Discussion on global fits

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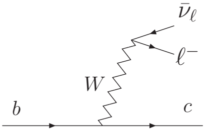
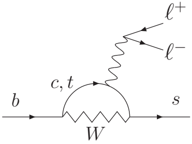
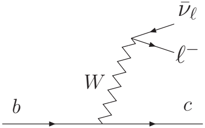
Two transitions of interest

	$b \to c\ell\bar{\nu}_\ell$	$b \to s\ell^+\ell^-$
		
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	$R_{D(*)} = \frac{Br(B \to D(^*)\tau\nu)}{Br(B \to D(^*)\ell\bar{\nu}_\ell)}$ $(\ell = e, \mu)$	$R_{K(*)} = \frac{Br(B \to K(^*)\mu\mu)}{Br(B \to K(^*)ee)}$ $Br\ (K, K^*, \phi + \mu\mu)$ angular obs (e.g., P_5')

Two transitions exhibiting interesting patterns of deviations from SM

A major tool: effective Hamiltonian

Starting from SM (or extensions) and integrating out heavy/energetic degrees of freedom



$$\mathcal{H}^{\rm eff} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$

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

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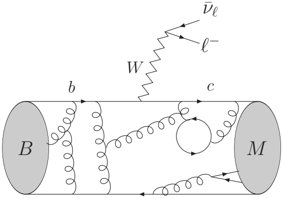

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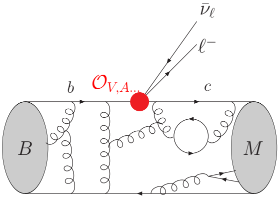

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involving hadronic quantities such as form factors (and others)

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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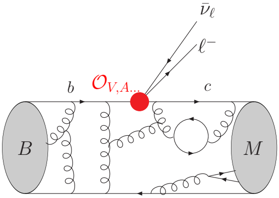

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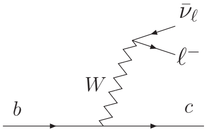
Two possible uses of effective approaches

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

How various analyses can differ ?

- Statistical treatment (Bayesian vs frequentist)
- Form factors
  - low q^2/large-meson recoil: light-cone sum rules (LCSR)
  - large q^2/low-meson recoil: lattice QCD (LQCD)
- Other hadronic inputs (intermediate resonances. . .)
- Help (or not) from effective theories ($m_b \to \infty$)
  - low q^2/large-meson recoil: Soft-Collinear Effective Theory (SCET)
  - large q^2/low-meson recoil: Heavy Quark Effective Theory (HQET)
- Sticking to one particular quark decay (e.g., $b \to s\mu\mu$ only) or trying to connect several of them through assumptions/symmetries
- NP scenarios considered
  - in all $\mathcal{C}_i$ or only some of them ?
  - correlating NP contributions among $\mathcal{C}_i$?
  - including imaginary parts or not ?
  - only violating lepton universality or also lepton universal ?

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



$$\mathcal{H}^{\rm eff}(b \to c\ell\nu) \propto G_F V_{cb} \sum \mathcal{C}_i \mathcal{O}_i$$

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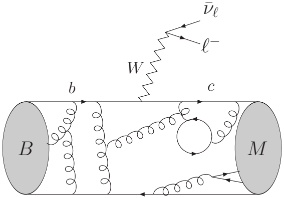

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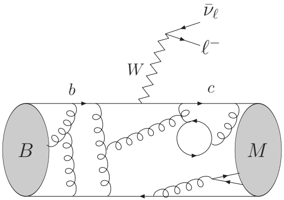

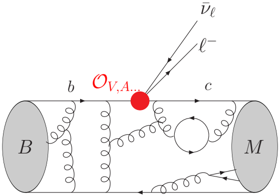

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- In the SM
  - $\mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$ [W exchange]
  - $\mathcal{C}_{V_L} = 1$ and universal for all three leptons
- Hadronic uncertainties all summarised in form factors defined from $\langle M|\mathcal{O}_i|B\rangle$

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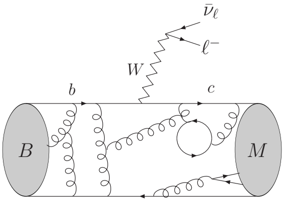

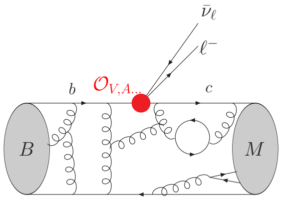

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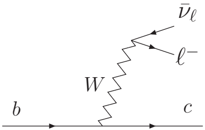
- NP changes short-distance $\mathcal{C}_i$ for SM or new long-distance ops $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_{V_L} \to \mathcal{O}_{V_R} \propto (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$
- (Pseudo)scalar ($W \to H^+$) $\mathcal{O}_{V_L} \to \mathcal{O}_{S_L} \propto (\bar{c} P_L b)(\bar{\ell} P_L \nu_\ell), \mathcal{O}_{S_R}$
- Tensor operators ($W \to T$) $\mathcal{O}_{V_L} \to \mathcal{O}_{T_L} \propto (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell)$

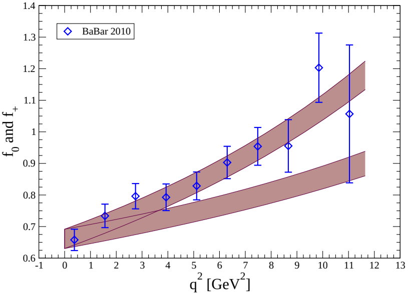
$b \to c\ell\bar{\nu}_\ell$ typical observables



$$
\begin{array}{cc}
B \to D^*\ell\nu & R_D = \frac{Br(B\to D\tau\nu)}{Br(B\to D\ell\nu)} \\
B \to D\ell\nu & R_{D^*} = \frac{Br(B\to D^*\tau\nu)}{Br(B\to D^*\ell\nu)},\ P_\tau,\ f_L(D^*) \\
B \to J/\psi\ell\nu & R_{J/\psi} = \frac{Br(B_c\to J/\psi\tau\nu)}{Br(B_c\to J/\psi\ell\nu)} \\
B_c \to \tau\nu & Br(B_c \to \tau\nu)\ [\text{bound from } \Gamma(B_c)]
\end{array}
$$

$\ell = e, \mu$ (integrated over all phase space)

Hadronic uncertainties



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

- SM: 2 form factors f_+ (vector) and f_0 (scalar)
- NP: 1 more f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range

[HPQCD, FNAL/MILC collaborations]

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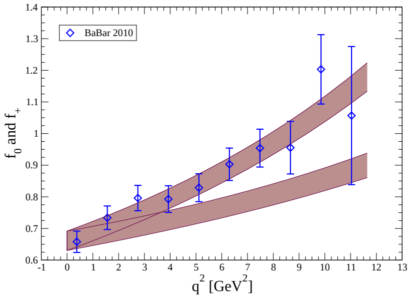

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$B \to D^*\ell\bar{\nu}_\ell$ branching ratios

- 4 form factors $V, A_{0.1,2}$ (vector/axial) + NP: 3 more $T_{1,2,3}$ (tensor)
- No complete lattice determination [Fajfer, Kamenik, Nisandzic]
  - Belle: $B \to D^*\ell\bar{\nu}_\ell$ ($\ell = e, \mu$) form factors, assuming no NP [Jung, Straub]
  - Supplemented by HQET considerations
    - relations in the limit $m_b \to \infty$, normalisation in the no-recoil limit
    - corrections to be estimated with theoretical prejudices (CLN param)
  - Or fit using a generic polynomial z-expansion (BGL param)
  - Ongoing discussion, potential impact on $|V_{cb}|$ but not much on R_{D^*}

[Bigi, Gambino, Schacht; Grinstein, Koback; Bernlochner, Ligeti, Papucci, Robinson]

Further data and questions

$R_{J/\psi}$ ($B_c \to J/\psi \ell \bar{\nu}_\ell$)

- LHCb measurement low compared to theoretical estimates, and rather interestingly

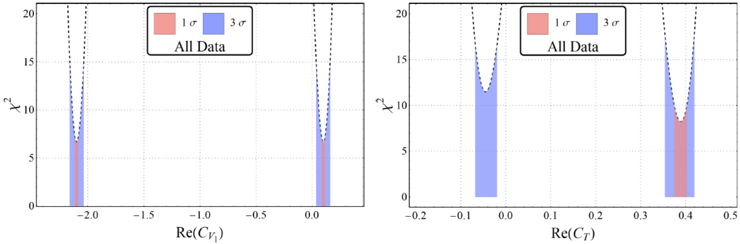
$$\frac{R_D}{R_{D;SM}} \simeq \frac{R_{D^*}}{R_{D^*;SM}} \simeq \frac{R_{J/\psi}}{R_{J/\psi;SM}}$$

- But current estimates of the form factors mainly based on models with uncertainties difficult to assess (compared to R_D and R_{D^*})

Potential issues

- Cross-checks of the form factors would be very welcome !
- Radiative corrs 3-4% for $E_\gamma^{\rm cut} = 20 - 40$ MeV [De Boer, Kitahira, Nisandzic]
- Width of the D^* in $D\pi$ [Chavez-Saab, Toledo; Le Yaouanc, Leroy, Roudeau]
  - Contribution from longitudinal polarisation to R_{D*} ?
    $\Longrightarrow$Possibly shift $\simeq$ 9% in SM direction,
    potentially reducing discrepancy from 3.4 σ to 2.2 σ
  - Tail of D^* at high $D\pi$ mass contributing to $B \to [D\pi]_{\rm broad}\ell\nu_\ell$?

Global fits in $b \to c\ell\bar{\nu}_\ell$

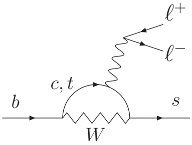


[Bhattacharyaa,Nandi,Patra;Alok,Kumar,Kumar,Kumbhakar,Uma Sankar;Kumar,London,Watanabe;Freytsis,Ligeti,Ruderman]

- Often NP only for $\ell = \tau$, assuming real Wilson coefficients (no CP violation), but some studies with also imaginary contributions
- Right-handed and (pseudo)scalar couplings disfavoured by B_c width (bound on $B_c \to \tau\nu$) and shape of $d\Gamma(B \to D^*\tau\nu)/dq^2$
- Tensor could describe the data, strong impact on P_τ and f_L
- Most simple explanation: NP in $\mathcal{C}_{V_L\tau}$, change of G_F for $b \to c\tau\bar{\nu}_\tau$

R_D and R_{D^*} not enough: more observables (angular analysis !)

$b \to s\ell\ell$ effective Hamiltonian



$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$

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

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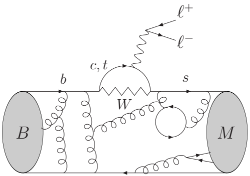

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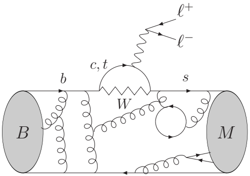

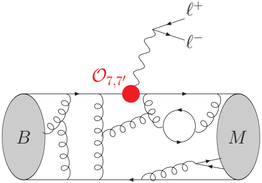

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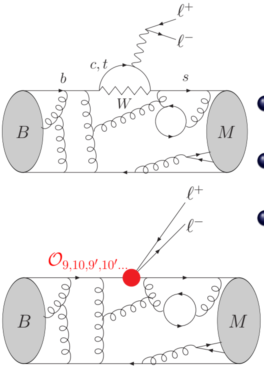

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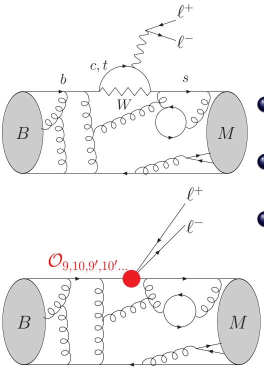
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

$b \to s\ell\ell$ effective Hamiltonian



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

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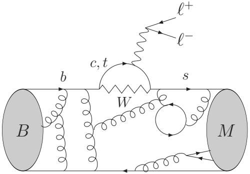

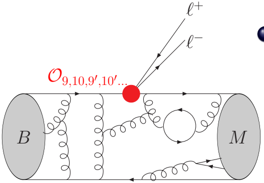

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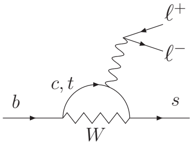
NP changes short-distance $\mathcal{C}_i$ or add new operators $\mathcal{O}_i$

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

$b \to s\ell\ell$ typical observables

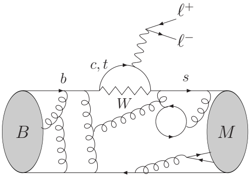


$B \to K^*\mu\mu$	Br, $P_{1,2}$, $P'_{4,5,6,8}$, F_L
$B \to K^*ee$	$P_{1,2,3}$, $P'_{4,5}$, F_L
$B \to K^*\ell\ell$	R_K, R_{K^*}, $Q_{4,5}$
$B_s \to \phi\mu\mu$	Br, P_1, $P'_{4,6}$, F_L
$B \to K\mu\mu$	Br
$B \to X_s\gamma$	Br
$B \to X_s\mu\mu$	Br
$B_s \to \mu\mu$	Br
$B_s \to \phi\gamma$	Br, $S_{\phi\gamma}$, $A_{\Delta\Gamma;\phi\gamma}$
$B \to K^*\gamma$	Br, $S_{K^*\gamma}$

binned in most cases, sometimes with CP asymmetries

Two sources of hadronic uncertainties

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



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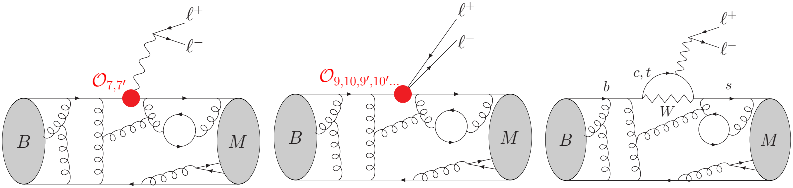

Form factors (local)

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

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

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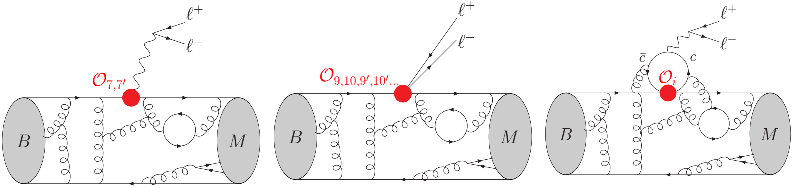


Form factors (local) Charm loop (non-local)

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

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

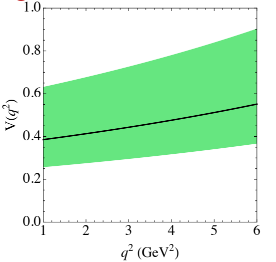
- Non-local contributions (charm loops): hadronic contribs.

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

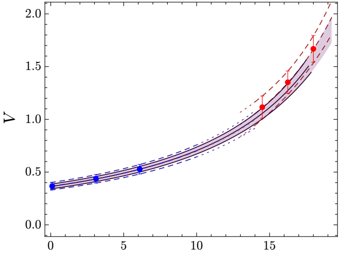
Hadronic uncertainties: form factors

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

- low recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: B-meson Light-Cone Sum Rule,
  large error bars and no correlations [Khodjamirian, Mannel, Pivovarov, Wang]
  recently reanalysed with correlations [Gubernari, Kokulu, van Dyk]
- all:fit light-meson LCSR + lattice, small errs, correls [Bharucha, Straub, Zwicky]



KMPW (LCSR, low q^2)



BSZ (fit LCSR + lattice)

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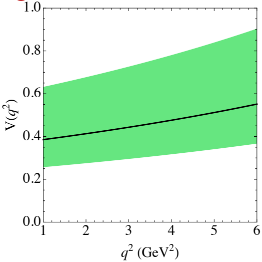

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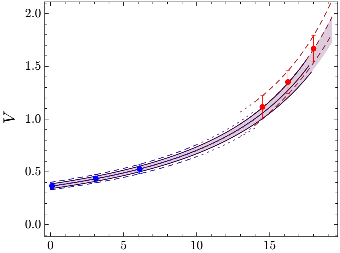

BSZ (fit LCSR + lattice)

- former controversies about EFT to obtain/restore correlations for form factors discussed and all approaches in good agreement

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

Hadronic uncertainties: charm loops

Charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_9$
- expected to depend on q^2
- …but lepton universal (little effect on R_K, even with NP)

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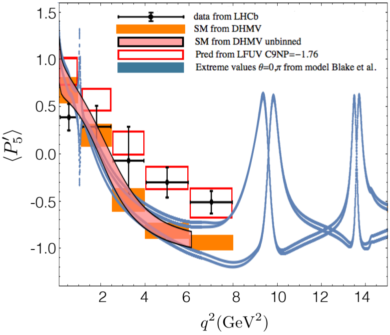

Several theo/pheno approaches

- LCSR estimate [Khodjamirian, Mannel, Pivovarov, Wang]
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
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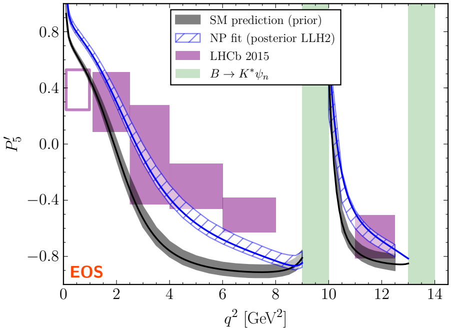

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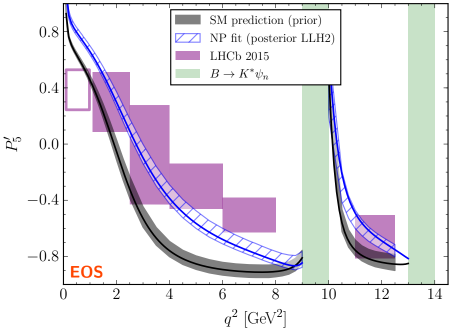

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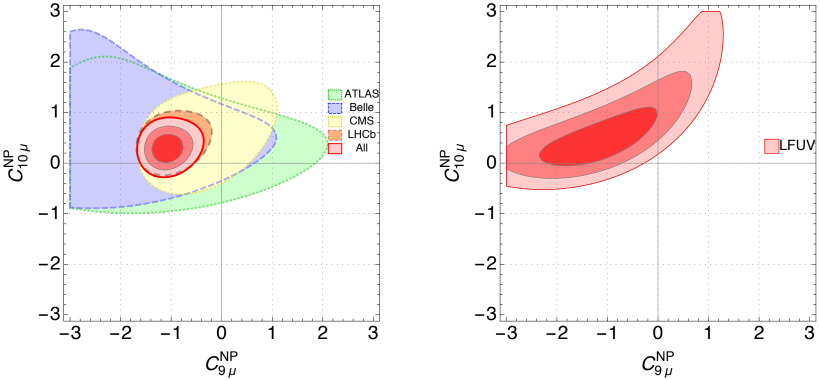
No hint in the fits of missing large q^2-dependent contribution

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

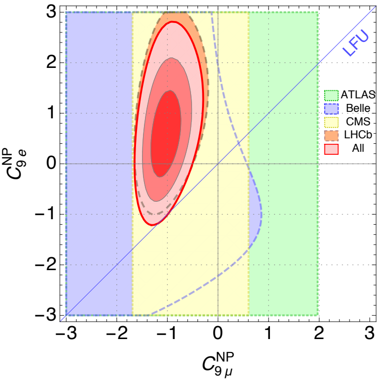
- 175 obs in [Capdevila, Crivellin, SDG, Matias, Virto], agree well with other global fits

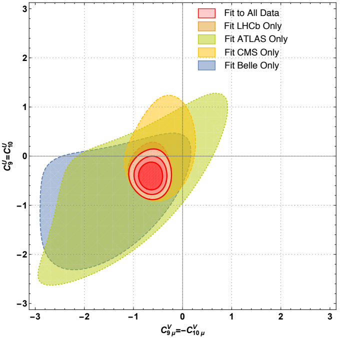
  [Straub, Stangl, Altmannshoffer; Hurth, Mahmoudi, Neshatpour; Geng, Grinstein, Jäger, Camalich, Ren, Shi]
- Real contributions, based on absence of CP violation
- Favoured $\mathcal{C}_{9\mu}^{NP} \simeq O(-1)$ + smaller corrections to other $\mathcal{C}_\rangle$
- $\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$ also good scenario (NP models with $SU(2)_L$)
- Overall consistency (All vs LFUV obs, channels, Brs vs angular)



Are we general enough ?

$C_{i\ell}^{NP}$ $\ell = e, \mu, \tau$ not related, to be fixed by data (scarce for e, none for τ)



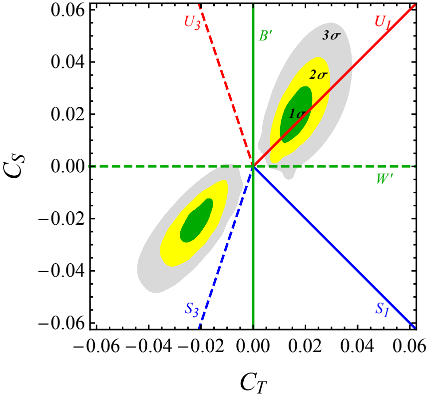


- Often no NP assumed in $b \to see$, but still room (eg NP in $\mathcal{C}_{9\mu}, \mathcal{C}_{9e}$)
- 4-par best-fit pt $(\mathcal{C}_{9e}, \mathcal{C}_{9\mu}, \mathcal{C}_{10e}, \mathcal{C}_{10\mu})^{NP} = -1.26, -1.18, 1.14, 0.23$
- Possibility of large LFU NP contribs, with preference for $V - A$ LFUV but $V + A$ for LFU

[Algueró, Capdevila, SDG, Masjuan, Matias]

$b \to c\ell\bar{\nu}_\ell$ and $b \to s\ell\ell$ combined analysis

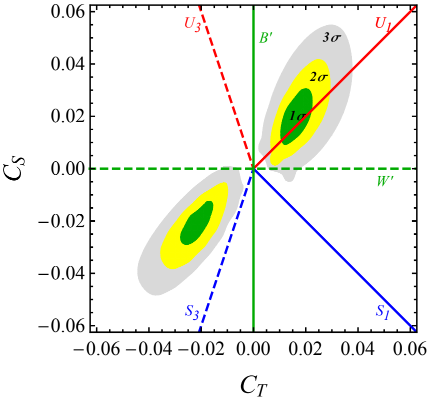
- SMEFT: NP higher-dim ops obeying $SU_C(3) \times SU_L(2) \times U_Y(1)$
- Restrictive (but reasonable) assumptions [Butazzo, Greljo, Isidroi, Marzocca]
  - Only left-handed fields
  - No lepton-flavour violating contributions
  - $U(2)_q \times U_\ell(2)$ symmetry for couplings with same structure



$$\lambda^q_{ij}\lambda^\ell_{ab}\left[\frac{C_S}{\Lambda^2}(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^a_L\gamma^\mu L^b_L) + \frac{C_T}{\Lambda^2}(\bar{Q}^i_L\gamma_\mu\sigma^\alpha Q^j_L)(\bar{L}^a_L\gamma^\mu\sigma^\alpha L^b_L)\right]$$

$$Q^i_L = \begin{pmatrix} V^*_{ji} u^j_L \\ d^i_L \end{pmatrix} \qquad L^a_L = \begin{pmatrix} \nu^a_L \\ \ell^a_L \end{pmatrix}$$

Single-mediator models and more



[Butazzo, Greljo, Isidroi, Marzocca]

- Disfavours colourless vectors (W', Z', green) and coloured scalars (S_1, S_3 leptoquarks, blue) + high p_T constraints
- Favours U_1 vector leptoquark $(3, 1, 2/3)$, which also passes direct LHC production limits
- Same conclusions taking a general structure of the couplings [Kumar, London, Watanabe]

Possible to consider models with more than 1 mediator

- Two scalar leptoquarks
- Three-generation Pati-Salam
- Composite models
- ...

[See P. Stangl's talk]

Outlook

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

- Many observables, more or less sensitive to hadronic unc.
- Global fit to $b \to c\ell\bar{\nu}$ still relying on limited amount of information, with questions on hadronic uncertainties (form factors, D^* width)
- 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
- Global fits of both sets using SMEFT, with many models proposed for either or both sets of deviations
- Several tools to perform some fits (flavio, EOS, Hammer…)

Where to go ?

- Better measurements of q^2 and angular dependence
- More info on processes with e and/or τ
- Other LFU violating observables
- Provide lattice form factors over larger range
- Further constraints on $c\bar{c}$ loops
- New observables (CP-violation, time-dep, LFUV and LFV obs…)