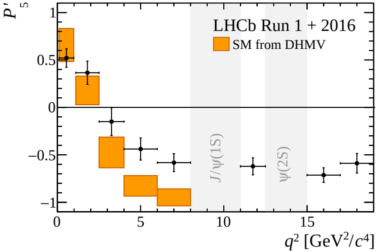
Exploiting the time evolution of rare decays of B_d and B_s mesons

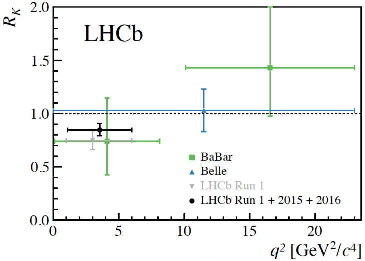
Sébastien Descotes-Genon

IJCLab
CNRS & Université Paris-Saclay, Orsay, France
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie

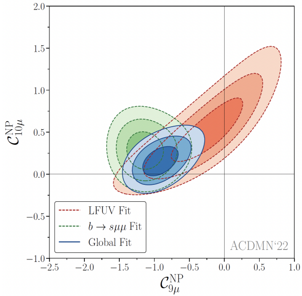
CEPC workshop, (e-)Beijing, 25/10/22

NP in $b \to s\ell\ell$





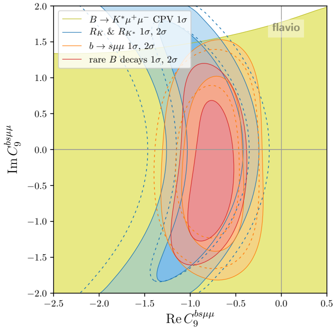
- A decade of deviations in $b \to s\mu\mu$
- Some indication of Lepton Flavour Universality Violation
- Consistently explained through NP shifts of $b \to s\ell\ell$ Wilson coeffs
- Compatible with NP leptoquark models (in particular)

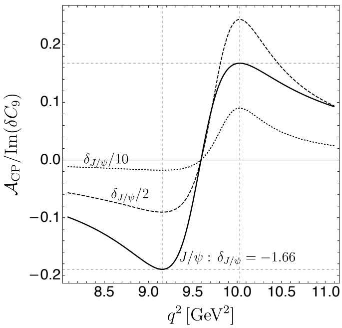


[Algueró et al, Altmanshoffer et al,Geng et al., Ciuchini et al, Hurth et al, Isidori et al. . .]

Complex NP in $b \to s\ell\ell$?

- Most studies consider only CP-conserving New Physics
- A few studies involving complex Wilson coeffs: space is allowed !
- But not many observables
  - mainly direct CP-asymmetries measured up to now
  - sensitive to weak phases only if strong phases
  - CKM studies: explore interference between decay and mixing ?

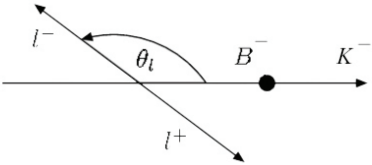




[Biswas, Nandi, Ray, Kumar Patra; Altmannshoffer, Stangl; Bečirević, Fajfer, Košnik, Smolkovič]]

A case study: $B \to K\ell\ell$

Consider first $B^- \to K^-\ell^+\ell^-$ (no mixing) [SDG, Novoa-Brunet, Vos]

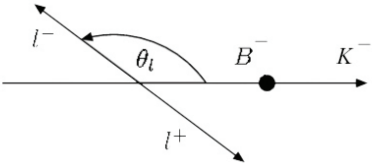


θ_ℓ: angle between $\vec{p}_{\ell^-}$ and $-\vec{p}_{B^-}$ in $\ell^+\ell^-$ rest frame

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell)}{dq^2\ d\cos\theta_\ell} = \bar{G}_0(q^2) + \bar{G}_1(q^2)\cos\theta_\ell + \bar{G}_2(q^2)\frac{1}{2}(3\cos^2\theta_\ell - 1)$$

A case study: $B \to K\ell\ell$

Consider first $B^- \to K^-\ell^+\ell^-$ (no mixing) [SDG, Novoa-Brunet, Vos]



θ_ℓ: angle between $\vec{p}_{\ell^-}$ and $-\vec{p}_{B^-}$ in $\ell^+\ell^-$ rest frame

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell)}{dq^2\, d\cos\theta_\ell} = \bar{G}_0(q^2) + \bar{G}_1(q^2)\cos\theta_\ell + \bar{G}_2(q^2)\frac{1}{2}(3\cos^2\theta_\ell - 1)$$

Angular coefficients in terms of several decay amplitudes ($m_\ell \simeq 0$)

$$\begin{aligned}
\bar{G}_0 &= \frac{4}{3}\left|\bar{h}_V\right|^2 + \frac{4}{3}\left|\bar{h}_A\right|^2 + 2\left|\bar{h}_S\right|^2 + 2\left|\bar{h}_P\right|^2 + \frac{8}{3}\left|\bar{h}_{T_t}\right|^2 + \frac{4}{3}\left|\bar{h}_T\right|^2 \\
\bar{G}_1 &= 4\mathrm{Im}\left[2\bar{h}_{T_t}\bar{h}_S^* + \sqrt{2}\bar{h}_T\bar{h}_P^*\right] \\
\bar{G}_2 &= -\frac{4}{3}\left(\left|\bar{h}_V\right|^2 + \left|\bar{h}_A\right|^2 - 2\left|\bar{h}_T\right|^2 - 4\left|\bar{h}_{T_t}\right|^2\right)
\end{aligned}$$

[Bobeth, Hiller, Piranishvil; Gratrex, Hopfer, Zwicky; Bečirević, Košnik, Mescia, Schneider]

Amplitudes in the charged case

Low-Energy Effective Theory (LEFT) at $\mu = m_b$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i \in I} \mathcal{C}_i \mathcal{O}_i + \ldots \qquad I = \{7, 7', 9\ell, 9'\ell, 10\ell, 10'\ell, S\ell, S'\ell, P\ell, P'\ell, T\ell, T'\ell\}$$

- Short distances: Wilson coeffs $\mathcal{C}$ of Low-Energy Effective Theory
- Long distances: Form factors $f_{0,+,T}$ for associated LEFT operators

Amplitudes in the charged case

Low-Energy Effective Theory (LEFT) at $\mu = m_b$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i\in I} \mathcal{C}_i \mathcal{O}_i + \dots \qquad I = \{7, 7', 9\ell, 9'\ell, 10\ell, 10'\ell, S\ell, S'\ell, P\ell, P'\ell, T\ell, T'\ell\}$$

- Short distances: Wilson coeffs $\mathcal{C}$ of Low-Energy Effective Theory
- Long distances: Form factors $f_{0,+,T}$ for associated LEFT operators

leading to the expressions for $\bar{h}$

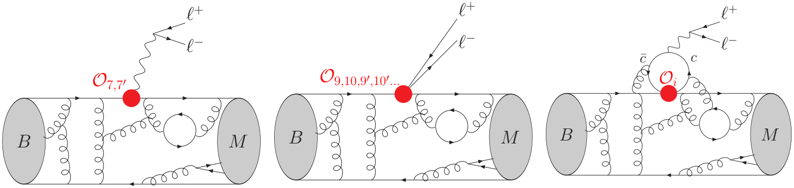
$$\bar{h}_V = \mathcal{N}\frac{\sqrt{\lambda_B}}{2\sqrt{q^2}}\left(\frac{2m_b}{m_B+m_K}(\mathcal{C}_7+\mathcal{C}_{7'})f_T + (\mathcal{C}_9+\mathcal{C}_{9'})f_+\right) \qquad \bar{h}_A = \mathcal{N}\frac{\sqrt{\lambda_B}}{2\sqrt{q^2}}(\mathcal{C}_{10}+\mathcal{C}_{10'})f_+$$

$$\bar{h}_S = \mathcal{N}\frac{m_B^2-m_K^2}{2(m_b-m_s)}(\mathcal{C}_S+\mathcal{C}_{S'})\,f_0 \qquad \bar{h}_P = \mathcal{N}\frac{m_B^2-m_K^2}{2(m_b-m_s)}(\mathcal{C}_P+\mathcal{C}_{P'})\,f_0$$

$$\bar{h}_T = -i\mathcal{N}\frac{\sqrt{\lambda_B}}{\sqrt{2}(m_B+m_K)}(\mathcal{C}_T-\mathcal{C}_{T'})\,f_T \qquad \bar{h}_{T_t} = -i\mathcal{N}\frac{\sqrt{\lambda_B}}{2(m_B+m_K)}(\mathcal{C}_T+\mathcal{C}_{T'})\,f_T$$

- up to a normalisation factor $\mathcal{N}$
- nonlocal contributions coming from $c\bar{c}$ loops absorbed in $\mathcal{C}_9$

CP conjugation in the charged case



Form factors   Charm loop

Defining θ_ℓ using ℓ^- (ℓ^-) for B^- (B^+) yields related CP-conjugate qties

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell)}{dq^2\ d\cos\theta_\ell} \leftrightarrow \frac{d^2\Gamma(B^+ \to K^+\ell\ell)}{dq^2\ d\cos\theta_\ell} \qquad \bar{G} \leftrightarrow G \qquad \bar{h} \leftrightarrow h$$

obtained by

- complex-conjugating all the weak phases
- keeping strong phases unchanged, in particular from $c\bar{c}$ loops

If all CP-violating effects are neglected, one gets $G_i = \bar{G}_i$

Observables in the charged case

CP-averaged differential decay rate

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell + B^+ \to K^+\ell\ell)}{dq^2\ d\cos\theta_\ell} = 2\Gamma_\ell \left[\frac{1}{2}F_H^\ell + A_{FB}^\ell \cos\theta_\ell + \frac{3}{4}(1-F_H^\ell)(1-\cos^2\theta_\ell)\right] .$$

in terms of the decay rate and two angular observables

$$\Gamma_\ell = G_0 + \bar{G}_0 , \qquad A_{FB}^\ell = \frac{G_1 + \bar{G}_1}{2(G_0+\bar{G}_0)} , \qquad F_H^\ell = 1 + \frac{G_2+\bar{G}_2}{G_0+\bar{G}_0} ,$$

Observables in the charged case

CP-averaged differential decay rate

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell + B^+ \to K^+\ell\ell)}{dq^2\ d\cos\theta_\ell} = 2\Gamma_\ell\left[\frac{1}{2}F_H^\ell + A_{FB}^\ell\cos\theta_\ell + \frac{3}{4}(1-F_H^\ell)(1-\cos^2\theta_\ell)\right].$$

in terms of the decay rate and two angular observables

$$\Gamma_\ell = G_0 + \bar{G}_0\,, \qquad A_{FB}^\ell = \frac{G_1+\bar{G}_1}{2(G_0+\bar{G}_0)}\,, \qquad F_H^\ell = 1 + \frac{G_2+\bar{G}_2}{G_0+\bar{G}_0}\,,$$

Direct CP-asymmetries of the form $A_i = \frac{G_i-\bar{G}_i}{G_i+\bar{G}_i}$

- probe differences of the form $|h_X|^2 - |\bar{h}_X|^2$
- vanish unless several strong and weak phases in amplitudes
- strong phases from $c\bar{c}$ in the SM (still under theoretical scrutiny)
- probing only CP-violating (weak) NP phases in $\mathcal{C}_{7,7'}$ and $\mathcal{C}_{9,9'}$

Observables in the charged case

CP-averaged differential decay rate

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell + B^+ \to K^+\ell\ell)}{dq^2\ d\cos\theta_\ell} = 2\Gamma_\ell \left[\frac{1}{2}F_H^\ell + A_{FB}^\ell \cos\theta_\ell + \frac{3}{4}(1-F_H^\ell)(1-\cos^2\theta_\ell)\right] .$$

in terms of the decay rate and two angular observables

$$\Gamma_\ell = G_0 + \bar{G}_0\,, \qquad A_{FB}^\ell = \frac{G_1+\bar{G}_1}{2(G_0+\bar{G}_0)}\,, \qquad F_H^\ell = 1 + \frac{G_2+\bar{G}_2}{G_0+\bar{G}_0}\,,$$

Direct CP-asymmetries of the form $A_i = \frac{G_i - \bar{G}_i}{G_i + \bar{G}_i}$

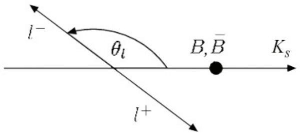
- probe differences of the form $|h_X|^2 - |\bar{h}_X|^2$
- vanish unless several strong and weak phases in amplitudes
- strong phases from $c\bar{c}$ in the SM (still under theoretical scrutiny)
- probing only CP-violating (weak) NP phases in $\mathcal{C}_{7,7'}$ and $\mathcal{C}_{9,9'}$

Neutral case will bring mixing, and new CP-violating observables

Adaptation to the neutral case

$B_d \to K_S\ell\ell$ not decay specific

same definition for θ_ℓ for B_d and $\bar{B}_d$ (from ℓ^-), leading to



$$\frac{d^2\Gamma[B_d \to K_S\ell^+\ell^-]}{ds\, d\cos\theta_\ell} = \sum_i G_i(s) P_i(\cos\theta_\ell)$$

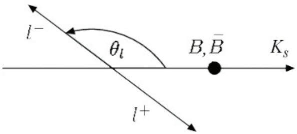
$$\frac{d^2\Gamma[\bar{B}_d \to K_S\ell^+\ell^-]}{ds\, d\cos\theta_\ell} = \sum_i \zeta_i \bar{G}_i(s) P_i(\cos\theta_\ell)$$

$\zeta_{0,2} = 1$ and $\zeta_1 = -1$ from B^- kinematics

Adaptation to the neutral case

$B_d \to K_S \ell\ell$ not decay specific

same definition for θ_ℓ for B_d and $\bar{B}_d$ (from ℓ^-), leading to



$$\frac{d^2\Gamma[B_d \to K_S \ell^+\ell^-]}{ds\, d\cos\theta_\ell} = \sum_i G_i(s) P_i(\cos\theta_\ell)$$

$$\frac{d^2\Gamma[\bar{B}_d \to K_S \ell^+\ell^-]}{ds\, d\cos\theta_\ell} = \sum_i \zeta_i \bar{G}_i(s) P_i(\cos\theta_\ell)$$

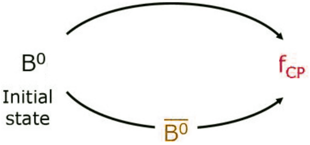
$\zeta_{0,2} = 1$ and $\zeta_1 = -1$ from B^- kinematics

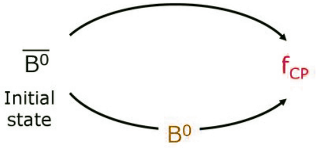
Discussion of CP-violation for non-decay specific modes

- Starting from $h_X(B_d \to f_{CP})$
- Theo $\bar{G}_i$: $\bar{h}_X \equiv h_X(\bar{B}_d \to \bar{f}_{CP})$ with CP-conjugation applied to f_{CP}, obtained by changing sign of weak phases
- Pheno $\widetilde{G}_i$: $\widetilde{h}_X \equiv h_X(\bar{B}_d \to f_{CP})$ without CP-conjugation on f_{CP}, useful for time evolution due to mixing before decay in f_{CP}
- $\widetilde{G}_i = \zeta_i \bar{G}_i$ from CP-parity of ampl. h, consistent with kinematics

Time evolution and mixing

$$h_X(t) = h_X(B(t) \to f_{CP}\ell^+\ell^-) \qquad \widetilde{h}_X(t) = h_X(\bar{B}(t) \to f_{CP}\ell^+\ell^-)$$



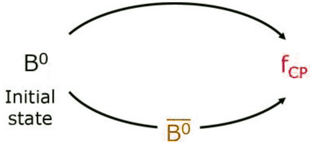


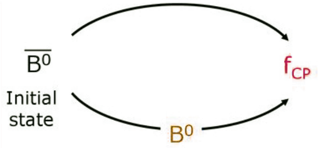
inducing a time-dependence of the angular observables

$$G_i(t) = G_i\big(h_X \to h_X(t)\big) \quad \widetilde{G}_i(t) = G_i\big(h_X \to \widetilde{h}_X(t)\big)$$

Time evolution and mixing

$$h_X(t) = h_X(B(t) \to f_{CP}\ell^+\ell^-) \qquad \widetilde{h}_X(t) = h_X(\bar{B}(t) \to f_{CP}\ell^+\ell^-)$$





inducing a time-dependence of the angular observables

$$G_i(t) = G_i\big(h_X \to h_X(t)\big) \quad \widetilde{G}_i(t) = G_i\big(h_X \to \widetilde{h}_X(t)\big)$$

$$G_i(t) + \widetilde{G}_i(t) = e^{-\Gamma t}\Big[(G_i + \widetilde{G}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big]$$

$$G_i(t) - \widetilde{G}_i(t) = e^{-\Gamma t}\Big[(G_i - \widetilde{G}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big]$$

- mixing angle $q/p = e^{i\phi}$ with $\phi_{B_d} = -2\beta$ and $\phi_{B_s} = 2\beta_s$
- mixing parameters $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/(2\Gamma)$

An illustration with G_0

The time-dependent analysis involves two new observables

$$
\begin{aligned}
s_0 &= 2\mathrm{Im}\left[e^{i\phi}\left[\frac{4}{3}\tilde{h}_V h_V^* + \frac{4}{3}\tilde{h}_A h_A^* + 2\tilde{h}_S h_S^* + 2\tilde{h}_P h_P^* + \frac{8}{3}\tilde{h}_{T_t} h_{T_t}^* + \frac{4}{3}\tilde{h}_T h_T^*\right]\right] , \\
h_0 &= 2\mathrm{Re}\left[e^{i\phi}\left[\frac{4}{3}\tilde{h}_V h_V^* + \frac{4}{3}\tilde{h}_A h_A^* + 2\tilde{h}_S h_S^* + 2\tilde{h}_P h_P^* + \frac{8}{3}\tilde{h}_{T_t} h_{T_t}^* + \frac{4}{3}\tilde{h}_T h_T^*\right]\right]
\end{aligned}
$$

An illustration with G_0

The time-dependent analysis involves two new observables

$$s_0 = 2\mathrm{Im}\left[e^{i\phi}\left[\frac{4}{3}\tilde{h}_V h_V^* + \frac{4}{3}\tilde{h}_A h_A^* + 2\tilde{h}_S h_S^* + 2\tilde{h}_P h_P^* + \frac{8}{3}\tilde{h}_{T_t} h_{T_t}^* + \frac{4}{3}\tilde{h}_T h_T^*\right]\right],$$

$$h_0 = 2\mathrm{Re}\left[e^{i\phi}\left[\frac{4}{3}\tilde{h}_V h_V^* + \frac{4}{3}\tilde{h}_A h_A^* + 2\tilde{h}_S h_S^* + 2\tilde{h}_P h_P^* + \frac{8}{3}\tilde{h}_{T_t} h_{T_t}^* + \frac{4}{3}\tilde{h}_T h_T^*\right]\right]$$

compared to the initial combination

$$\bar{G}_0 = \frac{4}{3}|\bar{h}_V|^2 + \frac{4}{3}|\bar{h}_A|^2 + 2|\bar{h}_S|^2 + 2|\bar{h}_P|^2 + \frac{8}{3}|\bar{h}_{T_t}|^2 + \frac{4}{3}|\bar{h}_T|^2$$

An illustration with G_0

The time-dependent analysis involves two new observables

$$
\begin{aligned}
s_0 &= 2\mathrm{Im}\left[e^{i\phi}\left[\frac{4}{3}\tilde{h}_V h_V^* + \frac{4}{3}\tilde{h}_A h_A^* + 2\tilde{h}_S h_S^* + 2\tilde{h}_P h_P^* + \frac{8}{3}\tilde{h}_{T_t} h_{T_t}^* + \frac{4}{3}\tilde{h}_T h_T^*\right]\right] ,\\
h_0 &= 2\mathrm{Re}\left[e^{i\phi}\left[\frac{4}{3}\tilde{h}_V h_V^* + \frac{4}{3}\tilde{h}_A h_A^* + 2\tilde{h}_S h_S^* + 2\tilde{h}_P h_P^* + \frac{8}{3}\tilde{h}_{T_t} h_{T_t}^* + \frac{4}{3}\tilde{h}_T h_T^*\right]\right]
\end{aligned}
$$

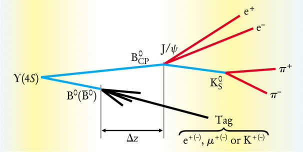
compared to the initial combination

$$
\bar{G}_0 = \frac{4}{3}\left|\bar{h}_V\right|^2 + \frac{4}{3}\left|\bar{h}_A\right|^2 + 2\left|\bar{h}_S\right|^2 + 2\left|\bar{h}_P\right|^2 + \frac{8}{3}\left|\bar{h}_{T_t}\right|^2 + \frac{4}{3}\left|\bar{h}_T\right|^2
$$

- illustration of interference between B_d-mixing and $B \to K\ell\ell$ decay
- involves complex conjugation and CP-conjugation
- additional information wrt CP-asymmetries
  from time dependent analysis of $G_0(t) + \widetilde{G}_0(t)$ and $G_0(t) - \widetilde{G}_0(t)$
- $y_{B_d} \simeq 0$: no h_0 but s_0 from $d\Gamma(B_d(t) \to K_S\ell\ell) - d\Gamma(\bar{B}_d(t) \to K_S\ell\ell)$

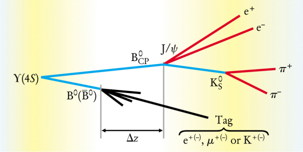
Time-integrated version

- Coherent production of $B\bar{B}$ pair
  - $\Upsilon(nS) \to B\bar{B}$ intricated (B-factories)
  - t time diff between tag B and reconstructed B decays, $t \in]-\infty, \infty[$
  - time integ washes away sin and sinh



- Incoherent production of $B\bar{B}$ pair
  - $pp \to b\bar{b}$ (LHC) or $Z \to b\bar{b}$ (Z factories) hadronising "separately"
  - t time after production of the B-meson of interest, $t \in [0, \infty[$

Time-integrated version



- Coherent production of $B\bar{B}$ pair
  - $\Upsilon(nS) \to B\bar{B}$ intricated (B-factories)
  - t time diff between tag B and reconstructed B decays, $t \in]-\infty, \infty[$
  - time integ washes away sin and sinh
- Incoherent production of $B\bar{B}$ pair
  - $pp \to b\bar{b}$ (LHC) or $Z \to b\bar{b}$ (Z factories) hadronising "separately"
  - t time after production of the B-meson of interest, $t \in [0, \infty[$

Integrating over time (no terms in h, s for B-factories)

$$\langle G_i + \widetilde{G}_i \rangle_{\rm Hadronic} = \frac{1}{\Gamma}\left[\frac{1}{1-y^2} \times (G_i + \widetilde{G}_i) - \frac{y}{1-y^2} \times h_i\right]$$

$$\langle G_i - \widetilde{G}_i \rangle_{\rm Hadronic} = \frac{1}{\Gamma}\left[\frac{1}{1+x^2} \times (G_i - \widetilde{G}_i) - \frac{x}{1+x^2} \times s_i\right]$$

- s_i same order as $G_i - \widetilde{G}_i$ for B_d, enhanced for B_s, but tagging
- h_i vanishes for B_d, suppressed w.r.t. $G_i + \widetilde{G}_i$ for B_s, no tagging

Exploiting the new observables

- $\sigma_i = \frac{s_i}{2(G_0+\bar{G}_0)} = \frac{s_i}{2\Gamma_\ell}$ directly related to $\sin\phi$ for SM
- combinations more sensitive (scalar/tensor/complex contributions)

$$R_S \equiv \frac{2}{\sin\phi}(-\sigma_2 + 2\sigma_0) - F_H^\ell + 3 \qquad R_{T_t} \equiv \frac{2}{\sin\phi}\sigma_2 + F_H^\ell - 1 \qquad R_W \equiv R_S + 3R_{T_t}$$

	SM	Scen. 1	Scen. 2	Scen. 3	$C_S = 0.2$	$C_T = 0.2$
σ_0	0.368(5)	0.273(6)	0.402(5)	0.43(1)	0.368(5)	0.368(5)
σ_2	−0.359(5)	−0.266(6)	−0.392(4)	−0.415(9)	−0.359(5)	−0.357(5)
R_S	−0.107(4)	0.69(2)	−0.39(2)	−0.59(9)	−0.105(4)	−0.107(4)
R_{T_t}	0.035(1)	−0.225(8)	0.128(7)	0.19(3)	0.035(1)	0.036(1)
$R_W \times 10^2$	−0.179(8)	1.09(4)	−0.63(4)	−1.0(1)	−0.01(1)	0.04(3)

Distinguishing different scenarios a priori allowed by the global fits

- Scenario 1: $\mathcal{C}_{9\mu}^{\rm NP} = -1.12 + i1.00$
- Scenario 2: $\mathcal{C}_{9\mu}^{\rm NP} = -1.14 - i0.22$, $\mathcal{C}_{9'\mu}^{\rm NP} = 0.40 - i0.38$
- Scenario 3: $\mathcal{C}_{9\mu}^{\rm NP} = -1.13 - i0.12$, $\mathcal{C}_{9'\mu} = 0.52 - i1.80$, $\mathcal{C}_{10\mu}^{\rm NP} = 0.41 + i0.13$
- Scenarios with scalar or tensor contributions

More time-dependent analysis for $b \to s\ell\ell$

We can play a similar game with

- $B_s \to f_0\ell\ell$ [SDG, Novoa-Brunet, Vos]
- $B_d \to K^*(\to K_S\pi^0)\ell\ell$ [SDG, Virto]
- $B_s \to \phi\ell\ell$ (in general and at low q^2) [SDG, Plakias, Sumensari]

In each case, new observables

- interference between mixing and decay
- sensitive to NP complex phases

accessible through

- time-dependent analysis
- time-integrated observables in incoherent productions (CepC !)
- values of mixing parameters favouring s_i,
  coming from $d\Gamma(B_q \to M\ell\ell) - d\Gamma(\bar{B}_q \to M\ell\ell)$, requiring tagging

Shifting to $b \to s\nu\bar{\nu}$

- Often related to $b \to s\ell\ell$ for NP for left-handed doublets

Shifting to $b \to s\nu\bar{\nu}$

- Often related to $b \to s\ell\ell$ for NP for left-handed doublets
- Much simpler LEFT (if only left-handed neutrinos)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_\nu (C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu) + \text{h.c.} \quad \mathcal{O}_{L,R}^\nu = \frac{e^2}{8\pi^2}(\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu}\gamma^\mu P_L \nu)$$

Shifting to $b \to s\nu\bar{\nu}$

- Often related to $b \to s\ell\ell$ for NP for left-handed doublets
- Much simpler LEFT (if only left-handed neutrinos)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_\nu (C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu) + \mathrm{h.c.} \quad \mathcal{O}_{L,R}^\nu = \frac{e^2}{8\pi^2}(\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu}\gamma^\mu P_L \nu)$$

- Not yet observed, with usual observables $R_X = X/X_{\rm SM}$

$$R_{\mathcal{B}(B\to K\nu\bar{\nu})} = \frac{1}{3}\sum_\nu (1-2\eta_\nu)\epsilon_\nu^2 \qquad R_{B(B\to K^*\nu\bar{\nu})} = \frac{1}{3}\sum_\nu (1+1.31\eta_\nu)\epsilon_\nu^2$$

$$R_{B(B\to X_s\nu\bar{\nu})} = \frac{1}{3}\sum_\nu (1+0.09\eta_\nu)\epsilon_\nu^2 \qquad R_{\langle F_L\rangle} = \frac{\sum_\nu (1+2\eta_\nu)\epsilon_\nu^2}{\sum_\nu (1+1.31\eta_\nu)\epsilon_\nu^2}$$

with numerical values from ratio of left- and right-helicities and

$$\epsilon_\nu = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\rm SM}^\nu|} \qquad \eta_\nu = \frac{-\mathrm{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

Shifting to $b \to s\nu\bar{\nu}$

- Often related to $b \to s\ell\ell$ for NP for left-handed doublets
- Much simpler LEFT (if only left-handed neutrinos)

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_\nu (C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu) + \text{h.c.} \quad \mathcal{O}_{L,R}^\nu = \frac{e^2}{8\pi^2} (\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu}\gamma^\mu P_L \nu)$$

- Not yet observed, with usual observables $R_X = X/X_{\text{SM}}$

$$R_{\mathcal{B}(B\to K\nu\bar{\nu})} = \frac{1}{3}\sum_\nu (1-2\eta_\nu)\epsilon_\nu^2 \qquad R_{B(B\to K^*\nu\bar{\nu})} = \frac{1}{3}\sum_\nu (1+1.31\eta_\nu)\epsilon_\nu^2$$

$$R_{B(B\to X_s\nu\bar{\nu})} = \frac{1}{3}\sum_\nu (1+0.09\eta_\nu)\epsilon_\nu^2 \qquad R_{\langle F_L\rangle} = \frac{\sum_\nu (1+2\eta_\nu)\epsilon_\nu^2}{\sum_\nu (1+1.31\eta_\nu)\epsilon_\nu^2}$$

with numerical values from ratio of left- and right-helicities and

$$\epsilon_\nu = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\text{SM}}^\nu|} \qquad \eta_\nu = \frac{-\text{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

- Complex NP accessible only through η_ν and only if right-handed currents (not necessarily favoured by $b \to s\ell\ell$)

Time-dependent observable for $B_d \to K_S \nu\bar{\nu}$

[SDG, Fajfer, Kamenik, Novoa-Brunet]

For $B_d \to K_S \nu\bar{\nu}$, few observables

- branching ratio $\mathcal{B}$
- no angular observables since no measurable θ_ν
- time-dependent asymmetry related to differential decay rate

$$A^{\mathcal{B}} = \frac{d\Gamma(B_d \to K_S\nu\bar{\nu}) - d\Gamma(\bar{B}_d \to K_S\nu\bar{\nu})}{d\Gamma(B_d \to K_S\nu\bar{\nu}) + d\Gamma(\bar{B}_d \to K_S\nu\bar{\nu})}$$

whose numerator involve the time-dependent angular coefficients

$$G_0^\nu(t) - \bar{G}_0^\nu(t) = e^{-\Gamma t}[(G_0^\nu - \bar{G}_0^\nu)\cos(x\Gamma t) - s_0^\nu \sin(x\Gamma t)]$$

with the interference between mixing and decay

$$s_0^\nu = \mathrm{Im}\left[e^{i\phi}\mathcal{N}^2(C_L^\nu + C_R^\nu)^2\right]\frac{8}{3}\frac{\lambda_B(q^2)}{q^2} f_+^2(q^2) \propto \mathrm{Im}[e^{i\phi}(V_{tb}V_{ts}^*)^2(C_L^\nu + C_R^\nu)^2]$$

which can also be integrated over time for incoherent production

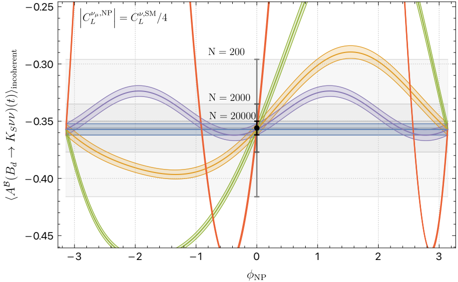
Vector final states

We can play similarly with the time dependence of

$$B_d \to K^{*0}(\to K_S\pi^0)\nu\bar{\nu} \qquad B_s \to \phi\nu\bar{\nu}$$

- Fewer angular observables than $b \to s\ell\ell$ (no measurable θ_ν)
- For some ratios of observables, cancellation of form factors, no hadronic uncertainties to be taken into account
- for $B_d \to K^*(\to K_S\pi^0)\nu\bar{\nu}$, only CP-asymmetries ($y = 0$)
  - A^{F_L} constrains $\mathrm{Im}[e^{-2i\beta}(V_{tb}V_{ts}^*)^2 \sum_\nu (C_L^\nu - C_R^\nu)^2]$ w/o form factors
  - $A^{\mathcal{B}}$ combination of $\mathrm{Im}[e^{-2i\beta}(V_{tb}V_{ts}^*)^2 \sum_\nu (C_L^\nu - C_R^\nu)^2]$ and $\mathrm{Im}[e^{-2i\beta}(V_{tb}V_{ts}^*)^2 \sum_\nu (C_L^\nu + C_R^\nu)^2]$ involving form factors.
- for $B_s \to \phi\nu\bar{\nu}$, CP-averaged quantities are also accessible
  - F_L constrains $\mathrm{Re}[\sum_\nu (C_L^\nu - C_R^\nu)^2]$ w/o form factors
  - $\mathcal{B}$ combination of $\mathrm{Re}[\sum_\nu (C_L^\nu - C_R^\nu)^2]$ and $\mathrm{Re}[\sum_\nu (C_L^\nu + C_R^\nu)^2]$ involving form factors.

Projections



NP models based on General Minimal Flavour Violation:

- $C_L^{\nu_\mu,\mathrm{NP}} = e^{-i\phi_{\mathrm{NP}}} \left| C_L^{\nu,\mathrm{SM}} \right| /4$
- $C_R^{\nu,\mathrm{NP}} = 0$

- Various rescaling for the couplings between leptons
  - the simplest case $\lambda^\ell_{ee} = \lambda^\ell_{\tau\tau} = 0$ [yellow]
  - the democratic scenario $\lambda^\ell_{ee} = \lambda^\ell_{\mu\mu} = \lambda^\ell_{\tau\tau}$ [green]
  - the anomaly-free assignment $\lambda^\ell_{\mu\mu} = -\lambda^\ell_{\tau\tau}$ and $\lambda^\ell_{ee} = 0$ [purple]
  - the hierarchical charge scenario $\lambda^\ell_{\alpha\alpha}/\lambda^\ell_{\mu\mu} = m_\alpha/m_\mu$ [orange]
- 3 gray bands: expected experimental uncertainties for N=200, N=2000, and N=20000 events (from Belle II 50 ab^{-1} to FCC ?)

Similar studies/projections for $B_d \to K^{*0}(\to K_S\pi^0)\ell\ell$ and $B_s \to \phi\ell\ell$

[SDG, Fajfer, Kamenik, Novoa-Brunet]

Summary

Complex NP in $b \to s\ell\ell$ and $b \to s\nu\nu$

- Currently allowed by experimental constraints
- Only direct CP-asymmetries for $b \to s\ell\ell$, requiring strong phases
- Usual $b \to s\nu\nu$ obs sensitive only if right-handed currents

CP-violation in interference in mixing and decay

- CP-eigenstates and thus not decay-specific modes
- Time-dependent analysis yielding new observables
- Also through time-integrated observables if incoherent production
- Mostly through $d\Gamma(B_q(t) \to f_{CP}\ell\ell) - d\Gamma(\bar{B}_q(t) \to f_{CP}\ell\ell)$
- Sensitive to weak phases, without relying on strong phases

[SDG, Virto; SDG, Novoa-Brunet, Vos; SDG, Plakias, Sumensari; SDG, Fajfer, Kamenik, Novoa-Brunet]

New probes of complex NP in $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$
Potentially interesting for CepC (?)