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]
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Outline

Motivation

- The Standard Model has passed all precision tests
  1. CERN: Z discovery, test of the gauge structure
  2. Flavour factories: Test of the flavour sector
  3. Tevatron: Discoveries, top, $B_s - \bar{B}_s$ oscillation, ...
  4. LHC: Up to now no significant new discoveries
- Only a few tensions $\sim 2 - 3\sigma$
- Most hints for New Physics in flavour physics sector

Promising Channels: Flavour changing neutral currents (FCNC)

- Forbidden at tree level $\Rightarrow$ NP can enter at the same order
- $\Delta F = 1$ processes: Rare decays
- $\Delta F = 2$ processes: Meson oscillation / mixing
- Focus here on $M - \bar{M}$ oscillation (especially $B_{d/s} - \bar{B}_{d/s}$)

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Mixing and CP Violation: Origin and Consequences

CKM Matrix

- Diagonalize up- and down-type quark mass matrices simultaneously

$\Rightarrow$ Missmatch in charged current described by CKM matrix

$$V_{\text{ckm}} = V^{(u)} W^{(d)\dagger}$$

- 3 generations $\Rightarrow$ V_{ckm} has 3 angles and 1 complex phase

Consequences

- CP violation if all masses are non-degenerate
- Transitions between different generations

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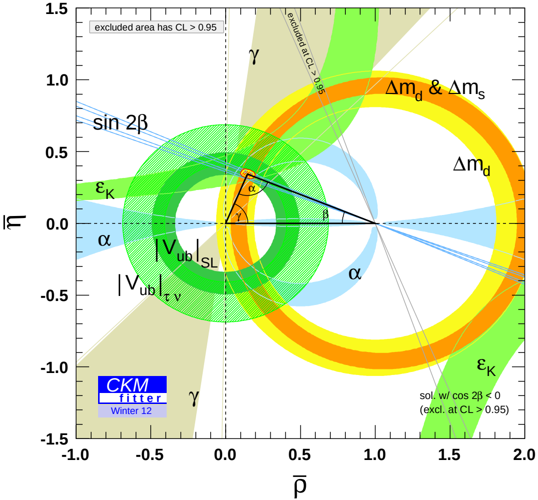
$$V^\dagger_{CKM} V_{CKM} = \begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ \boxed{V^*_{ub} \quad V^*_{cb} \quad V^*_{tb}} \end{pmatrix} \begin{pmatrix} \boxed{V_{ud}} & V_{us} & V_{ub} \\ \boxed{V_{cd}} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} \overset{!}{=} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \boxed{0} & 0 & 1 \end{pmatrix}$$

The CKM Matrix



[CKMfitter: http://ckmfitter.in2p3.fr/]

CP Violating in Mixing

General Comments [Bigi,Sanda: CP violation]

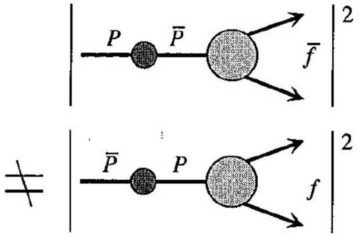
- Occurs in $P_0 \leftrightarrow \bar{P}_0$ oscillations

$\Rightarrow$ Flavor specific final states

$$P_0 \to f \not\leftarrow \bar{P}_0$$

- Neccessary condition: $\left|\frac{q}{p}\right| \neq 1$

$\Rightarrow$ Rates for B and $\bar{B}$ differ



Example of Process

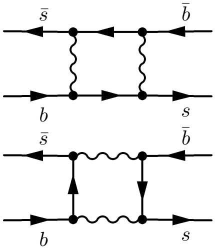
Semi-leptonic asymmetry: $P_0 \to X\ell^+\bar{\nu}_\ell$ and $\bar{P}_0 \to X\ell^-\nu_\ell$

$$A_{\text{sl}} \equiv \frac{\Gamma(P_0 \to X\ell^-) - \Gamma(\bar{P}_0 \to X\ell^+)}{\Gamma(P_0 \to X\ell^-) + \Gamma(\bar{P}_0 \to X\ell^+)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

Description of Neutral Meson Mixing

- Two state system with interplay of oscillation and decay
- Mass matrix M and decay width matrix Γ are hermitian

$$i\frac{\partial}{\partial t}\begin{pmatrix}|P_0\rangle \\ |\bar{P}_0\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12} \\ M_{12}^* & M_{11}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11}\end{pmatrix}\right]\begin{pmatrix}|P_0\rangle \\ |\bar{P}_0\rangle\end{pmatrix}$$



Diagonalization

- Solution for mass eigenstates

$$|P_{H,L}\rangle = \frac{p\,|P^0\rangle \mp q\,|\bar{P}_0\rangle}{\sqrt{|p|^2+|q|^2}}\,, \qquad \frac{q^2}{p^2} = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}$$

- Mass eigenstates do not need to coincide with CP eigenstates

$$\delta \equiv \langle P_H|P_L\rangle = \frac{|p|^2-|q|^2}{|p|^2+|q|^2} = \frac{1-|q/p|^2}{1+|q/p|^2} = \frac{1-\sqrt{1-A_{\mathrm{sl}}^2}}{A_{\mathrm{sl}}} \approx \frac{1}{2}A_{\mathrm{sl}}$$

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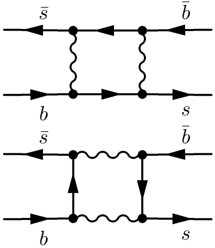

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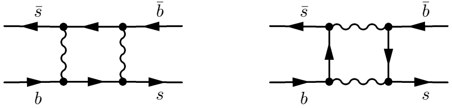
Test of the Standard Model

Need to predict three parameters to compare with SM



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

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

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

Mixing Parameter Input

[1008.1593,1203.0238]

- M_{12}: Dominated by dispersive part of $\Delta B = 2$ operator
- Γ_{12}: Dominated by absorpative part of $\Delta B = 1$ op. double insertion
- Main theoretical uncertainties
  1. Operator product expansion in physical region
  2. Expansion in small energy release $m_b - 2m_c < 2$ GeV

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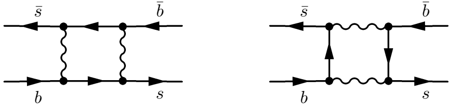

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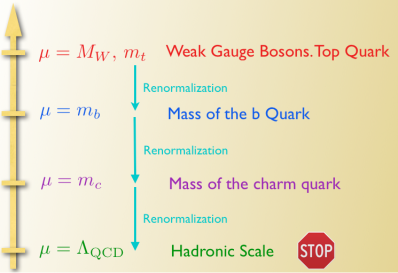
Effective Theory at the scale of the B

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \lambda_{\text{CKM}} \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

- Current-current operators
- Electroweak/QCD Penguins
- Magnetic Penguins
- Semi-leptonic operators
- $\Delta F = 2$ operators



Allows for Systematic Calculation: Heavy Quark Expansion (HQE)

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- Non-perturbative $1/m_{b,c}$ corrections

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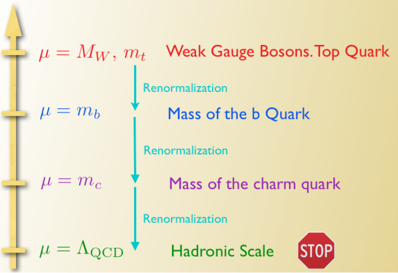

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The Hamilton Matrix: Computing Mixing Parameters

- Matrix to be understood in $M_1 \equiv M$ — $\bar{M} \equiv M_2$ space
- Weak interaction sets scale: "Wigner-Weisskopf" approximation

⇒ Expansion in powers of $G_F \hat{=}$ Number of $\mathcal{H}_{\text{weak}}$ Insertions

- Use rest-frame of the meson

$$\left[\mathcal{M} - \frac{i}{2}\Gamma\right]_{ij} = M_M \delta_{ij}^{(0)} + \frac{1}{2M_M} \sum_n \frac{\langle M_i|\mathcal{H}_{\text{weak}}|n\rangle\langle n|\mathcal{H}_{\text{weak}}|M_j\rangle}{M_M^{(0)} - E_n + i\epsilon} + \ldots$$

- Sum includes phase-space of final state
- Decompose into dispersive and absorpative part "optical theorem"

$$\frac{1}{\omega + i\epsilon} = \mathcal{P}\left(\frac{1}{\omega}\right) - i\pi\delta(\omega)$$

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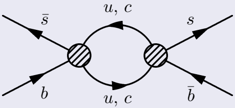
Calculation of Γ_{12}

Absorptive Part

$$\Gamma_{ij} = \frac{1}{2M_M} \sum_n \langle M_i|\mathcal{H}_{\text{weak}}|n\rangle\langle n|\mathcal{H}_{\text{weak}}|M_j\rangle(2\pi)\delta(M_M^{(0)} - E_n)$$

- On-shell production of intermediate particles
- $i = j$ recovers total width
- dominated by $\Delta B = 1$ operator
- Only u and c intermediate state quarks



Calculation

[arXiv:1102.4274]

- Perturbative corrections
  1. Up to NLO in $\alpha_s(m_b)$
  2. All-order summation of $\alpha_s^n(m_c^2/m_b^2)^n \log(m_c^2/m_b^2)$
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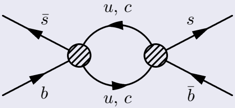

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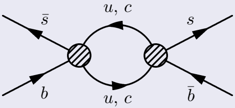

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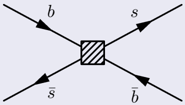
Calculation of M_{12}

[hep-ph/0612167]

Dispersive Part

$$M_{ij} = \frac{1}{2M_M}\langle M_i|\mathcal{H}_{\Delta F=2}|M_j\rangle + \frac{1}{2M_M}\sum_n \mathcal{P}\frac{\langle M_i|\mathcal{H}_{\Delta F=1}|n\rangle\langle n|\mathcal{H}_{\Delta F=1}|M_j\rangle}{M_M^{(0)} - E_n}$$

- dominated by $\Delta B = 2$ operator
- top quark dominate intermediate state



Result within SM

[hep-ph/0612167]

$$M_{12} = \frac{G_F^2 M_B}{12\pi^2} M_W^2 (V_{tb}V_{ts}^*)^2 \hat{\eta}_B S_0\left(\frac{m_t^2}{M_W^2}\right) f_{B_s}^2 B$$

- Lattice determination of Bag parameter B and decay constant f_{B_s}
- Mass difference measured precisely

$\Rightarrow$ Fixes $|M_{12}|$ for $|M_{12}| \gg \Gamma_{12}$

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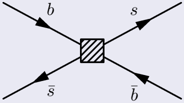

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In the Standard Model

- Naming scheme for $B_{s,d}$: $A_{\mathrm{SL}}^{d,s}$
- Sum of both including production asymmetry: A_{SL}^{b}
- SM phase orginates from CKM mechanism (convention dependent)

$$A_{\mathrm{SL}}^{d,s} \approx \mathrm{Im}\, \Gamma_{12}^{d,s}/M_{12}^{d,s} \approx \frac{\Delta\Gamma_{d,s}}{\Delta M_{d,s}} \tan\phi_{d,s}$$

- Highly suppressed: $|\Gamma_{12}/M_{12}| = \mathcal{O}(m_b^2/M_W^2, m_c^2/m_b^2)$

Beyond the Standard Model

- Additional phases can be introduced in M_{12} due to New Physics

$\Rightarrow$ Introduces sensitivity to $\mathrm{Re}\,(\Gamma_{12}/M_{12})_{\mathrm{SM}}$

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Standard Model Predictions [A.Lenz,U.Nierste: 1102.4274,hep-ph/0612167]

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- $2|\Gamma_{12}^s| = (0.087 \pm 0.021)\,\mathrm{ps}^{-1}$
- $\Delta M_s = (17.3 \pm 2.6)\,\mathrm{ps}^{-1}$
- $\phi_s = (0.22 \pm 0.06)^\circ$
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- $2|\Gamma_{12}^d| = (2.74 \pm 0.51) \times 10^{-3}\,\mathrm{ps}^{-1}$
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Current Experimental Situation

DØ Like-sign Di-muon measurement [1106.6308]

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

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

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

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

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

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

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

$$\phi_s = -0.001 \pm 0.101(\mathrm{stat}) \pm 0.027(\mathrm{syst})\,\mathrm{rad}$$

- New measurement tend to agree well with SM

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

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

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

$$\begin{aligned} \Delta\Gamma_s &= (0.116 \pm 0.019)\,\mathrm{ps}^{-1} && \text{LHCb} \\ \Delta\Gamma_s &= (0.068 \pm 0.027)\,\mathrm{ps}^{-1} && \text{CDF} \\ \Delta\Gamma_s &= (0.163^{+0.065}_{-0.064})\,\mathrm{ps}^{-1} && \text{DØ} \end{aligned}$$

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

$$\phi_s = -0.001 \pm 0.101(\mathrm{stat}) \pm 0.027(\mathrm{syst})\,\mathrm{rad}$$

- New measurement tend to agree well with SM

How Can New Physics Enter?

- Can induce new operator structures
- Can modify Wilson coefficients

Parametrization and Effects

- For B mesons: $|\Gamma_{12}/M_{12}| \ll 1$

$$\Delta m = |2M_{12}|, \quad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12}, \quad A_{\mathrm{sl}} = 2\delta = \mathrm{Im}\left(\Gamma_{12}/M_{12}\right)$$

- In general: Changing phase and absolute value possible

$$M_{12} = M_{12}^{\mathrm{SM}}|\Delta_s|e^{i\phi_s^\Delta}$$

1. Only relative phase relevant
2. M_{12}: Heavy intermediate particles, but $|M_{12}|$ constrained by exp.
3. Γ_{12} dominated by on-shell charm intermediate states

$\Rightarrow$ Believed not to change dramatically by New Physics contribtions

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 Γ matrix

$\Rightarrow$ Γ 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", in R. G. Moorhouse et al., Eds., Proceedings of the Oxford Int. Conf. on Elementary Particles, Rutherford Laboratory, Chilton, England, 1965, p. 195.]

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Reminder: Sketching Derivation of Unitarity Bound

Definitions

- $a_i = \sqrt{2\pi\rho_i}\,\langle f_i|\mathcal{H}|B\rangle\,, \qquad \bar{a}_i = \sqrt{2\pi\rho_i}\,\langle f_i|\mathcal{H}|\bar{B}\rangle$

$\Rightarrow$ $a_i^*\,a_i = \Gamma_{11}\,, \qquad \bar{a}_i^*\,\bar{a}_i = \Gamma_{22}\,, \qquad \bar{a}_i^*\,a_i = \Gamma_{12}$

- In the physical basis we have

  $a_i = \frac{1}{2p}\left(a_{Hi} + a_{Li}\right)\,, \qquad \bar{a}_i = \frac{1}{2q}\left(a_{Li} - a_{Hi}\right)$

$\Rightarrow$ $a_{Hi}^*\,a_{Hi} = \Gamma_H\,, \quad a_{Li}^*\,a_{Li} = \Gamma_L\,, \quad a_{Hi}^*\,a_{Li} = -i(m_H - m_L + i\Gamma)\,\delta$

Sketch of Derivation

- Apply optical theorem and Cauchy Schwartz inequality

$\Rightarrow$ Forces Γ to have positive semi-definit eigenvalues

$$\Gamma_{11} \geq |\Gamma_{12}|$$

- Apply the same to the physical basis with unitarity condition
- Leads to the unitarity bound $\delta^2 < \frac{\Gamma_H\Gamma_L}{(m_H-m_L)^2+(\Gamma_H+\Gamma_L)^2/4} = \frac{1-y^2}{1+x^2}$

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Implication for the Three Neutral Mesons

Neutral K Mesons

- Very limited amount of final states
- Unitarity bound developed for this case

Neutral D Mesons

- Difficult in theory as well as in experiment
  1. Non-perturbative methods?
  2. Huge GIM suppression
- Interesting because of only up-type

Neutral $B_{d,s}$ Mesons

- Lots of possible final states
- Experimental precision is increasing
- Systematic expansion for theoretical calculations possible

$\Rightarrow$ Good opportunity to search for New Physics

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Improvement: Using Theoretical Input

Assumptions

- Assume knowledge of $|\Gamma_{12}|$

$\Rightarrow$ Can be computed in a reliable, systematical expansion in the B system

- Define $y_{12} \geq 0$ with

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

Goals

- Use precise measurement of mass difference
- Use a reliable theory prediction

$\Rightarrow$ Obtain a relation between two measurable quantities

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Deriving the Relation

Sketch of the Steps

- Start with the same equations as for the unitarity bound
- Use y_{12} instead of unitarity constraint
- Proceed with same steps

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
- Relation is exact
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Scaling Argument and CPT

Obtain a Physical Understanding

- Relation can also be obtained from a scaling argument
- δ depends only on mixing parameters and independent of Γ
- Scale Γ by y_{12}
  1. Does not affect δ
  2. Changes $x \to x/y_{12}$ and $y \to y/y_{12}$

$\Rightarrow$ Combining argument with unitarity bound recovers exact relation

Derivation not Assuming CPT invariance

- Assuming no CPT invariance implies $M_{11} \neq M_{22}$ and $\Gamma_{11} \neq \Gamma_{22}$
- Mixing parameters depend on difference of diagonal components

$\Rightarrow$ Relation applies for $|\delta|^2$

- Usual derivation do not go through if CPT is violated

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Combined Bound on A^b_{SL}

Experimental Situation

- Hadron colliders produce admixture of B_s and B_d

$\Rightarrow$ Production asymmetry is known at DØ

$$A^b_{\mathrm{SL}} = (0.594 \pm 0.022)\, A^d_{\mathrm{SL}} + (0.406 \pm 0.022)\, A^s_{\mathrm{SL}}$$

- B factories can access $B_d \Rightarrow$ need Super-B for sufficient precision

Implication for Unitarity Relation with Theory Input

- Relation (bound) on $|\delta|$

$\Rightarrow$ Relation for individual $|A^{d,s}_{\mathrm{SL}}|$

$\Rightarrow$ With know production asymmetry we can give a bound on

$$|A^b_{\mathrm{SL}}| \leq (1.188 \pm 0.044)\, \delta^d_{\max} + (0.812 \pm 0.044)\, \delta^s_{\max}$$

- Bound is the same, if difference is measured

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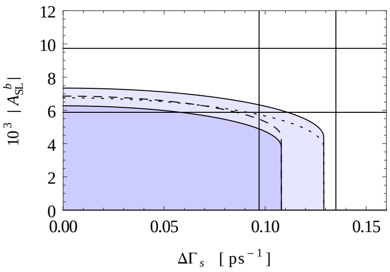
Plot of the Bound



- Assuming $\Delta\Gamma_d = 0$
- Horizontal lines: 1σ range of $|A^b_{\rm SL}|$ DØ measurement
- Vertical lines correspond to $\Delta\Gamma_s$ LHCb measurement
- Shaded regions are allowed by theory prediction
  1. Darker uses 1σ upper range
  2. Lighter uses 2σ upper range
- Dashed [dotted] curves: Mixed sigma interval of theory predictions
- The vertical boundaries of the shaded regions arise because $|\Delta\Gamma_s| > 2\,|\Gamma^s_{12}|$ is unphysical.

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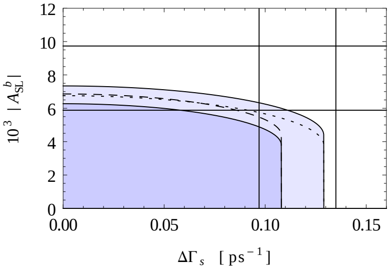

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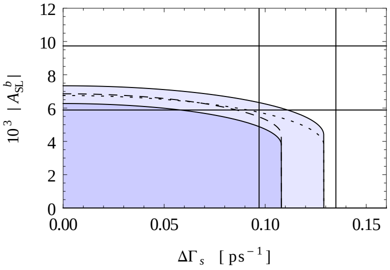

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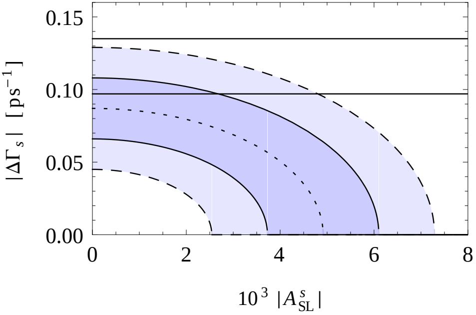
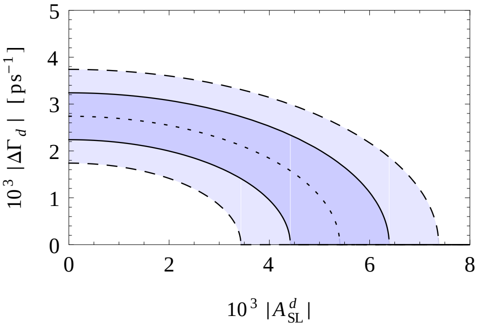
Plot on Individual Bound on B_s



Interpretation

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

Plot on Individual Bound on B_d



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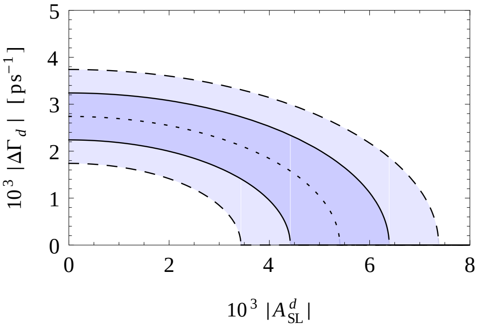
Plot on Individual Bound on B_d



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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 2σ theory prediction for a conservative estimate

Results

- For B_s system, we obtain by propagating the uncertainties, taking into account the unphysical region

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

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

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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 $A_{\rm SL}$ measurement: 3.9σ discrepancy with SM

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

1. SM prediction of $A_{\rm SL}$ uses calculation of Γ_{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 Γ_{12} to NP is generally weak
- Interesting to determine δ additionally from this relation

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1. SM prediction of A_{SL} uses calculation of Γ_{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 Γ_{12} to NP is generally weak
- Interesting to determine δ additionally from this relation

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

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No Go Theorem (preliminary)

The Claim

There is no generic bound, stronger than the unitarity bound

Sketch of Derivation

- Unitarity bound is satured if

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

- 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 Γ_{12}
- Varying M_{12} keeping mass and width of states physical

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

$$|A^s_{\mathrm{SL}}| < 4.2 \times 10^{-3} \qquad |A^d_{\mathrm{SL}}| < 7.4 \times 10^{-3}$$

  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^b_{SL}
- Once an unambiguous determination of A_{SL} or $\Delta\Gamma$ is made, we can use it to constrain the other observable.

Backup Slides

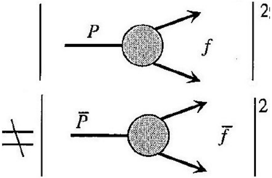
Direct CP Violation

General Comment [Bigi,Sanda: CP violation]

- Need CP even and odd phases
$$\Gamma \propto |A_1(f) + A_2(f)|^2$$

$\Rightarrow$ Interference of CP conserving (strong) and violating (weak) phases

- Occurs in neutral and charged meson decays
- Neccessary condition: $|A(f)| \neq |\bar{A}(\bar{f})|$



Example of Process

Only source of CP violation in charged meson decays

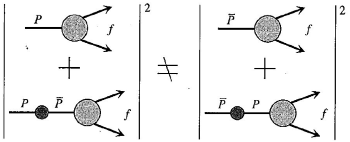
$$A_{f^\pm} \equiv \frac{\Gamma(P^- \to f^-) - \Gamma(P^+ \to f^+)}{\Gamma(P^- \to f^-) + \Gamma(P^+ \to f^+)} = \frac{\left|\bar{A}(f^-)/A(f^+)\right|^2 - 1}{\left|\bar{A}(f^-)/A(f^+)\right|^2 + 1}$$

CP Violation in Interference of Mixing and Decay

General Comments [Bigi,Sanda: CP violation]

- Interference between decay and mixing to common final state
- Neccessary condition:

$$\mathrm{Im}\left[\frac{q}{p}\frac{\bar{A}(f)}{A(f)} \neq 0\right]$$



Example of Process

- CP Asymmetry (easy form only in limits, e.g. B mesons)

$$\begin{aligned} A_{f_{CP}}(t) &\equiv \frac{\Gamma(\bar{P}_0 \to f_{CP}) - \Gamma(P_0 \to f_{CP})}{\Gamma(\bar{P}_0 \to f_{CP}) + \Gamma(P_0 \to f_{CP})} \\ &= \frac{-\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} \cos(\Delta M t) - \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}} \sin(\Delta M t)}{\cosh(\Delta\Gamma t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma t/2)} \end{aligned}$$

- $B_s \to J/\Psi\phi$ and $B_s \to J/\Psi f_0$