New Physics in the Flavor Sector

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Standard Model... and Beyond...

So far Standard Model (SM) impressive... But...

(1) Gauge Hierarchy Problem

- SM fine-tuned. $\delta m_H^2 \sim \Lambda^2$

  Supersymmetry? Technicolor? Extra dimensions? Little-Higgs? Higgsless?

(2) Flavor Problem

- Quark/lepton masses, CKM elements not explained.

  "Horizontal" Symmetry? : Abelian? NonAbelian? (U(2))

(3) ν mass non-zero

- Why is the ν so light?

  (Type I seesaw? Type II seesaw? Extra dimensions?)

- Is the ν Majorana? (Is $L_{\#}$ good?)

Flavor Sector Probes

SM extensions may lead to new flavor signatures

Look for them in Flavor Changing Neutral Currents (FCNC)
...since SM contributions loop suppressed

Look for new sources of CP violation

Need SM/lattice calculations to sufficient accuracy

Lepton Sector probes:

- $\mu \to e\gamma$, $\mu \to eee$, $0\nu\beta\beta$, e^- EDM, ...

Quark Sector probes:

- $b \to s\gamma$, $b \to s\bar{s}s$, $s \to d\nu\bar{\nu}$, n EDM, ...

Can we fi nd hints of unifi cation in Quark & Lepton sectors?

Supersymmetry (SUSY)

Add opposite spin partner: Fermion $\Leftrightarrow$ Boson

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

No longer fine-tuned. $\delta m_H^2 \sim \log \Lambda$

Other nice features:

Gauge couplings unify
Dark Matter candidate (LSP)

But SUSY has to be broken!

SUSY breaking/mediation not unique $\rightarrow$ MSSM

U(2) Flavor Symmetry

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

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

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

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

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

$$\left[\psi_i H \psi_j \equiv U_i^c Q_j \cdot H + Q_i \cdot H U_j^c + D_i^c H^\dagger Q_j + H^\dagger Q_i D_j^c\right]$$

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):

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

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

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:

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

$$\left[\psi_i H \psi_j \equiv Q_i U_j^c H_u + U_i^c Q_j H_u - Q_i D_j^c H_d - D_i^c Q_j H_d\right]$$

SUSY breaking terms:

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

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

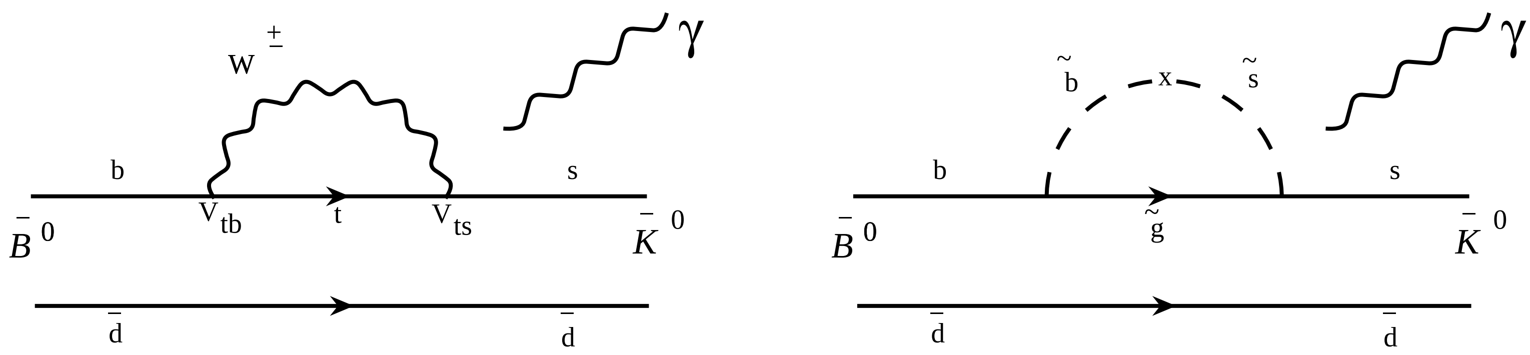
$$\mathcal{M}_{RR}^2 = \begin{pmatrix} m_1^2 & i\epsilon' m_5^2 & 0 \\ -i\epsilon' m_5^2 & m_1^2 + \epsilon^2 m_2^2 & \epsilon m_4^{2*} \\ 0 & \epsilon m_4^2 & m_3^2 \end{pmatrix} \qquad \mathcal{M}_{RL}^2 = v_d \begin{pmatrix} O & -A_1\epsilon' & O \\ A_1\epsilon' & A_2\epsilon & A_4\epsilon \\ O &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

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

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

$$
\begin{aligned}
\mathcal{H}^{eff}_{\Delta B=1} &= -\frac{G_F}{\sqrt{2}} V_{ts} V^*_{tb} \left(\sum_{i=1\ldots6,9,10} C_i(\mu) O_i(\mu) + C_{7\gamma}(\mu) O_{7\gamma}(\mu) + C_{8g}(\mu) O_{8g}(\mu) \right) \\
O_2 &= (\bar{s}c)_{V-A} (\bar{c}b)_{V-A} \\
O_{7\gamma} &= \frac{e m_b}{8\pi^2}\, \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu} \\
O_{8g} &= \frac{g_s m_b}{8\pi^2}\, \bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}
\end{aligned}
$$

Renormalization group evolution from high scale to m_b

New physics contribution to Wilson coeffi cients:

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

B-meson (and Kaon) FCNC

FCNC Effects in:

- $\Delta S = 2$:

  $K^0 - \bar{K}^0$ mixing (ϵ_K)

- $\Delta B = 2$:

  $B_d \bar{B}_d$ mixing (Δm_{B_d}), $B_d \to \psi K_s$ ($\sin 2\beta$)

  $B_s \bar{B}_s$ mixing (Δm_{B_s})

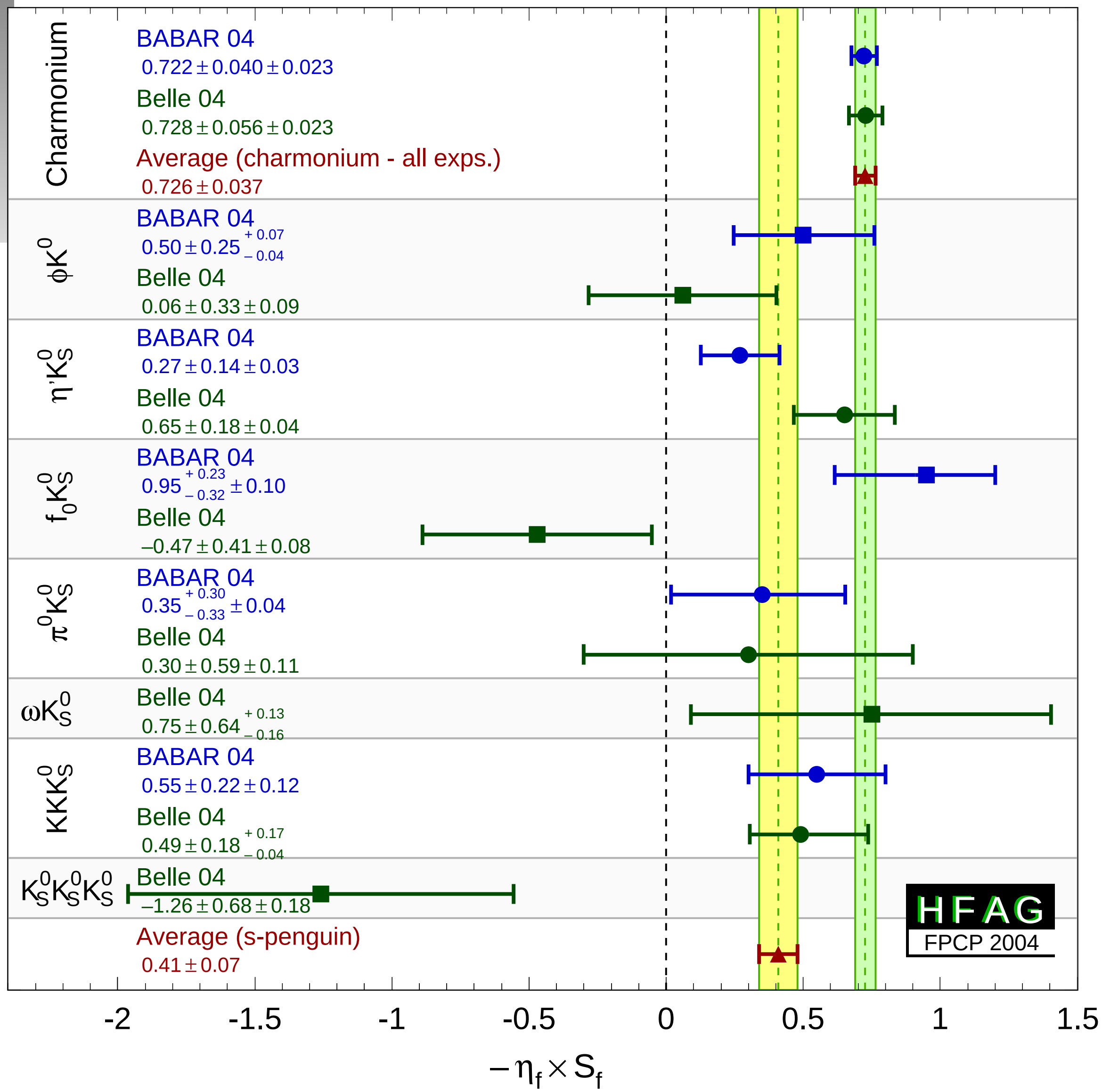
- $\Delta B = 1$ (B.R. and CP Violation):

  $B_d \to X_s \gamma$, $B_d \to X_s\, g$

  $B_d \to X_s \ell^+ \ell^-$

  $B_d \to \phi K_s$

Recent $\sin 2\beta$ *data*



Model 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	μ	$200\, e^{i\,2.2}$
$m_{\tilde{d}_R,\tilde{s}_R}$	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

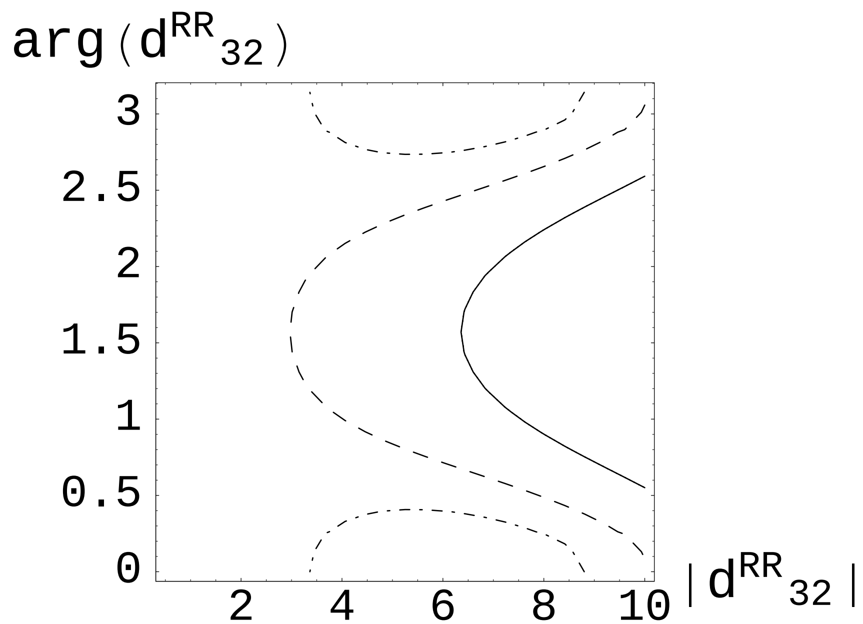
Neutron EDM suppressed in effective SUSY in spite of new $\mathcal{O}(1)$ phases

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

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

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) ps^{-1} contours of Δm_{B_s}

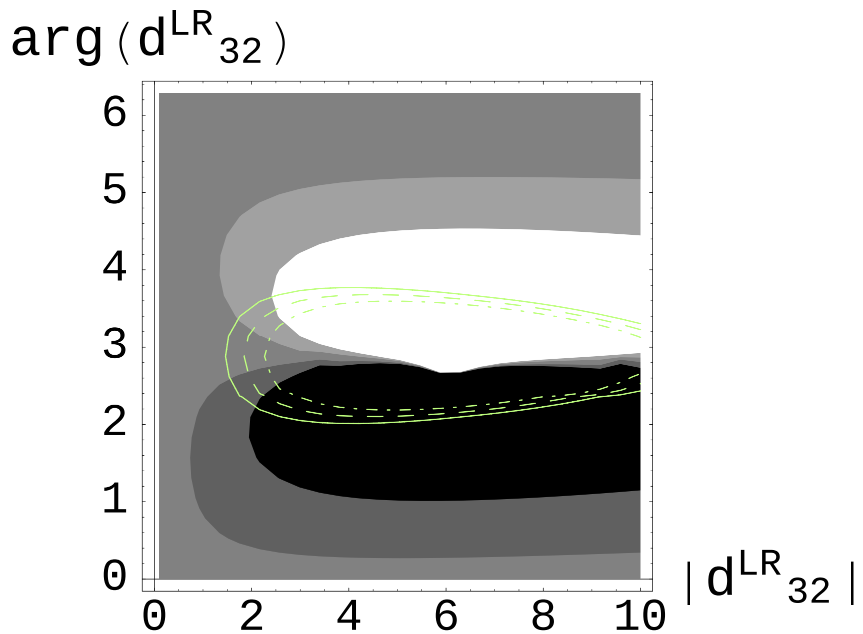
$\Delta B = 1$: $B_d \to X_s\gamma$ $(b \to s\gamma)$

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

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

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

$\tilde{g}$ contribution strongly constrains δ_{32}^{RL}



(-7, -3, 3, 7) % contours of $A_{CP}^{B_d\to X_s\gamma}$

$\Delta B = 1$: $B_d \to \phi K_s$ ($b \to s\bar{s}s$)

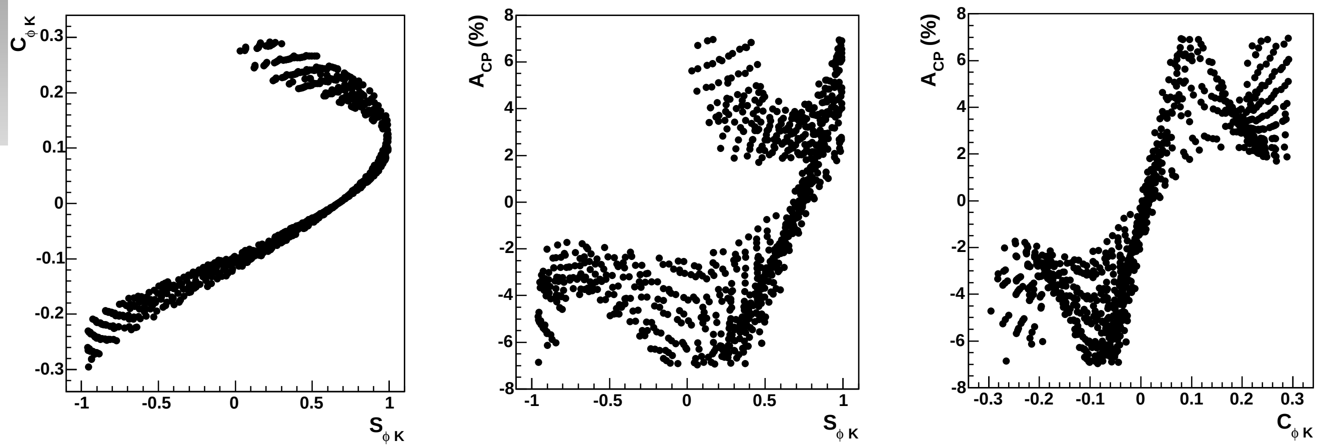
$$A_{CP}^{B_d \to \phi K_s} \equiv \frac{\Gamma\left(\bar{B}_d(t) \to \phi K_s\right) - \Gamma\left(B_d(t) \to \phi K_s\right)}{\Gamma\left(\bar{B}_d(t) \to \phi K_s\right) + \Gamma\left(B_d(t) \to \phi K_s\right)}$$

$$= -C_{\phi K} \cos\left(\Delta m_{B_d} t\right) + S_{\phi K} \sin\left(\Delta m_{B_d} t\right)$$

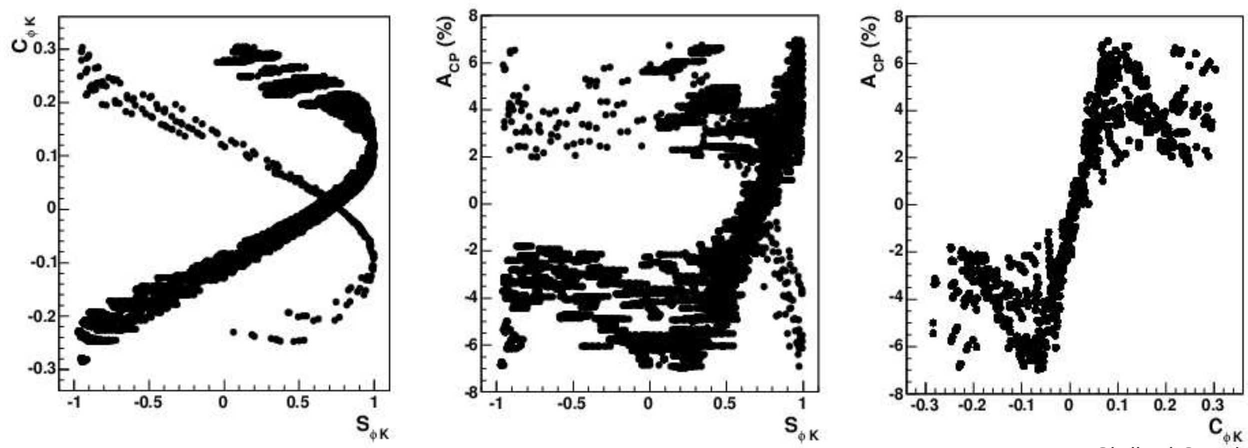
	Experiment [HFAG-ICHEP04]	SM prediction
$B.R.(B_d \to \phi K_s)$	$8.3^{+1.2}_{-1.0} \times 10^{-6}$	$\sim 5 \times 10^{-6}$
$S_{\phi K}$	0.34 ± 0.2	0.725 ± 0.037
$C_{\phi K}$	-0.04 ± 0.17	0

$B_d \to \phi K_s$ **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

SM has (theoretical) problems

- Expect new physics $\Rightarrow$ new FCNC contributions

Lepton sector probes:

- $\mu \to e\gamma$, $\mu \to eee$, $0\nu\beta\beta$, e^- EDM, ...

Quark sector probes:

- $b \to s\gamma$, $b \to s\bar{s}s$, $s \to d\nu\bar{\nu}$, n EDM, ...
- Considered example of B-meson FCNC in SUSY U(2)
  - Consistent with known data
  - Can explain current $B_d \to \phi K_s$ anomaly
  - Await $B_d \to \phi K_s$, $A_{CP}^{B_d \to X_s \gamma}$, Δm_{B_s}

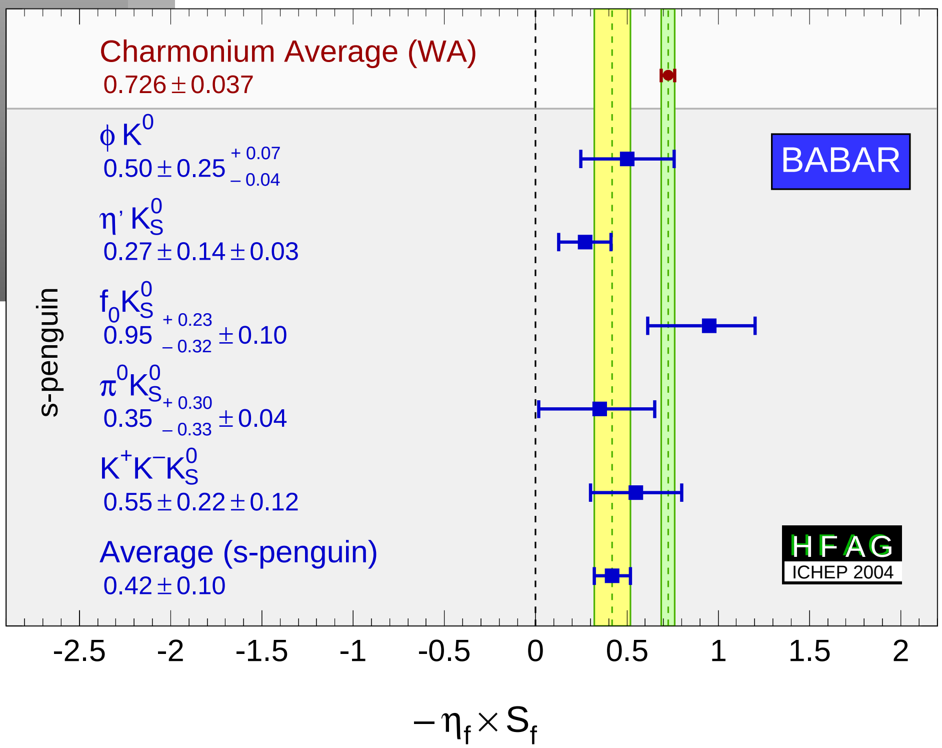
Complimentary probes:

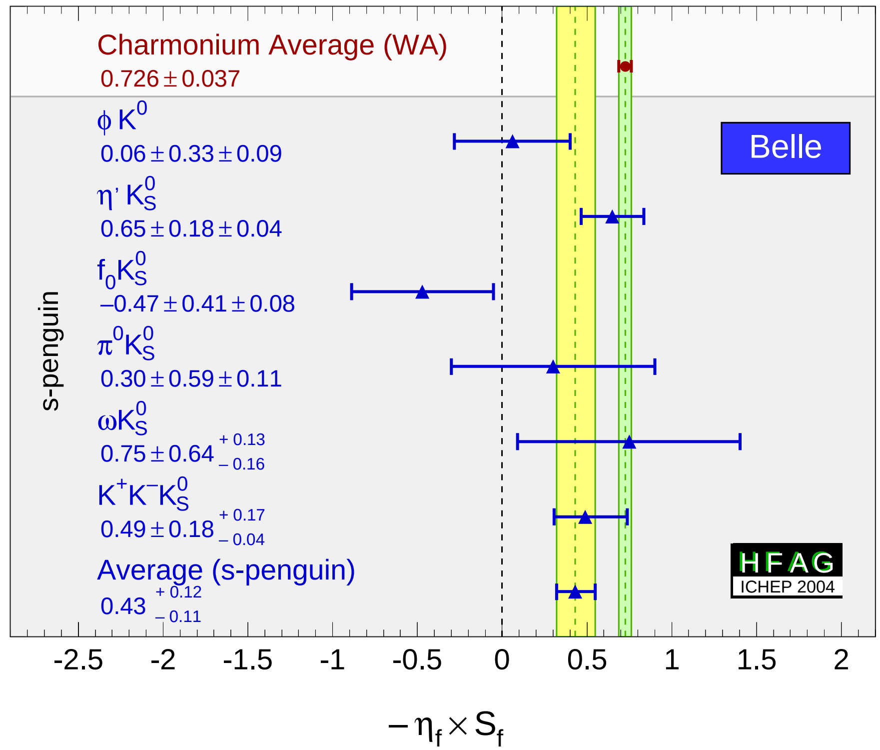
- Direct (LHC/ILC) $\leftrightarrow$ Indirect (Low-energy, B-factories etc.)

BACKUP SLIDES

BACKUP SLIDES FOLLOW

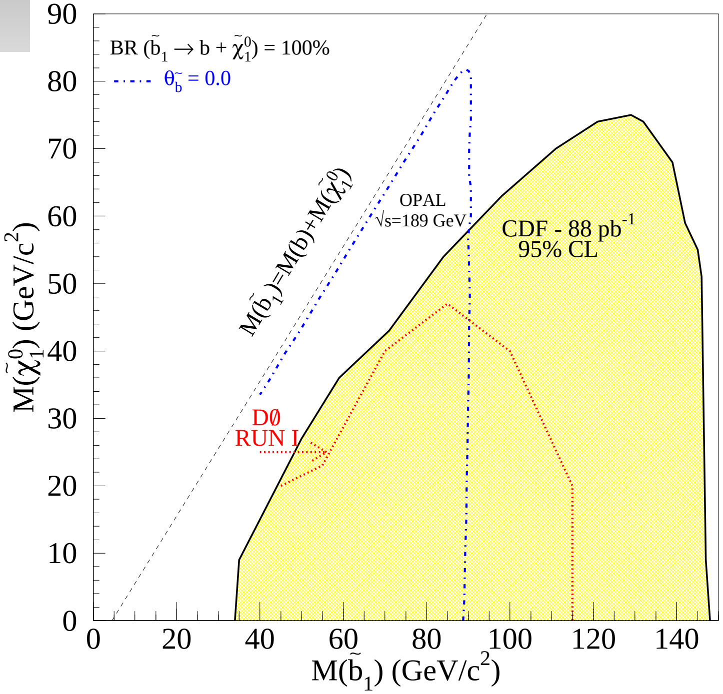
Recent $\sin 2\beta$ data

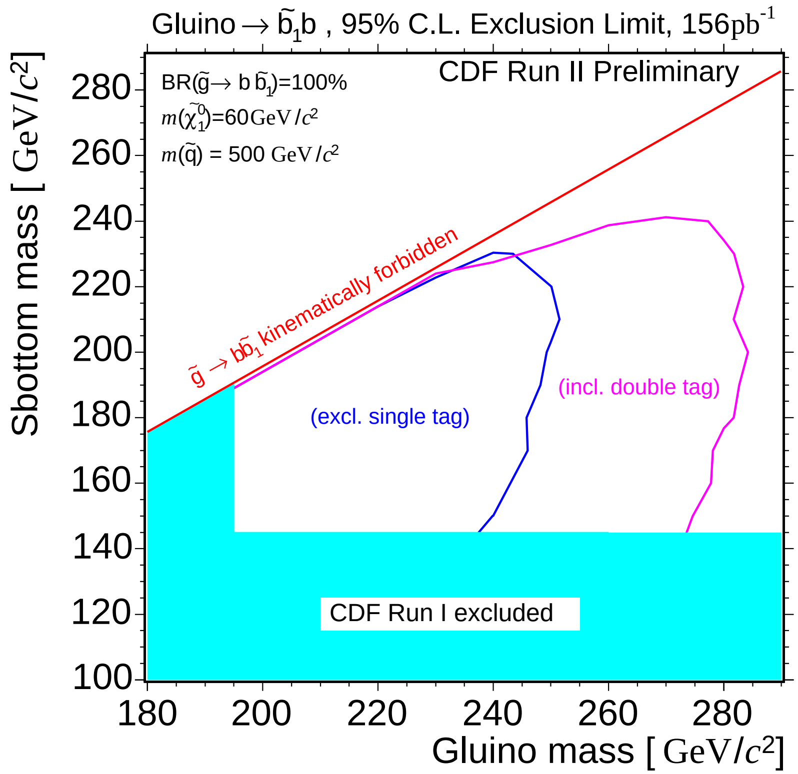




Tevatron bounds

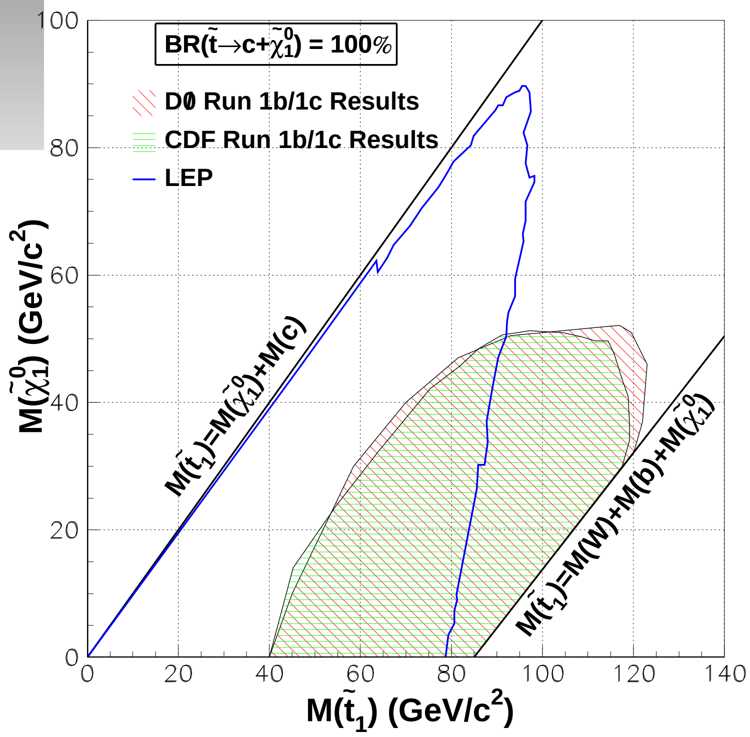
Source: [D. Bortoletto, C. Rott]
[hep-ex/9910049, 0410007]





Tevatron bounds

[hep-ex/0404028]



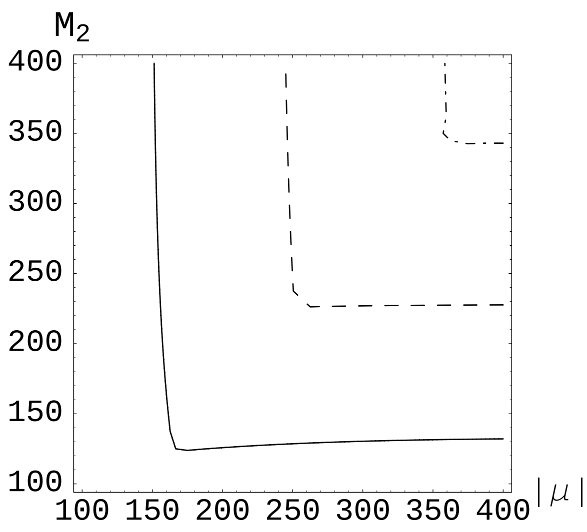
$\Delta S = 2$: Kaon mixing

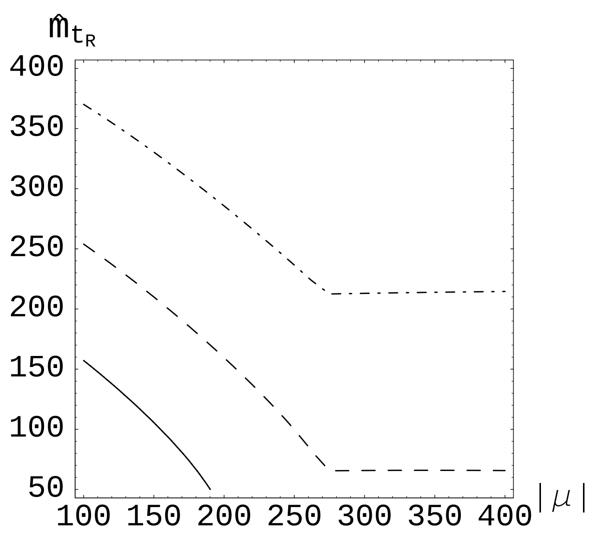
CP violation due to mixing: $|\epsilon_K| = (2.284 \pm 0.014) \times 10^{-3}$ [PDG2004]

- 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 $\frac{\epsilon_K^{MFV}}{\epsilon_K^{SM}}$:





ϵ'_K/ϵ_K has large hadronic uncertainties

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

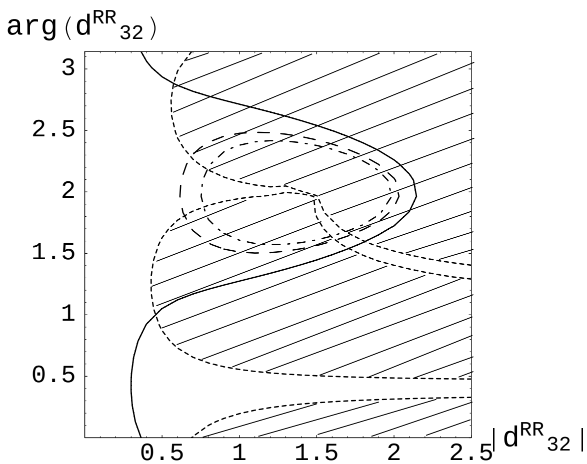
$\Delta m_d = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$
$a_{\psi K_s} = 0.725 \pm 0.037$ ($\sin 2\beta$ in SM) [PDG2004, HFAG-ICHEP04]

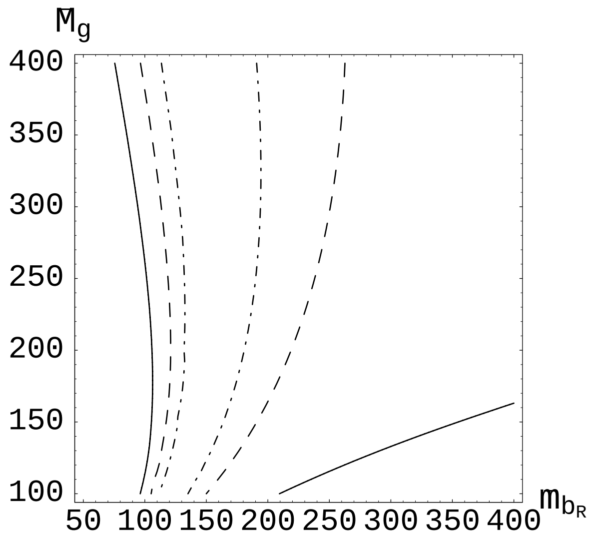
MFV constraints similar to Kaon case

For large $\tilde{d}_R \tilde{s}_R$ (squark) mixing, NMFV ($\tilde{g}$) contribution strongly constrains δ^{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*

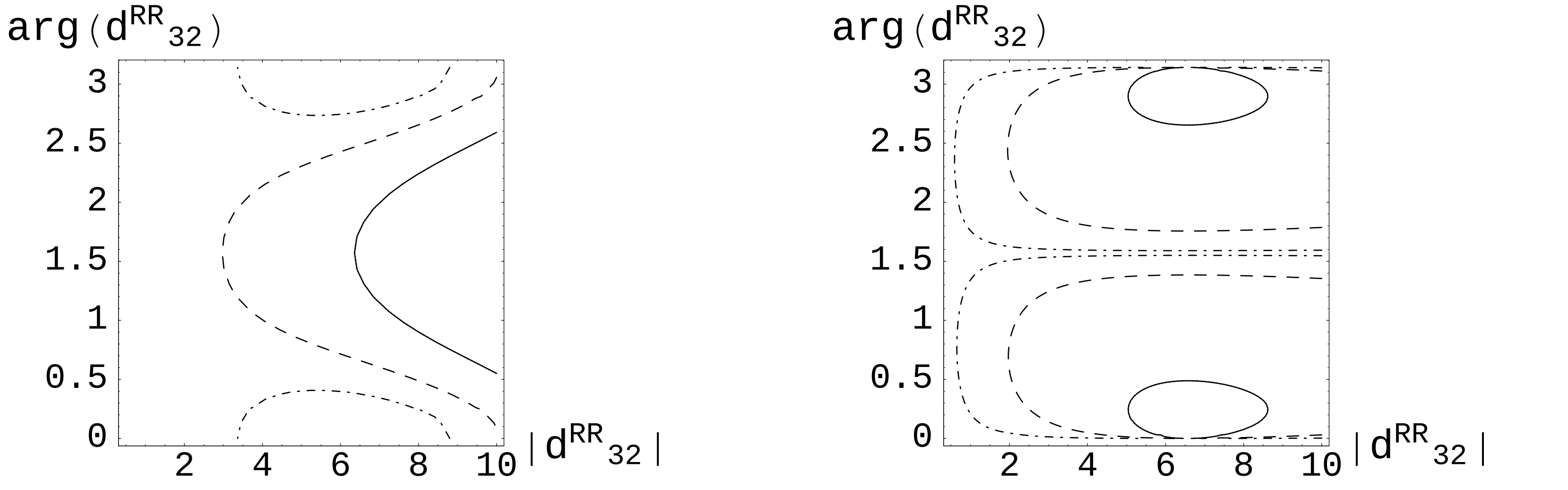
Limit: $\Delta m_{B_s} > 14.4\, ps^{-1}$ @ 95% C.L. [PDG2004]
SM prediction: $14\ \mathrm{ps}^{-1} < \Delta m_{B_s} < 20\ \mathrm{ps}^{-1}$

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) ps^{-1} contours of Δm_{B_s} (10^{-4}, 10^{-3} and 10^{-2}) contours of $|A_{ll}^{B_s}|$



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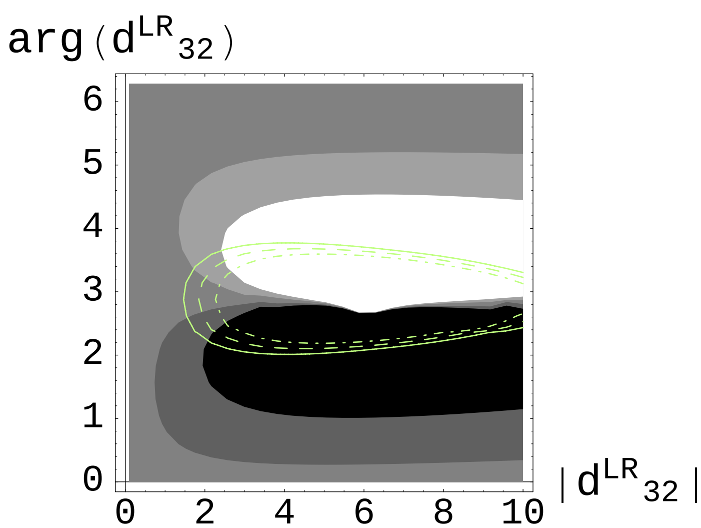
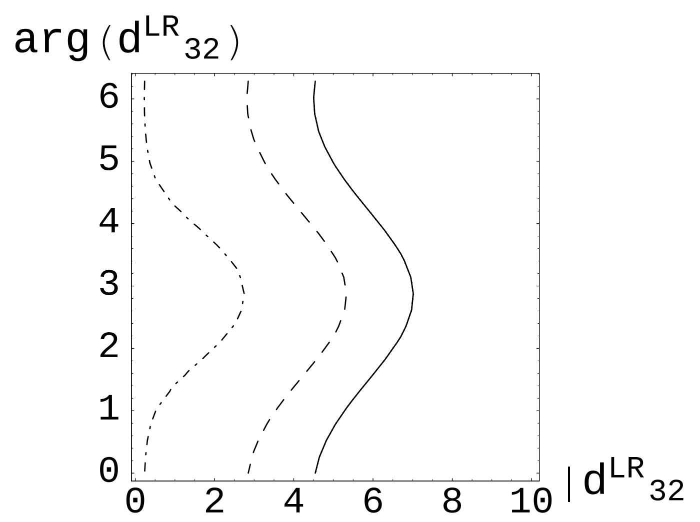
with $E_\gamma > (1-\delta)E_\gamma^{max}$

$\tilde{g}$ contribution strongly constrains δ_{32}^{RL}

(-7, -3, 3, 7) % cont of $A_{CP}^{B_d\to X_s\gamma}$ $(1,\ 7.5,\ 15$ %) 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
$B.R.(B_d \to X_s \ell^+ \ell^-)$	$4.46^{+0.98}_{-0.96} \times 10^{-6}$	5.3×10^{-6}

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

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