Probing New Physics Through B_s Mixing

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Phenomenology of B_s Mixing

- $\bar{B}^0 = (b\bar{s})$ and $B^0 = (s\bar{b})$ with definite flavour content, but not mass eigenstates $\rightsquigarrow$ **Mixing!**
- mixing induces mass and width mixing matrices M_{ab}^s, Γ_{ab}^s
- M_{12}^s is loop-induced: sensitive to new physics!
- observables:
  - $\Delta M_s = 2|M_{12}^s|, \qquad \phi_s = \arg(-M_{12}^s/\Gamma_{12}^s) \approx \arg M_{12}^s$
  - CP asymmetry in $B_s \to J/\psi\phi$
  - $\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\phi_s$
  - semileptonic CP asymmetry

$$A_{\rm SL}^s = \frac{N(\bar{B}_s^0 \to \ell^+ X) - N(B_s^0 \to \ell^- X)}{N(\bar{B}_s^0 \to \ell^+ X) + N(B_s^0 \to \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

Experimental status of B_s Observables

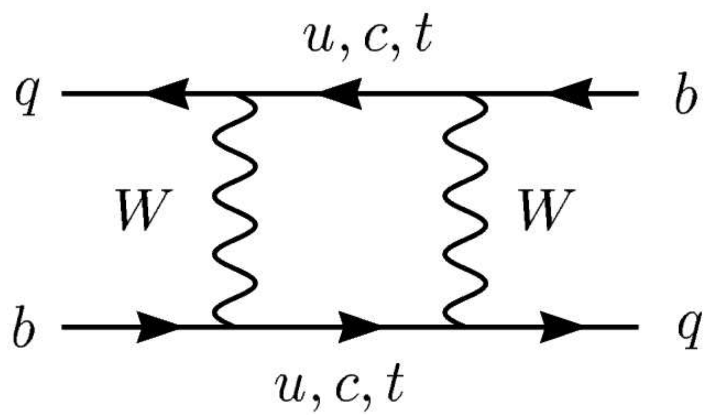
- $\Delta M_s = (17.77 \pm 0.10 \pm 0.07)\,\mathrm{ps}^{-1}$ (CDF) (2006!)
- $\Delta\Gamma_s = (0.17 \pm 0.09 \pm 0.02)\,\mathrm{ps}^{-1}$ (D0) (2007!)
- $A^s_{SL} = 0.001 \pm 0.0090$ (D0) (2007)!
- $\phi_s = -0.70^{+0.47}_{-0.39}$ from A^s_{SL} and $B_s \to J/\psi\phi$ (D0) (2007)!

For LHCb, expect (van Hunen CKM06)

- sensitivity $\sigma_{\phi_s} = 0.04$ rad @ 0.5 fb^{-1}, $\sigma_{\phi_s} = 0.02$ rad @ 2 fb^{-1}
- first results promised for 2008

ΔM_s in the SM

$$M_{12}^{\rm SM} \quad = \quad$$



$$= \quad \frac{G_{\rm F}^2 M_W^2}{12\pi^2} M_{B_s} \hat{\eta}^B \hat{B}_{B_s} f_{B_s}^2 (V_{ts}^* V_{tb})^2 S_0(x_t)$$

- $S_0(x_t = m_t^2/M_W^2) = 2.35 \pm 0.06$: Inami-Lim function
- $\hat{\eta}^B = 0.552$: NLO QCD correction (Buras/Jamin/Weiss '90)
- $\hat{B}_{B_s} f_{B_s}^2 \propto \langle B_s^0 | (\bar{s}b)_{V-A} (\bar{s}b)_{V-A} | \bar{B}_s^0 \rangle$: hadronic matrix element, from lattice
- $V_{ts}^* V_{tb}$: from tree-level processes

Status of Input Parameters

- $\sqrt{\hat{B}_{B_s}} f_{B_s} = (0.281 \pm 0.021)\,\mathrm{GeV}$ (HPQCD 06, unquenched, $N_f = 2+1$ staggered light quarks)
- $\sqrt{\hat{B}_{B_s}} f_{B_s} = (0.245 \pm 0.021^{+0.003}_{-0.002})\,\mathrm{GeV}$ (JLQCD 03, unquenched, $N_f = 2$ Wilson light quarks)
- $|V_{ts}^* V_{tb}| = (41.3 \pm 0.7) \times 10^{-3}$
- SM predictions:

$$\Delta M_s|_{\mathrm{JLQCD}} = (16.1 \pm 2.8)\,\mathrm{ps}^{-1}, \qquad \Delta M_s|_{\mathrm{HPQCD}} = (21.3 \pm 3.2)\,\mathrm{ps}^{-1}$$

- recall CDF result: $(17.77 \pm 0.12)\,\mathrm{ps}^{-1}$

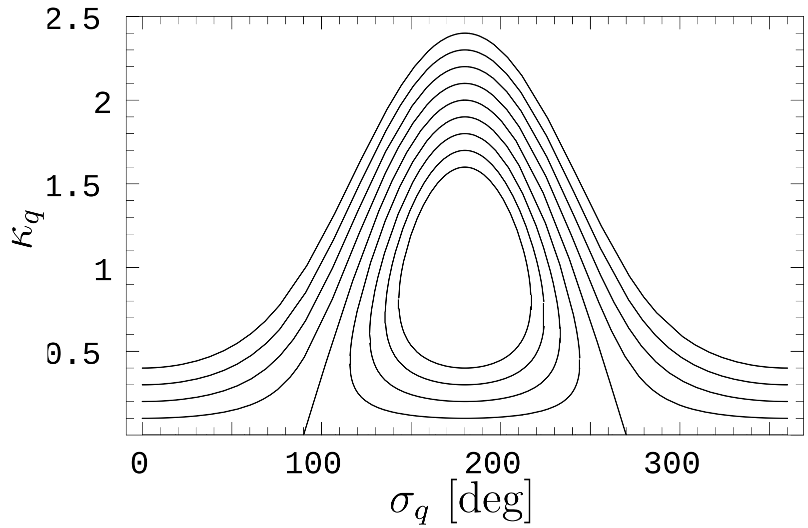
New Physics Models with impact on ΔM_s

- SUSY: gluino-squark loops (Ball hep-ph/0604249)
- SUSY: Higgs penguins at large $\tan\beta$ (Freitas hep-ph/0702267)
- SUSY GUT (Dutta hep-ph/0607147)
- SUSY: R-parity violation (Xiang-Dong hep-ph/0609269)
- tree-level: Z' with flavour-non-diagonal couplings (Baek hep-ph/0607113)
- warped extra dimension (Chang hep-ph/0607313)
- littlest Higgs model (Buras hep-ph/0605214)

Generic Parametrisation of New Physics

- new physics can significantly affect M_{12}^s, but not Γ_{12}^s: tree-dominated
- model-independent parametrisation of NP effects in terms of only two real parameters

Lines of ρ_s =const.:



- $$M_{12}^s = M_{12}^{s,\mathrm{SM}}(1 + \kappa_s e^{i\sigma_s})$$
- $\kappa_s > 0$: NP amplitude
- σ_s: new CP-violating phase

Deviation from SM measured by

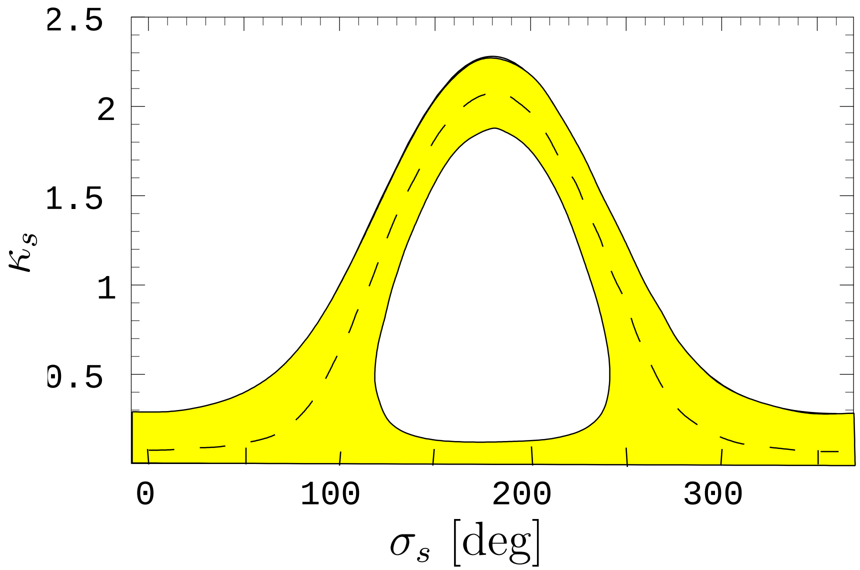
$$\rho_s \equiv \left| \frac{\Delta M_s}{\Delta M_s^{\mathrm{SM}}} \right| = (1 + 2\kappa_s \cos\sigma_s + \kappa_s^2)^{1/2}$$

Constraints from $\Delta M_s^{\rm SM}$

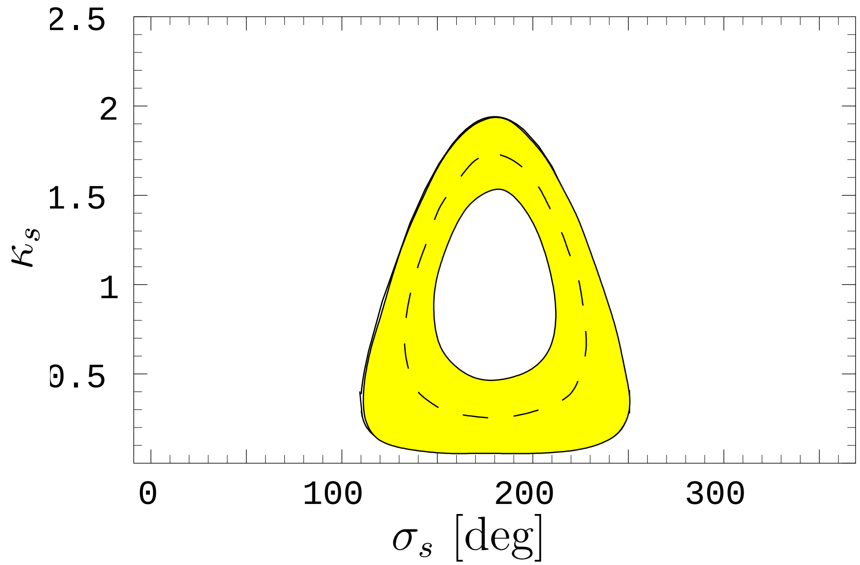
Recall: two unquenched calculations available:

- JLQCD: $N_f = 2$ Wilson fermions + NRQCD heavy fermions
- HPQCD: $N_f = 2+1$ staggered light + NRQCD heavy fermions

1σ constraints from JLQCD:



from HPQCD:



$\Delta M_s|_{\rm exp}$ compatible...

not compatible with SM (at 1σ)

Constraints from $\Delta M_s^{\rm SM}$

Conclusions:

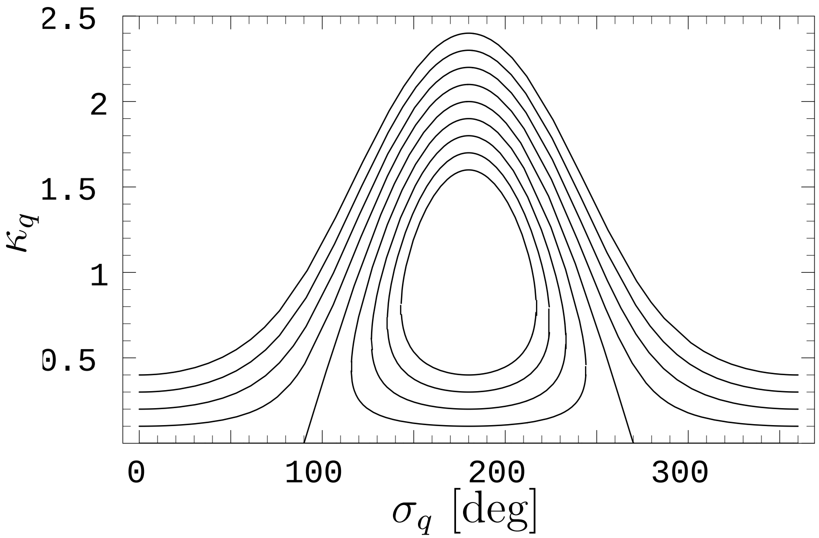
- $\Delta M_s|_{\rm th}$ not yet known accurately enough to exclude even $|M_{12}^{s,{\rm NP}}| \approx |M_{12}^{s,{\rm SM}}|$ (i.e. $\kappa_s < 1$)
- improved predictions expected in due course thanks to recent breakthrough in lattice algorithms to reduce the cost of simulations of light quark masses for Wilson fermions

  (Del Debbio, Lüscher 06)
- timescale? Current uncertainty of $\Delta M_s|_{\rm th} \sim 14\%$. Sachrajda quoted 1-2% for 2015 (LHCb upgrade workshop Jan 2007)
- also use alternative constraints $\boxed{\rightarrow \phi_s}$

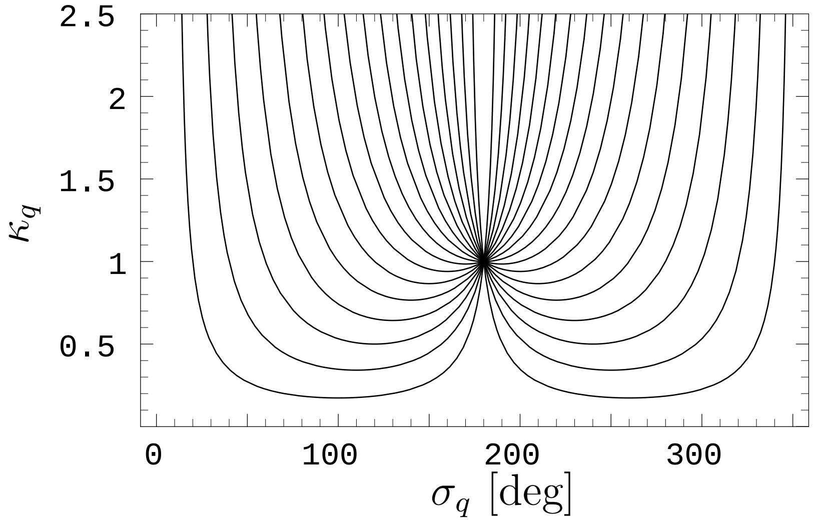
Constraints from ϕ_s

$$\phi_s = \arg M_{12}^s = \phi_s^{\rm SM} + \phi_s^{\rm NP} \text{ with } \phi_s^{\rm SM} = -2\lambda^2 R_b \sin\gamma \approx -2^\circ$$

lines of ρ_s =const.:



lines of $\phi_s^{\rm NP}$ =const.:



Observables sensitive to ϕ_s:
CP asymmetries in $B_s \to J/\psi\phi$ (and related), $\Delta\Gamma_s$, $A_{\rm SL}^s$

Status of ϕ_s

ϕ_s from $b \to ccs$ decays, e.g. $B_s \to J/\psi\phi$:

$$\Gamma(t) \propto e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} - \eta_f \cos\phi_s \sinh \frac{\Delta\Gamma_s t}{2} + \eta_f q D \sin\phi_s \sin(\Delta M_s t) \right\}$$

η_f: CP eigenvalue of final state (± 1), $q = +1(-1)$ if tagged as B_s ($\bar{B}_s$) at production, $q = 0$ if untagged, D: tagging dilution factor

Untagged events: $\cos\phi_s$ and $\Delta\Gamma_s$ from 2nd term: Tevatron 2007 (up to discrete ambuities, $\phi_s \leftrightarrow -\phi_s$, $\Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$; theory-indep.):

D0: $\Delta\Gamma_s = (0.17 \pm 0.09 \pm 0.02)\,\mathrm{ps}^{-1}, \quad \phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01}$

Tagged events: $\sin\phi_s$ from 3rd term: LHCb 200x (up to dilution factor D, to be determined from control channels, and discrete ambiguity $\phi_s \leftrightarrow \pi - \phi_s$; theory-indep.)

Status of ϕ_s

ϕ_s from flavour-specific (vulgo: semileptonic) CP-asymmetry $a_{\rm fs}^s$, e.g.

$$A_{\rm SL}^s = \frac{N(\bar{B}_s^0 \to \ell^+ X) - N(B_s^0 \to \ell^- X)}{N(\bar{B}_s^0 \to \ell^+ X) + N(B_s^0 \to \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

Also measurement of dimuon charge asymmetry: (D0 06)

$$A_{\rm SL}^{\mu\mu} = \frac{N(b\bar{b} \to \mu^+\mu^+ X) - N(b\bar{b} \to \mu^-\mu^- X)}{N(b\bar{b} \to \mu^+\mu^+ X) + N(b\bar{b} \to \mu^-\mu^- X)} = (-0.92 \pm 0.44 \pm 0.32) \times 10^{-2}$$

- contains contributions from B_d and B_s, but not B_u, Λ_b etc.

D0 translates both into $A_{\rm SL}^s = (-0.64 \pm 1.01) \times 10^{-2}$.
Using the constraint from $A_{\rm SL}^s$ in the analysis of $B_s \to J/\psi\phi$:

D0: $\Delta\Gamma_s = (0.13 \pm 0.09)\,{\rm ps}^{-1}, \quad \phi_s = -0.70^{+0.47}_{-0.39}$

Theory Predictions for $\Delta\Gamma_s$ and $A_{\rm SL}^s$

$\Delta\Gamma = 2|\Gamma_{12}^s|\cos\phi_s$ with

$$\Gamma_{12}^s = -\frac{G_F^2 m_b^2}{24\pi M_{B_s}} (V_{cs}^* V_{cb})^2 \left[C_1 \langle O_1^s \rangle + C_2 \langle O_2^s \rangle + \delta_{1/m_b} \right]$$

Lenz/Nierste hep-ph/0612167 improve upon Beneke et al. hep-ph/9808385 by switching to a different operator basis (reduced sensitivity to power-suppressed contributions):

$$\Delta\Gamma_s = (0.088 \pm 0.017)\,\mathrm{ps}^{-1}\,, \qquad A_{\rm SL}^s = (2.06 \pm 0.57) \times 10^{-5}$$

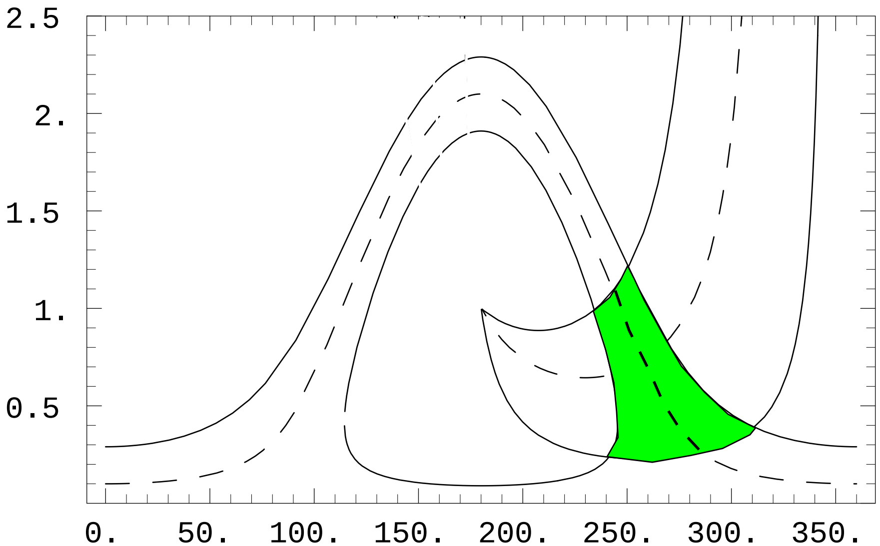
Using theory predictions for the B_d contribution to $A_{\rm SL}^{\mu\mu}$ (instead of exp. data from the B factories), and the D0 data for $B_s \to J/\psi\phi$, LN find

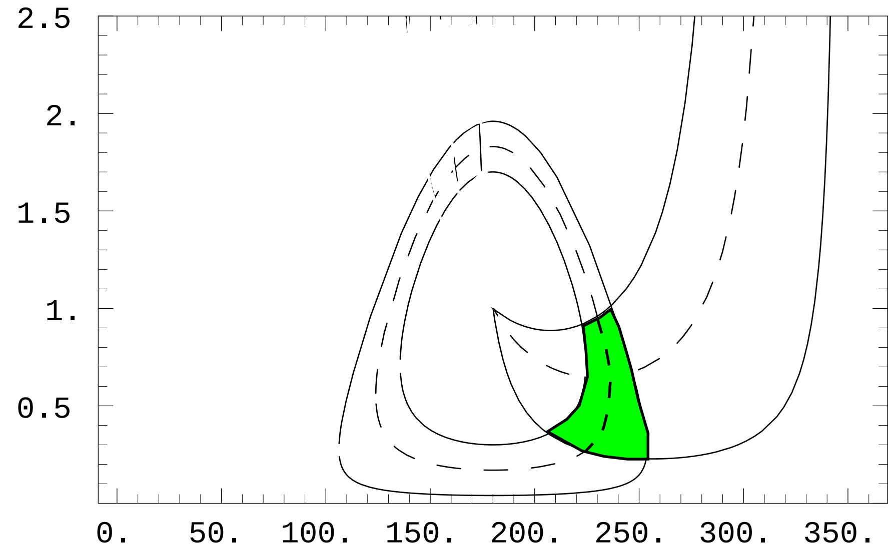
$\sin\phi_s = -0.77 \pm 0.04(\mathrm{th}) \pm 0.34(\mathrm{exp})$: $\phi_s \neq 0$ at 2σ

Combined Constraint on κ_s, σ_s

Using D0 combined result:

1σ constraints from JLQCD: from HPQCD:





- $|M_{12}^{s,\mathrm{NP}}| \approx |M_{12}^{s,\mathrm{SM}}|$ still allowed
- $\sigma_s < 180^\circ$ disfavoured

Constraints on Specific NP Models: Z'

- assume absence of Z–Z' mixing, i.e. flavour-diagonal Z couplings
- assume flavour non-diagonal Z' couplings only to q_L
- constrain $\rho_L \exp(i\phi_L) \equiv (g' M_Z)/(g M_{Z'}) B^L_{sb}$ with B^L_{sb} being $\bar{s} Z' b$ coupling
- $\kappa_s < 1.2 \quad \longleftrightarrow \quad \rho_L < 1.3 \cdot 10^{-3}$
- can translate this into bound on Z' mass:

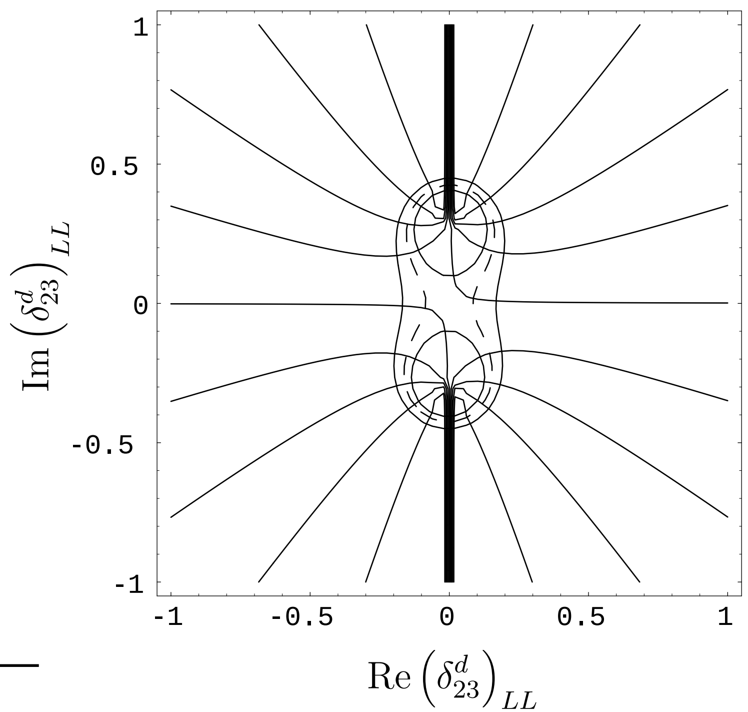
$$3.0\,\text{TeV} \left(\frac{g'}{g}\right) \left|\frac{B^L_{sb}}{V_{ts}}\right| < M_{Z'}$$

- very strong constraint!

MSSM (in MIA)

- MSSM (box diagram) contributions from charged Higgs, neutralinos, photinos, gluinos and charginos*
- for B_s mixing, only gluino contributions relevant
- full NLO Wilson coefficients available (Ciuchini hep-ph/0606197)

* also from double Higgs penguins, which are however only relevant for large $\tan\beta$



Constraints on $(\delta^d_{23})_{LL}$ insertion using JLQCD lattice data.
Open lines: constraints from ϕ_s.

Summary

- new physics in B_s mixing can be described, in a model-independent way, by 2 real parameters
- constraints from ΔM_s not very strong, despite excellent experimental accuracy: large hadronic (lattice) uncertainties $\sim 14\%$
- more decisive constraints from NP mixing phase
- present constraints on ϕ_s from $A_{\rm SL}^s$ and untagged $B_s \to J/\psi\phi$ (Tevatron) not very strong, although slight hint at NP (2σ acc. to Lenz/Nierste)
- expect much more precise constraints on/measurement of ϕ_s from LHCb: $\sigma_{\phi_s} = 0.04$ with 0.5 fb^{-1}: 1st year of running
- together with improved lattice calculations, the B_s system will prove a powerful tool to constrain/find NP