SuFla: A New SUSY Flavour Code

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Interplay of Collider and Flavour Physics, 3rd general meeting
CERN, Geneva
December 15, 2009

History of SuFla

G. Isidori – *NP benchmarks in flavour physics*

Flavour in the era of the LHC

Low-energy (LE) and Electroweak (EW) Constraints

Work started at the LHC Flavour workshop (collaboration from Experimentalist & Theorist)

S.Heinemeyer, G.I., P.Paradisi [TH],
O. Buchmuller, R. Cavanaugh,... [EXP]
work documented in the Yellow Report

A first start: Combine LE and EW calculations in one common code.
New Physics Parameter Space: MSSM

"Master Layer"
steers communication between the individual calculations / codes

"FeynHiggs"
http://www.feynhiggs.de/
calculation of the masses and mixing angles of the Higgs sector of the (real or complex) MSSM
&
EW observables in MSSM

"Flavour Observables"
Phys.Lett.B639:499-507,2006

Isidori & Paradisi
Calculation of B physics observables in MSSm (&MFV)

"other observables"
e.g. cosmology constraints

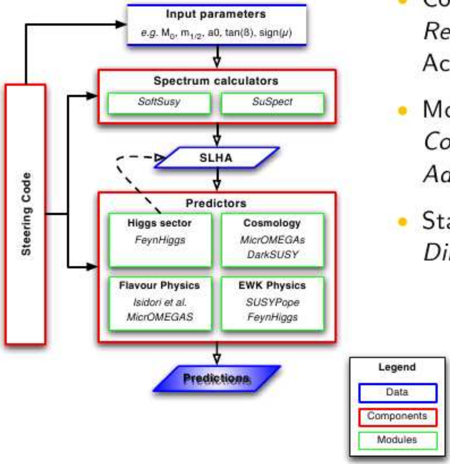
NOT yet included but on to-do-list

SuFla

- **Main purpose of the code**: evaluation of **"selected"** (clean & sensitive) flavour-changing **observables** in the MSSM, both within and beyond MFV.
- **Languange**: Fortran (**F77**)
- The program is **NOT** standalone, but is conceived to be linked to other programs (spectrum calculators, etc...) as in the famous **"Mastercode"**.
- The **SUSY inputs** are generic soft mass terms at the TeV scale, with squark mass matrices in the super CKM basis according to **SLHA**
- For the **SM inputs** see later... & **Altmannshofer et al. '09**
- **SUSY amplitudes taken into account**: Higgs, gluino & chargino loops, including the leading BLO effect stemming from susy-QCD corrections & large tan β enhanced effects
- **Main startegy**: compute $\Gamma_{SUSY+SM}/\Gamma_{SM}$ (whenever possible). This minimise non-perturbative uncertainites and dependence on SM inputs.

Mastercode

Common framework for indirect constraints



- Consistency
  Relies on the SUSY Les Houches Accord *(SLHA)*
- Modularity
  Compare calculations
  Add/remove predictions
- State-of-the art calculations
  Direct use of code from experts

Observables

observable	experiment	SM prediction	exp./SM
ΔM_K	$(5.292 \pm 0.009) \times 10^{-3}$ ps^{-1} [81]		
$\lvert\epsilon_K\rvert$	$(2.229 \pm 0.010) \times 10^{-3}$ [81]	$(1.91 \pm 0.30) \times 10^{-3}$	1.17 ± 0.18
ΔM_d	(0.507 ± 0.005) ps^{-1} [1]	(0.51 ± 0.13) ps^{-1}	0.99 ± 0.25
$S_{\psi K_S}$	0.672 ± 0.023 [1]	0.734 ± 0.038	0.92 ± 0.06
ΔM_s	(17.77 ± 0.12) ps^{-1} [82]	(18.3 ± 5.1) ps^{-1}	0.97 ± 0.27
$\Delta M_d/\Delta M_s$	$(2.85 \pm 0.03) \times 10^{-2}$	$(2.85 \pm 0.38) \times 10^{-2}$	1.00 ± 0.13

Table 1: Experimental values and SM predictions for $\Delta F = 2$ observables. The SM predictions are obtained using CKM parameters from the NP UTfit [83]. The last column shows the ratio of the measured value and the SM prediction, signaling the room left for NP effects in the corresponding observable. We do not give a SM prediction for ΔM_K because of unknown long distance contributions.

Altmannshofer et al. '09

Observables

observable	SM prediction	exp. current	exp. future
$S_{\psi\phi}$	$\simeq 0.036$ [81]	$0.81^{+0.12}_{-0.32}$ [1]	$\simeq 0.02$ [191]
$S_{\phi K_S}$	$\sin 2\beta + 0.02 \pm 0.01$ [2]	0.44 ± 0.17 [1]	$(2-3)\%$ [192]
$S_{\eta' K_S}$	$\sin 2\beta + 0.01 \pm 0.01$ [2]	0.59 ± 0.07 [1]	$(1-2)\%$ [192]
$A_{\rm CP}(b \to s\gamma)$	$\left(-0.44^{+0.14}_{-0.24}\right)\%$ [193]	$(-0.4 \pm 3.6)\%$ [1]	$(0.4-0.5)\%$ [192]
$\langle A_7 \rangle$	$(3.4^{+0.4}_{-0.5})10^{-3}$ [138]		
$\langle A_8 \rangle$	$(-2.6^{+0.4}_{-0.3})10^{-3}$ [138]		
$\langle A_9 \rangle$	$(0.1^{+0.1}_{-0.1})10^{-3}$ [138]		
$\lvert d_e \rvert$ $(e\,{\rm cm})$	$\simeq 10^{-38}$ [194]	$< 1.6 \times 10^{-27}$ [195]	$\simeq 10^{-31}$ [194]
$\lvert d_n \rvert$ $(e\,{\rm cm})$	$\simeq 10^{-32}$ [194]	$< 2.9 \times 10^{-26}$ [196]	$\simeq 10^{-28}$ [194]
${\rm BR}(B_s \to \mu^+\mu^-)$	$(3.60 \pm 0.37)10^{-9}$	$< 5.8 \times 10^{-8}$ [144]	$\simeq 10^{-9}$ [197]
${\rm BR}(B_d \to \mu^+\mu^-)$	$(1.08 \pm 0.11)10^{-10}$	$< 1.8 \times 10^{-8}$ [144]	
${\rm BR}(B \to X_s\gamma)$	$(3.15 \pm 0.23)10^{-4}$ [198]	$(3.52 \pm 0.25)10^{-4}$ [1]	
${\rm BR}(B \to X_s\ell^+\ell^-)$	$(1.59 \pm 0.11)10^{-6}$ [199]	$(1.59 \pm 0.49)10^{-6}$ [200, 201]	
${\rm BR}(B \to \tau\nu)$	$(1.10 \pm 0.29)10^{-4}$	$(1.73 \pm 0.35)10^{-4}$ [112]	

Table 6: SM predictions and current/expected experimental sensitivities for the observables most relevant for our analysis. The branching ratio of $B \to X_s\ell^+\ell^-$ refers to the low dilepton invariant mass region, $q^2_{\ell^+\ell^-} \in [1,6]\,{\rm GeV}^2$. For the SM prediction of ${\rm BR}(B \to \tau\nu)$, see also (3.54): ${\rm BR}(B \to \tau\nu) = (0.80 \pm 0.12) \times 10^{-4}$.

SM input parameters

parameter	value	parameter	value
$\hat{B}_K$	$0.724 \pm 0.008 \pm 0.028$ [89]	$m_t(m_t)$	(163.5 ± 1.7) GeV [98, 99]
F_{Bs}	(245 ± 25) MeV [100]	$m_c(m_c)$	(1.279 ± 0.013) GeV [101]
F_B	(200 ± 20) MeV [100]	η_{cc}	1.44 ± 0.35 [85, 102]
F_K	(156.1 ± 0.8) MeV [103]	η_{tt}	0.57 ± 0.01 [84]
$\hat{B}_{B_d}$	1.22 ± 0.12 [100]	η_{ct}	0.47 ± 0.05 [86, 87, 102]
$\hat{B}_{B_s}$	1.22 ± 0.12 [100]	η_B	0.55 ± 0.01 [84, 104]
$F_{Bs}\sqrt{\hat{B}_{Bs}}$	(270 ± 30) MeV [100]	λ	0.2258 ± 0.0014 [8]
$F_B\sqrt{\hat{B}_{Bd}}$	(225 ± 25) MeV [100]	A	0.808 ± 0.014 [8]
ξ	1.21 ± 0.04 [100]	$\bar{\varrho}$	0.177 ± 0.044 [8]
V_{cb}	$(41.2 \pm 1.1) \times 10^{-3}$ [81]	$\bar{\eta}$	0.360 ± 0.031 [8]

Table 3: Input parameters used in the numerical analysis.

SuperIso

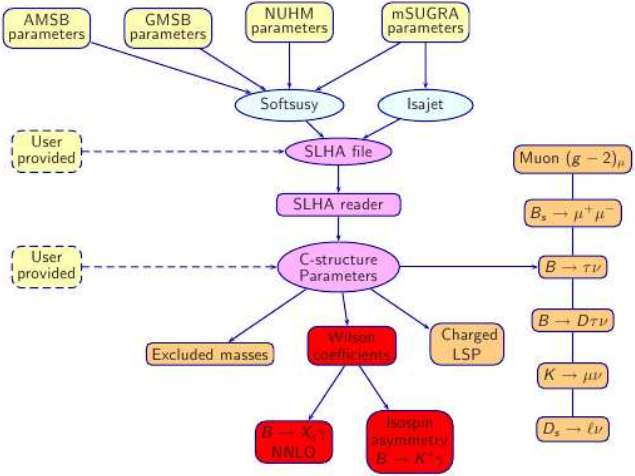
Calculation of flavor physics observables

Nazila Mahmoudi

Laboratoire de Physique Corpusculaire
Clermont-Ferrand, France

CERN, 17 March 2009

How does it work?



Observables

G. Isidori – *Interplay of Collider and Flavour Physics*

▶ *General considerations on the (quark) flavour observables*

Two main roads

→ MFV
- Small tanβ [and small μ]
  - Most of the (present) flavour constraints naturally satisfied after imposing EWPO
  - Only notable exception provided by $B \to X_s \gamma$
- Large tanβ [or moderate tanβ + large μ]
  - A few more helicity suppressed observ. play a key role: $B \to ll$, $B(K) \to l\nu$
  - LR ΔF=2 ops. in B(K) mixing might also be relevant in specific corners of the param. space)

→ non -MFV
- Long list of useful observables (B and K physics: leptonic, radiative & non-leptonic channels)
- The absence of significant deviations from the SM in any of these, makes generic non-MFV scenarios highly contrived / fine-tuned
- In several realistic cases (MFV-GUT scenarios, new couplings only for the 3rd family, etc...) the most significant constraints are derived from Kaon physics (λ^5 suppression in the SM, because of $1 \leftrightarrow 3 \leftrightarrow 2$).

Observables

FLAVOUR COUPLING

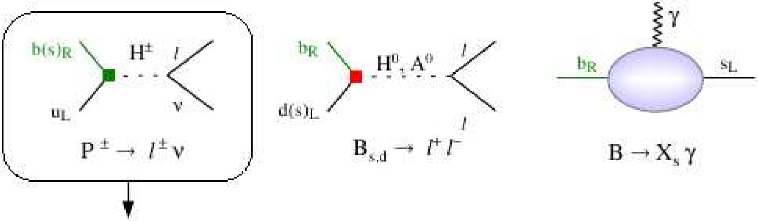
ELECTROWEAK STRUCTURE

	$b \to s$ [~ λ^2 in SM]	$b \to d$ [~ λ^3 in SM]	$s \to d$ [~ λ^5 in SM]
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$, ε_{Bs}	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$, ε_{Bd}	ε_K
$\Delta F=1$ 4-quark ops.	$A_{CP}(B_d \to \phi K)$	$A_{CP}(B_s \to \phi K)$	
gluon penguin	$A_{CP}(B_d \to \phi K)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, \gamma)$	$\Gamma(K_L \to \pi^0 l^+ l^-)$
γ penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s l^+ l^-)$ $A_{FB}(B \to X_s l^+ l^-)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, l^+ l^-)$ $A_{FB}(B \to \rho/\pi\, l^+ l^-)$	$\Gamma(K_L \to \pi^0 l^+ l^-)$
Z^0 penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s l^+ l^-)$ $A_{FB}(B \to X_s l^+ l^-)$ $\Gamma(B_s \to \mu\mu)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\, l^+ l^-)$ $A_{FB}(B \to \rho/\pi\, l^+ l^-)$ $\Gamma(B_d \to \mu\mu)$	$\Gamma(K^+ \to \pi^+ \nu\nu)$ $\Gamma(K_L \to \pi^0 \nu\nu)$ $\Gamma(K_L \to \pi^0 l^+ l^-)$
H^0 penguin	$\Gamma(B_s \to \mu\mu)$	$\Gamma(B_d \to \mu\mu)$	

G. Isidori – *Interplay of Collider and Flavour Physics*

The flavour constraints at large $\tan\beta$

Three most interesting sets of observables:



Simplest M_H & $\tan\beta$ dependence [mild dependence on other parameters]

$$BR = BR_{SM} \times \left(1 - \frac{m_P^2 \tan\beta^2}{M_H^2 (1 + \epsilon_0 \tan\beta)} \right)^2$$

G. Hou, '93; Ackeroid, Recksiegel, '03

G.I. Paradisi '06

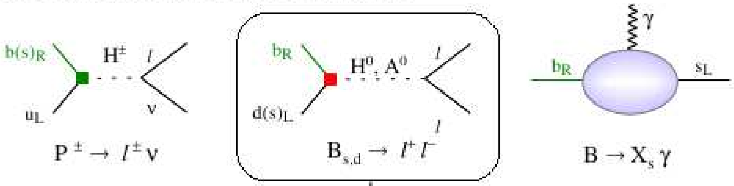
- $O(100\%)$–$O(10\%)$ in $B^\pm \to l^\pm \nu$ [most likely $BR_{SUSY} < BR_{SM}$]
- $O(1\%)$–$O(0.1\%)$ in $K^\pm \to l^\pm \nu$ [necessarily $BR_{SUSY} < BR_{SM}$]

Observables

G. Isidori – *Interplay of Collider and Flavour Physics*

The flavour constraints at large tanβ

Three most interesting sets of observables:



Crucial dependence on μ and A_U [in addition to M_H & tanβ]

$$A(B\to ll)_H \sim \frac{m_b m_l}{M_A^2} \frac{\mu A_U}{\tilde{M}_q^2} \tan^3\beta$$

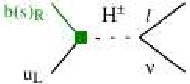
Possible large enhancement over the SM
but size (and magnitude) of the effect can change
substantially in different SUSY-breaking scenarios

Observables

G. Isidori – *Interplay of Collider and Flavour Physics*

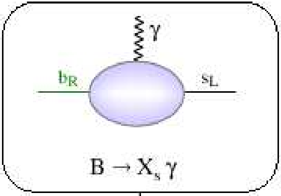
The flavour constraints at large tanβ

Three most interesting sets of observables:

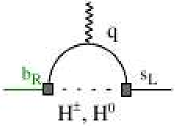


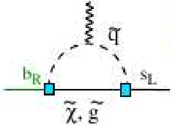
$P^{\pm} \to l^{\pm}\nu$

$B_{s,d} \to l^+ l^-$



Most complicated observable with several, naturally competitive, contributions:





- positive
- decreasing with tanβ

- sign ~ sgn(μ,A)
- increasing with tanβ

One of the most significant constraint of the MSSM (even at small tanβ)

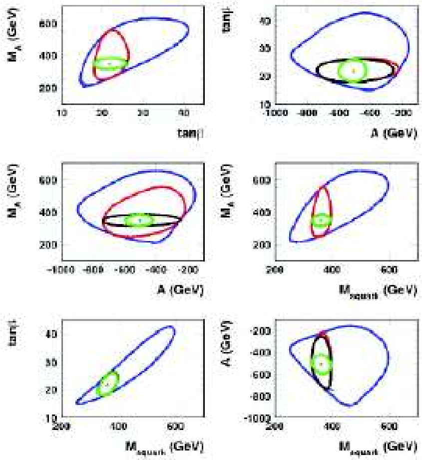
$B(B \to X_s\gamma)^{exp} = (3.55 \pm 0.26)\ 10^{-4}$ [HFAG '06]

$B(B \to X_s\gamma)^{SM} = (3.15 \pm 0.23)\ 10^{-4}$ [Misiak et al. '06]

Mastercode

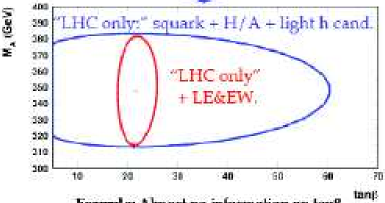
G. Isidori – NP benchmarks in flavour physics | *Flavour in the era of the LHC*

Interpretation & Consistency



- LE&EW: low-energy (LE) and EW constraints
- LE&EW + squark candidate
- LE&EW + squark cand. + H/A cand.
- LE&EW + squark + H/A + light h cand.

Including LW&EW constraints facilitates the determination of fundamental MSSM parameters



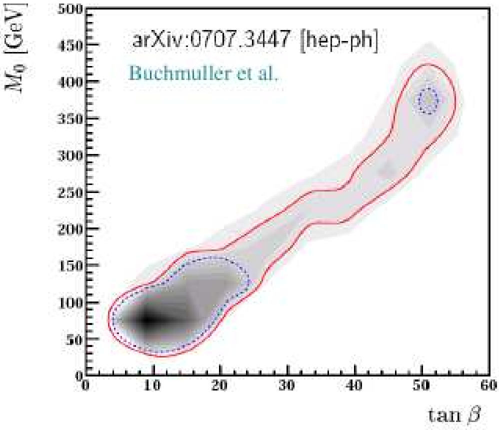
Example: Almost no information on tanβ without external constraints. Note that a direct measurement of tanβ is very difficult at the LHC

Illustrative Example

Mastercode

G. Isidori – Interplay of Collider and Flavour Physics

- Multi-parameter χ^2 fit
- fitting for all CMSSM parameters: M_0, $M_{1/2}$, A_0, $\tan\beta$;
- including relevant SM uncertainties (*e.g.* m_{top});



- overall preferred minimum at low $\tan\beta$, low squark mass;
- less preferred region at high $\tan\beta$, higher squark mass;
- consistent with previous studies.

Key role played by $(g\text{-}2)_\mu$, Ω_{CDM} & $B \to X_s\gamma$

Mastercode

III. *Rare B decays*

Present status:

$B(B_s \to \mu\mu) < 4.8 \times 10^{-8}$ (95%CL)

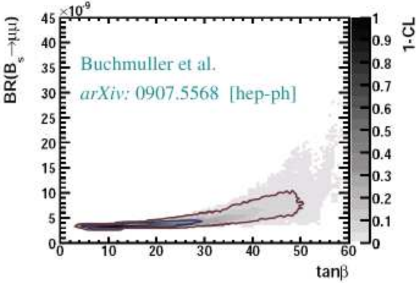
$B(B_s \to \mu\mu) < 7.6 \times 10^{-9}$ (95%CL)

[CDF '09]

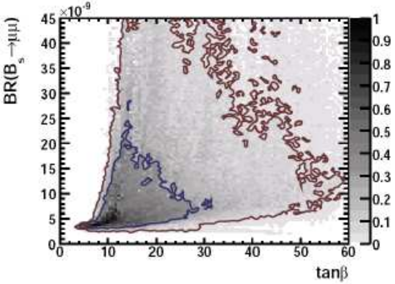
$B(B_s \to \mu\mu)_{SM} = 3.2(2) \times 10^{-9}$

$B(B_d \to \mu\mu)_{SM} = 1.0(1) \times 10^{-10}$

Constrained - MSSM

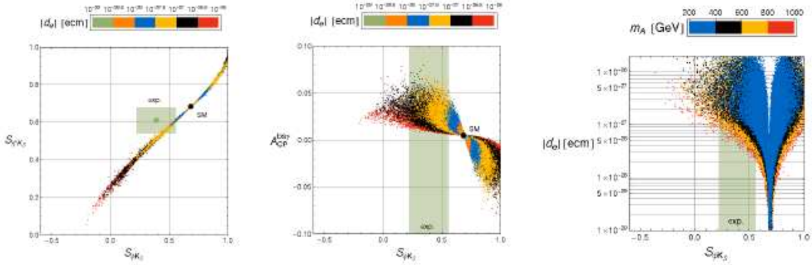


Constrained – MSSM with non-universal Higgs masses (NUHM)



Reaching the SM level would lead to a very significant constraint in the (C)MSSM

Flavor blind MSSM ≈ MFV + CPV



- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- lower bounds on the electron and neutron EDMs at the level of $d_{e,n} \gtrsim 10^{-28}$ecm
- large and correlated effects in the CP asymmetries in $B \to K^* \mu^+ \mu^-$ (WA, Ball, Bharucha, Buras, Straub, Wick)

- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

Beyond MFV

- Soft squark masses and trilinear couplings can contain additional flavor structures beyond the CKM matrix.
- Such structures lead to flavor off-diagonal entries in the squark masses.

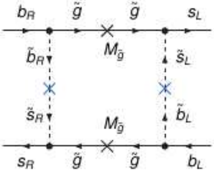
Complex mass insertions lead to flavor and CP violating gluino-quark-squark interactions that will generate the dominant contributions to FCNCs

The largest gluino contributions to the mixing amplitudes are generated if both LL and RR mass insertions are present simultaneously

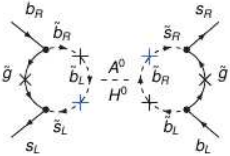
Convenient parametrization through mass insertions

$$M_q^2 = \tilde{m}^2 \mathbb{1} + \tilde{m}^2 \delta_q$$

$$\delta_q = \begin{pmatrix} \delta_q^{LL} & \delta_q^{LR} \\ \delta_q^{RL} & \delta_q^{RR} \end{pmatrix} \quad , \quad q = u, d$$



$$\propto \frac{\alpha_s^2}{\tilde{m}^2} (\delta_d^{LL})_{32} (\delta_d^{RR})_{32}$$



$$\propto \frac{\alpha_2}{4\pi} \frac{\alpha_s^2}{M_A^2} \frac{m_b^2}{M_W^2} \tan^4 \beta$$
$$\times (\delta_d^{LL})_{32} (\delta_d^{RR})_{32}$$

Flavour Models

Example: Agashe, Carone '03 (AC)

- Abelian flavor model based on a $U(1)$ horizontal symmetry
- "remarkable level of alignment"

$$(\delta_d^{LL}) \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix}$$

$$(\delta_d^{RR}) \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

Expected phenomenology:

- Small effects in $b \to d$ and $s \to d$ transitions
- Large effects in D_0-$\bar{D}_0$ mixing (general feature of abelian models)
- Large effects in B_s-$\bar{B}_s$ mixing (in particular in $S_{\psi\phi}$ for complex δs)

Example: Ross, Velasco-Sevilla, Vives '04 (RVV)

- Non abelian flavor model based on a $SU(3)$ flavor symmetry
- 1^{st} and 2^{nd} generation of squarks approximately degenerate

$$(\delta_d^{LL}) \sim \begin{pmatrix} \lambda^4 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

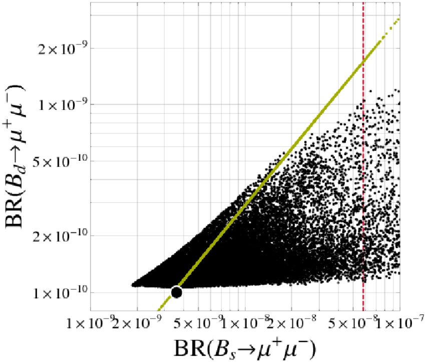
$$(\delta_d^{RR}) \sim \begin{pmatrix} \lambda^3 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^3 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

Expected phenomenology:

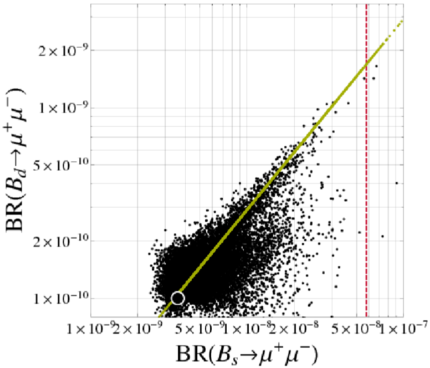
- Moderate effects in $b \to d$ and $s \to d$ transitions (large effects in ϵ_K)
- Small effects in D_0-$\bar{D}_0$ mixing
- Sizeable effects in B_s-$\bar{B}_s$ mixing (in particular in $S_{\psi\phi}$ for complex δs)

Phenomenology of Flavour Models

Abelian (AC)



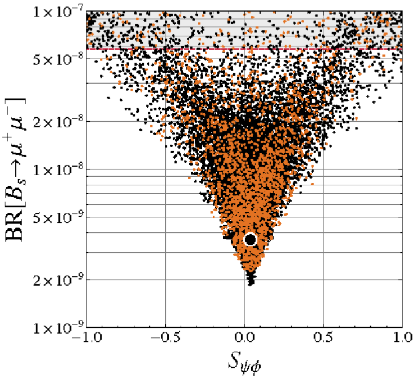
Non abelian (RVV)



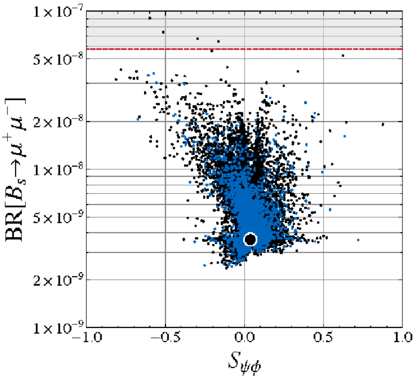
Altmannshofer et al. ’09

Phenomenology of Flavour Models

Abelian (AC)



Non abelian (RVV)



Altmannshofer et al. ’09

“DNA-Flavour Test”

	GMSSM	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	■	★★★	★★★	SuperB
$A_{CP}(B \to X_s\gamma)$	★★★	■	■	■	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	●●	■	■	■	■	■	
$\tau \to \mu\gamma$	★★★	★★★	★★★	■	★★★	★★★	
$D^0 - \bar{D}^0$	★★★	★★★	■	■	■	■	
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	★★★	★★★	vs.
$A_9(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	■	■	
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	■	■	LHCb
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★★★	
ϵ_K	★★★	■	★★★	★★★	■	■	
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	■	■	■	■	■	
$K_L \to \pi^0\nu\bar{\nu}$	★★★	■	■	■	■	■	
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	
d_n	★★★	★★★	★★★	★★★	●●	★★★	
d_e	★★★	★★★	★★★	●●	■	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	

Altmannshofer et al. ’09

Isidori's view

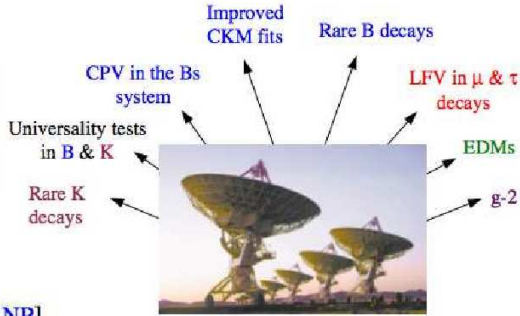
▸ *Flavour physics in the LHC era*

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

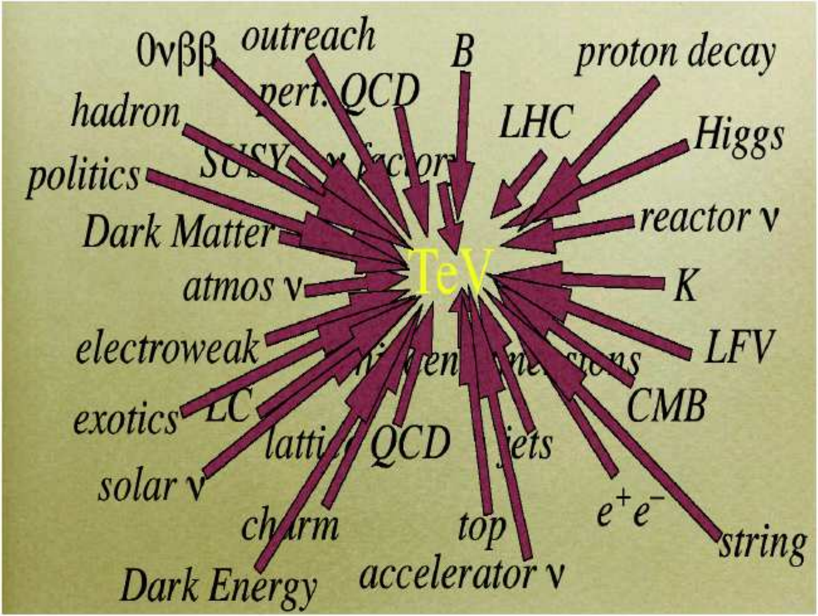
Flavour physics



A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]

Murayama's view



Masiero's view