Rare Decays & New Physics At Super Flavour Factories

Marco Ciuchini

INFN Roma Tre

Selected topics for this WG:

* $B \to X_s \gamma$
  2HDM-II, SUSY
* $B \to X_s \ell\ell$
  model independent, SUSY
* $B \to K^{(*)} \nu\nu$
  model independent, modified Z & Z'

CKM 2010

Super Flavour Factory Physics Program

- improve precision/sensitivity of B-factories x5-10
- test the CKM paradigm and determine V_{CKM} at 1% level
- increase sensitivity to LFV in τ decays by one order of magnitude
- explore CPV with charm
- many other studies...

T. Browder at al., arXiv:0710.3799
T. Browder et al., arXiv:0802.3201
SuperB: arXiv:0709.0451, arXiv:0810.1312, arXiv:1008.1541
SuperKEKB: hep-ex/0406071, arXiv:1002.5012

feasible with ~75 ab^{-1} collected at $\Upsilon(4S)$ (+ $D\bar{D}$ & $\tau\bar{\tau}$ thresholds)

Twofold Purpose

look for any deviation from the SM signalling NP in the energy region up to ~100 TeV

determine the FV and CPV couplings of the NP Lagrangian, characterizing the NP model

SuperB physics in tables

arXiv:0709.0451
arXiv:0810.1312

B_d physics @$\Upsilon(4S)$

Observable	B factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ $(J/\psi\, K^0)$	0.018	0.005 (†)
$\cos(2\beta)$ $(J/\psi\, K^{*0})$	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi\, \pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (∗)
$S(K^0_S \pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_S)$	0.17	0.03 (∗)
$S(f_0 K^0_S)$	0.12	0.02 (∗)
γ $(B\to DK,\ D\to CP$ eigenstates$)$	$\sim 15^\circ$	2.5°
γ $(B\to DK,\ D\to$ suppressed states$)$	$\sim 12^\circ$	2.0°
γ $(B\to DK,\ D\to$ multibody states$)$	$\sim 9^\circ$	1.5°
γ $(B\to DK,$ combined$)$	$\sim 6^\circ$	1–2°
α $(B\to\pi\pi)$	$\sim 16^\circ$	3°
α $(B\to\rho\rho)$	$\sim 7^\circ$	1–2° (∗)
α $(B\to\rho\pi)$	$\sim 12^\circ$	2°
α (combined)	$\sim 6^\circ$	1–2° (∗)
$2\beta+\gamma$ $(D^{(*)\pm}\pi^\mp,\ D^\pm K^0_S\pi^\mp)$	20°	5°
$\lvert V_{cb}\rvert$ (exclusive)	4% (∗)	1.0% (∗)
$\lvert V_{cb}\rvert$ (inclusive)	1% (∗)	0.5% (∗)
$\lvert V_{ub}\rvert$ (exclusive)	8% (∗)	3.0% (∗)
$\lvert V_{ub}\rvert$ (inclusive)	8% (∗)	2.0% (∗)
$BR(B\to\tau\nu)$	20%	4% (†)
$BR(B\to\mu\nu)$	visible	5%
$BR(B\to D\tau\nu)$	10%	2%
$BR(B\to\rho\gamma)$	15%	3% (†)
$BR(B\to\omega\gamma)$	30%	5%
$A_{CP}(B\to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B\to\rho\gamma)$	~ 0.20	0.05
$A_{CP}(b\to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b\to(s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S\pi^0\gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B\to K^*\ell\ell)$	7%	1%
$A^{FB}(B\to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B\to X_s\ell\ell)s_0$	35%	5%
$BR(B\to K\nu\overline{\nu})$	visible	20%
$BR(B\to\pi\nu\bar{\nu})$	–	possible

charm physics

Mode	Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$D^0\to K^+K^-$	y_{CP}	2–3×10^{-3}	5×10^{-4}
$D^0\to K^+\pi^-$	y'_D	2–3×10^{-3}	7×10^{-4}
	x'^2_D	1–2×10^{-4}	3×10^{-5}
$D^0\to K^0_s\pi^+\pi^-$	y_D	2–3×10^{-3}	5×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}
Average	y_D	1–2×10^{-3}	3×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}

Channel	Sensitivity
$D^0\to e^+e^-,\ D^0\to\mu^+\mu^-$	1×10^{-8}
$D^0\to\pi^0e^+e^-,\ D^0\to\pi^0\mu^+\mu^-$	2×10^{-8}
$D^0\to\eta e^+e^-,\ D^0\to\eta\mu^+\mu^-$	3×10^{-8}
$D^0\to K^0_s e^+e^-,\ D^0\to K^0_s\mu^+\mu^-$	3×10^{-8}
$D^+\to\pi^+e^+e^-,\ D^+\to\pi^+\mu^+\mu^-$	1×10^{-8}
$D^0\to e^\pm\mu^\mp$	1×10^{-8}
$D^+\to\pi^+e^\pm\mu^\mp$	1×10^{-8}
$D^0\to\pi^0e^\pm\mu^\mp$	2×10^{-8}
$D^0\to\eta e^\pm\mu^\mp$	3×10^{-8}
$D^0\to K^0_s e^\pm\mu^\mp$	3×10^{-8}
$D^+\to\pi^-e^+e^+,\ D^+\to K^-e^+e^+$	1×10^{-8}
$D^+\to\pi^-\mu^+\mu^+,\ D^+\to K^-\mu^+\mu^+$	1×10^{-8}
$D^+\to\pi^-e^\pm\mu^\mp,\ D^+\to K^-e^\pm\mu^\mp$	1×10^{-8}

Mode	Observable	$\Upsilon(4S)$ (75 ab^{-1})	$\psi(3770)$ (300 fb^{-1})	LHCb (10 fb^{-1})
$D^0\to K^+\pi^-$	x'^2	3×10^{-5}		6×10^{-5}
	y'	7×10^{-4}		9×10^{-4}
$D^0\to K^+K^-$	y_{CP}	5×10^{-4}		5×10^{-4}
$D^0\to K^0_S\pi^+\pi^-$	x	4.9×10^{-4}		
	y	3.5×10^{-4}		
	$\lvert q/p\rvert$	3×10^{-2}		
	ϕ	2°		
$\psi(3770)\to D^0\overline{D}^0$	x^2		$(1-2)\times10^{-5}$	
	y		$(1-2)\times10^{-3}$	
	$\cos\delta$		$(0.01-0.02)$	

τ physics

Process	Sensitivity
$\mathcal{B}(\tau\to\mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau\to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau\to\mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau\to eee)$	2×10^{-10}
$\mathcal{B}(\tau\to\mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau\to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau\to\ell K^0_s)$	2×10^{-10}

+ τ FC physics (CPV, …)

+B_s physics @$\Upsilon(5S)$

SuperB a "treasure chest" of new physics-sensitive observables

Expected sensitivies for rare decays

	SuperB(75/ab)	SKEKB(50/ab)	SM Th.Err.
$BR(B \to X_s \gamma)$	3%	6%	7%
$A_{CP}(B \to X_s \gamma)$	0.004	0.005	0.002
$BR(B \to X_s \ell\ell)$(low)	8%		7%
$A_{FB}(B \to X_s \ell\ell)$(low)	4%	4%*	10%
$s_0(B \to X_s \ell\ell)$	5-9%	5%*	5%
$BR(B^+ \to K^+ \nu\nu)$	15%	30%	15%
$BR(B^0 \to K^* \nu\nu)$	16%	35%	15%

*estimate for exclusive modes

based on arXiv:1002.5012 & arXiv:1008.1541

inclusive modes only

$B \to X_s\, \gamma$

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu) O_i(\mu) + \text{H.c.}$$

$$O_{1,2} = (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b) \qquad O_{3,4,5,6} = (\bar{s}\Gamma_i b)\textstyle\sum_q (\bar{q}\Gamma_i' q)$$

$$O_7 = \frac{e m_b}{16\pi^2}\, \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu} \qquad O_8 = \frac{g m_b}{16\pi^2}\, \bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu}$$

SM prediction: $E_\gamma > 1.6$ GeV

M. Misiak et al., hep-ph/0609232

$$\mathcal{B}(\bar{B} \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

World average:

$$B(\bar{B} \to X_s \gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$$

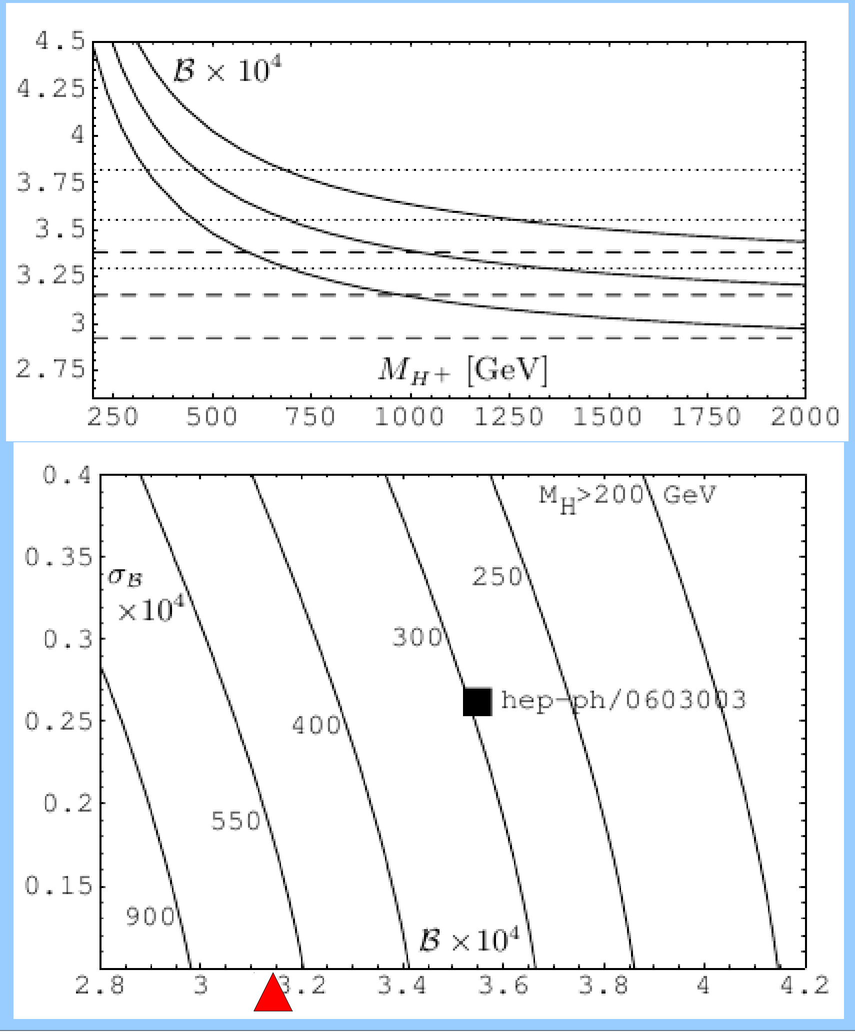
Already gives the best lower limit on the charged Higgs mass:

$M_{H^+} > 295$ GeV@95%CL

Assuming the SM central value and δBR~3%, this roughly extrapolates to

$M_{H^+} >$ ~700 GeV@95%CL

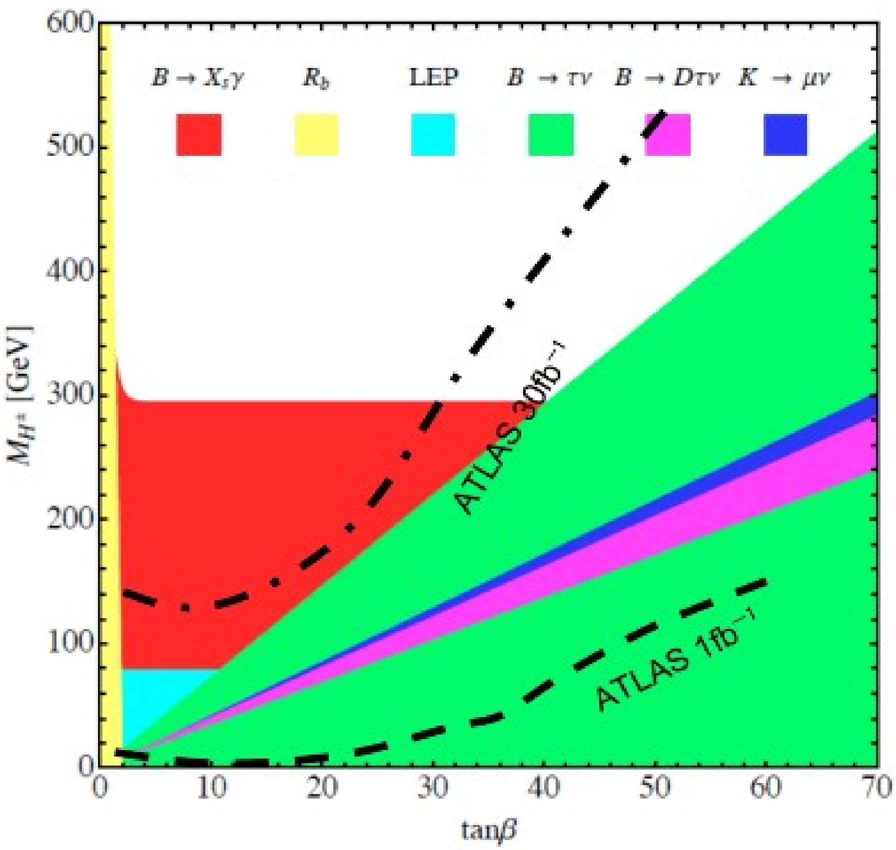
2HDM-II

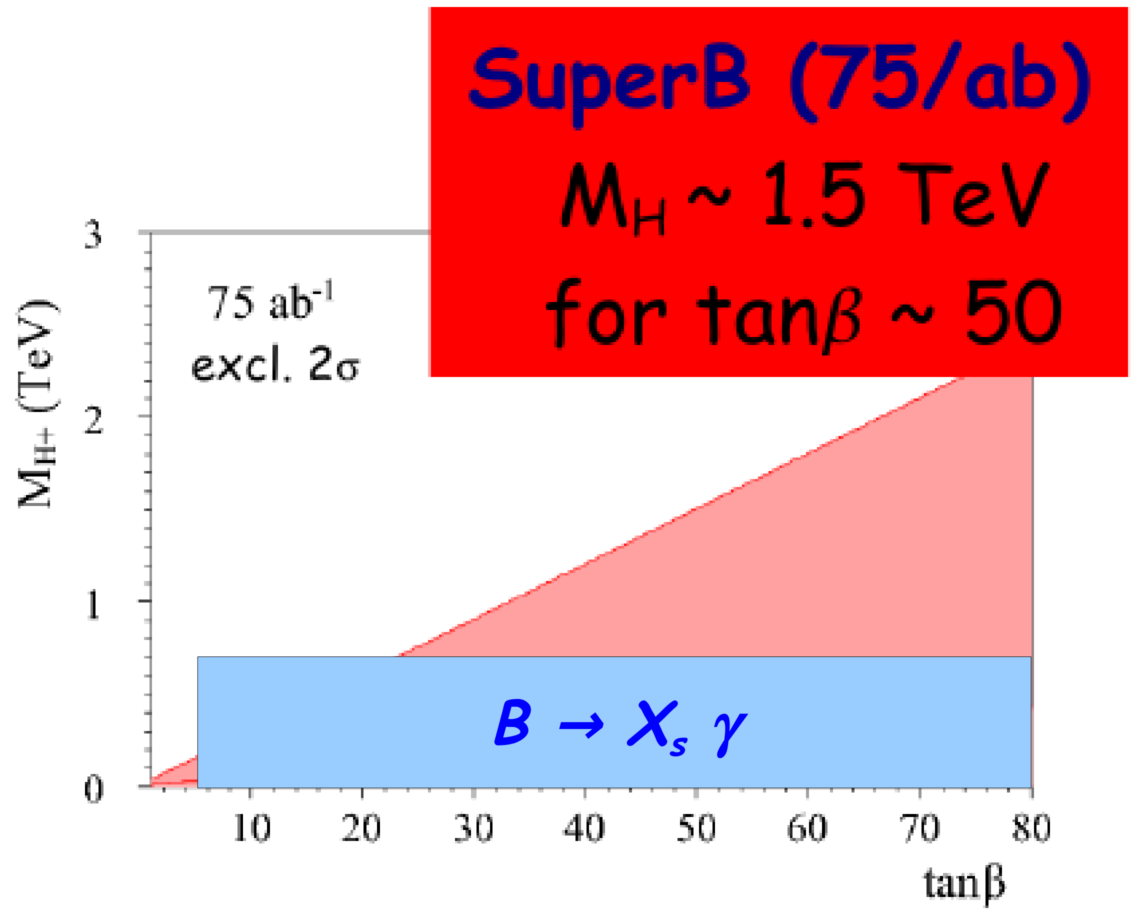


2Higgs-Doublet-Model Type II

- * $B \to \tau \nu$ & $B \to D \tau \nu$ on the $\tan\beta - M_{H^+}$ plane
- * direct searches are not competitive
- * strong bounds also from $B_s \to \mu\mu$

U. Haisch, arXiv:0805.2141





CP violation in B → $X_s \gamma$

$$A_{\rm CP}^{b\to q\gamma} \equiv \frac{\Gamma[\bar{B}\to X_q\gamma]-\Gamma[B\to X_{\bar{q}}\gamma]}{\Gamma[\bar{B}\to X_q\gamma]+\Gamma[B\to X_{\bar{q}}\gamma]}$$

SM prediction: Hurth, Lunghi, Porod, hep-ph/0312260

$$A_{\rm CP}^{b\to s\gamma} = \left[0.44\ {}^{+0.15}_{-0.10}\Big|_{\frac{m_c}{m_b}} \pm 0.03_{\rm CKM}\ {}^{+0.19}_{-0.09}\Big|_{\rm scale}\right]\%$$

$$A_{\rm CP}^{b\to d\gamma} = \left[-10.2\ {}^{+2.4}_{-3.7}\Big|_{\frac{m_c}{m_b}} \pm 1.0_{\rm CKM}\ {}^{+2.1}_{-4.4}\Big|_{\rm scale}\right]\%$$

HFAG average: $A_{\rm CP}^{b\to s\gamma} = -0.012 \pm 0.028$

Within the SM, in the SU(3) limit: $A_{\rm CP}^{b\to(s+d)\gamma} = \frac{\Delta\Gamma_s + \Delta\Gamma_d}{\Sigma\Gamma_s + \Sigma\Gamma_d} = 0$

Estimates of the SU(3) breaking gives

$$|\Delta\mathcal{B}(B\to X_s\gamma) + \Delta\mathcal{B}(B\to X_d\gamma)| \sim 1\cdot 10^{-9}$$

Hurth, Mannel, hep-ph/0103331

To an excellent approximation, $A_{CP}^{b\to(s+d)\gamma}$ is a null test of the SM!

(BaBar: $A_{CP}^{b\to(s+d)\gamma} = -0.22 \pm 0.26$)

$B \to X_s \ell\ell$

$$H_{eff} = H_{eff}^{b\to s\gamma} - \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left(C_9(\mu) O_9(\mu) + C_{10}(\mu) O_{10}(\mu) \right) + \text{H.c.}$$

$$O_9 = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu \ell$$

$$O_{10} = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu \gamma_5 \ell$$

$$\frac{d^2\Gamma}{dq^2\, dz} = \frac{3}{8} \left[(1+z^2) H_T(q^2) + 2z H_A(q^2) + 2(1-z^2) H_L(q^2) \right]$$

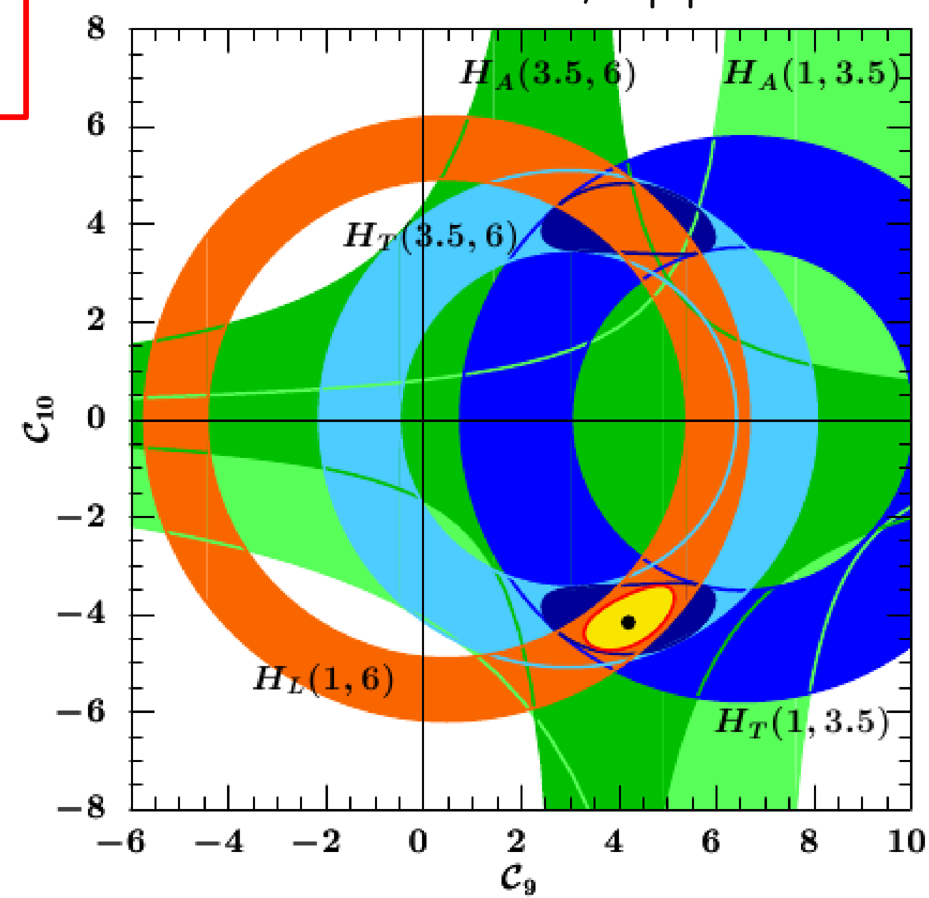
$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2) \qquad \frac{dA_{FB}}{dq^2} = \frac{3}{4} H_A(q^2)$$

$$H_T(q^2) \propto 2(1-s)^2 s \left[\left(\mathcal{C}_9 + \frac{2}{s} \mathcal{C}_7 \right)^2 + \mathcal{C}_{10}^2 \right],$$

$$H_A(q^2) \propto -4(1-s)^2 s\, \mathcal{C}_{10} \left(\mathcal{C}_9 + \frac{2}{s} \mathcal{C}_7 \right),$$

$$H_L(q^2) \propto (1-s)^2 \left[(\mathcal{C}_9 + 2\mathcal{C}_7)^2 + \mathcal{C}_{10}^2 \right].$$

K.S. Lee et al., hep-ph/0612156

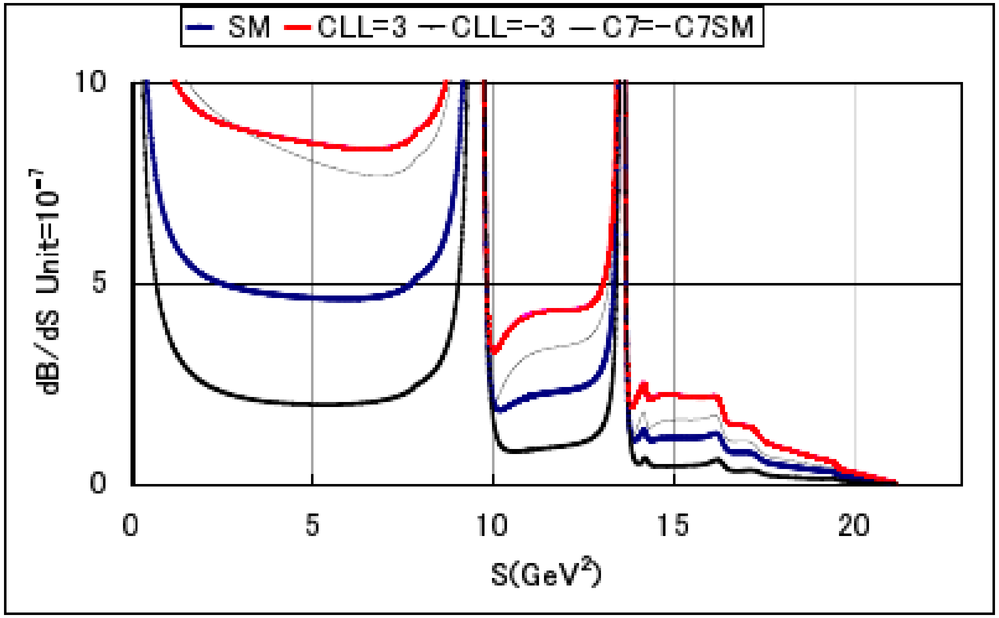


Experimental access to all the relevant short-distance functions

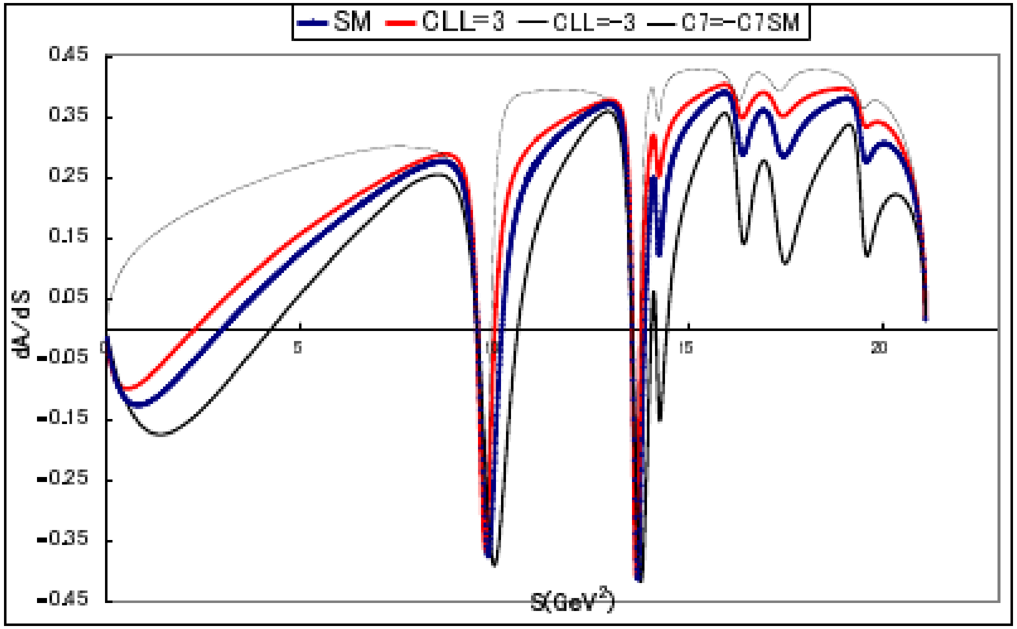
Model-independent analysis of $B \to X_s \ell\ell$

S. Fukae et al., hep-ph/9807254
A. Ali et al., hep-ph/0112300

$$\begin{aligned}\mathcal{M}(b \to s l^+ l^-) \;=\; & \frac{G_F \alpha}{\sqrt{2}\pi} V_{ts}^* V_{tb} \Big\{ (C_{LL} + C_9^{\rm eff} - C_{10})(\bar{s}_L \gamma_\mu b_L)(\bar{l}_L \gamma^\mu l_L) \\ & + (C_{LR} + C_9^{\rm eff} + C_{10})(\bar{s}_L \gamma_\mu b_L)(\bar{l}_R \gamma^\mu l_R) \\ & + C_{RL}(\bar{s}_R \gamma_\mu b_R)(\bar{l}_L \gamma^\mu l_L) + C_{RR}(\bar{s}_R \gamma_\mu b_R)(\bar{l}_R \gamma^\mu l_R) \\ & + C_{LRLR}(\bar{s}_L b_R)(\bar{l}_L l_R) + C_{RLLR}(\bar{s}_R b_L)(\bar{l}_L l_R) \\ & + C_{LRRL}(\bar{s}_L b_R)(\bar{l}_R l_L) + C_{RLRL}(\bar{s}_R b_L)(\bar{l}_R l_L) \\ & + C_T(\bar{s}\sigma_{\mu\nu} b)(\bar{l}\sigma^{\mu\nu} l) + i C_{TE}(\bar{s}\sigma_{\mu\nu} b)(\bar{l}\sigma_{\alpha\beta} l)\epsilon^{\mu\nu\alpha\beta} \\ & - i2m_b \left[C_{7L}^{\rm eff}(\bar{s}\sigma_{\mu\nu} b_R) + C_{7R}^{\rm eff}(\bar{s}\sigma_{\mu\nu} b_L) \right] (\bar{l}\gamma^\mu l) \frac{q^\nu}{q^2} \Big\}\end{aligned}$$



Akeroyd et al., arXiv:1002.5012



NP effects measurable at SFF can be present in $B \to X_s \ell\ell$ observables

B physics on LHC benchmarks: SNOWMASS points

arXiv:0810.1312

Typical points in the mSUGRA parameter space

SPS	$M_{1/2}$ (GeV)	M_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ
1 a	250	100	-100	10	> 0
1 b	400	200	0	30	> 0
2	300	1450	0	10	> 0
3	400	90	0	10	> 0
4	300	400	0	50	> 0
5	300	150	-1000	5	> 0

	SPS1a	SPS4	SPS5
$\mathcal{R}(B \to s\gamma)$	0.919 ± 0.038	0.248	0.848 ± 0.081
$\mathcal{R}(B \to \tau\nu)$	0.968 ± 0.007	0.436	0.997 ± 0.003
$\mathcal{R}(B \to X_s l^+ l^-)$	0.916 ± 0.004	0.917	0.995 ± 0.002
$\mathcal{R}(B \to K\nu\bar{\nu})$	0.967 ± 0.001	0.972	0.994 ± 0.001
$\mathcal{B}(B_d \to \mu^+\mu^-)/10^{-10}$	1.631 ± 0.038	16.9	1.979 ± 0.012
$\mathcal{R}(\Delta m_s)$	1.050 ± 0.001	1.029	1.029 ± 0.001
$\mathcal{B}(B_s \to \mu^+\mu^-)/10^{-9}$	2.824 ± 0.063	29.3	3.427 ± 0.018
$\mathcal{R}(K \to \pi^0\nu\bar{\nu})$	0.973 ± 0.001	0.977	0.994 ± 0.001

SPS4 is likely incompatible with the measurement of BR($b \to s\gamma$)

SPS1a is the nightmare point for flavour physics, yet SuperB may still observe 2σ deviations in few observables

MSSM with generic soft breaking terms

All flavour violation in squark (and slepton) mass matrices

LHCb, SuperB

$$M^2_{\tilde d} \approx \begin{pmatrix} m^2_{\tilde d_L} & m_d(A_d - \mu \tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde d_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde s_L} & m_s(A_s - \mu \tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde s_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde b_L} & m_b(A_b - \mu \tan\beta) \\ & & & & & m^2_{\tilde b_R} \end{pmatrix}$$

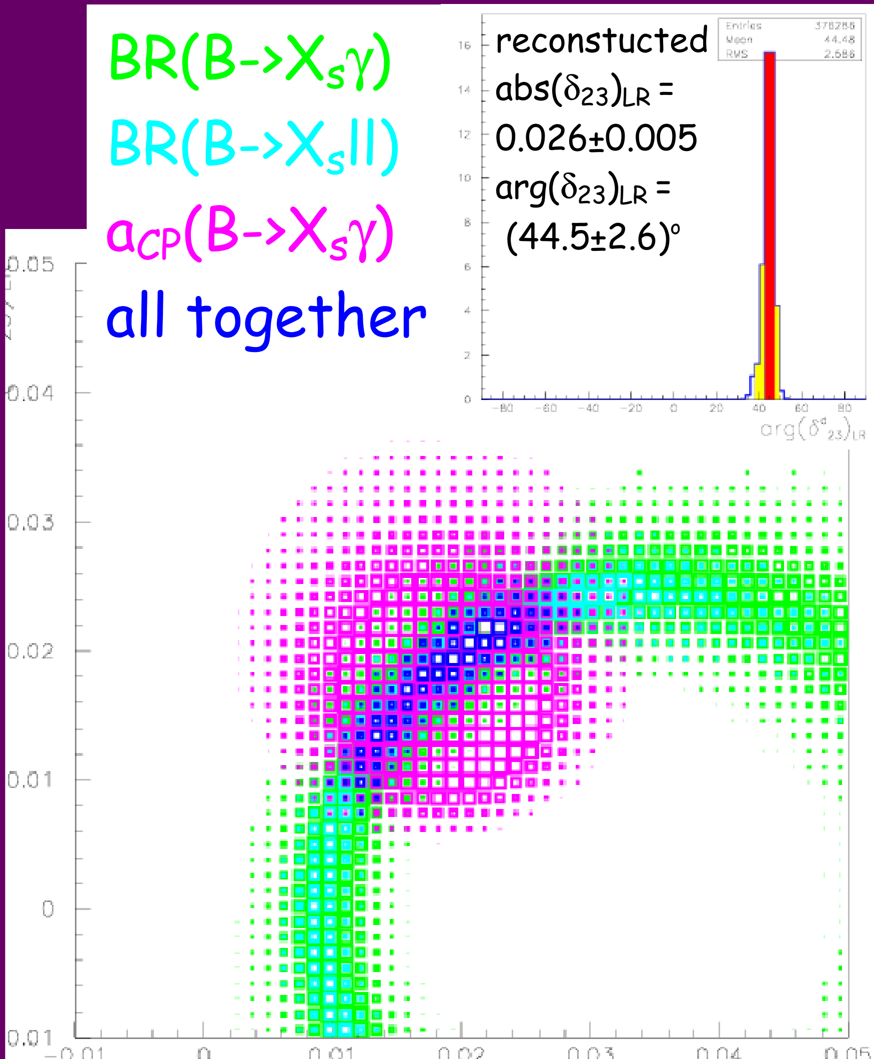
LHC, ILC – HE frontier

and similarly for $M^2_{\tilde u}$

NP scale: $m_{\tilde q}$

FV & CPV couplings: $(\delta^{d/u}_{ij})_{AB} = (\Delta^{d/u}_{ij})_{AB}/m_{\tilde q}^2$

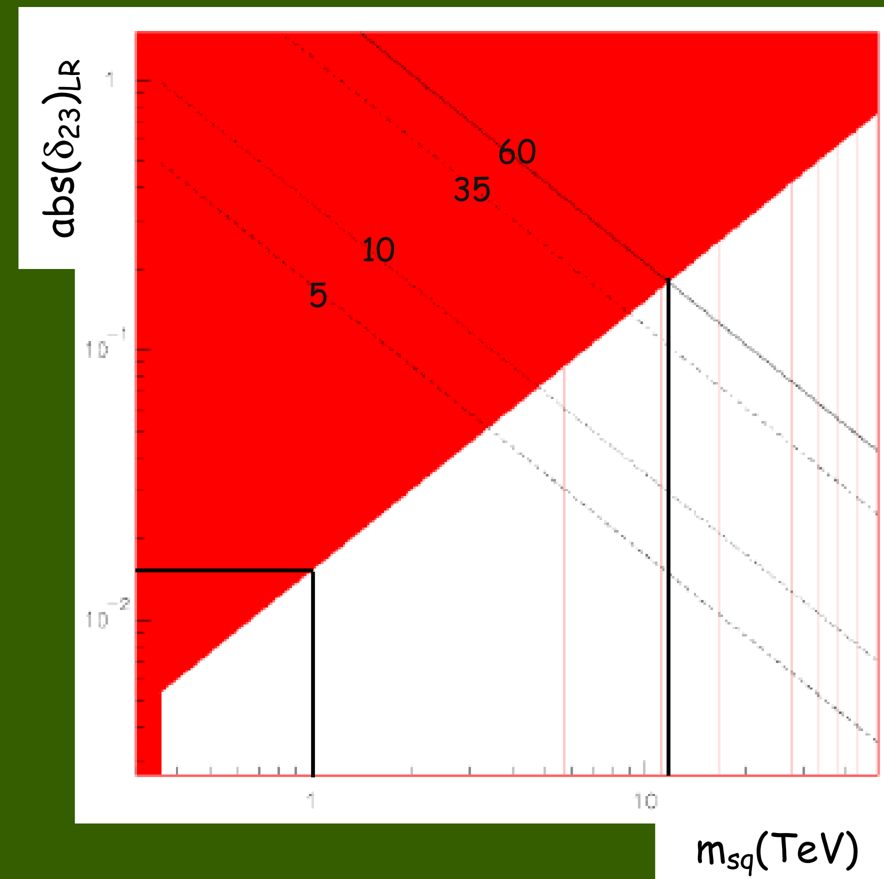
Determination of $(\delta^d_{23})_{LR}$ using SuperB data



$Im(\delta^d_{23})_{LR}$ vs $Re(\delta^d_{23})_{LR}$

reconstruction of $(\delta^d_{23})_{LR}=0.028\ e^{i\pi/4}$ for $\Lambda = m_{\tilde{g}} = m_{\tilde{q}} =$ 1 TeV

"3σ" sensitivity plot



i) sensitive to $m_{\tilde{q}}$ < 20 TeV

ii) sensitive to $|(\delta^d_{23})_{LR}| > 10^{-2}$ for $m_{\tilde{q}}$ < 1 TeV

An explict example: hierarchical soft terms

Nardecchia, Giudice, Romanino, arXiv:0812.3610
Cohen, Kaplan, Nelson, hep-ph/9607394
Dine, Kagan, Samuel, PLB243 (1990)

Sparticles at the EW scale

but for 1st and 2nd generation squarks and sleptons

- no "unnatural" correction to the Higgs mass
- alleviate the flavour problem
- indicate "natural" values for the δ's:

$$\hat{\delta}^{LL}_{db} \approx V^*_{td} \sim \mathbf{0.01} \qquad \hat{\delta}^{LL}_{sb} \approx V^*_{ts} \sim \mathbf{0.05}$$

$$\hat{\delta}^{LR}_{i3} \equiv \frac{\mathcal{M}^2_{L3,R3}}{\tilde{m}^2}\hat{\delta}^{LL}_{i3} \qquad i,j=1,2$$

$$\hat{\delta}^{LL}_{ij} \equiv \hat{\delta}^{LL}_{i3}\hat{\delta}^{LL*}_{j3} \qquad \hat{\delta}^{LR}_{ij} \equiv \frac{\mathcal{M}^2_{L3,R3}}{\tilde{m}^2}\hat{\delta}^{LL}_{i3}\hat{\delta}^{RR*}_{j3}$$

these figures are in the ballpark of SuperB sensitivities

FC right-handed quark currents

New FC right-handed d-quark currents may:

- change the effective γ/g vertex, particularly the magnetic dipole term

  constraints: $b \to s\gamma$, $b \to s\ell\ell$
- change the effective Z vertex (+box)
- introduce a new effective Z' vertex

  constraints: $b \to s\ell\ell$, $b \to s\nu\nu$

Disentangling the different contributions helps identifying the NP model

An extreme example: leptofobic Z'

$B \to K^{(*)} \nu\nu$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu\right) \; + \; \text{h}$$

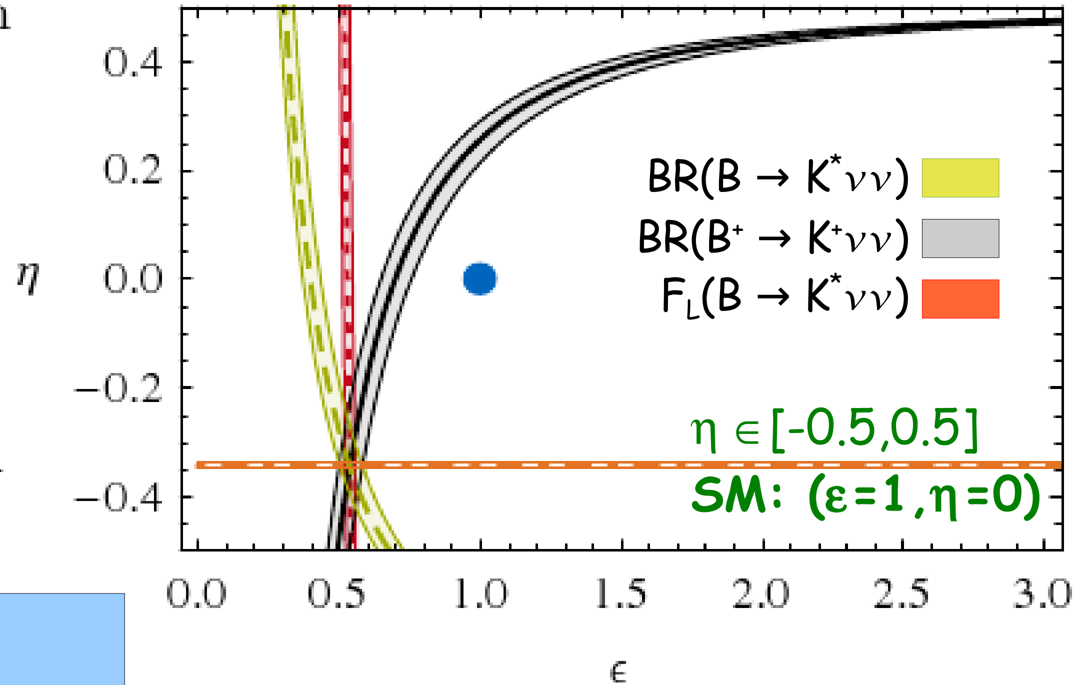
$$\mathcal{O}_L^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

$$\mathcal{O}_R^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

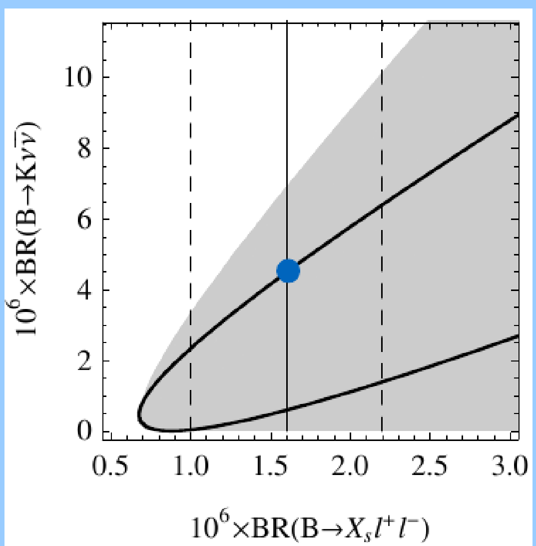
Model-independent parameters:

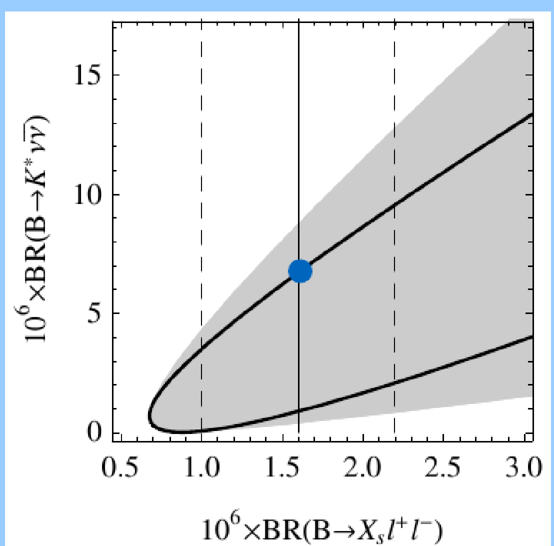
$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\rm SM}|} \qquad \eta = \frac{-{\rm Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

Altmannshofer et al, arXiv:0902.0160



modified Z couplings





$${\rm BR}(B \to K^*\nu\bar{\nu}) = 6.8 \times 10^{-6}\,(1 + 1.31\,\eta)\epsilon^2$$

$${\rm BR}(B \to K\nu\bar{\nu}) = 4.5 \times 10^{-6}\,(1 - 2\,\eta)\epsilon^2$$

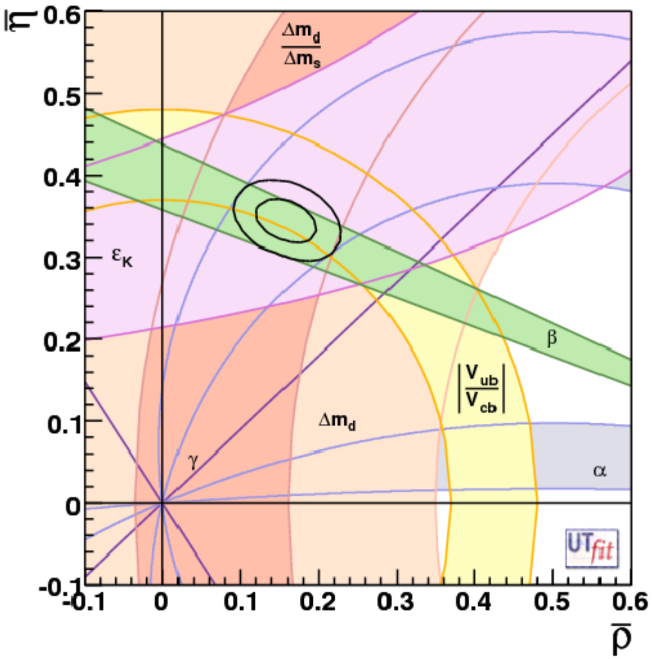
$$\langle F_L \rangle = 0.54\,\frac{(1+2\,\eta)}{(1+1.31\,\eta)}$$

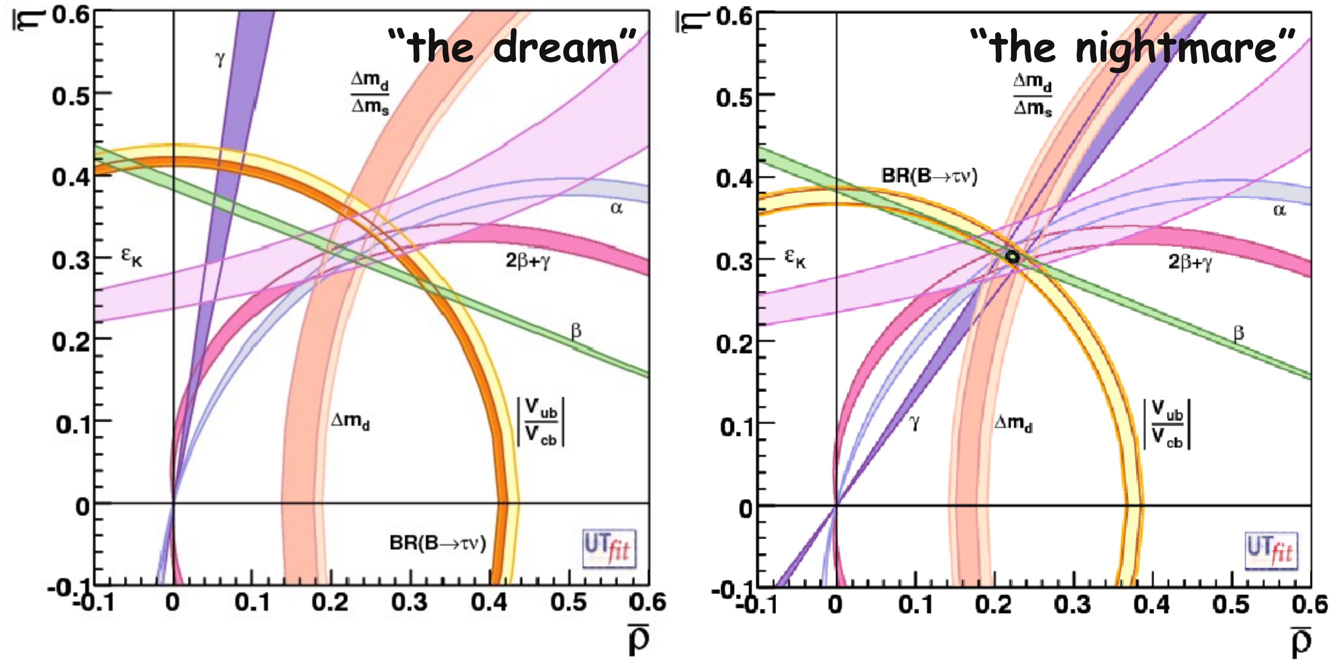
SM th. error
BR ~15%, $\langle F_L \rangle$~2%

Details on future sensitivities in Alejandro Perez's talk

SFF and rare K decays

Today	With a SuperB in 2015





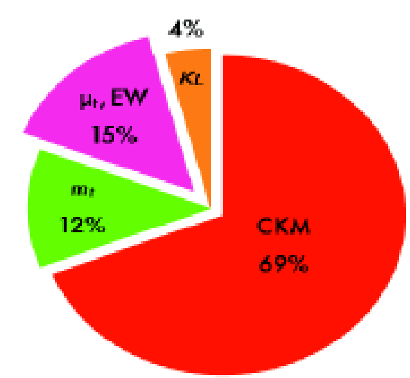
Generalized UT fits:
CKM at 1% in the presence of NP!

	today	SuperB
$\bar{\rho}$	0.187±0.056	±0.005
$\bar{\eta}$	0.370±0.036	±0.005

- crucial for many NP searches with flavour (not only in the B sector!)

error budget

$K_L \to \pi^0 \nu \bar{\nu}$



U. Haisch, Kaon '07

Conclusions

Rare decays are one of the handles to study New Physics at SFF. The expected sensitivities allow for exploring interesting regions in the NP parameter space, disentangling various NP scenarios

Besides the examples presented in this talk, rare decays provide additional observables, both in inclusive and exclusive modes, making the study of NP in electroweak penguins at SFF an extremely interesting task