# Explaining $B$-meson data with a Supersymmetric U(2) flavor model

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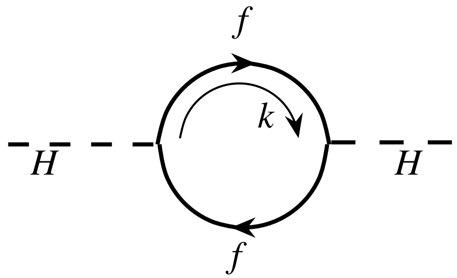
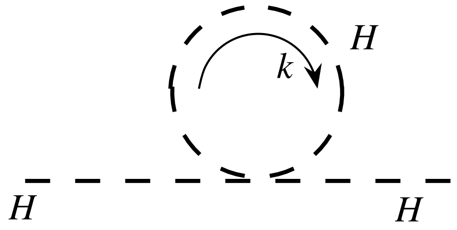
# *Introduction*

## Hierarchy Problem: SM fine-tuned

- $M_{EW} \sim 1/\sqrt{G_F} \sim 10^2\,\mathrm{GeV}, \qquad M_{Pl} \sim 1/\sqrt{G_N} \sim 10^{19}$ GeV.




- $(\delta m^2)$ Quadratically Divergent.
- $m_H^2 = m_0^2 + \delta m^2 \qquad \delta m^2 \sim \Lambda^2$

Cured by:

- Supersymmetry
- Extra dimensions
- Technicolor
- Higgsless

# *Introduction*

Flavor Problem:

- Quark/Fermion masses, CKM elements not explained.

Cured by:

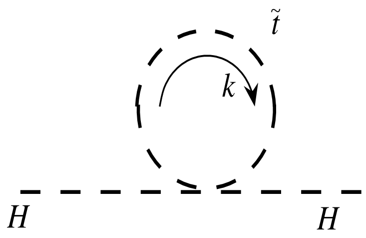
- “Horizontal” Symmetry. U(2)?

# *Supersymmetry (SUSY)*

Put in opposite spin partner: Fermion $\Leftrightarrow$ Boson

Example: $t_{L,R} \Leftrightarrow \tilde{t}_{L,R}, \quad b_{L,R} \Leftrightarrow \tilde{b}_{L,R}$

Superfield: $\Phi = (\tilde{t}_L,\ t_L,\ F)$




$$\delta m^2 \sim \log \Lambda$$

So no longer fine-tuned

Other nice features:

Gauge couplings unify
Dark Matter candidate (LSP)

SUSY has to be broken!

SUSY breaking/mediation not unique $\rightarrow$ MSSM

# U(2) Flavor Symmetry

[Pomarol, Tommasini]
[Barbieri, Dvali, Hall]

$$\boxed{\begin{matrix}u\\ d\end{matrix}} \leftrightarrow \boxed{\begin{matrix}c\\ s\end{matrix}} \quad \begin{matrix}t\\ b\end{matrix}$$

$a, b = (1, 2) \rightarrow$ U(2) index

$$\mathcal{L} = -\lambda_1 \psi H \psi - \lambda_2 \frac{\phi^a}{M} \psi H \psi_a - \lambda_3 \frac{\phi^{ab}}{M} \psi_a H \psi_b - \lambda_4 \frac{S^{ab}}{M} \psi_a H \psi_b + \cdots + \text{h.c.}$$

$\phi^a$, $\phi^{[ab]}$, $S^{\{ab\}}$ : $U(2)$ tensor “flavon” fields

$$\left[\psi_i H \psi_j \equiv U^c_i Q_j \cdot H + Q_i \cdot H U^c_j + D^c_i H^\dagger Q_j + H^\dagger Q_i D^c_j\right]$$

## U(2) symmetric mass:

$$M^u = m_t \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \qquad M^d = m_b \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix}$$

## U(2) breaking (gives $1^{st}$ & $2^{nd}$ gen mass):

$$\frac{<\phi^2>}{M} = \frac{<S^{22}>}{M} \equiv \epsilon \approx 0.02 \qquad \frac{<\phi^{12}>}{M} \equiv \epsilon' \approx 0.004$$

$$M^u = m_t \begin{pmatrix} 0 & -\epsilon' & 0 \\ \epsilon' & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix} \qquad M^d = m_b \begin{pmatrix} 0 & -\epsilon' & 0 \\ \epsilon' & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix}$$

in the gauge basis ($W^\pm$ diagonal)

Gauge basis $\rightarrow$ Mass Basis implies CKM matrix

# SUSY U(2)

SUSY and U(2) dictate structure of the theory

SUSY preserving Superpotential:

$$\mathcal{W} = \psi H \psi + \frac{\phi^a}{M} \psi H \psi_a + \frac{\phi^{ab}}{M} \psi_a H \psi_b + \frac{\phi^a \phi^b}{M^2} \psi_a H \psi_b + \frac{S^{ab}}{M} \psi_a H \psi_b + \mu H_u H_d$$

$$\left[ \psi_i H \psi_j \equiv Q_i U^c_j H_u + U^c_i Q_j H_u - Q_i D^c_j H_d - D^c_i Q_j H_d \right]$$

SUSY breaking terms:

$$\mathcal{L} \supset -\left( \tilde{d}^*_L \quad \tilde{s}^*_L \quad \tilde{b}^*_L \right) \mathcal{M}^2_{LL} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \end{pmatrix} - \left( \tilde{d}^*_R \quad \tilde{s}^*_R \quad \tilde{b}^*_R \right) \mathcal{M}^2_{RR} \begin{pmatrix} \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix} +$$

$$+ \left( \tilde{d}^*_R \quad \tilde{s}^*_R \quad \tilde{b}^*_R \right) \mathcal{M}^2_{RL} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \end{pmatrix} + h.c.$$

$$\mathcal{M}^2_{RR} = \begin{pmatrix} m_1^2 & i\epsilon' m_5^2 & 0 \\ -i\epsilon' m_5^2 & m_1^2 + \epsilon^2 m_2^2 & \epsilon m_4^{2*} \\ 0 & \epsilon m_4^2 & m_3^2 \end{pmatrix} \qquad \mathcal{M}^2_{RL} = v_d \begin{pmatrix} O & -A_1 \epsilon' & O \\ A_1 \epsilon' & A_2 \epsilon & A_4 \epsilon \\ O & A'_4 \epsilon & A_3 \end{pmatrix}$$

SUSY br scale $\equiv m_0^2$ $\qquad$ $A$-term scale $\equiv A$

# Parameters

Define $\delta^{RL,RR,LL}_{32,23} \equiv \frac{(\mathcal{M}^2_{RL,RR,LL})_{32,23}}{m_0^2}$

Natural sizes: $\delta^{RL}_{32,23} = 6.82 \times 10^{-4}\, d^{RL}_{32,23}$ $\delta^{RR}_{32} = 0.02\, d^{RR}_{32}$

SUSY spectrum: (“effective” SUSY)

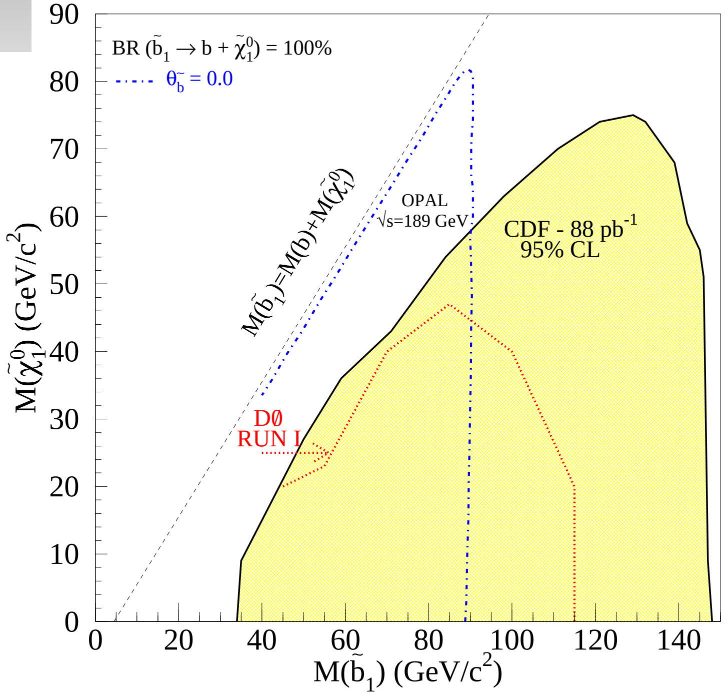
| | | | |
|---|---|---|---|
| $m_0$ | $1000$ | $\tan\beta$ | $5$ |
| $m_{\tilde{b}_R,\tilde{t}_R}$ | $100$ | $\mu$ | $200\, e^{i\,2.2}$ |
| $m_{\tilde{d}_R,\tilde{s}_R}$ | $1000$ | $M_2$ | $250$ |
| $m_{\tilde{q}_L}$ | $1000$ | $M_{\tilde{g}}$ | $300$ |
| $A$ | $1000$ | $m_{H^\pm}$ | $250$ |
| $d^{LR}_{32}$ | $2\, e^{i\,3.2}$ | $d^{RR}_{32}$ | $1.75\, e^{i\,1.6}$ |

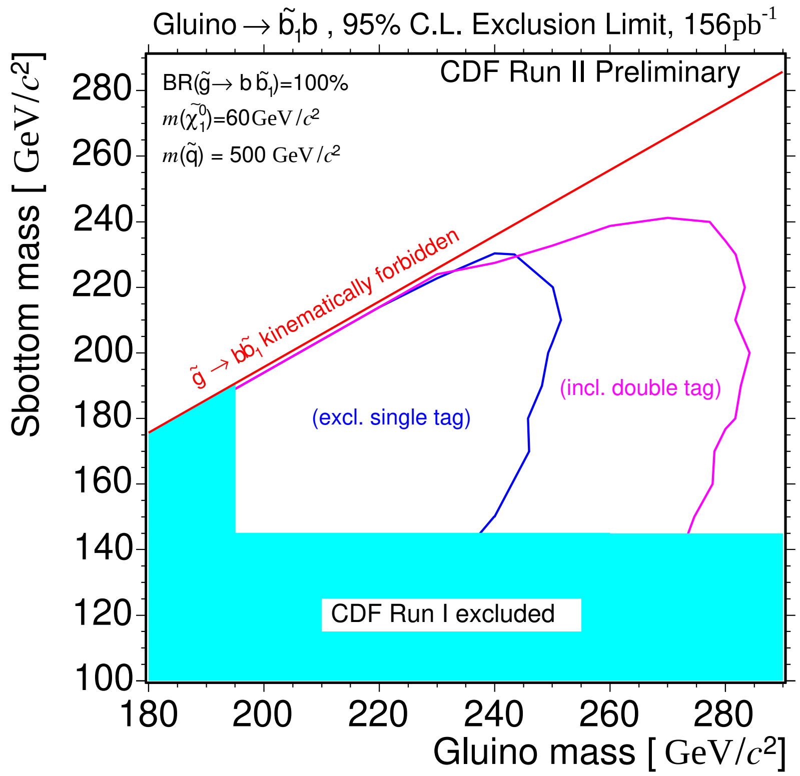
All masses are in GeV

Neutron EDM suppressed in effective SUSY in spite of new $\mathcal{O}(1)$ phases

# Tevatron bounds

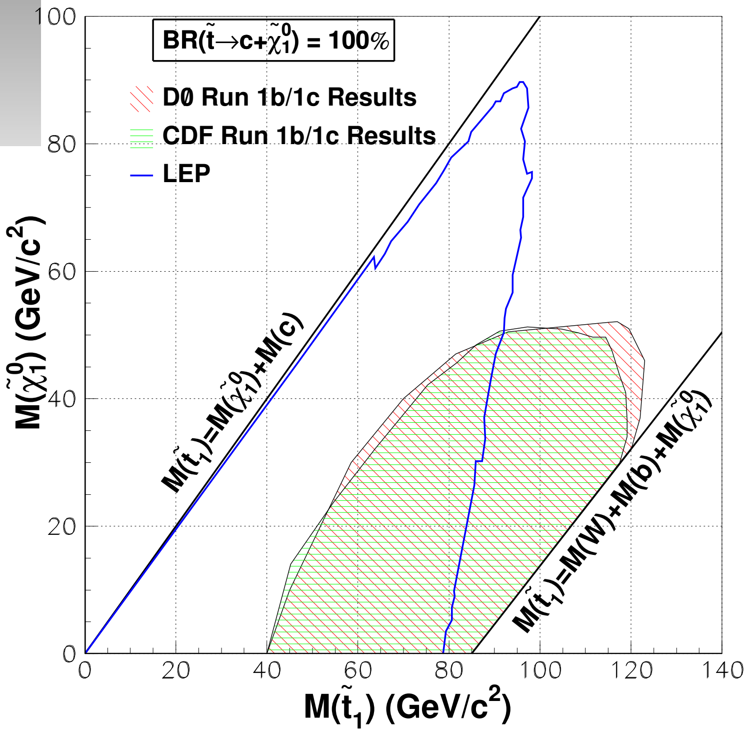
Source: [D. Bortoletto, C. Rott]
[hep-ex/9910049, 0410007]



# Tevatron bounds

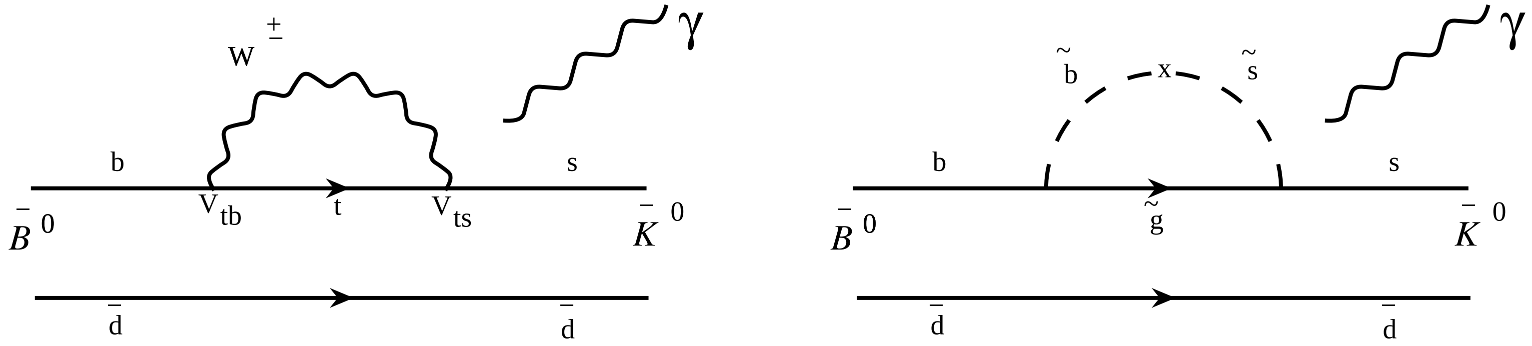
[hep-ex/0404028]



# *Flavor Changing Neutral Currents (FCNC)*

- Minimal flavor violation (MFV)
  - $A$-terms aligned w/ SM Yukawas. So FCNC $\propto V_{CKM}$
  - SM, $H^{\pm}$, $\tilde{\chi}^{\pm}$
- Non-minimal flavor violation (NMFV)
  - General $A$-terms. So FCNC $\propto$ new phases
  - Gluino ($\tilde{g}$)

Example: $\Delta B = 1$ $B_d \to X_s \gamma$



# Operator product expansion (OPE)

Example: $\Delta B = 1$ effective Hamiltonian

$$\begin{aligned}
\mathcal{H}^{eff}_{\Delta B=1} &= -\frac{G_F}{\sqrt{2}} V_{ts} V^*_{tb} \left( \sum_{i=1\ldots 6,9,10} C_i(\mu) O_i(\mu) + C_{7\gamma}(\mu) O_{7\gamma}(\mu) + C_{8g}(\mu) O_{8g}(\mu) \right) \\
O_2 &= (\bar{s}c)_{V-A} (\bar{c}b)_{V-A} \\
O_{7\gamma} &= \frac{e m_b}{8\pi^2}\, \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu} \\
O_{8g} &= \frac{g_s m_b}{8\pi^2}\, \bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}
\end{aligned}$$

Renormalization group evolution from high scale to $m_b$

New physics contribution to Wilson coefficients:

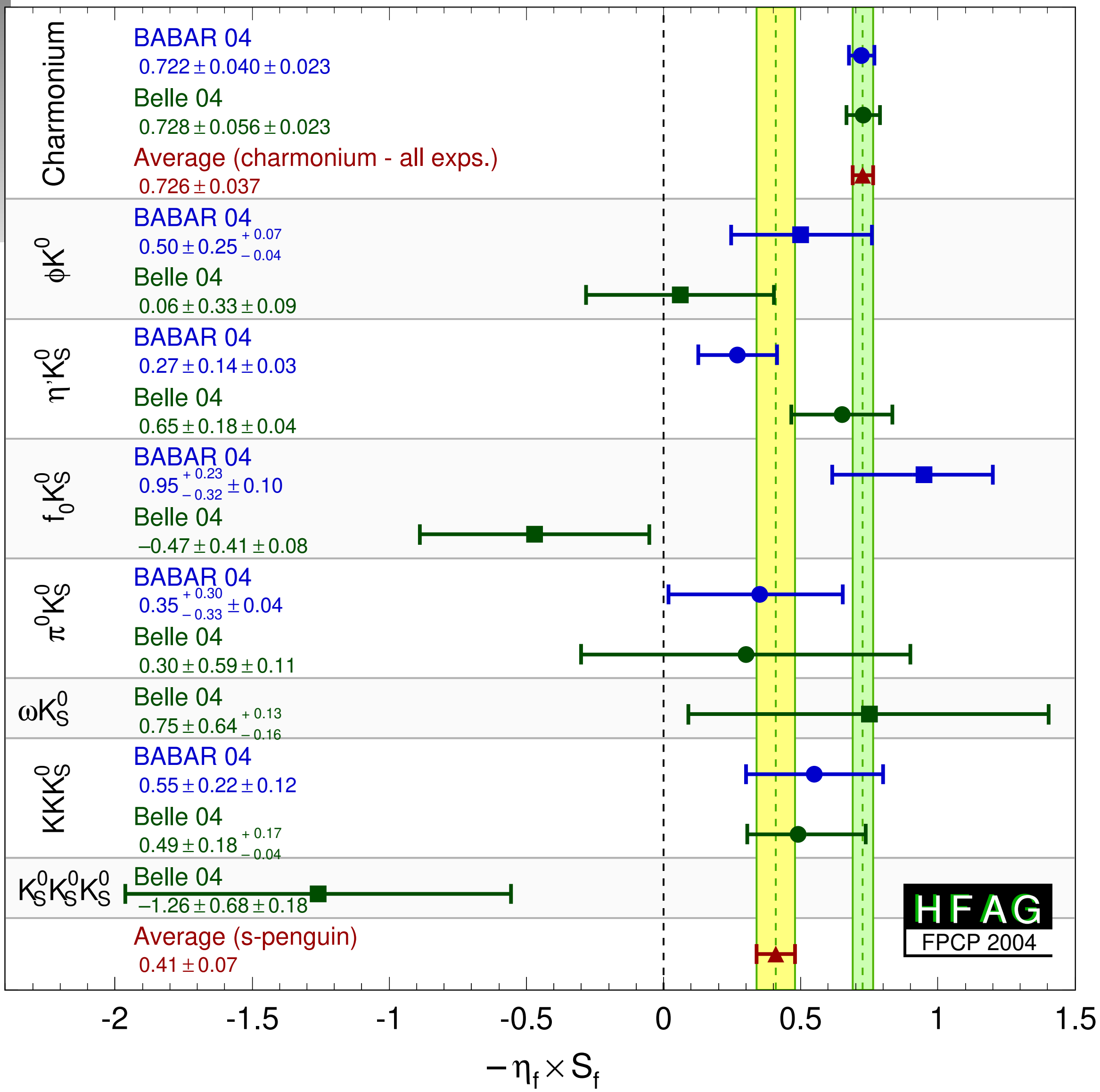
$$\begin{aligned}
C_2 &= C_2^{SM} \\
C_{7\gamma} &= C_{7\gamma}^{SM} + 0.67 C_{7\gamma}^{new}(M_W) + 0.09 C_{8g}^{new}(M_W) \\
C_{8g} &= C_{8g}^{SM} + 0.70 C_{8g}^{new}(M_W)
\end{aligned}$$

# $B$-meson (and $K$) FCNC

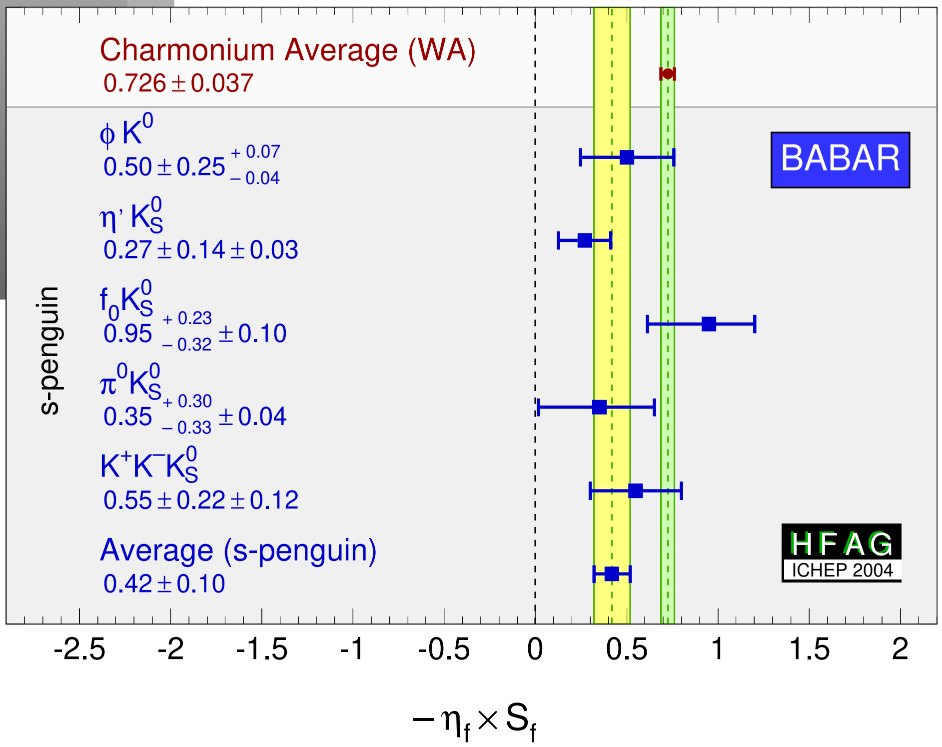
FCNC Effects in:

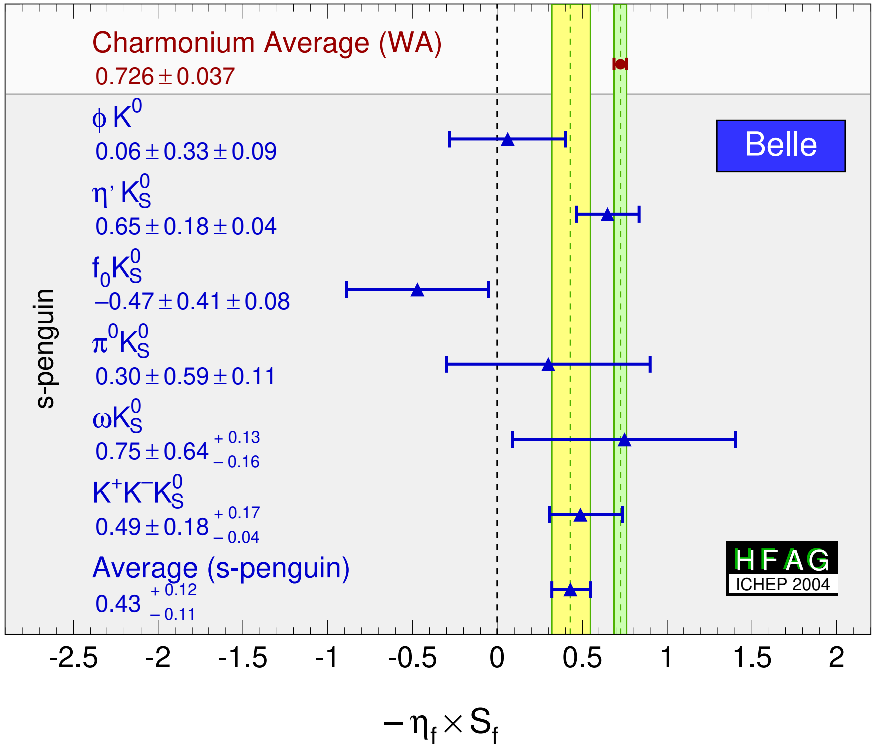
- $\Delta S = 2$:
  - $K^0 - \bar{K}^0$ mixing ($\epsilon_K$)
- $\Delta B = 2$:
  - $B_d \bar{B}_d$ mixing ($\Delta m_{B_d}$), $B_d \to \psi K_s$ ($\sin 2\beta$)
  - $B_s \bar{B}_s$ mixing ($\Delta m_{B_s}$)
- $\Delta B = 1$ (B.R. and C.P. Violation):
  - $B_d \to X_s \gamma$, $B_d \to X_s\, g$
  - $B_d \to X_s \ell^+ \ell^-$
  - $B_d \to \phi K_s$

# ***Recent*** $\sin 2\beta$ ***data***



# Recent $\sin 2\beta$ data



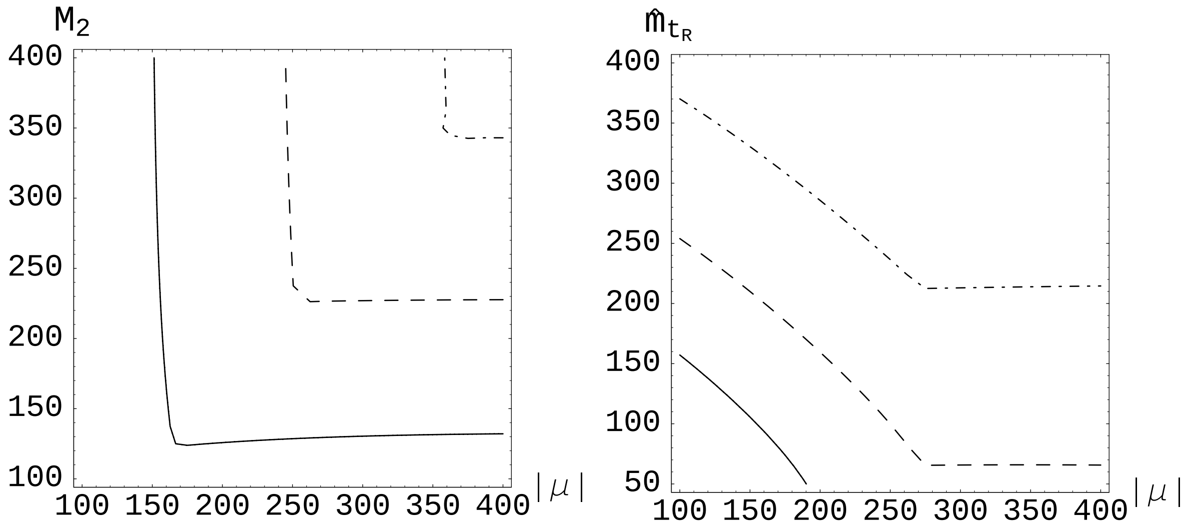
# $\Delta S = 2$: *Kaon mixing*

CP violation due to mixing: $|\epsilon_K| = (2.284 \pm 0.014) \times 10^{-3}$ [PDG2004]

- Constrains MFV contributions (SM, $H^{\pm}$, $\tilde{\chi}^{\pm}$)
- NMFV gluino contributions not constrained

About 25 % uncertainty in calculating hadronic matrix element (in Bag factor $B_K$)

(1.05, 1.1, 1.2) contours of $\frac{\epsilon_K^{MFV}}{\epsilon_K^{SM}}$:




$\epsilon'_K/\epsilon_K$ has large hadronic uncertainties

# $\Delta B = 2$: $B_d \bar{B}_d$ *mixing*

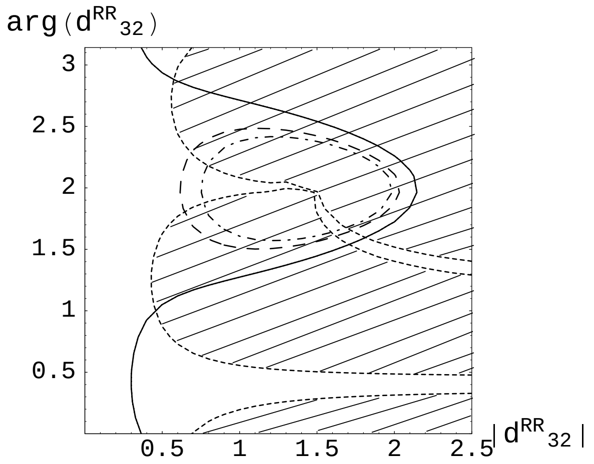
$\Delta m_d = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$
$a_{\psi K_s} = 0.725 \pm 0.037$ ($\sin 2\beta$ in SM) [PDG2004, HFAG-ICHEP04]

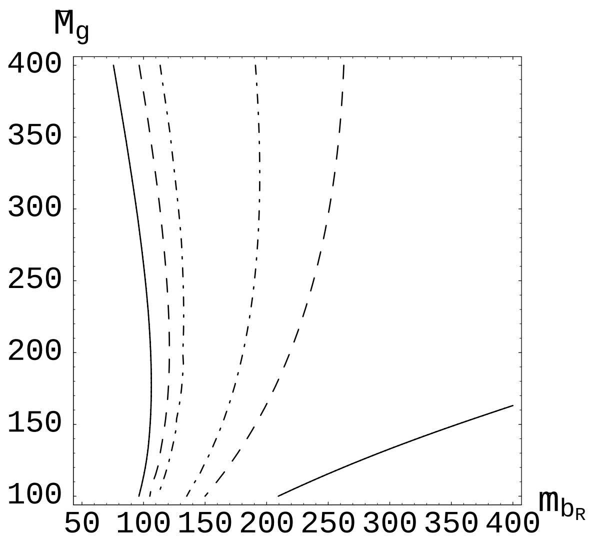
MFV constraints similar to Kaon case

For large $\tilde{d}_R \tilde{s}_R$ (squark) mixing, NMFV ($\tilde{g}$) contrib strongly constrains $\delta^{RR}_{32}$

About 15% uncertainty in decay constant $f_B$

(0.9, 1.0, 1.25) contours of $\frac{\Delta m_d}{\Delta m_d^{SM}}$




Hatched area excluded by $a_{\psi K_s}$

# $\Delta B = 2$: $B_s \bar{B}_s$ *mixing*

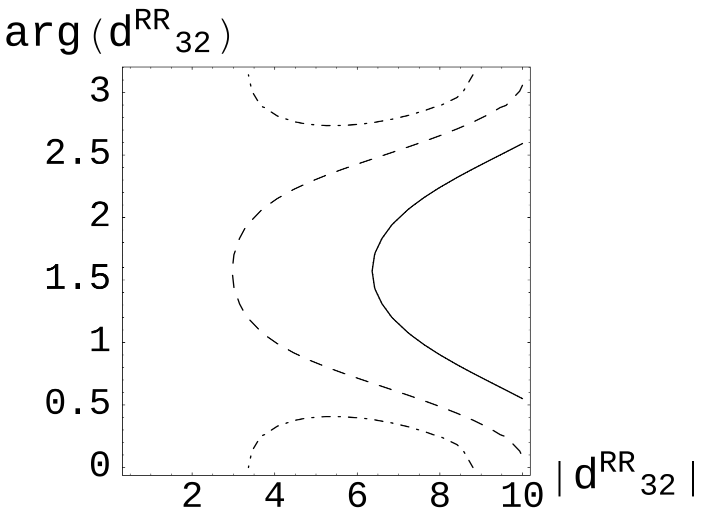
Limit: $\Delta m_{B_s} > 14.4\, ps^{-1}$ @ 95% C.L. [PDG2004]
SM prediction: $14\ \mathrm{ps}^{-1} < \Delta m_{B_s} < 20\ \mathrm{ps}^{-1}$

Dilepton asymmetry: $A_{ll}^{B_q} \equiv \frac{N(B_q B_q) - N(\bar{B}_q \bar{B}_q)}{N(B_q B_q) + N(\bar{B}_q \bar{B}_q)}$ SM prediction: $A_{ll}^{B_s} \approx 10^{-4}$

For large $\tilde{d}_R \tilde{s}_R$ mixing (with $B_d \bar{B}_d$ mixing constraints): $\Delta m_{B_s} \approx 22\, ps^{-1}$

For small $\tilde{d}_R \tilde{s}_R$ mixing (no $B_d \bar{B}_d$ mixing constraints):

(15, 25, 40) $\mathrm{ps}^{-1}$ contours of $\Delta m_{B_s}$ ($10^{-4}$, $10^{-3}$ and $10^{-2}$) contours of $|A_{ll}^{B_s}|$



# $\Delta B = 1$: $B_d \to X_s\gamma$, $B_d \to X_s\, g$

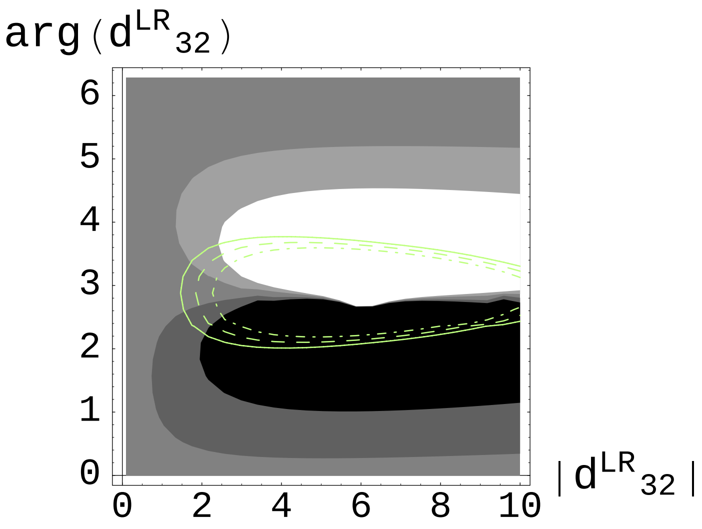
$B.R.(B_d \to X_s\gamma) = (3.52^{+0.3}_{-0.28}) \times 10^{-4}$ [HFAG-ICHEP04]

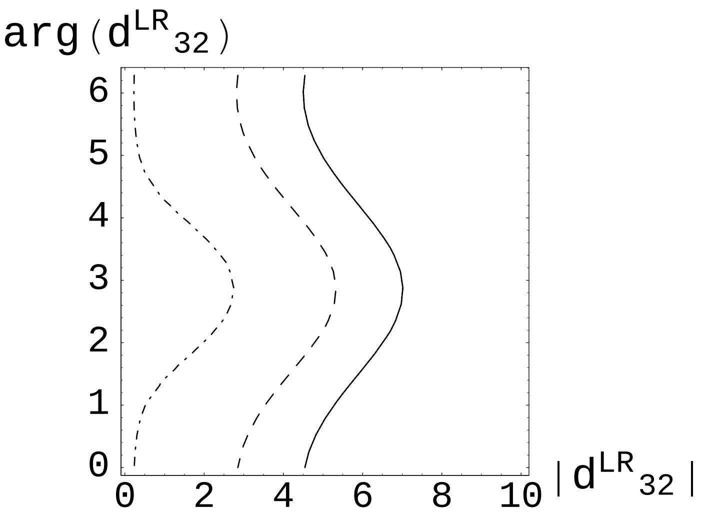
$A_{CP}^{B_d \to X_s\gamma}(\delta) = \frac{\Gamma(\bar{B}_d \to X_s\gamma) - \Gamma(B_d \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B}_d \to X_s\gamma) + \Gamma(B_d \to X_{\bar{s}}\gamma)}$ $\quad -0.07 < A_{CP}^{B_d \to X_s\gamma} < 0.07$ @ 95% C.L.

with $E_\gamma > (1-\delta)E_\gamma^{max}$

$\tilde{g}$ contrib strongly constrains $\delta_{32}^{RL}$

(-7, -3, 3, 7) % cont of $A_{CP}^{B_d \to X_s\gamma}$ $\quad$ $(1,\ 7.5,\ 15\ \%)$ cont of B.R.$(B_d \to X_s\, g)$



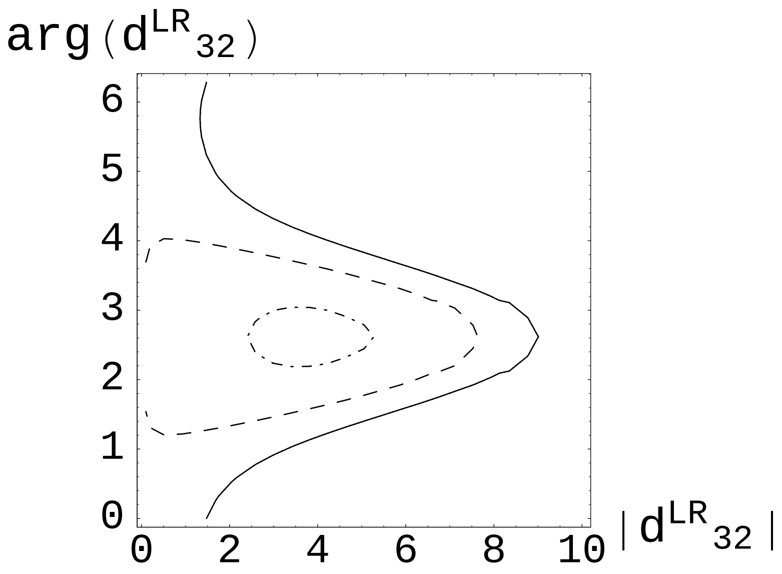



# $\Delta B = 1$: $B_d \to X_s \ell^+ \ell^-$

| | Experiment [HFAG-ICHEP04] | SM prediction |
|---|---|---|
| $B.R.(B_d \to X_s \ell^+ \ell^-)$ | $4.46^{+0.98}_{-0.96} \times 10^{-6}$ | $5.3 \times 10^{-6}$ |

$(p_{\ell^+} + p_{\ell^-})^2 > (0.2\ \mathrm{GeV})^2$

(5.25, 6.25, 7.25)$\times 10^{-6}$ contours of $B_d \to X_s \ell^+ \ell^-$



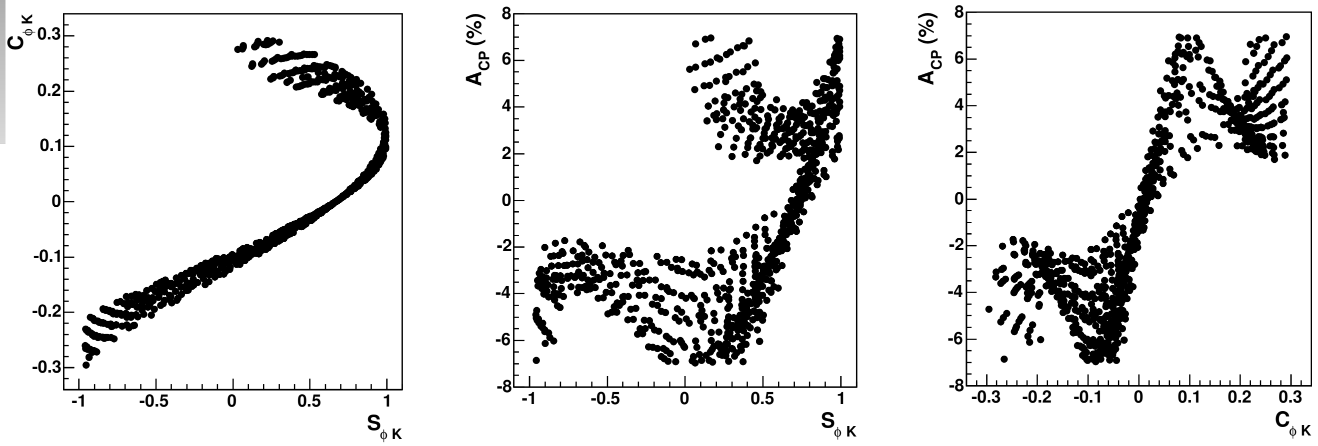
# $\Delta B = 1$: $B_d \to \phi K_s$

$$A_{CP}^{B_d \to \phi K_s} \equiv \frac{\Gamma\left(\bar{B}_d(t) \to \phi K_s\right) - \Gamma\left(B_d(t) \to \phi K_s\right)}{\Gamma\left(\bar{B}_d(t) \to \phi K_s\right) + \Gamma\left(B_d(t) \to \phi K_s\right)}$$
$$= -C_{\phi K} \cos\left(\Delta m_{B_d} t\right) + S_{\phi K} \sin\left(\Delta m_{B_d} t\right)$$

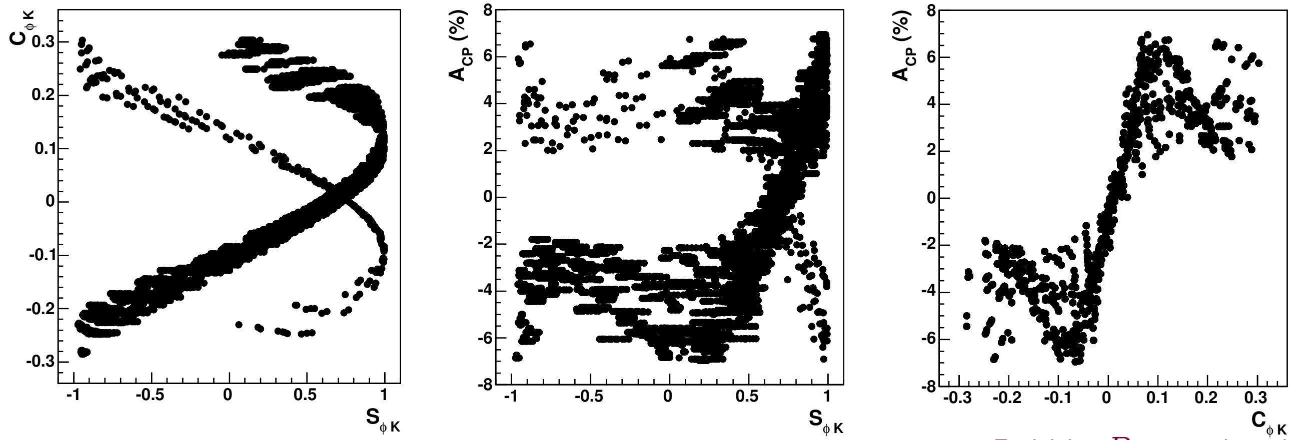
| | Experiment [HFAG-ICHEP04] | SM prediction |
|---|---|---|
| $B.R.(B_d \to \phi K_s)$ | $8.3^{+1.2}_{-1.0} \times 10^{-6}$ | $\sim 5 \times 10^{-6}$ |
| $S_{\phi K}$ | $0.34 \pm 0.2$ | $0.725 \pm 0.037$ |
| $C_{\phi K}$ | $-0.04 \pm 0.17$ | $0$ |

# $B_d \to \phi K_s$ and $B_d \to X_s\gamma$ scan

For small $\tilde{d}_R \tilde{s}_R$ mixing (no new phase in $B_d \bar{B}_d$ mixing):




For large $\tilde{d}_R \tilde{s}_R$ mixing (with new phase in $B_d \bar{B}_d$ mixing):



# Conclusions

SUSY U(2) theory solves flavor and hierarchy problems of the SM

Considered resulting FCNC in $B$-meson (and $K$) sector

Can accommodate known data

Can account for deviations from SM predictions in $B_d \to \phi K_s$

Await more data (improved accuracy) in:

$B_s \bar{B}_s$ mixing, $A_{CP}^{B_d \to X_s \gamma}$, $B_d \to \phi K_s$