The like-sign dimuon asymmetry and New Physics

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Based on work done in collaboration with:
G.C. Branco (Lisbon), F.J. Botella & A. Sánchez (Valencia),
arXiv:1402.1181

- Meson evolution

$$i\frac{d}{dt}\begin{pmatrix}B_q(t)\\ \bar{B}_q(t)\end{pmatrix} = \mathscr{H}\begin{pmatrix}B_q(t)\\ \bar{B}_q(t)\end{pmatrix}$$

$\mathscr{H}$ has hermitian and anti-hermitian parts M and $-i\Gamma/2$:

$$\mathscr{H} = M - \frac{i}{2}\Gamma\,,\ M = M^\dagger\,,\ \Gamma = \Gamma^\dagger$$

- To second order in (weak) perturbation theory

$$[M]_{ij} = m_0\delta_{ij} + \langle i|\mathscr{H}_{\text{w}}|j\rangle + \sum_n \mathcal{P}\frac{\langle i|\mathscr{H}_{\text{w}}|n\rangle\langle n|\mathscr{H}_{\text{w}}|j\rangle}{m_0 - E_n}$$

$$[\Gamma]_{ij} = 2\pi\sum_n \delta(m_0 - E_n)\langle i|\mathscr{H}_{\text{w}}|n\rangle\langle n|\mathscr{H}_{\text{w}}|j\rangle$$

- Genuinely mixing CP violation

$$\mathrm{Im}\,(\Gamma_{12}/M_{12}) \neq 0$$

- Eigenvalues of $\mathscr{H}$: μ_H & μ_L

$$\Delta\mu = \mu_H - \mu_L = \Delta M - \frac{i}{2}\Delta\Gamma = 2\sqrt{[\mathscr{H}]_{12}\,[\mathscr{H}]_{21}}$$

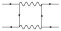
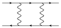
- Some algebra gives, for B_d^0–$\bar{B}_d^0$ and B_s^0–$\bar{B}_s^0$ systems, (i.e. at leading order in Γ_{12}/M_{12})

$$\Delta M = 2|M_{12}| \;\; \& \; \Delta\Gamma = -\Delta M\,\mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right) \;\; \& \; A_{SL} = \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)$$

Branco, Lavoura & Silva; Bigi & Sanda

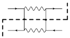
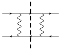
- Dispersive amplitude (SM):

$$M_{12}^{(q)} = \frac{G_F^2 M_W^2}{12\pi^2} M_{B_q} f_{B_q}^2 B_{B_q} \eta_B S_0(x_t) (V_{tb}V_{tq}^*)^2$$

from  + 

- Absorptive amplitude:

$$\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}} = -\left(\frac{\Gamma_{12}^{cc}}{M_{12}^{(q)}} (V_{cb}V_{cq}^*)^2 + 2\frac{\Gamma_{12}^{uc}}{M_{12}^{(q)}} (V_{ub}V_{uq}^* V_{cb}V_{cq}^*) + \frac{\Gamma_{12}^{uu}}{M_{12}^{(q)}} (V_{ub}V_{uq}^*)^2 \right)$$

from  + 

- HQE expansion

$$-\Gamma_{12}^{cc} = 10^{-4}\,c\,,\quad -2\Gamma_{12}^{uc} = 10^{-4}(2c-a)\,,\quad -\Gamma_{12}^{uu} = 10^{-4}(b+c-a)$$

with

$$a = 10.5 \pm 1.8\,,\quad b = 0.2 \pm 0.1\,,\quad c = -53.3 \pm 12.0$$

Beneke et al. PLB459, PLB576, Ciuchini et al. JHEP0308
Lenz & Nierste JHEP0706, Lenz 1405.3601

- Important: in powers of $(m_c/m_b)^2$, only $c \neq 0$ at zero-th order
- Rewrite (N.B. $V_{ab}V_{aq}^* \equiv \lambda_{bq}^a$)

$$\left[\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}}\right]_{\text{SM}} = K_{(q)} \frac{c\left(\lambda_{bq}^u + \lambda_{bq}^c\right)^2 - a\lambda_{bq}^u\left(\lambda_{bq}^u + \lambda_{bq}^c\right) + b\left(\lambda_{bq}^u\right)^2}{\left(\lambda_{bq}^t\right)^2}$$

- Clamorous call for use of 3×3 unitarity of CKM

- $\lambda_{bq}^{u} + \lambda_{bq}^{c} + \lambda_{bq}^{t} = 0$,

$$\left[\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}}\right]_{\text{SM}} = K_{(q)}\left[c + a\,\frac{V_{ub}V_{uq}^*}{V_{tb}V_{tq}^*} + b\left(\frac{V_{ub}V_{uq}^*}{V_{tb}V_{tq}^*}\right)^2\right]$$

- Some numbers (exp):

$$[A_{SL}^{d}]_{\text{exp}} = (0.3 \pm 2.3)\cdot 10^{-3}\,, \qquad [\Delta\Gamma_d]_{\text{exp}} = (0.001 \pm 0.012)\,\text{ps}^{-1}$$

$$[A_{SL}^{s}]_{\text{exp}} = (-3 \pm 5)\cdot 10^{-3}\,, \qquad [\Delta\Gamma_s]_{\text{exp}} = (0.091 \pm 0.008)\,\text{ps}^{-1}$$

- Some numbers (fit):

$$[A_{SL}^{d}]_{\text{SM}} = (-4.2 \pm 0.7)\cdot 10^{-4}\,, \qquad [\Delta\Gamma_d]_{\text{SM}} = (2.6 \pm 0.4)\cdot 10^{-3}\,\text{ps}^{-1}$$

$$[A_{SL}^{s}]_{\text{SM}} = (2.0 \pm 0.4)\cdot 10^{-5}\,, \qquad [\Delta\Gamma_s]_{\text{SM}} = (0.090 \pm 0.008)\,\text{ps}^{-1}$$

- Central to SM expectations:
  1. $M_{12}^{(q)}$ dominated by a single weak amplitude
  2. use of 3×3 unitarity of CKM

The D0 like-sign dimuon asymmetry A^b_{SL}

1. $b\bar{b}$ pairs are strongly produced
2. they hadronize into B_d or B_s mesons/antimesons
3. they decay weakly
4. Semileptonic decays tag the nature of the decaying B depending on the charge of the produced ℓ: $B \leftarrow \ell^+$ or $\bar{B} \leftarrow \ell^-$

Without $B_q - \bar{B}_q$ oscillations,

both decays cannot give same charge leptons

Asymmetry

$$A^b_{SL} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

N^{++} (N^{--}): # of events with both mesons decaying to μ^+ (μ^-)

The D0 like-sign dimuon asymmetry A_{SL}^b

- In terms of the individual B_d^0–$\bar{B}_d^0$ and B_s^0–$\bar{B}_s^0$ systems, A_{SL}^b is a weighted combination

$$A_{SL}^b = \frac{A_{SL}^d + gA_{SL}^s}{1+g}$$

- with

$$g = f\,\frac{\Gamma_d}{\Gamma_s}\frac{(1-y_s^2)^{-1}-(1+x_s^2)^{-1}}{(1-y_d^2)^{-1}-(1+x_d^2)^{-1}}\,, \quad y_q = \frac{\Delta\Gamma_q}{2\Gamma_q},\, x_q = \frac{\Delta M_{B_q}}{\Gamma_q}\,.$$

f is the B_s–B_d fragmentation fraction ratio in the B sample

$$A_{SL}^b \simeq 0.59 A_{SL}^d + 0.41 A_{SL}^s$$

- N.B. Simplified picture Borissov & Hoeneisen PRD87

The D0 like-sign dimuon asymmetry A^b_{SL}

- From the same SM fit

$$\left[A^b_{SL}\right]_{\rm SM} = (-2.3 \pm 0.4)\cdot 10^{-4}$$

- "but" the measured value is

$$\left[A^b_{SL}\right]_{\rm D0} = (-4.96 \pm 1.69)\cdot 10^{-3}$$

D0 collaboration PRD89

- Stubborn 3σ "situation"

D0 collaboration PRD82, PRD84, PRL105

- Burst of activity with New Physics (NP) contributions to $M_{12}^{(s)}$ and/or $\Gamma_{12}^{(s)}$ in specific models
  - SUSY: Ko & Park PRD82, Parry PLB694, Ishimori et al. PTP 126
  - Extra Dimensions: Datta et al. PRD83, Goertz & Pfoh PRD84
  - Z': Deshpande et al. PRD82, Alok et al. JHEP1107, Kim et al. PRD83, Kim et al. PRD88
  - Left-Right: Lee & Nam PRD85
  - Extended scalar sector: Jung et al. JHEP1011, Dobrescu et al. PRL105, Trott & Wise JHEP1011, Bai & Nelson PRD82
  - Axigluons: Chen & Faisel PLB696
  - Extended fermionic sector: Hou et al. PRD75, Soni et al. PRD82, Chen et al. JHEP1011, Botella et al. PRD79, JHEP1212, Alok et al. PRD86

- "Model independent" analyses with NP in B_q^0–$\bar{B}_q^0$ mixings:
  Ligeti et al. PRL105, Bauer & Dunn PLB696,
  Bobeth & Haisch APPB 44
- NP in $\Delta\Gamma_d$ Bobeth et al. JHEP06 (2014)
- NP in SM highly suppressed additional contributions
  Descotes-Genon & Kamenik PRD87
- . . .

- Scenarios in which the CKM matrix is no longer 3×3 unitary,
  it is, on the contrary, part of a larger unitary matrix
  Branco et al. PLB306, Eyal & Nir JHEP9909,
  Barenboim et al. PLB422, Barenboim & Botella PLB433,
  Botella, Branco & MN PRD79, JHEP1212
  ...

$$V_{ub}V_{uq}^{*} + V_{cb}V_{cq}^{*} + V_{tb}V_{tq}^{*} \equiv -N_{bq} \neq 0$$

- Modified $M_{12}^{(q)}$ with generic structure

$$M_{12}^{(q)} \propto \left((V_{tb}V_{tq}^{*})^2 S_0(x_t) + (V_{tb}V_{tq}^{*})\, N_{bq}\, C_1 + {N_{bq}}^2\, C_2\right)$$

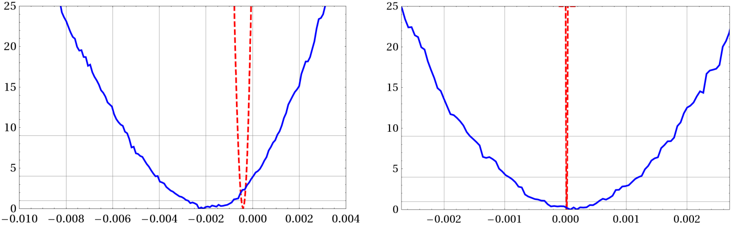
$C_1, C_2 \in \mathbb{R}$, model dependent, common to both $M_{12}^{(d)}$ and $M_{12}^{(s)}$

- Controlled removal of SM ingredients
  1. $M_{12}^{(q)}$ dominated by a single weak amplitude
  2. use of 3×3 unitarity of CKM

Input

$\|V_{ud}\|$	0.97425 ± 0.00022	$\|V_{us}\|$	0.2252 ± 0.0009
$\|V_{cd}\|$	0.230 ± 0.011	$\|V_{cs}\|$	1.023 ± 0.036
$\|V_{ub}\|$	0.00375 ± 0.00040	$\|V_{cb}\|$	0.041 ± 0.001
$\|V_{tb}\|$	0.95 ± 0.05	γ	$(68 \pm 8)^\circ$
$A_{J/\Psi K_S}$	0.68 ± 0.02	$A_{J/\Psi\Phi}$	0.01 ± 0.07
$\sin(2\bar{\alpha})$	0.10 ± 0.15	$\sin(2\bar{\beta}+\gamma)$	0.95 ± 0.40
ΔM_{B_d}	(0.507 ± 0.004) ps^{-1}	ΔM_{B_s}	(17.768 ± 0.024) ps^{-1}
$\Delta\Gamma_d$	(0.001 ± 0.012) ps^{-1}	$\Delta\Gamma_s$	(0.091 ± 0.008) ps^{-1}
A^s_{SL}	$(3 \pm 5) \times 10^{-3}$	A^d_{SL}	$(3 \pm 23) \times 10^{-4}$
A^b_{SL}	$(-4.96 \pm 1.69) \times 10^{-3}$		

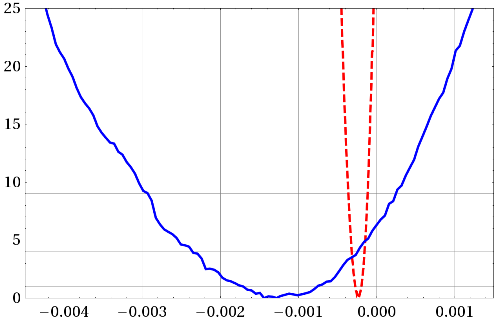
Individual SL asymmetries



(a) $\Delta\chi^2$ vs. A^d_{SL} (b) $\Delta\chi^2$ vs. A^s_{SL}

– NP – SM

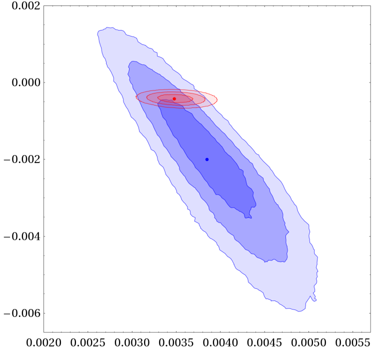
Dimuon asymmetry A^b_{SL}



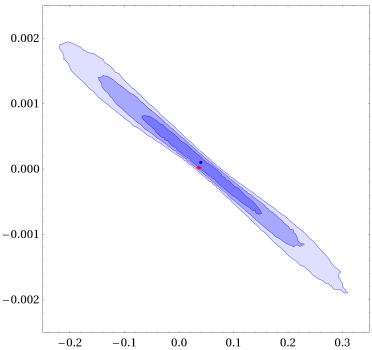
(c) $\Delta\chi^2$ vs. A^b_{SL}

- Enhancement falls short of the mark
- How is this enhancement “accommodated”?

Correlations – Individual SL asymmetries

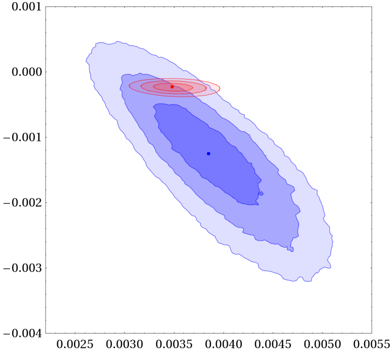


(d) $\Delta\chi^2$ contours, A^d_{SL} vs. $|V_{ub}|$

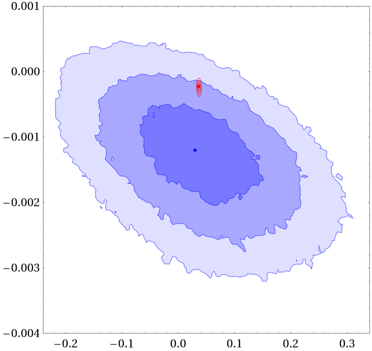


(e) $\Delta\chi^2$ contours, A^s_{SL} vs. $A_{J/\Psi\Phi}$

Correlations – Dimuon asymmetry A^b_{SL}

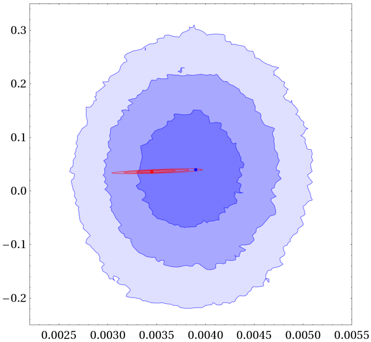


(f) $\Delta\chi^2$ contours, A^b_{SL} vs. $|V_{ub}|$

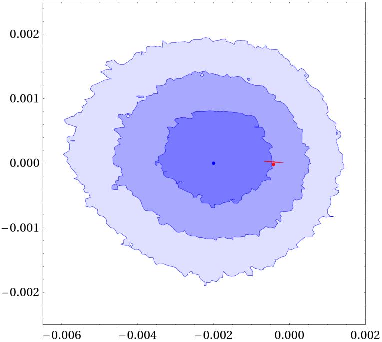


(g) $\Delta\chi^2$ contours, A^b_{SL} vs. $A_{J/\Psi\Phi}$

bs & bd “independence”



(h) $\Delta\chi^2$ contours, $A_{J/\Psi\Phi}$ vs. $|V_{ub}|$



(i) $\Delta\chi^2$ contours, A^s_{SL} vs. A^d_{SL}

- SM

$$\lambda_{bq}^u + \lambda_{bq}^c + \lambda_{bq}^t = 0$$

$$\left[\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}}\right]_{\text{SM}} = K_{(q)}\left[c + a\,\frac{\lambda_{bq}^u}{\lambda_{bq}^t} + b\left(\frac{\lambda_{bq}^u}{\lambda_{bq}^t}\right)^2\right]$$

...not anymore

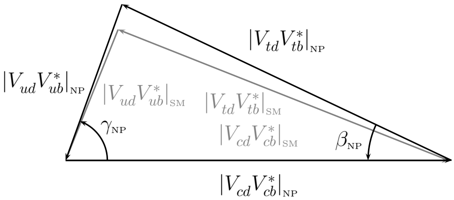
- NP with deviation from 3×3 unitarity in CKM

$$\lambda_{bq}^u + \lambda_{bq}^c + \lambda_{bq}^t = -\lambda_{bq}^4$$

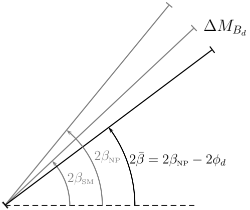
$$\frac{\Gamma_{12}^{(q)}}{M_{12}^{(q)}} = K_{(q)} S_0(x_t)\left[\frac{c\,(\lambda_{bq}^u + \lambda_{bq}^c)^2 - a\,\lambda_{bq}^u \lambda_{bq}^u + \lambda_{bq}^c) + b\,(\lambda_{bq}^u)^2}{(\lambda_{bq}^t)^2 S_0(x_t) + 2(\lambda_{bq}^t \lambda_{bq}^4) C_1 + (\lambda_{bq}^4)^2 C_2}\right],$$

$$A_{J/\Psi K_S} = \sin 2\bar{\beta} \neq \sin 2\beta \qquad A_{J/\Psi\Phi} = \sin 2\bar{\beta}_s \neq \sin 2\beta_s$$

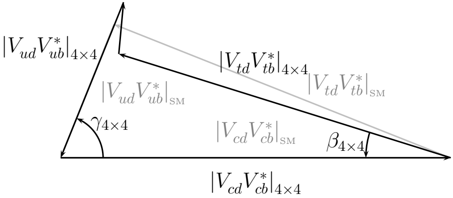
Pictorial



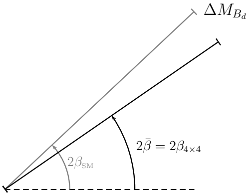
(j) *bd* unitarity triangle with NP in mixings.



(k) $M_{12}^{(d)}$ with NP.

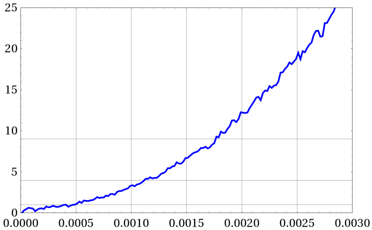


(l) *bd* unitarity quadrangle.

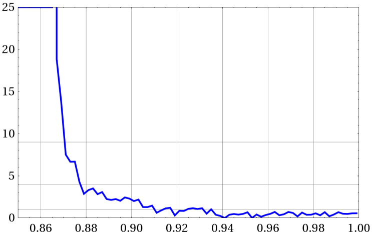


(m) $M_{12}^{(d)}$ beyond 3×3 unitarity.

Unitarity deviations



(n) $\Delta\chi^2$ vs. $1-|V_{ud}|^2-|V_{us}|^2-|V_{ub}|^2$



(o) $\Delta\chi^2$ vs. $|V_{tb}|$

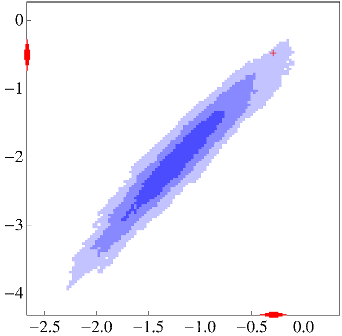
Summary/Conclusions

- CKM not 3×3 unitary, *model independent* approach
  1. breaks the SM $|V_{ub}|$-$\sin 2\beta$ connection with NP in B_d^0–$\bar{B}_d^0$ $\Rightarrow$ enhancement of A_{SL}^d
  2. NP in B_s^0–$\bar{B}_s^0$ $\Rightarrow$ enhancement of A_{SL}^s
- Enhancement of A_{SL}^b up to $-2 \cdot 10^{-3}$ (N.B. SM fit $-2.3 \cdot 10^{-4}$)
- …requires $|V_{ub}| \uparrow$ and/or $A_{J/\Psi\Phi} \uparrow$
- Closer to the D0 measurement $(-4.96 \pm 1.69) \times 10^{-3}$, but insufficient
- Results similar to NP in mixings $M_{12}^{(q)} = \left[M_{12}^{(q)}\right]_{\text{SM}} r_q^2 \, e^{-i\,2\phi_q}$, direct access to unitarity deviations to distinguish
- $\Delta\Gamma_d$ enhancement "for free"
- Wait for LHCb progress …

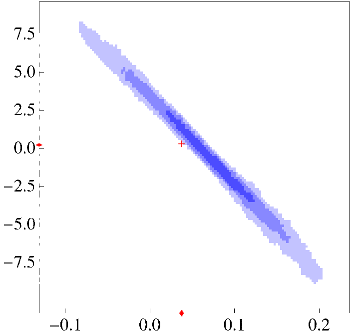
Backup – Example

Example for an up vector-like quark model, complete analysis with EW precision observables, rare decays, ...

Botella, Branco & MN, JHEP1212, 1207.4440

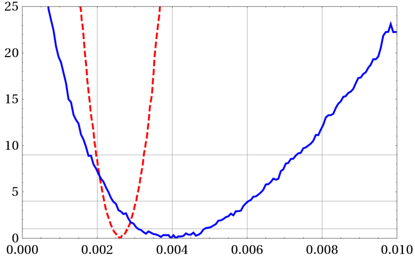


(p) $\Delta\chi^2$, $A^d_{SL} \times 10^3$ vs. $A^b_{SL} \times 10^3$



(q) $\Delta\chi^2$, $A^s_{SL} \times 10^4$ vs. $A_{J/\Psi\Phi}$

Backup – $\Delta\Gamma_d$



(r) $\Delta\chi^2$ vs. $\Delta\Gamma_d$ ($\times$ ps)