scheme 2
1	-0.72 ± 0.05	-0.72 ± 0.12
2	-0.72 ± 0.03	-0.72 ± 0.03
3	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	-0.72 ± 0.03	

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

NP interpretations: leptoquarks (1)

Vector leptoquark $(3,2)_{2/3}$ [Fajfer, Kosnik]

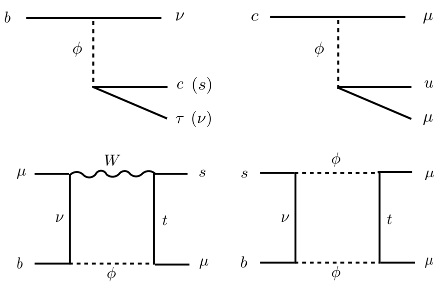
- $g_{s\mu}, g_{b\mu}, g_{b\tau}$ only large couplings
- both R_K and $R_{D^{(*)}}$ at tree level
- flavour constraints: $t \to b\tau^+\nu$, LFU tests for kaon, $B \to K^{(*)}\bar{\nu}\nu$, $B \to K\mu\tau$, $b \to c\mu^-\bar{\nu}$...



NP interpretations: leptoquarks (2)

Scalar leptoquark $(3, 1)_{-1/3}$ [Bauer, Neubert]

- near 1 TeV with $O(1)$ generation-diagonal couplings
- tree-level $b \to c\tau\nu$, $b \to s\nu\nu$ (and other semileptonic decays)
- loop-level $b \to s\mu\mu$, $(g-2)_\mu$
- need discrete symmetry to avoid proton decay
- bounds from $B \to K^{(*)}\nu\bar{\nu}$, $D^0 \to \mu\mu$, $D^+ \to \pi^+\mu\mu$

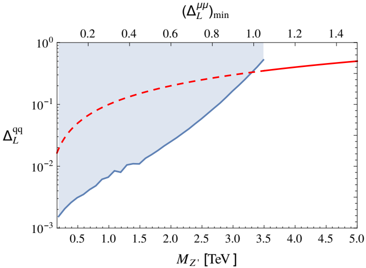


NP interpretations: Z' coupling

Z' coupling to $\mu\mu$ and $\bar{b}s$: $\bar{f}_i\gamma^\mu[\Delta_L^{f_if_j}P_L + \Delta_R^{f_if_j}P_R]f_jZ'_\mu$

[Altmannshofer, Straub, Buras, Girrbach, Gauld, Goertz, Haish. . .]

- contributes to $\mathcal{C}_9$ and $\mathcal{C}_{10}$ via $\Delta_L^{bs}\Delta_{L,R}^{\mu\mu}$
- Δ_L^{bs} constrained from B_s mixing
- Δ_L^{qq} for $q = u, d$ constrained by $q_L\bar{q}_L \to \mu\mu$ at ATLAS/CMS
- $M_{Z'} \geq 3$ TeV with weak-interaction strength couplings to u, d, but strong coupling to muons $\Delta_L^{\mu\mu} \geq 1$
- Same with vector-like coupling to muons



- blue shaded: excluded by $Z' \to \mu\mu$,
- above red: excluded by contact interactions
- upper axis: minimal Z' coupling to $\mu_L\mu_L$ for C_9, C_{10}

NP interpretations: heavy gauge bosons

Heavy gauge bosons from G(221) [Boucenna, Celis, Fuentes-Martin, Vicente, Virto]

- Gauge group symmetry breaking
  - L-breaking: $SU_L(2) \otimes SU_H(2) \otimes U(1)_H \to SU_L(2) \otimes U(1)_Y$
  - Y-breaking: $SU_1(2) \otimes SU_2(2) \otimes U(1)_Y \to \otimes SU_L(2) \otimes U(1)_Y$
- Non universality from
  - gauge coup. (non-univ. embedding of SM fermions in larger group)
  - Yukawas (non-universal mixing between SM fermions and extra particles coupled to new vector bosons)

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	L-breaking	Y-breaking
gauge coupling non univ	No left-handed current	Nonperturbativity
Yukawa non univ	No GIM	OK

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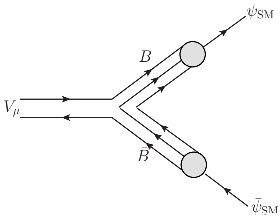
Explicit model (but no pheo analysis) with

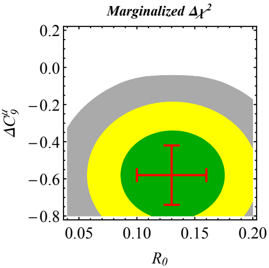
- $SU_C(3) \otimes SU_1(2) \otimes SU_2(2) \otimes U(1)_Y$
- breaking through $\phi = (1,1,2)_{1/2}$ and $\Phi = (1,2,\bar{2})_0$
- several generations of vector-like fermions $Q_L, Q_R = (3,2,1)_{1/6}, L_L, L_R = (1,2,1)_{-1/2}$
- left-handed fermions: anomalous W, Z couplings + W', Z' coupl

NP interpretations: partial compositeness

[Niehoff, Stangl, Straub, Butazzo, Greljo, Isidori, Marzocca]

- SM-like elementary sector
- strongly interacting BSM sector with symmetry H
- elementary fermions mix with fermion composite operators (measured by s_L)
- several examples fitting both $R_{D^{(*)}}$ and R_K





For instance

- new $SU(N_{TC})$
- vector-like techniquarks $(N_{TC}, 3, 2, Y_Q)$ and technileptons $(N_{TC}, 1, 2, Y_L)$

- mixing between quarks and technibaryons
- up to slight fine tuning

$|V_{ub}|$ from semileptonic B decays

Two ways of getting $|V_{ub}|$:

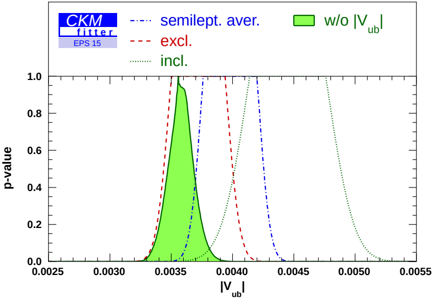
- Inclusive : $b \to u\ell\nu$ + Operator Product Expansion [HFAG BLNP]
- Exclusive : $B \to \pi\ell\nu$ + Form factors [J. A. Bailey et al., Fermilab-MILC]

$$|V_{ub}|_{inc} = 4.45 \pm 0.18 \pm 0.31$$
$$|V_{ub}|_{exc} = 3.72 \pm 0.09 \pm 0.22$$

$$|V_{ub}|_{ave} = 4.01 \pm 0.08 \pm 0.22$$

with all values $\times 10^{-3}$

- HFAG, with theory errors added linearly
- systematics combined using Educated Rfit



Indirect det. from global fit: $|V_{ub}|_{fit} = 3.57^{+0.15}_{-0.14}$ (4%)

$|V_{cb}|$ from semileptonic B decays

Two ways of getting $|V_{cb}|$:

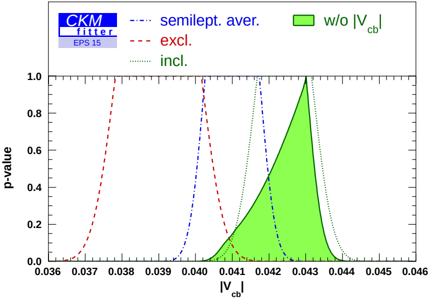
- Inclusive : $b \to c\ell\nu$ + OPE for moments [HFAG, Gambino and Schwanda]
- Exclusive : $B \to D(^*)\ell\nu$ + Form factors [J. A. Bailey et al., Fermilab-MILC]

$$|V_{cb}|_{inc} = 42.42 \pm 0.44 \pm 0.74$$
$$|V_{cb}|_{exc} = 38.99 \pm 0.49 \pm 1.17$$

$$|V_{cb}|_{ave} = 41.00 \pm 0.33 \pm 0.74$$

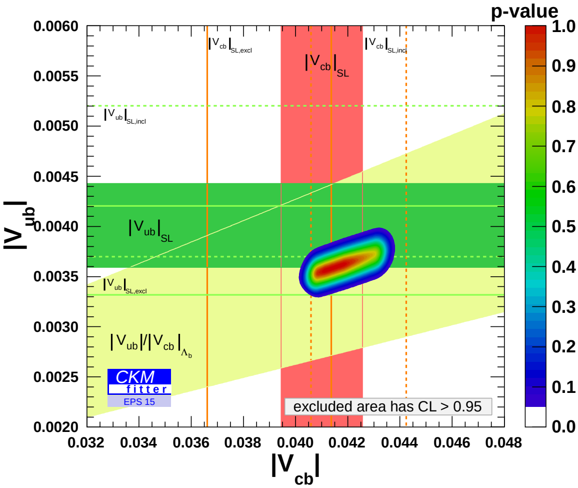
with all values $\times 10^{-3}$

- HFAG, with theory errors added linearly
- systematics combined using Educated Rfit



Indirect det. from global fit: $|V_{cb}|_{fit} = 43.0^{+0.4}_{-1.4}$ (4%)

$|V_{ub}|, |V_{cb}|$



- Information on $|V_{ub}|$ from $Br(B \to \tau\nu)$
- New LHCb result on $|V_{ub}/V_{cb}|$ from $\Gamma(\Lambda_b \to p\mu\nu)/\Gamma(\Lambda_b \to \Lambda_c\mu\nu)$ at high q^2

[Detmold, Lehner and Meinel]

- Global fit favours exclusive $|V_{ub}|_{SL}$ but inclusive $|V_{cb}|_{SL}$