EDMs and Meson Mixing in Z' Models

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Introduction

Models with extra $U(1)$ gauge group are well motivated

In a sub class of Z' models, there are flavor changing Z' couplings to SM fermions, *e.g.* family non-universal models

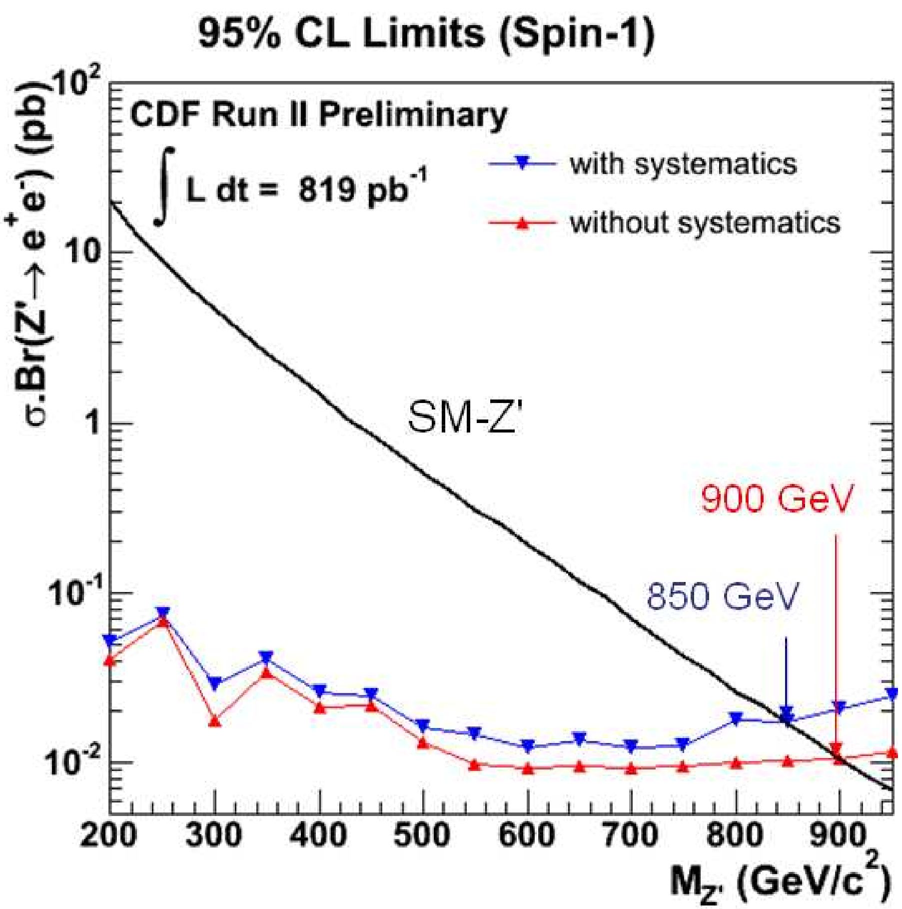
Flavor changing and/or CP violating effects can be induced by Z', many constraints have been studied [Langacker and Plumacher, hep-ph/0001204]

- B_s mixing [Barger, Chiang, Jiang and Langacker, hep-ph/0405108; Cheung, Chiang, Deshpande and Jiang, hep-ph/0604223]
- Electric dipole moments, K meson mixing, B_d mixing [Chiang, Deshpande, Jiang, in preparation]

Direct Search

Z' can be looked for through Drell-Yan processes at hadron colliders

The search at Tevatron with 819 pb^{-1} excludes Z' of mass less than 850 GeV [http://www-cdf.fnal.gov/∼harper/diEleAna.html]



Precision Constraints

Electroweak precision measurements provide strong constraints [Erler and Langacker, hep-ph/9910135]

$$
\begin{aligned}
m_{Z'} &> O(500\ \mathrm{GeV}) \\
\theta &< O(10^{-3})
\end{aligned}
$$

Two convenient parameters

$$
\begin{aligned}
y &= \left(\frac{g_2}{g_1}\right)^2 (\sin^2\theta + \frac{M_Z^2}{M_{Z'}^2}\cos^2\theta) \sim \left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 \sim 10^{-3} \\
w &= \frac{g_2}{g_1}\sin\theta\cos\theta(1 - \frac{M_Z^2}{M_{Z'}^2}) \sim 10^{-3}
\end{aligned}
$$

for TeV scale Z', mixing of $\theta \sim 10^{-3}$ and $g_2 \sim g_1$

Flavor Changing Couplings

In the flavor eigenbasis, Z' coupling matrix to down type quarks

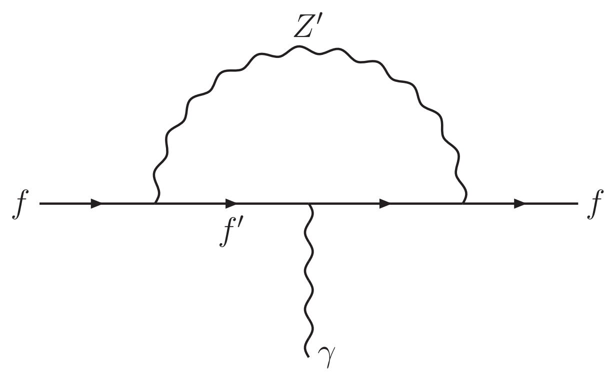
$$\epsilon_L^d = Q_L^d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & x \end{pmatrix} \qquad \text{and} \qquad \epsilon_R^d = Q_R^d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

In the quark mass eigenbasis

$$\begin{aligned} B_L^d &\equiv V_{dL}^\dagger \epsilon_L^u V_{dL} = V_{\mathrm{CKM}}^\dagger \epsilon_L^d V_{\mathrm{CKM}} \\ &= Q_L^d \begin{pmatrix} 1 & (x-1)V_{ts}V_{td}^* & (x-1)V_{tb}V_{td}^* \\ (x-1)V_{td}V_{ts}^* & 1 & (x-1)V_{tb}V_{ts}^* \\ (x-1)V_{td}V_{tb}^* & (x-1)V_{ts}V_{tb}^* & x \end{pmatrix} \end{aligned}$$

Electric Dipole Moments

Through a one-loop diagram



electric dipole moments are generated for fermions

$$d_f = -\frac{1}{16\pi^2} g_2^2 Q_f e \frac{m_{f'}}{m_{Z'}^2} \mathrm{Im}({B_{ff'}^L}^* B_{ff'}^R) \int_0^1 dx \frac{ax^4 + 4x(1-x)}{ax^2 + bx + 1}$$

with $a = m_f^2/m_{Z'}^2$ and $b = (m_{f'}^2 - m_f^2)/m_{Z'}^2 - 1$ and simplification

$$d_f = -\frac{g_1^2}{8\pi^2} Q_f e \frac{m_{f'}}{m_Z^2}\, y\, \mathrm{Im}({B_{ff'}^L}^* B_{ff'}^R)$$

Constraints from EDMs

Experimental limit on electron EDM is $d_e < 1.6 \times 10^{-27}$ e cm

We require both μ and τ diagram contribute less than the limit

$$y\,\mathrm{Im}(B^{L\,*}_{e\mu} B^R_{e\mu}) < 1 \times 10^{-6}$$

Compared to coherent μ-e conversion by Sindrum-II [Wintz, 1998]

$$w^2(|B^L_{e\mu}|^2 + |B^R_{e\mu}|^2) < 4 \times 10^{-14}$$

$$y\,\mathrm{Im}(B^{L\,*}_{e\tau} B^R_{e\tau}) < 8 \times 10^{-8}$$

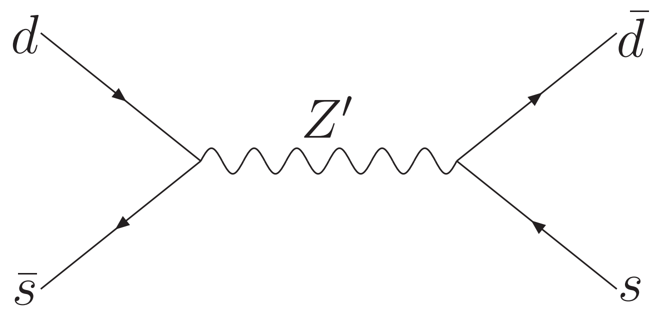
compared to decays $\tau \to 3e$

$$w^2(|B^L_{e\tau}|^2 + |B^R_{e\tau}|^2) < 2 \times 10^{-5}$$

Neutron EDMs can be used for B_{uc}, B_{ds}, B_{ut} and B_{db}

Meson Mixing

Flavor changing Z' couplings induce meson mixing at tree level



Relevant operators are

$$O^{LL} = [\bar{s}\gamma_\mu(1-\gamma_5)d][\bar{s}\gamma^\mu(1-\gamma_5)d] \qquad O_1^{LR} = [\bar{s}\gamma_\mu(1-\gamma_5)d][\bar{s}\gamma^\mu(1+\gamma_5)d]$$

$$O_2^{LR} = [\bar{s}(1-\gamma_5)d][\bar{s}(1+\gamma_5)d] \qquad O^{RR} = [\bar{s}\gamma_\mu(1+\gamma_5)d][\bar{s}\gamma^\mu(1+\gamma_5)d]$$

NLO Wilson coefficients [Buchalla et al, hep-ph/9512380; Buras et al, hep-ph/0102316]

$$\Delta M = 2|M_{12}|$$

K meson mixing

Because the K meson mixing mass difference contains large long distance effect

$$\Delta M_K^{\text{exp}} = \Delta M_K^{\text{SD}} + \Delta M_K^{\text{LD}} + \Delta M_K^{\text{NP}}$$

we require $\Delta M_K^{\text{NP}} < \Delta M_K^{\text{exp}}$

With LH coupling only

$$|y\,\mathrm{Re}\left(B_{ds}^{L}\right)^{2}| < 3 \times 10^{-8}$$

Include both LH and RH couplings

$$y\left|0.01\,\mathrm{Re}\left[\left(B_{ds}^{L}\right)^{2} + \left(B_{ds}^{R}\right)^{2}\right] - \mathrm{Re}\left(B_{ds}^{L}B_{ds}^{R}\right)\right| < 4 \times 10^{-10}$$

hence keeping the dominant term

$$y\left|\mathrm{Re}\left(B_{ds}^{L}B_{ds}^{R}\right)\right| < 4 \times 10^{-10}$$

The LR mixed term is dominant due to chiral enhancement in the form factor and RG enhancement in Wilson coefficients

ΔM_s

Recently the mixing of B_s meson has been observed at D0 and CDF

D0 [hep-ex/0603029]:

$$\Delta M_s = 19.0 \pm 1.215 \text{ ps}^{-1}$$

CDF [Gomez-Ceballos, http://fpcp2006.triumf.ca/talks/day3/1500/fpcp2006.pdf]:

$$\Delta M_s = 17.33 \,^{+0.42}_{-0.21} \text{ (stat.) } \pm 0.07 \text{ (syst.) ps}^{-1}$$

Combined

$$\Delta M_s^{\rm exp} = 17.46 \,^{+0.47}_{-0.30} \text{ ps}^{-1}$$

Is there indication of new physics? Or is it in agreement with the SM?

New Physics?

From UTfit [http://utfit.roma1.infn.it/], the fitted result is

$$\Delta M_s^{\mathrm{exp}} = 17.4 \pm 0.3 \text{ ps}^{-1}$$

the SM prediction is

$$\Delta M_s^{\mathrm{SM}} = 21.5 \pm 2.5 \text{ ps}^{-1}$$

using $f_{B_s}\sqrt{\hat{B}_{B_s}}$ with a smaller error bar than $f_{B_s}\sqrt{\hat{B}_{B_s}} = 0.276 \pm 0.038$ GeV

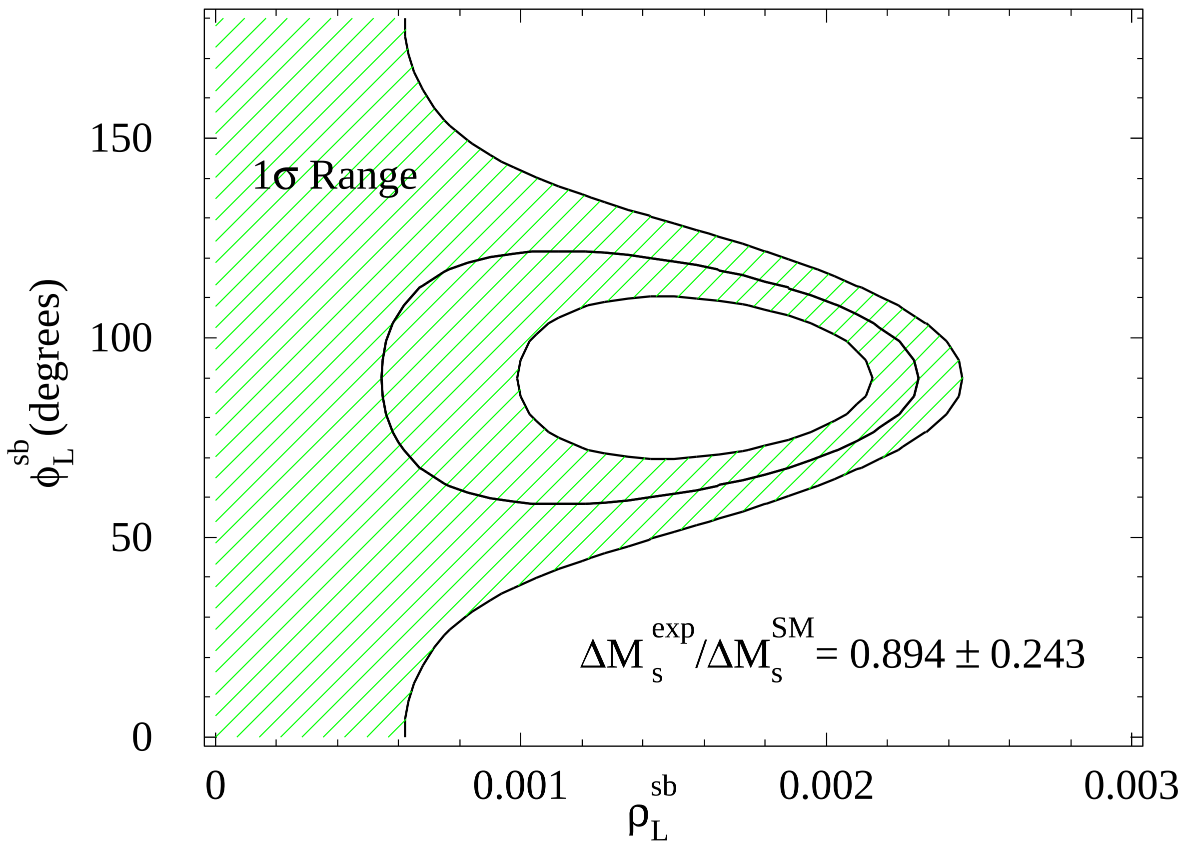
Our estimate is

$$\Delta M_s^{\mathrm{SM}} = 19.5 \pm 5.3 \text{ ps}^{-1}$$

$|\Delta M_s^{\rm exp}/\Delta M_s^{\rm SM}|$

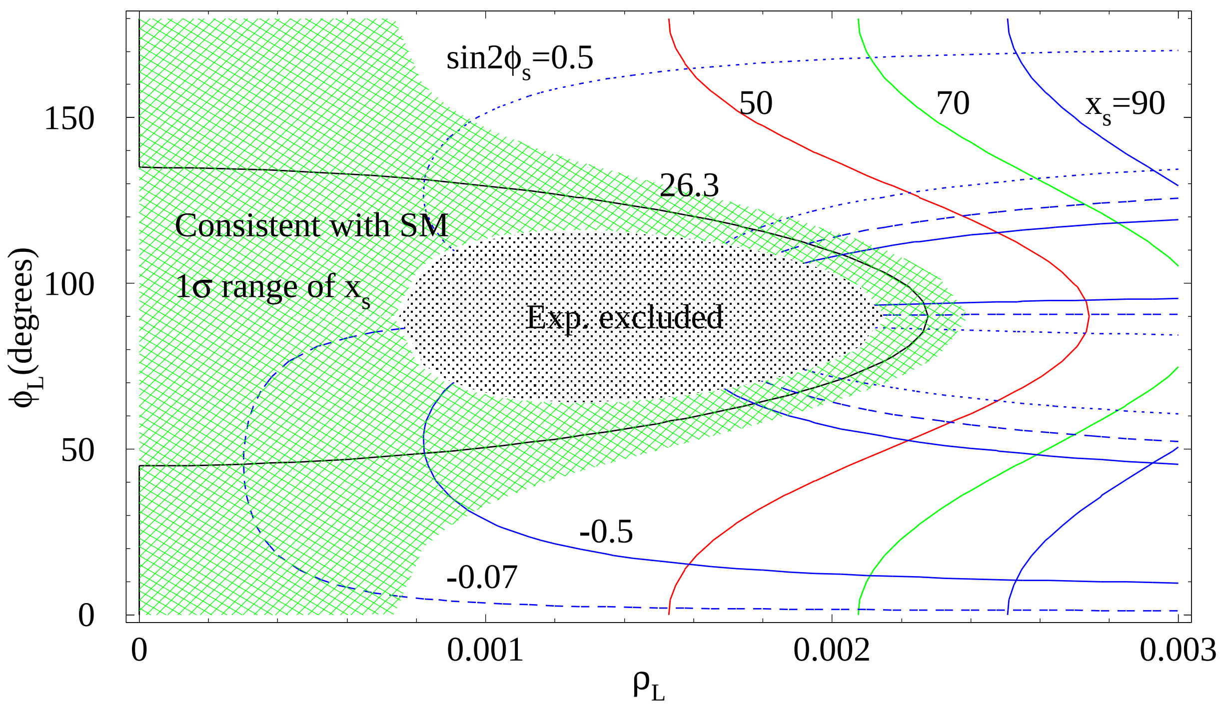
The effect of including Z' (or other new physics) contribution

$$\frac{\Delta M_s^{\rm exp}}{\Delta M_s^{\rm SM}} = \left|1 + 3.57 \times 10^5 \left(\rho_L^{sb}\right)^2 e^{2i\phi_L^{sb}}\right| = 0.894 \pm 0.242$$



INPUT FROM $\sin \phi_s$

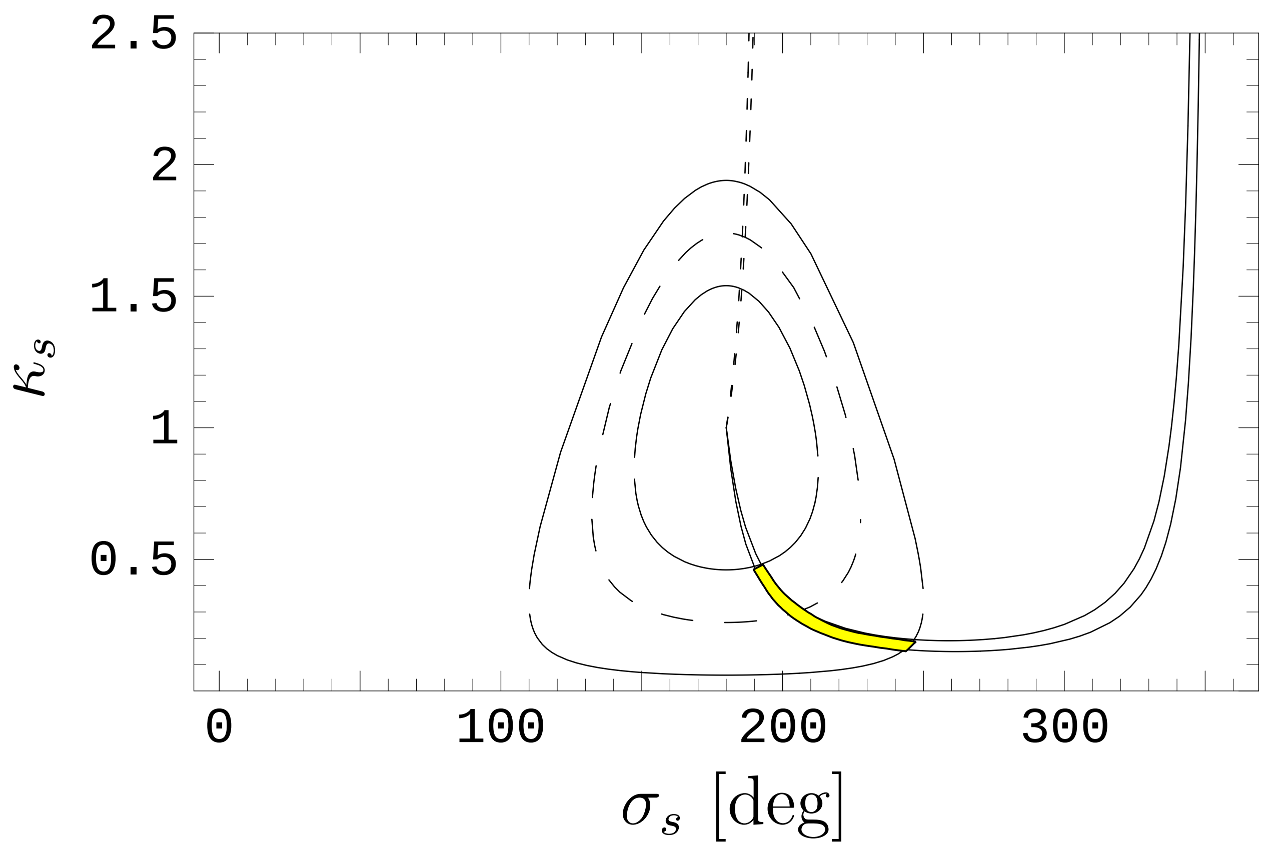
Another observable $\sin \phi_s$ with $2\phi_s = \arg(M_{12})$ can be helpful [Barger et al, hep-ph/0405108]



INPUT FROM $\sin \phi_s$

Using (HP+JL)QCD lattice results, there is a 1.5σ difference between $\Delta M_s^{\rm exp}$ and $\Delta M_s^{\rm SM}$ [Ball and Fleischer, hep-ph/0604249]

Combined with a $(\sin \phi_s)_{\rm exp} = -0.20 \pm 0.02$ measurement, the discrepancy is 10σ



$\Delta M_d / \Delta M_s$

Both $\Delta M_d \propto f_{B_d}^2 B_{B_d}$ and $\Delta M_s \propto f_{B_s}^2 B_{B_s}$ contain large hadronic uncertainties, their ratio $\Delta M_d / \Delta M_s \propto f_{B_d}^2 B_{B_d} / f_{B_s}^2 B_{B_s}$, which is better determined from lattice calculation

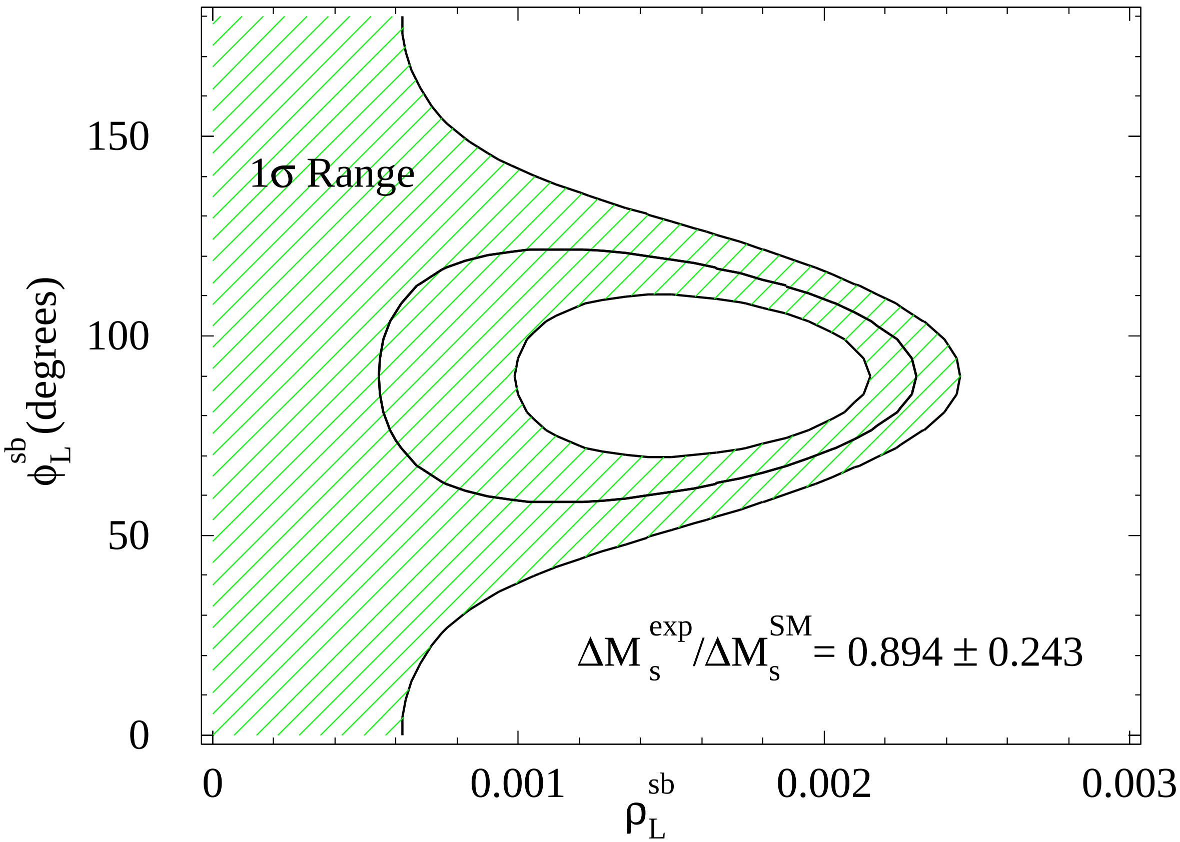
Within the SM, $\Delta M_d / \Delta M_s$ measures $|V_{td}/V_{ts}| = 0.208 \pm 0.008$

From measuring $b \to d\gamma$ and $b \to s\gamma$ branching ratios,
$|V_{td}/V_{ts}| = 0.199 \pm 0.29$ [Belle Preprint 2006-5]

The new ΔM_s result is consistent with the SM, at the same time it does not exclude possible new physics

CONSTRAINING Z' COUPLING

We use it to constraint Z' coupling as in $\rho_L^{sb} < 1 \times 10^{-3}$



$Br(B_s \to \mu\mu)$

Within the simple model outlined before,

$$B_L^d = Q_L^d \begin{pmatrix} 1 & (x-1)V_{ts}V_{td}^* & (x-1)V_{tb}V_{td}^* \\ (x-1)V_{td}V_{ts}^* & 1 & (x-1)V_{tb}V_{ts}^* \\ (x-1)V_{td}V_{tb}^* & (x-1)V_{ts}V_{tb}^* & x \end{pmatrix}$$

constraint on ρ_L^{sb} is translated to flavor diagonal Z'-q-$\bar{q}$ coupling

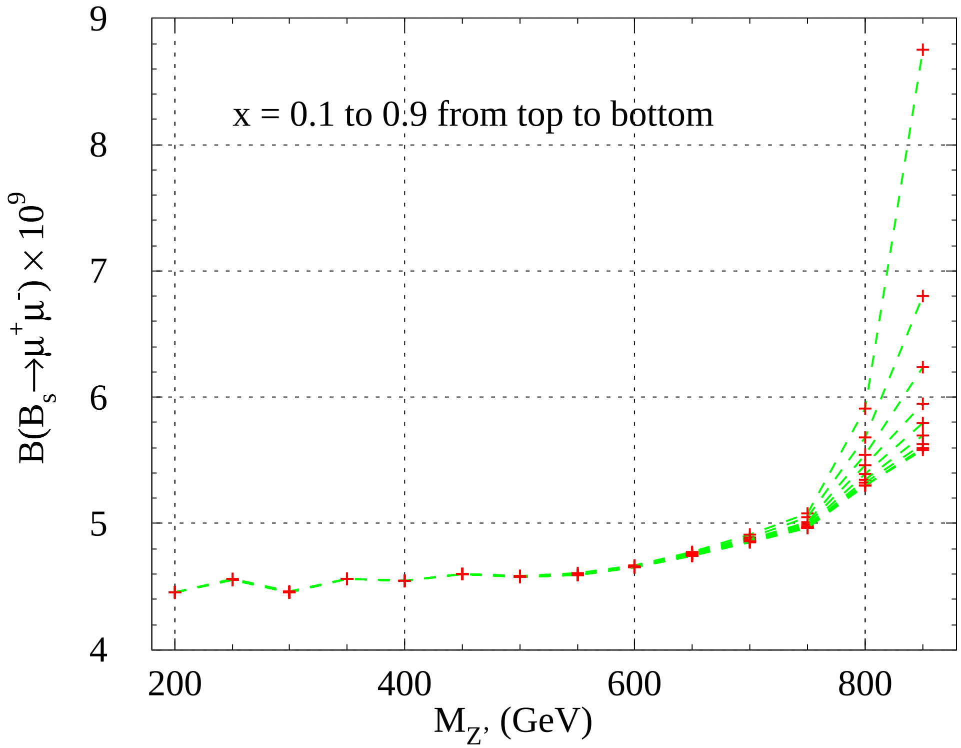
Bound on

$\sigma(Z')\,B(Z' \to e^+e^-)$[http://www-cdf.fnal.gov/~harper/diEleAna.html] can be used to limit Z'-e-e coupling

Assuming the flavor diagonal couplings the same for electron and muon, we can predict $Br(B_s \to \mu^+\mu^-)$

$Br(B_s \to \mu\mu)$

The branching ratio is predicted to be a few $\times 10^{-9}$



Currently with 819 ps^{-1}, the reach is $Br(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7}$ (CDF) and $< 2.3 \times 10^{-7}$ (D0)

10^{-9} may be difficult for Tevatron

Compared to SUSY

[See Fleischer talk, Menon's talk; Carena et al, hep-ph/0603106; Ball and Fleischer, hep-ph/0604249; Isidori and Paradisi, hep-ph/0605012]

Contribution to ΔM_s occurs at one-loop level, which is enhanced by large $\tan\beta$

$Br(B_s \to \mu^+\mu^-)$ is also enhanced by large $\tan\beta$

Predicts a larger $Br(B_s \to \mu^+\mu^-) \geq 3 \times 10^{-8}$

Summary

We propose to use EDM measurements to constrain Z' flavor changing couplings to fermions, they can be effective for couplings involving heavy fermions

In K meson mixing, the LH and RH cross term dominates Z' contributions

The recently measured ΔM_s is consistent with the SM, it can be used to constrain Z' couplings to quarks

Within a more specific model, the predicted $Br(B_s \to \mu^+\mu^-)$ is too small to be seen at the Tevatron

Appendix

CKM Matrix

$$
\begin{aligned}
V &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}
\end{aligned}
$$

Hadronic Parameters

JLQCD numbers:

$$\left. f_{B_d}\hat{B}_{B_d}^{1/2}\right|_{\mathrm{JLQCD}} = (0.215 \pm 0.019^{+0}_{-0.023})\,\mathrm{GeV}$$

$$\left. f_{B_s}\hat{B}_{B_s}^{1/2}\right|_{\mathrm{JLQCD}} = (0.245 \pm 0.021^{+0.003}_{-0.002})\,\mathrm{GeV}$$

$$\xi_{\mathrm{JLQCD}} \equiv \frac{f_{B_s}\hat{B}_{B_s}^{1/2}}{f_{B_d}\hat{B}_{B_d}^{1/2}} = 1.14 \pm 0.06^{+0.13}_{-0}$$

HPQCD+JLQCD numbers:

$$\left. f_{B_d}\hat{B}_{B_d}^{1/2}\right|_{\mathrm{(HP+JL)QCD}} = (0.244 \pm 0.026)\,\mathrm{GeV}$$

$$\left. f_{B_s}\hat{B}_{B_s}^{1/2}\right|_{\mathrm{(HP+JL)QCD}} = (0.295 \pm 0.036)\,\mathrm{GeV}$$

$$\xi_{\mathrm{(HP+JL)QCD}} = 1.210^{+0.047}_{-0.035}$$