Like-sign dimuon charge asymmetry in Randall-Sundrum model

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Outline of Talk

- **Motivation**
- **Theory**
- **Model independent analysis**
- **New Vector/Axial vector (V/A) type operators contribution to $\Delta\Gamma_s$ and ΔM_s**
- **Numerical results for Randall-Sundrum model**
- **Conclusion**

Motivation

Dimuon charge asymmetry

- **Like-sign dimuon charge asymmetry of semileptonic B decays in $p\bar{p}$ collision:**

$$A^b_{sl} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

N_b^{++}: **Number of same-sign $\mu^+\mu^+$ events**
N_b^{--}: **Number of same-sign $\mu^-\mu^-$ events**

Wrong-sign charge asymmetry

- **"Right-sign" decay:** $B \rightarrow \mu^+ X$
- **"Wrong-sign" decay:** $\bar{B} \rightarrow \mu^+ X$

$\Rightarrow$**only possible via** $B^0_{q(d,s)} - \bar{B}^0_{q(d,s)}$*oscillation*

- **Wrong-sign charge asymmetry of semileptonic B decays:**

$$a^q_{sl} = \frac{\Gamma(\bar{B}_q \rightarrow \mu^+ X) - \Gamma(B_q \rightarrow \mu^- X)}{\Gamma(\bar{B}_q \rightarrow \mu^+ X) + \Gamma(B_q \rightarrow \mu^- X)} \qquad (\mathrm{q} = \mathrm{d/s})$$

Tevatron has access to measure both a^d_{sl} and a^s_{sl}

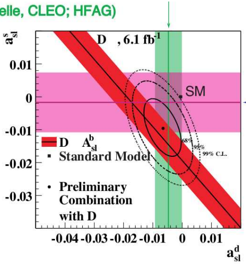
B Factories can provide independent measurement of a^d_{sl}

Dimuon charge asymmetry

- A^b_{sl} **measured at the Tevatron : a linear combination of** a^d_{sl} **and** a^s_{sl}

$$A^b_{sl} = (0.506 \pm 0.043) a^d_{sl} + (0.49 \pm 0.043) a^s_{sl}$$

(BaBar, Belle, CLEO; HFAG)



- Consistent with D direct measurement of $a^s_{sl} = (-0.17 \pm 0.91)\%$ using $B^0_s \to D_s \mu\nu$ (arXiv:0904.3907, sub. to PRD)

Figure from Rick Van Kooten, HEP Seminar Indiana University, Dept. of Physics, 10 June 2010

A^b_{sl} *and* a^s_{sl} *Results*

- **DØ results for A^b_{sl}**

$$A^b_{sl} = -(9.57 \pm 2.51(stat) \pm 1.46(syst)) \times 10^{-3}$$

- **SM prediction:** $A^b_{sl} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ **about 3.2 σ deviation**

a_{sl}^{s} *Results*

- **Further, DØ and CDF average results for a_{sl}^{s}**

$$(a_{sl}^{s})_{avg} \approx -(12.7 \pm 5.0) \times 10^{-3}$$

- **SM prediction:**

$$a_{sl}^{s} = (2.1 \pm 0.6) \times 10^{-5}$$ $\sim 2.5\sigma$ **deviation**

- **A confirmation of this deviation $\Rightarrow$ Evidence for New Physics**

New physics models

- **Many NP model explanations for above deviations**
- **Most of them considered only NP contribution to ΔM_{12}^s of $B_s^0 - \overline{B_s^0}$ mixing**
- **A general case: NP with V/A type operators contribute to both ΔM_{12}^s and $\Delta\Gamma_{12}^s$**

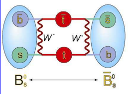
  $\Rightarrow$ **can apply for several extensions of the SM**

We considered RS-model as our example

$B_s^0 - \overline{B_s^0}$ *mixing*

- **Time evolution of Weak Eigenstates:**

$$i\frac{d}{dt}\begin{bmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{bmatrix} = \begin{bmatrix} M_{11}^q - \frac{i}{2}\Gamma_{11}^q & M_{12}^q - \frac{i}{2}\Gamma_{12}^q \\ M_{12}^{q*} - \frac{i}{2}\Gamma_{12}^{q*} & M_{11}^q - \frac{i}{2}\Gamma_{11}^q \end{bmatrix} \begin{bmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{bmatrix}$$



- **Diagonalize to get Mass Eigenstates**

Light: $|B_q^L\rangle = p\,|B_q\rangle + q\,|\bar{B}_q^0\rangle$

Heavy: $|B_q^H\rangle = p\,|B_q\rangle - q\,|\bar{B}_q^0\rangle$

If CP conserved in mixing, p = q

$|B_q^L\rangle = |B_q^{even}\rangle \qquad |B_q^H\rangle = |B_q^{odd}\rangle$

- **To a good approximation: Three main observables**

$$\boxed{\Delta M_s = M_H - M_L = 2|M_{12}|}$$ **sensitive to new physics**

$$\boxed{\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi_s}$$ **Sensitive to new physics ?**

with CP violating weak phase

$$\boxed{\phi_s = arg\left[-\frac{M_{12}^s}{\Gamma_{12}^s}\right]}$$ **very sensitive to new physics**

$B_s^0 - \overline{B_s^0}$ *mixing*

- $\Delta M_s^{exp} = 17.77 \pm 0.12 \mathrm{ps}^{-1}$; $\Delta M_s^{SM} = 19\ ps^{-1}$
- $\Delta \Gamma_s = \pm(0.154^{+0.054}_{-0.070}) \mathrm{ps}^{-1}$; $\Delta\Gamma_s^{\mathrm{SM}} = (0.096 \pm 0.039)\ \mathrm{ps}^{-1}$

  $\Uparrow\ \phi_s^{SM} \sim 0.004$
- **Another important CP violating quantity**

$$\left(\frac{q}{p}\right)_q = -\frac{M_{12}^{q*}}{|M_{12}^q|}\left(1 - \frac{a_{sl}^q}{2}\right)$$

  - **Wrong-charge asymmetry** $a_{sl}^q = Im[\frac{\Gamma_{12}^q}{M_{12}^q}] = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi_q$

$\phi_s^{SM} \sim 0.04 \Rightarrow a_{sl}^s = (2.1 \pm 0.6) \times 10^{-5} \sim 2.5\sigma$

deviation from data

- **New physics contributions to both ΔM_{12}^s and $\Delta\Gamma_{12}^s$ (with new phases) can modify a_{sl}^s**

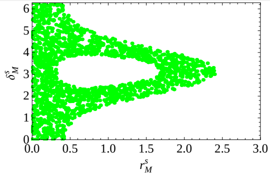
Case: NP only contributes to ΔM^s_{12}

- **Mass difference modify as:**

$$\boxed{\Delta M_q = \Delta M^{SM}_{B_q} R^q_M}$$

$R^s_M = |1 + r^s_M e^{i\delta^s_M}|$; $\phi^s_M = arg[1 + r^s_M e^{i\delta^s_M}]$; **with** $r^s_M e^{i\delta^s_M} = M^{s,NP}_{12} / M^{s,SM}_{12}$

  - $\Delta M_d = 0.507 \pm 0.004\ \mathrm{ps}^{-1}$: **consistent with SM ;** $R^d_M \simeq 1.$
    - $\Delta M^{s,exp}_s$ **constraint: requires** $0.7 \lesssim R^s_M \lesssim 1.4$



- **Wrong-charge asymmetry modify as:**

$$\boxed{a^s_{sl} = \frac{1}{R^s_M} \frac{|\Gamma^{s,SM}_{12}|}{|M^{s,SM}_{12}|} \sin[\phi^s_M]}$$

- **Using DØ results :**

$$a^s_{sl} = (-14.6 \pm 7.5) \times 10^{-3}$$

$\Rightarrow \sin\phi^s_M = -(2.9 \pm 1.5)|R^s_M|$ **(neglected ϕ^{SM}_s)**

Unphysical for $|R_{M_s}| \simeq 1$

- **NP contribution to $\Delta\Gamma_s$ is necessary to explain observed a^s_{sl}**

Case: NP contributes to both ΔM^s_{12} and $\Delta\Gamma^s_{12}$

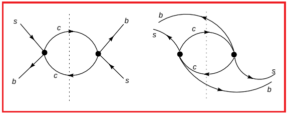
- **Wrong-charge asymmetry modify as:**

$$a^s_{sl} = \frac{R^s_\Gamma}{R^s_M} \frac{|\Gamma^{s,SM}_{12}|}{|M^{s,SM}_{12}|} \sin[\phi^s_M - \phi^s_\Gamma]$$

$R^s_\Gamma = |1 + r^s_\Gamma e^{i\delta^s_\Gamma}|$; $\phi^s_\Gamma = arg[1 + r^s_\Gamma e^{i\delta^s_\Gamma}]$; **with** $r^s_\Gamma e^{i\delta^s_\Gamma} = \Gamma^{NP}_{12}/\Gamma^{SM}_{12}$

- **A model independent scan using ΔM_s, $\Delta\Gamma_s$, $(a^s_{sl})_{(avg)}$ data**

$\Rightarrow r^s_\Gamma \lesssim 0.4$ **NP to $\Delta\Gamma_s$ highly constrained**



SM contribution to the decay width Γ^s_{12}

- **Width difference :** $\Delta\Gamma_s = 2|\Gamma^s_{12}| \cos\phi_s$
- **Γ^s_{12} of Γ matrix related to absorptive part of transition amplitude from B_s to $\bar{B}_s$**

$$\Gamma^s_{12} = \frac{1}{2m_{B_s}} \langle \bar{B}_s | \, Im\left[i \int d^4x T \mathcal{H}^{\Delta B=1}_{eff}(x) \mathcal{H}^{\Delta B=1}_{eff}(0) \right] | B_s \rangle$$

- **$\Delta B = 1$ transition amplitude dominated by intermediate $c\bar{c}$ states, neglect CKM-suppressed terms. SM Hamiltonian:**

$$\mathcal{H}^{\Delta B=1}_{eff} = \frac{G_F}{\sqrt{2}} V^*_{cb} V_{cs} \sum_{n=1}^{6} (C_n Q_n + h.c)$$

- **First two operators:**

$Q_1 = (\bar{b}_i c_j)_{V-A}(\bar{c}_j s_i)_{V-A}$ $\quad$ $Q_2 = (\bar{b}_i c_i)_{V-A}(\bar{c}_j s_j)_{V-A}$

NP contribution to the decay width Γ_{12}^s

- **NP Hamiltonian:**

$$\mathcal{H}_{eff}^{NP} = \Big(\lambda_{LL} Q_{LL} + \lambda'_{LL} Q'_{LL} + \lambda_{LR} Q_{LR} + \lambda'_{LR} Q'_{LR} + \lambda_{RR} Q_{RR} + \lambda'_{RR} Q'_{RR} + \lambda_{RL} Q_{RL} + \lambda'_{RL} Q'_{RL}\Big)$$

- **Eight V/A type operators for $b \to c\bar{c}s$ transitions:**

- $Q_{L(R)L(R)} = (\bar{b}_i s_i)_{V\mp A} (\bar{c}_j c_j)_{V\mp A}$
- $Q'_{L(R)L(R)} = (\bar{b}_i s_j)_{V\mp A} (\bar{c}_j c_i)_{V\mp A}$

- **Couplings λ's model dependent. We used RS model couplings.**
  - **After very lengthy QCD calculation, NP contributions to Γ_{12}^s :**

$$\boxed{\Gamma_{12}^{s,NP} = \Gamma_{12}^{s,LL} + \Gamma_{12}^{s,RR} + \Gamma_{12}^{s,mix}}$$

$\Rightarrow \Gamma_{12}^{s,LL}$ **and** $\Gamma_{12}^{s,RR}$ **: Pure NP contributions**

$\Rightarrow \Gamma_{12}^{s,mix}$ **: SM-NP interference contribution**

NP contribution to the mass parameter M_{12}^s

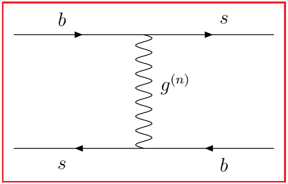
- M_{12}^s **of mass matrix related to** $\Delta B = 2$ **transition amplitude**

$$M_{12}^s = \frac{1}{2m_{B_s}} \left\langle \bar{B}_s^0 \right| H_{eff}^{\Delta B=2} \left| B_s^0 \right\rangle$$

- $\Delta B = 2$ **SM Hamiltonian:**

$$\mathcal{H}_{eff}^{\Delta B=2,SM} = \frac{G_F^2}{16\pi^2} M_W^2 (V_{tb} V_{ts}^*)^2 \eta_{B_s} S_0(x_t) (\bar{b}s)_{V-A} (\bar{b}s)_{V-A}$$

- **Again, we consider eight** $\Delta B = 2$ **V/A type NP operators**
- **Using vacuum insertion method, very easy to find SM and NP contributions to** M_{12}^s



Effective Hamiltonian in RS Model

- **In RS model, effective Hamiltonian for $\Delta B = 2$ transition can be generated at tree-level via exchange of a KK gluon**

$$\mathcal{H}_{eff}^{\Delta B=2,KK} = \sum_{A,B} \frac{1}{4m_{KK}^2}(U_A^{d(1)})_{32}(U_B^{d(1)})_{32}\Big[(\bar{b}_i\gamma^\mu P_A s_j)(\bar{b}_j\gamma_\mu P_B s_i) - \frac{1}{3}(\bar{b}_i\gamma^\mu P_A s_i)(\bar{b}_j\gamma_\mu P_B s_j)\Big]$$

A, B = L,R

- **Also, $\Delta B = 1$ effective Hamiltonian in this model:**

$$\mathcal{H}_{eff}^{\Delta B=1,KK} = \frac{1}{4m_{KK}^2}(U_A^{d(1)})_{32}(U_B^{u(1)})_{22}\Big[(\bar{b}_i\gamma^\mu P_A s_j)(\bar{c}_j\gamma_\mu P_B c_i) - \frac{1}{3}(\bar{b}_i\gamma^\mu P_A s_i)(\bar{c}_j\gamma_\mu P_B c_j)\Big]$$

RS Model couplings

- **Flavor dependent couplings U's in mass basis:**

$$(U^{u,d(n)}_{L(R)})_{\alpha\beta} = (V^{u,d^{+}}_{L(R)})_{\alpha\gamma}\ g^{(n)}_{L(R)}(c_{f_\gamma})\ (V^{u,d}_{L(R)})_{\gamma\beta}$$

$$g^{(1)}_{L(R)}(c_{f_\alpha}) = g\left(\frac{1-2c_{f_\alpha}}{e^{\pi\kappa r_c(1-2c_{f_\alpha})}-1}\right)\frac{\kappa}{N_0}\int_0^{\pi r_c} e^{(1-2c_{f_\alpha})\kappa y}\left[J_1\left(\frac{m^{(1)}_A}{\kappa}e^{\kappa y}\right)+b_A(m^{(1)}_A)Y_1\left(\frac{m^{(1)}_A}{\kappa}e^{\kappa y}\right)\right]$$

⋆ **tree-level relation between 5D and 4D couplings:**

$g = g_5/\sqrt{2\pi r_c}$; r_c **compactification radius**

⋆ $V^{u,d}_{L(R)}$ **diagonalize the up/down quark mass matrix**

$$M^{u,d}_{\alpha\beta} = (v/\sqrt{2})Y^{u,d}_{\alpha\beta}$$

- **Bulk parameter c_{f_α} in $g^{(n)}$ specify position of fermion's localized wavefunction in the bulk.**

$\Rightarrow$ **choice of c's are model dependent**

Numerical procedure

- **Do not consider any specific values for c's**
- **Need only flavor couplings $(U^{d(1)}_{L(R)})_{32}$, and $(U^{u(1)}_{L(R)})_{22}$, they varied within allowed ranges, and constrained them by ΔM_s and $\Delta\Gamma_s$ measurements within 1σ errors**
- **All SM input parameters are uniformly varied within their errors. SM Wilson coefficients are evaluated at $\mu_b = 4.2$ GeV**
- **m_{KK} varied in [1.2, 10.0] TeV**

Numerical results

- ΔM_s(exp) allows

$$r_M^{s,KK} = |M_{12}^{s,KK}/M_{12}^{s,SM}| \lesssim 1$$

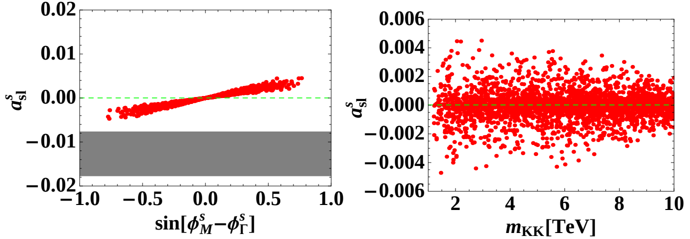
- Fit results allows

$$r_\Gamma^{s,KK} = |\Gamma_{12}^{s,KK}/\Gamma_{12}^{s,SM}| \lesssim 10\%$$

for $m_{KK} < 1.5$ TeV and this ratio falls quite quickly for m_{KK} beyond 1.5 TeV

- Our result indicates KK contribution to $\Delta\Gamma_{12}^s \lesssim 10\%$

$\Rightarrow$ same order of hadronic uncertainties ; can not detect experimentally



gray band: avg exp value of a_{sl}^s green line: SM prediction

Final results

- **Fit results allow**

$$a_{sl}^s \sim -0.00498$$

$\Rightarrow$ 1.54σ **away from its experimental average value**

$\Rightarrow$ **corresponding**

$$\sin\left(\phi_M - \phi_\Gamma^s\right) \approx -0.76$$

Conclusion

- **RS model can cause deviations from SM predictions for wrong-charge asymmetry**
- **It cannot explain experimental average value of a^s_{sl} within 1σ range**

★ **Due its inability to generate sufficient new contribution to width difference $\Delta\Gamma^s_{12}$**