# Constraining CP violation in neutral meson mixing with theory input

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Work in collaboration with M. Freytsis and Z. Ligeti [1203.3545 hep-ph]
Lawrence Berkeley National Laboratory

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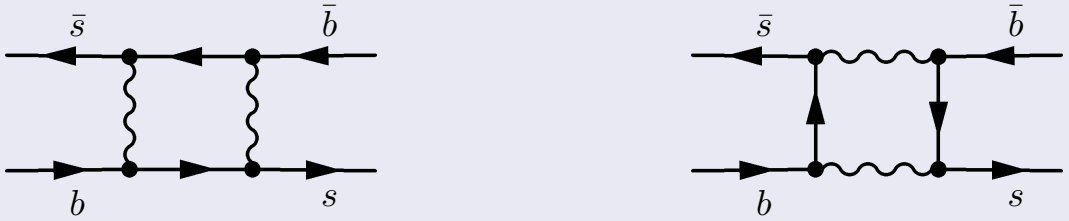
# Neutral Meson Oscillation

## Description

- $\Delta F = 2$ Flavor changing neutral current interactions




- Interplay of Weak diagrams $\Rightarrow$ (Convention dependent) phases

## Sensitive to New Physics

$$\Delta M = 2\mathrm{Re}\sqrt{(M_{12} - i/2\Gamma_{12})(M_{12}^* - i/2\Gamma_{12}^*)} \approx 2|M_{12}|$$

$$\Delta\Gamma = -4\mathrm{Im}\sqrt{(M_{12} - i/2\Gamma_{12})(M_{12}^* - i/2\Gamma_{12}^*)} \approx 2|\Gamma_{12}|\cos[\mathrm{Arg}(-\Gamma_{12}/M_{12})]$$

$$\delta = (1 - |q/p|^2)/(1 + |q/p|^2) \approx \frac{1}{2}\,\mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}} \approx \frac{1}{2}\frac{\Delta\Gamma}{\Delta M}\tan\phi$$

$$\approx \frac{1}{2}A_{\mathrm{SL}}$$

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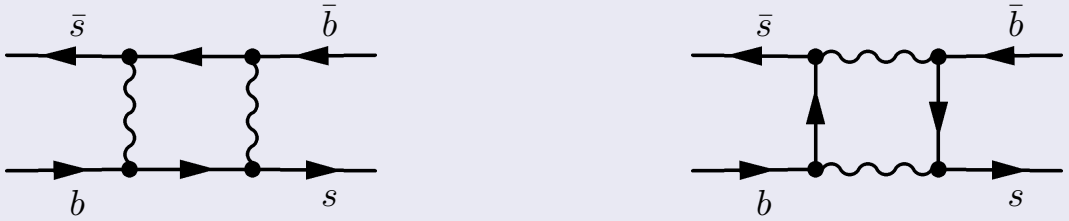


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# Current Experimental Situation

**DØ Like-sign Di-muon measurement** [1106.6308]

$$A^b_{\rm SL} = -[7.87 \pm 1.72\,(\text{stat}) \pm 0.93\,(\text{syst})] \times 10^{-3}$$
$$= (0.594 \pm 0.022)\, A^d_{\rm SL} + (0.406 \pm 0.022)\, A^s_{\rm SL}$$

$\Delta M_s = (17.719 \pm 0.043)\,\text{ps}^{-1}$ [hep-ex/0609040,LHCb-CONF-2011-050(005)]

$\Delta M_d = (0.507 \pm 0.004)\,\text{ps}^{-1}$ Heavy Flavor Averaging Group (HFAG)

$\Delta\Gamma_s = (0.116 \pm 0.019)\,\text{ps}^{-1}$ LHCb

$\Delta\Gamma_s = (0.068 \pm 0.027)\,\text{ps}^{-1}$ CDF

$\Delta\Gamma_s = (0.163^{+0.065}_{-0.064})\,\text{ps}^{-1}$ DØ

**LHCb measurement of time dependent CP asymmetry** [LHCb-CONF-2012-002]

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- New measurement tend to agree well with SM [1102.4274,hep-ph/0612167]

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# Generic Conditions on Mixing Parameter

## Physical Constraints

- Mass and width of physical states have to be positive
- Unitarity has to be conserved
- Time evolution of any linear combination of $|B^0\rangle$ and $|\bar{B}^0\rangle$ determined entirely by the $\Gamma$ matrix

$\Rightarrow$ $\Gamma$ itself has positive eigenvalues

- Defining $\Gamma = (\Gamma_H + \Gamma_L)/2$, $x = (m_H - m_L)/\Gamma$ and $y = (\Gamma_L - \Gamma_H)/(2\Gamma)$

$$\delta^2 < \frac{\Gamma_H \Gamma_L}{(m_H - m_L)^2 + (\Gamma_H + \Gamma_L)^2/4} = \frac{1 - y^2}{1 + x^2}$$

- Known as unitarity bound or Bell-Steinberger inequality

[J.S. Bell, J. Steinberger, "Weak interactions of kaons", T. D. Lee, L. Wolfenstein, Phys. Rev. 138, B1490-B1496 (1965).]

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# Deriving the Relation

## Sketch of the Steps

- Assume theoretical knowledge

$$0 \leq y_{12} = |\Gamma_{12}| \,/\, \Gamma \leq 1$$

  instead of unitarity constraint $\Gamma_{11} \geq |\Gamma_{12}|$
- Two ways of deriving
  1. Proceed with same steps as unitarity bound, but use $y_{12}$ definition
  2. Scaling argument: Scale $\Gamma$ by $y_{12}$

  $\Rightarrow$ Only way to derive bound in CPT violating case for $|\delta|^2$

## The Result

$$\delta^2 = \frac{y_{12}^2 - y^2}{y_{12}^2 + x^2} = \frac{|\Gamma_{12}|^2 - (\Delta\Gamma)^2/4}{|\Gamma_{12}|^2 + (\Delta m)^2}$$

- Entirely determined by solving the eigenstate problem
- Monotonic function in $y_{12}$

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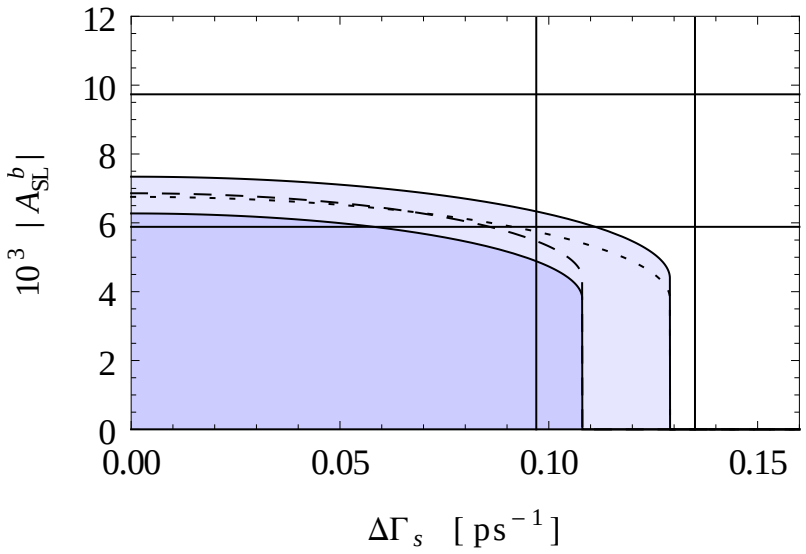
# Plot of the Bound




- Combined bound assuming DØ production asymmetry
- Setting $\Delta\Gamma_d = 0$ and use $\Delta M^{\mathrm{exp}}$
- Horizontal lines: $1\sigma$ range of $|A_{\mathrm{SL}}^b|$ DØ measurement
- Vertical lines correspond to $\Delta\Gamma_s$ LHCb measurement

- Shaded regions are allowed by theory prediction of $|\Gamma_{12}|$ [A.Lenz,U.Nierste: 1102.4274,hep-ph/0612167]
  1. Darker uses $1\sigma$ upper range
  2. Lighter uses $2\sigma$ upper range
- Dashed [dotted] curves: Mixed sigma interval of theory predictions
- The vertical boundaries of the shaded regions arise because $|\Delta\Gamma_s| > 2\,|\Gamma_{12}^s|$ is unphysical.

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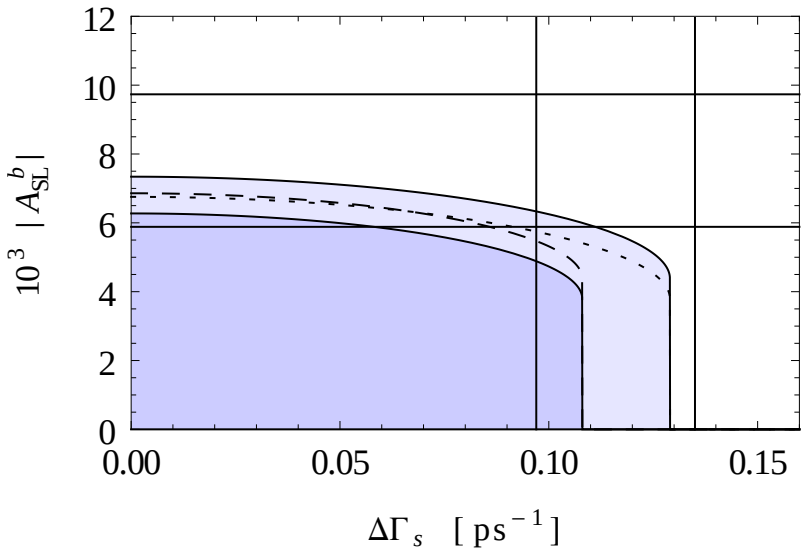


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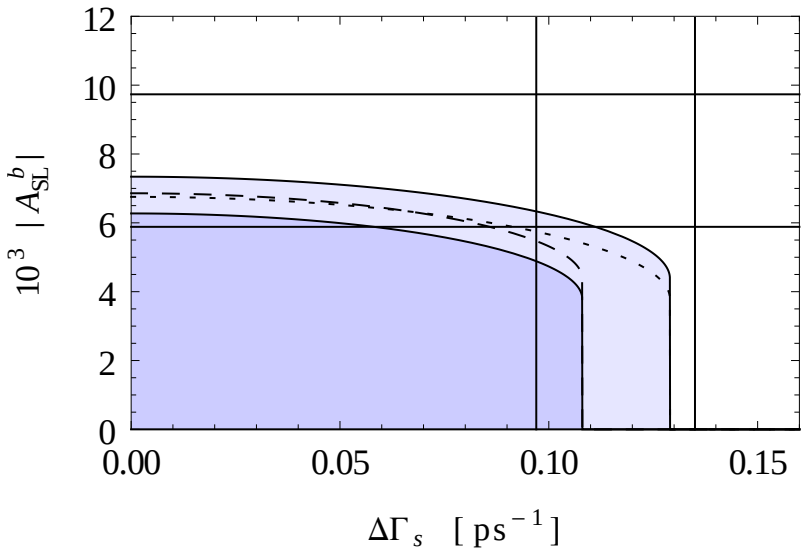


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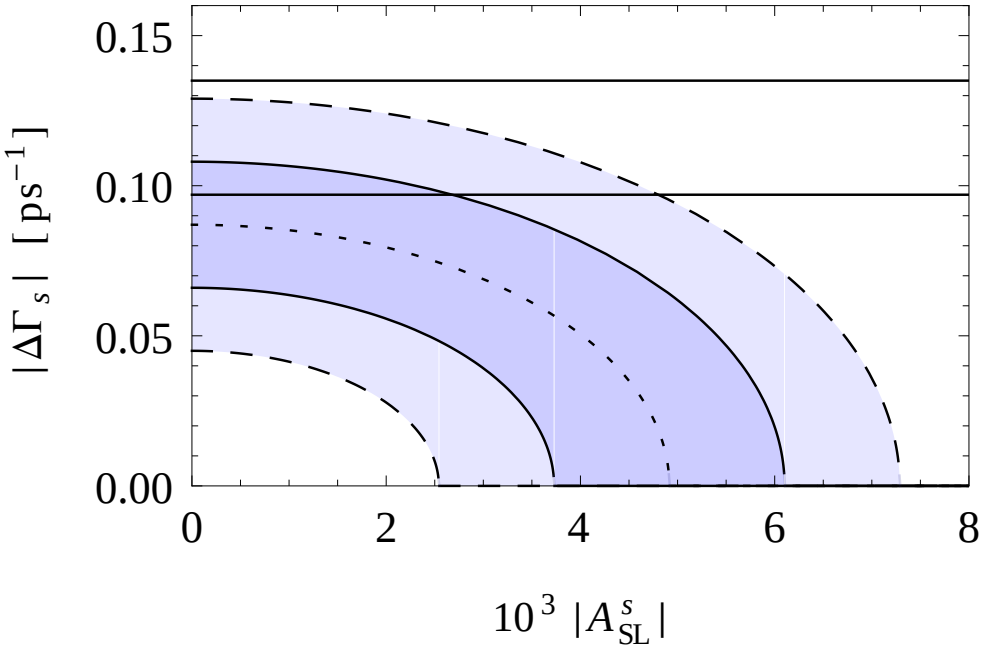
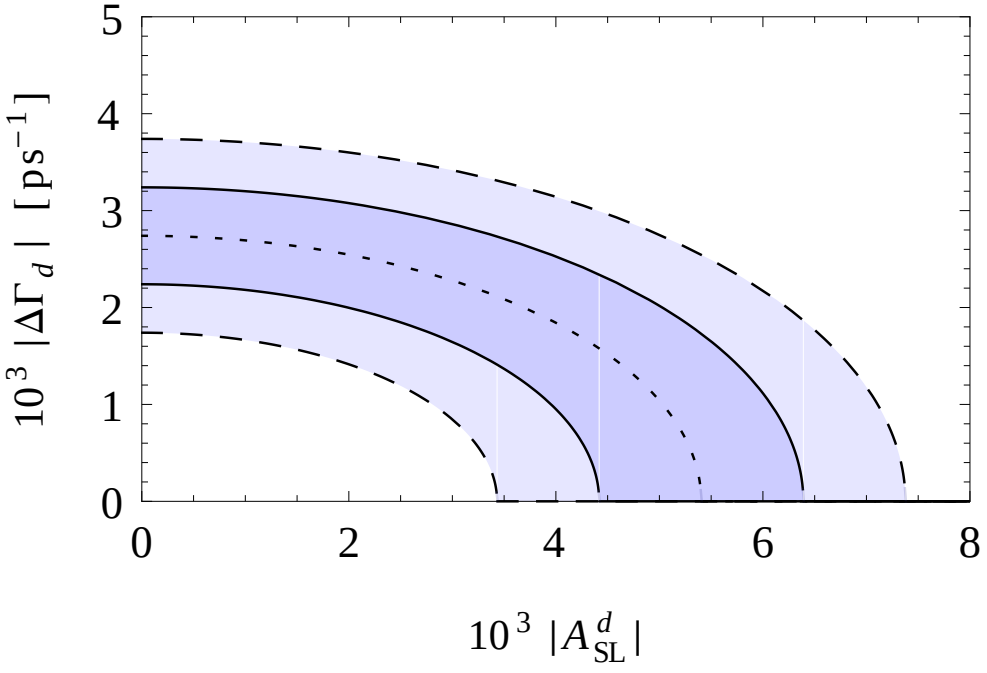



## Interpretation

- Horizontal lines correspond to LHCb measurement
- Dark [light] shaded allowed by $1\sigma$ [$2\sigma$] theory variation
- No discrepancy claimed in experiment

# Plot on Individual Bound on $B_d$

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- Non-zero measurement of $\Delta\Gamma_d$ would strengthen upper bound

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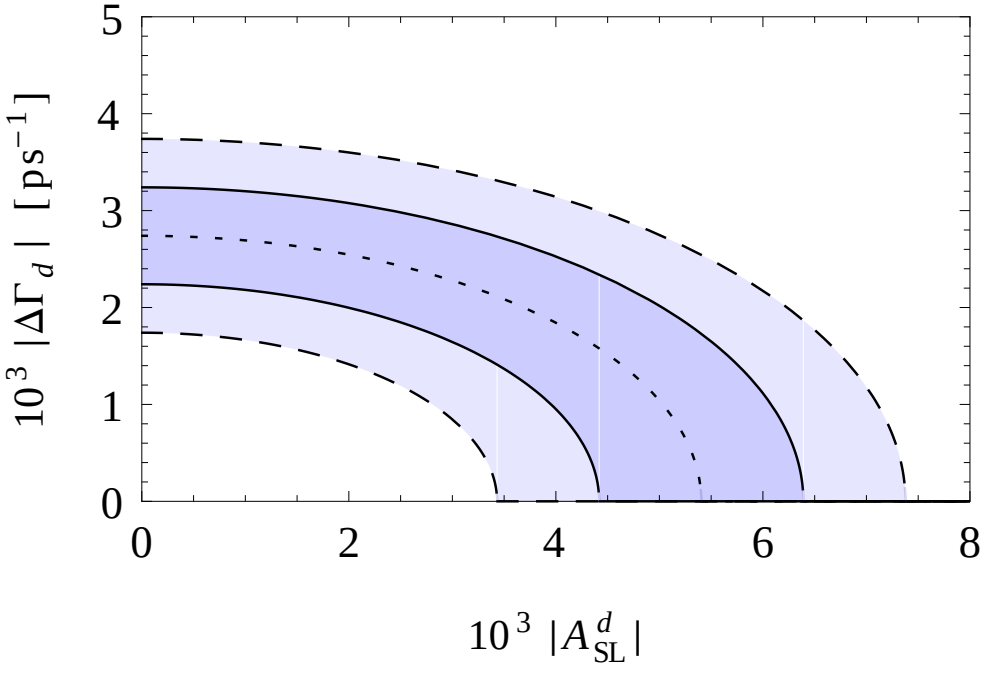


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# Numerical Interpretation

## Remarks

- Problematic: $|\Delta\Gamma_s|^{\text{meas.}} > 2\,|\Gamma_{12}^s|$ is unphysical
- Numerator of Relation can vanish $\Rightarrow$ Upper bound
- Assume $2\sigma$ theory prediction for a conservative estimate

## Results

- For $B_s$ system we obtain taking, into account the unphysical region

$$|A_{\text{SL}}^s| < 4.2 \times 10^{-3}$$

- 2-3 times better than best current experimental bound
- For the $B_d$ system we obtain a comparable bound

$$|A_{\text{SL}}^d| < 7.4 \times 10^{-3}$$

- Significant improvement possible by observing $|\Delta\Gamma_d| > 0$

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# Discussion of the Results

## Strength of the Bound

- Upper bound on $y_{12}$ implies an upper bound on $|\delta|$
- Relation is much stronger for small $y_{12}$, as e.g. in the $B_d$ system

## Comparing to Known Results

- DØ $A_{\mathrm{SL}}$ measurement: $3.9\sigma$ discrepancy with SM

$\Rightarrow$ Correlated with the discrepancy found in our analysis

1. SM prediction of $A_{\mathrm{SL}}$ uses calculation of $\Gamma_{12}$
2. The relation uses $|\Gamma_{12}|$ as an input
3. Calculation of $|\Gamma_{12}|$ and $\mathrm{Im}(\Gamma_{12})$ rely on the same OPE

- Large cancellations in $\mathrm{Im}(\Gamma_{12}) \Rightarrow$ Uncertainties could be larger than expected from NLO calculation [hep-ph/0308029, hep-ph/0307344]
- The sensitivity of $\Gamma_{12}$ to NP is generally weak
- Interesting to determine $\delta$ additionally from this relation

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# No Go Theorem (preliminary)

## The Claim

There is no generic bound, stronger than the unitarity bound (UB)

## Sketch of Derivation

- Unitarity bound is satured if

$$\langle f|\mathbf{T}|B_H\rangle \propto \langle f|\mathbf{T}|B_L\rangle$$

- Start with an arbitrary, generic decaying two-state system
- Wigner-Weisskopf approximation: Any choice of parameters OK

$\Rightarrow$ Orthogonal, non CP violating system as starting point

- Arbitrary new UV physics can change $M_{12}$ independently of $\Gamma_{12}$
- Varying $M_{12}$ keeping mass and width of states physical

$\Rightarrow$ Unitarity bound can be satured (relax constraint Arg $M_{12}$ = Arg $\Gamma_{12}$)

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## Summary

- Provided a physical derivation of the exact relation allowing for theoretical input on $|\Gamma_{12}|$
  1. Input is typically insensitive to New Physics
  2. Avoids largest uncertainties of theory calculation
  3. Valid even if CPT is violated
- Independent of the discrepancy found from a global fit
  1. Application to $B_{d,s}$ systems leads to the individual bounds

$$|A_{\rm SL}^s| < 4.2 \times 10^{-3} \qquad |A_{\rm SL}^d| < 7.4 \times 10^{-3}$$

  2. Providing a bound on the individual asymmetries at comparable or better levels than the current experimental bounds
  3. Bounds are in tension with the DØ measurement of $A_{\rm SL}^b$
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