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The dimuon CP asymmetry, $D^0 - \bar{D}^0$ mixing & General Minimal Flavor Violation

Gilad Perez*
Department of Particle Physics and Astrophysics,
Weizmann Institute of Science, Rehovot 76100, Israel
E-mail: gilad.perez@weizmann.ac.il

The DØ Collaboration reported a 3.2 σ deviation from the standard model prediction in the like-sign dimuon asymmetry. Assuming that new physics contributes only to $B_{d,s}$ mixing, we study the general implications of the measurement, and then in the contest of the general minimal flavor violation (GMFV) framework. We find that this framework gives a good fit to the data. Universal new physics with similar contributions relative to the SM in the B_d and B_s systems are possible, but the data favors a larger deviation in B_s than in B_d mixing. We also briefly discuss the GMFV contributions to CP violation in $D^0 - \bar{D}^0$ mixing.

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*Speaker.

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1. Introduction

In the last decade an immense amount of measurements determined that the standard model (SM) is responsible for the dominant part of flavor and CP violation (CPV) in meson decays. However, in some processes, mainly related to B_s decays, possible new physics (NP) contributions are still poorly constrained, and motivated NP scenarios predict sizable deviations from the SM. Recently the DØ Collaboration reported a measurement of the like-sign dimuon charge asymmetry in semileptonic b decay with improved precision [1],

$$a^b_{\rm SL} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}, \tag{1.1}$$

where N_b^{++} is the number of $b\bar{b} \to \mu^+\mu^+ X$ events (and similarly for N_b^{--}). This result is 3.2σ from the quoted SM prediction, $\left(a^b_{\rm SL}\right)^{\rm SM} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ [2]. At the Tevatron both B^0_d and B^0_s are produced, and hence $a^b_{\rm SL}$ is a linear combination of the two asymmetries [1]

$$a^b_{\rm SL} = (0.506 \pm 0.043)\, a^d_{\rm SL} + (0.494 \pm 0.043)\, a^s_{\rm SL}\,. \tag{1.2}$$

The above result should be interpreted in conjunction with three other measurements: (i) the B_d semileptonic asymmetry, measured by the B factories, $a^d_{\rm SL} = -(4.7 \pm 4.6) \times 10^{-3}$ [3]; (ii) the flavor specific asymmetry measured from time dependence of $B^0_s \to \mu^+ D^-_s X$ decay and its CP conjugate, $a^s_{\rm fs} = -(1.7 \pm 9.1 \pm 1.5) \times 10^{-3}$ [4]; and (iii) the measurements of $\Delta\Gamma_s$ and $S_{\psi\phi}$ (the CP asymmetry in the CP-even part of the $\psi\phi$ final state in B_s decay) [5, 6, 7, 8]. Here $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, is the width difference of the heavy and light B_s mass eigenstates. If CP violation is negligible in the relevant tree-level decays, then $a^s_{\rm fs} = a^s_{\rm SL}$. The SM predictions for the asymmetries $a^d_{\rm SL}$ and $a^s_{\rm SL}$ are negligibly small, beyond the reach of the Tevatron experiments [9, 10, 11]. If the evidence for the sizable dimuon charge asymmetry in Eq. (1.1) is confirmed, it would unequivocally point to CP violation beyond the CKM mechanism of the SM.

The present experimental uncertainties of $a^d_{\rm SL}$ and $a^s_{\rm SL}$ separately are larger than that of their combination, $a^b_{\rm SL}$. Thus, from Eq. (1.1) alone it is not clear if the tension with the SM is in the B_d or in the B_s system. Bounds from other observables imply (see below) that new physics contributions in B_d mixing with a generic weak phase cannot exceed roughly 20% of the SM, while in B_s mixing much larger NP contributions are still allowed.

We focus on interpreting the data *assuming* that the above measurements are associated with new CP violating physics which contributes to $B_{d,s}$ mixing, while its contribution to CP violation in tree-level decay amplitudes is negligible. Under this assumption the DØ result in Eq. (1.1) is correlated with the Tevatron measurements of $S_{\psi\phi}$ [12] (and $\Delta\Gamma_s$). These measurements provide nontrivial tests of our hypothesis (see [13] for relaxing these assumptions). Neglecting the small SM contribution to $S_{\psi\phi}$, the following relation holds between experimentally measurable quantities [14]

$$a^s_{\rm SL} = -\frac{|\Delta\Gamma_s|}{\Delta m_s} S_{\psi\phi} \Big/ \sqrt{1 - S^2_{\psi\phi}}\,, \tag{1.3}$$

where $\Delta m_s \equiv m_H - m_L$. Using the new measurement in Eq. (1.1) together with Eq. (1.2), the above relation implies

$$|\Delta\Gamma_s| \simeq -\Delta m_s \left(2.0\, a^b_{\rm SL} - 1.0\, a^d_{\rm SL}\right) \sqrt{1 - S^2_{\psi\phi}} \Big/ S_{\psi\phi}\,. \tag{1.4}$$

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For simplicity we do not display the $\mathscr{O}(10\%)$ uncertainties of the two numerical factors. The CDF and DØ time-dependent $B_s \to \psi\phi$ analyses provide a measurement of $\Delta\Gamma_s$ vs. $S_{\psi\phi}$. Hence all quantities in Eq. (1.4) are constrained, and our analysis can be performed without the theoretical prediction of $\Delta\Gamma_s$ [15], using its determination from data instead.

Using the measured values of Δm_s and $a_{\rm SL}^{b,d}$, we find

$$|\Delta\Gamma_s| \sim \left[(0.28 \pm 0.15)\,{\rm ps}^{-1}\right] \sqrt{1-S_{\psi\phi}^2}\,/S_{\psi\phi}\,. \tag{1.5}$$

The recent CDF [8] and DØ [5] results give best fit values around $(\Delta\Gamma_s, S_{\psi\phi}) \sim (\pm 0.15\,{\rm ps}^{-1}, 0.5)$. This shows that the new $a_{\rm SL}^b$ measurement in Eq. (1.1) is consistent with the data on $\Delta\Gamma_s$ and $S_{\psi\phi}$. This consistency is a nontrivial test of the assumption that NP contributes only to neutral meson mixing.

2. Model independent analysis

New physics in the mixing amplitudes of the $B_{d,s}$ mesons can in general be described by four real parameters, two for each neutral meson system,

$$M_{12}^{d,s} = \left(M_{12}^{d,s}\right)^{\rm SM}\left(1+h_{d,s}\,e^{2i\sigma_{d,s}}\right). \tag{2.1}$$

We denote by M_{12}^q (Γ_{12}^q) the dispersive (absorptive) part of the $B_q^0 - \bar{B}_q^0$ mixing amplitude and SM superscripts denote the SM values (for quantities not explicitly defined here, see Ref. [16]). This modifies the SM predictions for some observables used to constrain h_q and σ_q as

$$\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM}\left|1+h_q e^{2i\sigma_q}\right|, \\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM}\cos\left[\arg\left(1+h_s e^{2i\sigma_s}\right)\right], \\
A_{\rm SL}^q &= {\rm Im}\left\{\Gamma_{12}^q/\left[M_{12}^{q,\rm SM}\left(1+h_q e^{2i\sigma_q}\right)\right]\right\}, \\
S_{\psi K} &= \sin\left[2\beta + \arg\left(1+h_d e^{2i\sigma_d}\right)\right], \\
S_{\psi\phi} &= \sin\left[2\beta_s - \arg\left(1+h_s e^{2i\sigma_s}\right)\right].
\end{aligned} \tag{2.2}$$

Here $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = (1.04 \pm 0.05)^\circ$ is an angle of a squashed unitarity triangle.

As already discussed, the new DØ measurement directly correlates the possible NP contributions in the B_d and B_s systems [see Eq. (1.2)]. In order to quantitatively assess our NP hypothesis we perform a global fit using the `CKMfitter` package [17] to determine simultaneously the NP parameters $h_{d,s}$ and $\sigma_{d,s}$, as well as the $\bar{\rho}$ and $\bar{\eta}$ parameters of the CKM matrix.

The results presented here use the post-Beauty2009 `CKMfitter` input values [17], except for the lattice input parameters where we use [18], and the most recent experimental data. For $S_{\psi\phi}$ vs. $\Delta\Gamma_s$, we use the $2.8\,{\rm fb}^{-1}$ 2d likelihood of DØ [5] and the $5.2\,{\rm fb}^{-1}$ 1d likelihood of the recent CDF measurement [8] (the 2d likelihood is not available); these fits are done without assumptions on the strong phases. As already mentioned, neither the CDF nor the DØ result gives a significant tension in the fit, so we expect that a real 2d Tevatron combination of the ICHEP 2010 results [8, 19] will not alter our results significantly. For the results presented here, we marginalize over $|\Gamma_{12}^s|$ in the range $0-0.3\,{\rm ps}^{-1}$, finding that the data prefer values for $\Delta\Gamma_s$ about 2.5 times larger

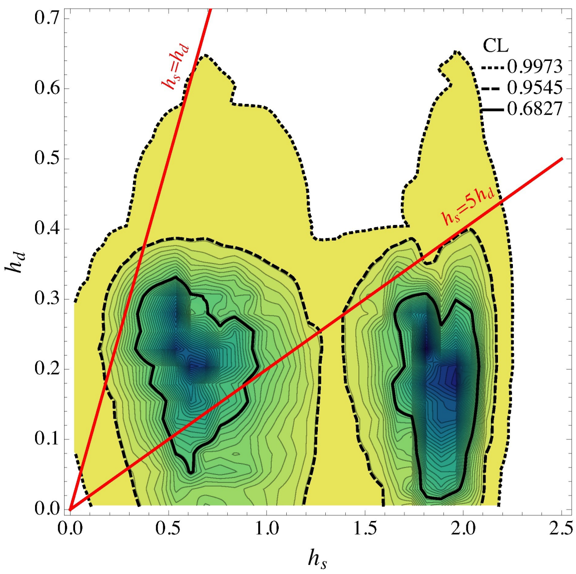

Figure 1: The allowed range of h_s and h_d from the combined fit. The solid, dashed, and dotted contours show 1σ, 2σ, and 3σ, respectively.

than the prediction [2]. If we use the theory prediction, our conclusions about NP do not change substantially, but the goodness of fit is reduced significantly.

Figure 1 shows the results of the global fit projected onto the $h_d - h_s$ plane with 1σ (solid), 2σ (dashed), and 3σ (dotted) contours. We find that the data show evidence for disagreement with the SM or, differently stated, the no NP hypothesis $h_s = h_d = 0$ is disfavored at the 3.3σ level. Figure 2 shows the $h_s - \sigma_s$ and $h_d - \sigma_d$ fits. The two best fit regions are for $h_s \sim 0.5$ and $h_s \sim 1.8$ with sizable NP phases, $\sigma_s \sim 120^\circ$ and $\sigma_s \sim 100^\circ$ respectively. Here the point $h_s = 0$ is disfavored at only 2.6σ, since h_s and h_d are correlated. In the $h_d - \sigma_d$ case the data is consistent with no new physics contributions in $B_d - \bar{B}_d$ mixing ($h_d = 0$) below the 2σ level.

To interpret the pattern of the current experimental data in terms of NP models, one should investigate if NP models that respect the SM approximate $SU(2)_q$ symmetry are favored (in the SM this is due to the smallness of the masses in the first two generations and the smallness of the mixing with the third generation quarks), or if a hierarchy, such as $h_s \gg h_d$, is required. In Fig. 1 we show the $h_d = h_s$ line, which makes it evident that while $h_d = h_s$ is not disfavored, most of the favored parameter space has $h_s > h_d$. Actually, a non-negligible fraction of the allowed parameter space corresponds to $h_s \gg h_d$, as indicated by the $h_s = 5h_d$ line on Fig. 1.

A particularly interesting NP scenario is to assume $SU(2)_q$ universality ($q = s, d$), defined as

$$h_b \equiv h_d = h_s \,, \qquad \sigma_b \equiv \sigma_d = \sigma_s \,. \tag{2.3}$$

The relevant $h_b - \sigma_b$ plane is shown in Fig. 3. The best fit region, near $h_b \sim 0.25$ and $\sigma_b \sim 120^\circ$, is obtained as a compromise between the Babar and Belle bounds in the B_d system and the tensions in the Tevatron B_s data with the SM predictions. This compromise mostly arises from the different magnitudes of $h_{d,s}$: while the best fit h_d value is a few times smaller than the best fit h_s value, the best fit values of the phases $\sigma_{d,s}$ are remarkably close to each other, as can be seen in Fig. 2.

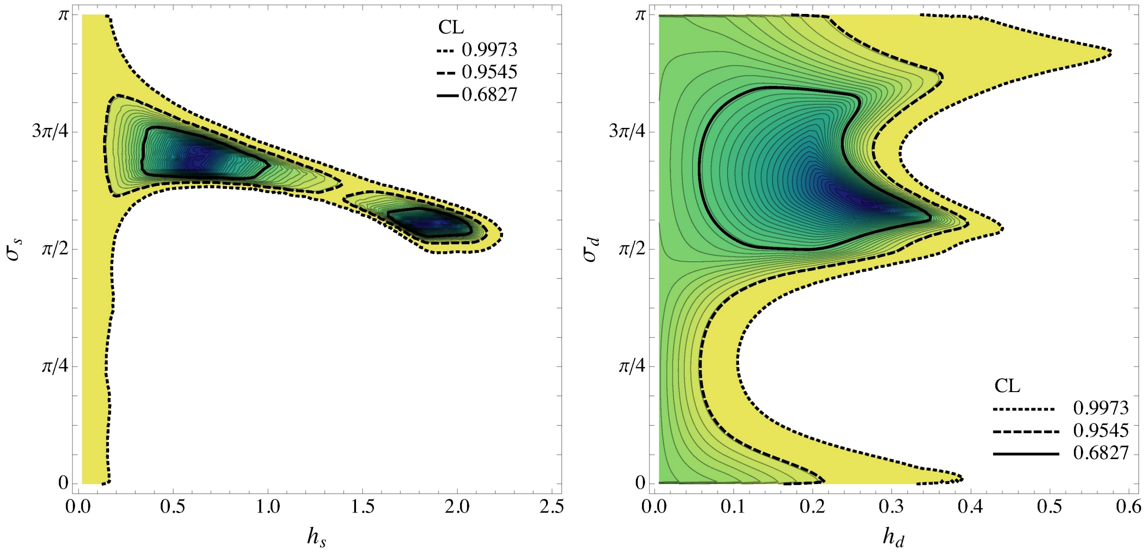

Figure 2: The allowed ranges of h_s, σ_s (left) and h_d, σ_d (right) from the combined fit to all four NP parameters.

Note that while the SM limit, $h_b = 0$, is obtained at less than 3σ CL, the goodness of the fit is significantly degraded compared with the non-universal case.

3. The dimuon asymmetry & GMFV

We now move to interpreting the above results, assuming that the dimuon asymmetry is indeed providing evidence for deviation from the SM. Interestingly, without restricting our discussion to a specific model, we can still make the following general statements:

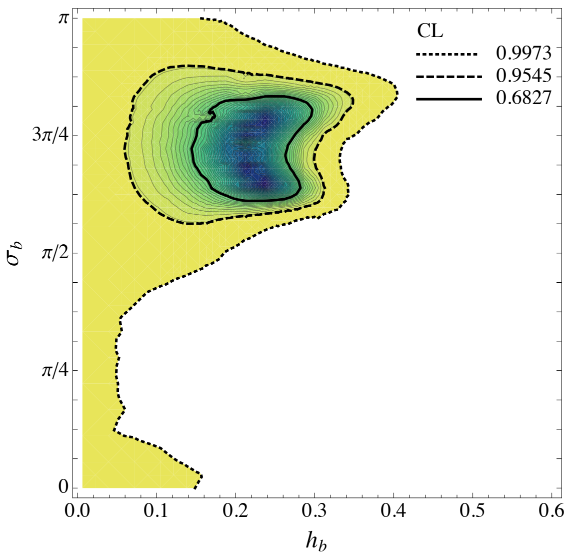

Figure 3: The allowed h_b, σ_b range assuming $SU(2)$ universality.

(i) The present data support the hypothesis that new sources of CP violation are present and that they contribute mainly to $\Delta F = 2$ processes via the mixing amplitude. As is well known, these processes are highly suppressed in the SM.

(ii) The SM extensions with $SU(2)_q$ universality, where the new contributions to B_d and B_s transition are similar in size (relative to the SM), can accommodate the data but are not the most preferred scenarios experimentally. Universality is expected in a large class of well motivated models with approximate $SU(2)_q$ invariance, for instance when flavor transitions are mediated by the third generation sector [20]. The case where the NP contributions are $SU(2)_q$ universal (see Eq. (2.3) and Fig. 3) is also quite generically obtained in the minimal flavor violation (MFV) framework [21] where new diagonal CP violating phases are present [22, 23]. In an effective theory approach such a contribution may arise from the four-quark operators (see also [24]) $O_1^{bq} = \bar{b}_L^\alpha \gamma_\mu q_L^\alpha \, \bar{b}_L^\beta \gamma_\mu q_L^\beta$, $O_2^{bq} = \bar{b}_R^\alpha q_L^\alpha \, \bar{b}_R^\beta q_L^\beta$, $O_3^{bq} = \bar{b}_R^\alpha q_L^\beta \, \bar{b}_R^\beta q_L^\alpha$, suppressed by scales $\Lambda_{\mathrm{MFV};1,2,3}$, respectively. We find that the data require

$$\Lambda_{\mathrm{MFV};1,2,3} \gtrsim \{8.8,\ 13\, y_b,\ 6.8\, y_b\} \sqrt{0.2/h_b}\ \mathrm{TeV}\,. \tag{3.1}$$

If the central value of the measurement in Eq. (1.1) is confirmed, this inequality would become an equality. Note that the dependence on the bottom Yukawa, y_b, is not shown for $\Lambda_{\mathrm{MFV};1}$, since sizable CP violation in this case requires resummation of large effective bottom Yukawa coupling [23, 25]. In general the presence of flavor diagonal phases could contribute to the neutron electric dipole moment [26]. However, this effect arises from a different class of operators and requires a separate investigation. Another interesting aspect of these flavor diagonal phases is that there are examples where these can contribute to the generation of matter-antimatter asymmetry, another issue which deserves further investigation.

(iii) While case (ii) is not excluded by the data, Fig. 1 shows that most of the allowed parameter space prefers $h_s > h_d$. This raises the following question: *What kind of new physics can generate a large breaking of the approximate $SU(2)_q$ symmetry without being excluded by CP violation in the K or D systems?* Remarkably, even this case can be accounted for by the general MFV (GMFV) framework [23]. Consider models where operators with O_4-type chiral and color structure (defined in [27]) are the dominant ones. This may be possible because their contributions are RGE enhanced. An example of such an operator is (similar O_5-type operators are typically suppressed compared to the O_4-type ones)

$$O_4^{\mathrm{NL}} = \frac{c}{\Lambda^2_{\mathrm{MFV};4}} \left[\bar{Q}_3 (A_d^m A_u^n Y_d)_{3i} d_i\right] \left[\bar{d}_3 (Y_d^\dagger A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i\right]. \tag{3.2}$$

Here $A_{u,d} \equiv Y_{u,d} Y_{u,d}^\dagger$ and n,m,l,p are integer powers and c is an $\mathcal{O}(1)$ complex number. We focus on the nonlinear MFV regime, where the contributions of higher powers of the Yukawa couplings are equally important, so a resummation of the third generation eigenvalues is required (both for the up and down Yukawas), due to large logarithms or large anomalous dimensions. In Eq. (3.2) we adopt a linear formulation where the resummation of the third generation is not manifest; see [23, 25] for a more rigorous treatment. Such operators can carry a new CP violating phase and may contribute dominantly to $b \to s$ and *not* to $b \to d$ transition, because of the chiral suppression induced by Y_d.

We find that the data requires

$$\Lambda_{\mathrm{MFV};4} \gtrsim 13\, y_b \sqrt{\frac{m_s}{m_b}\frac{0.5}{h_s}}\,\mathrm{TeV} \approx 2\, y_b \sqrt{\frac{0.5}{h_s}}\,\mathrm{TeV}\,. \tag{3.3}$$

Thus, remarkably, $h_s \gg h_d$ can arise in MFV models with flavor diagonal CP violating phases, where large chirality flipping sources exist at the TeV scale. Such models have not been studied in great detail, but possible interesting examples are supersymmetric extensions of the SM at large $\tan\beta$ [28] or warped extra dimension models with MFV structure in the bulk [29]. We finally note that the operator O_4^{NL} predicts contributions to the B_d system suppressed by $m_d/m_s \sim 5\%$, which may be accessible in the near future and provide a direct test for the above scenario.

(iv) The fact that the data can be accounted for within the MFV framework makes it clear that it can be accommodated in models with even more general flavor structure [30, 31]. Several conditions need to be met, though. For instance, the operators $O_{2,3,4}$ require large chirality violating sources in addition to the CP violating phases, which are generically strongly constrained by neutron electric dipole moment and $b \to s\gamma$. Contributions to the O_1 operator from $SU(2)_{\mathrm{w}}$ invariant new physics, on the other hand, are constrained by CP violation in $D-\bar{D}$ mixing. They may also induce observable $\Delta t = 1$ and $\Delta t = 2$ top flavor violation at the LHC [32, 33].

4. GMFV and CPV in $D^0 - \overline{D}^0$ mixing

Another example where recent progress has been achieved is in measurements of CPV in $D^0 - \overline{D}^0$ mixing, which led to an important improvement of the NP constraints. However, in this case the SM contributions are unknown [34], and the only robust SM prediction is the absence of CPV (see [35] for instance). The three relevant physical quantities related to the mixing can be defined as

$$y_{12} \equiv |\Gamma_{12}|/\Gamma, \qquad x_{12} \equiv 2|M_{12}|/\Gamma, \qquad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})\,, \tag{4.1}$$

where M_{12}, Γ_{12} are the total dispersive and absorptive part of the $D^0 - \overline{D}^0$ amplitude, respectively. Fig. 4 shows (in grey) the allowed region in the $x_{12}^{\mathrm{NP}}/x - \sin\phi_{12}^{\mathrm{NP}}$ plane. x_{12}^{NP} corresponds to the NP contributions and $x \equiv (m_2 - m_1)/\Gamma$, with m_i, Γ being the neutral D meson mass eigenstates and average width, respectively. The pink and yellow regions correspond to the ranges predicted by, respectively, the linear MFV and general MFV classes of models [36] (see [25] for details). We see that the absence of observed CP violation removes a sizable fraction of the possible NP parameter space, in spite of the fact that the magnitude of the SM contributions cannot be computed!

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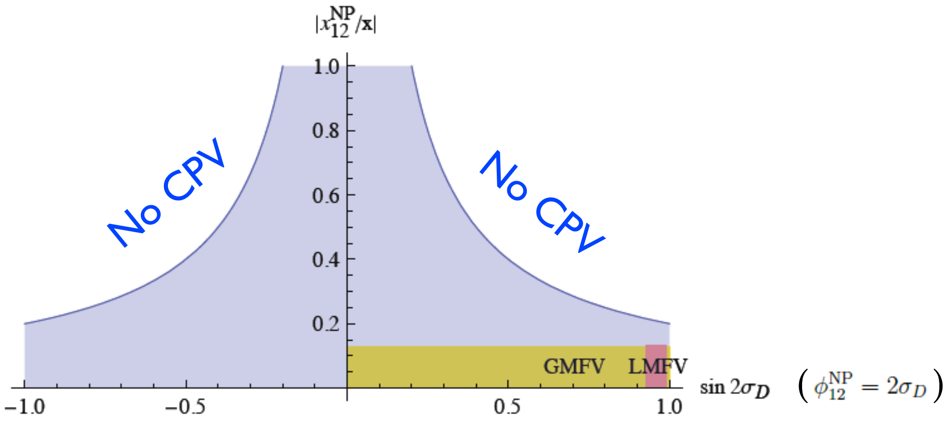

Figure 4: The allowed region, shown in grey, in the $x_{12}^{\rm NP}/x_{12} - \sin\phi_{12}^{\rm NP}$ plane. The pink and yellow regions correspond to the ranges predicted by, respectively, the linear MFV and general MFV classes of models [36].

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