New Physics Searches in Flavour Physics
a theoretical (over)view

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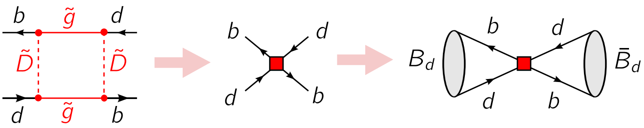
Rencontres de Physique de la Vallée d'Aoste
La Thuile

Probing new physics through flavour

Flavour physics allows to probe new physics through virtual contributions to low energy precision observables:



Effective coupling (depends on NP flavour structure)

$$\mathscr{L} = \mathscr{L}_{\mathsf{SM}} + \sum_i \frac{c_i^{(d)}}{\Lambda^{4-d}} O_i^{(d)}$$

Operator made of SM fields

New physics scale (waiting for LHC input!)

Bounds on new physics flavour structure

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(d)}}{\Lambda^{4-d}} O_i^{(d)}$$

Operator	Bounds on c_i ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9×10^{-7}	3×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	7×10^{-9}	3×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	6×10^{-7}	1×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6×10^{-8}	1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	3×10^{-6}	1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	6×10^{-7}	2×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	8×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	1×10^{-5}		Δm_{B_s}

[Isidori, Nir, Perez 1002.0900]

The flavour puzzle(s)

- The NP flavour puzzle: the flavour structure of TeV new physics must be highly **non-generic**.

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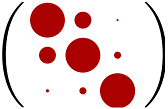
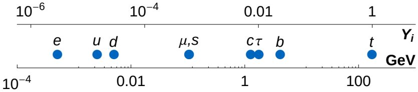
- The SM flavour puzzle: even the flavour structure of the Standard Model is highly **non-generic**!

$|V_{\text{CKM}}| \sim$ 



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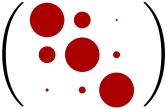
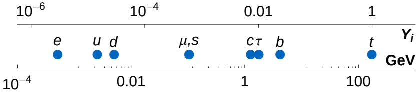
$|V_{\text{CKM}}| \sim$ 



1. Are there sources of flavour breaking beyond the ones in the SM or not (= **Minimal Flavour Violation**)?

2. Are there sources of CP violation beyond the CKM phase?

Outline

1. Introduction

2. Selected highlights in the early LHC era

- $B_{s,d} \to \mu^+\mu^-$
- CP violation in B_s mixing
- $B \to K^*\ell^+\ell^-$

3. A case for precision flavour physics

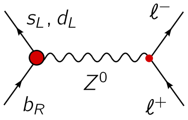
- Supersymmetry with hierarchical squark masses

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

Strongly **helicity suppressed** decays that will be measured by LHCb

mode	SM	exp. 95% C.L.
$\text{BR}(B_s \to \mu^+\mu^-)$	$(3.2 \pm 0.2) \times 10^{-9}$	$< 43 \times 10^{-9}$
$\text{BR}(B_d \to \mu^+\mu^-)$	$(0.10 \pm 0.01) \times 10^{-9}$	$< 7.6 \times 10^{-9}$

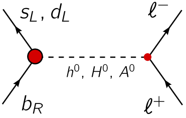
SM and many models with 1 Higgs doublet: dominated by ***Z* penguin**



Enhancement of $B_s \to \mu^+\mu^-$ above $\sim 10^{-8}$ ruled out by other constraints

In models with 2 Higgs doublets, the helicity suppression can be lifted by neutral **Higgs penguin**

MSSM with MFV:



$$\sim \frac{m_b m_\ell}{M_A^2} \frac{\mu A_t}{M_{\tilde{t}}^2} \tan\beta^3$$

$B_{s,d} \to \mu^+\mu^-$ in the MSSM

In models with 2 Higgs doublets, the helicity suppression can be lifted by neutral **Higgs penguin**

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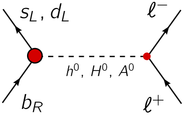
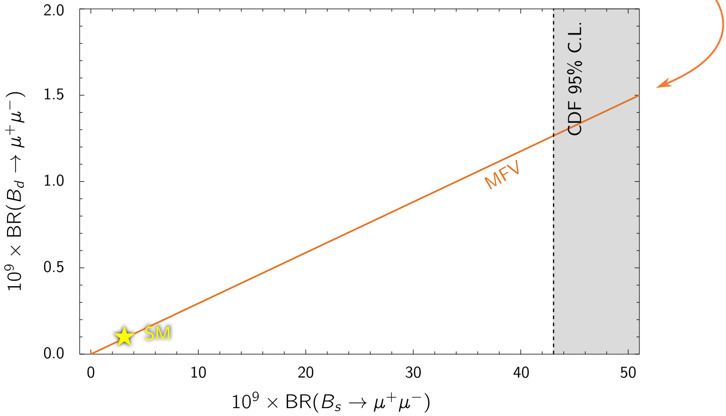


$$\sim \frac{m_b m_\ell}{M_A^2} \frac{\mu A_t}{M_{\tilde{t}}^2} \tan\beta^3$$

- Several SUSY scenarios predict a large enhancement of BR($B_s \to \mu^+\mu^-$) and would be in trouble if no evidence is found **this year** (e.g. SUSY GUTs with Yukawa unification)

$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$

A stringent test of the MFV paradigm: $\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \frac{|V_{ts}|^2}{|V_{td}|^2}$



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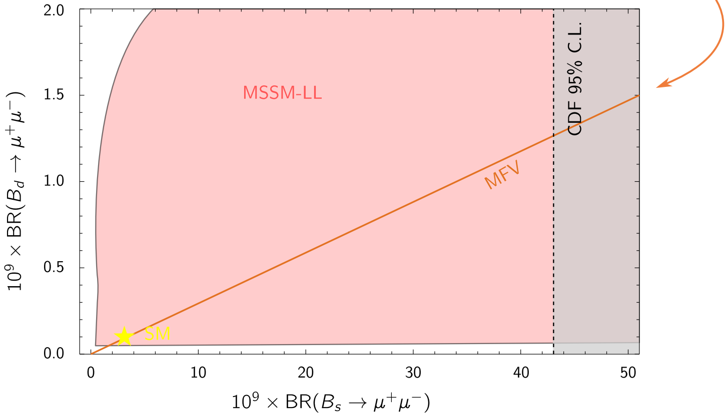

SUSY flavour model [Altmannshofer et al. 0909.1333]

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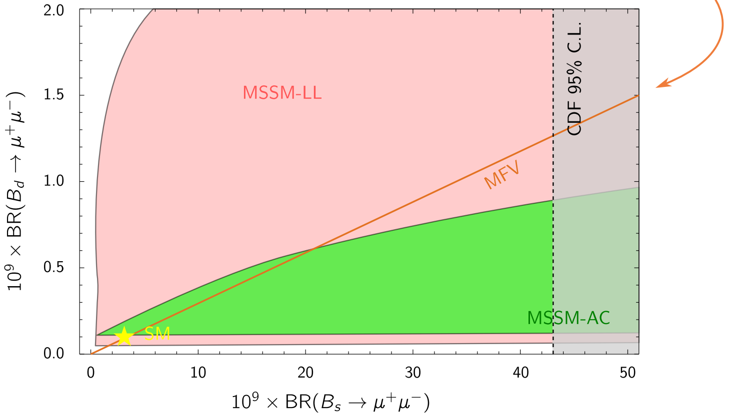

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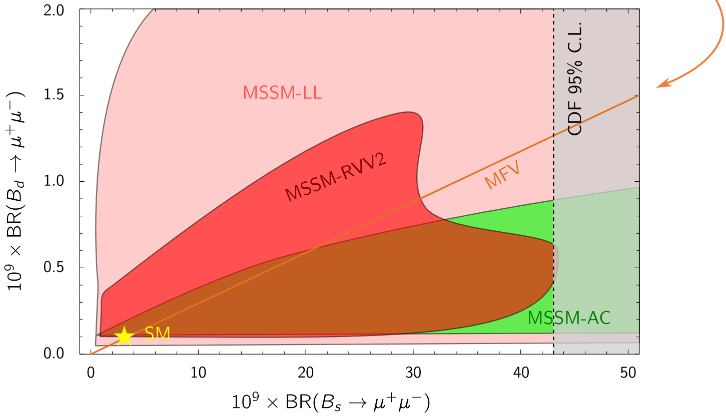

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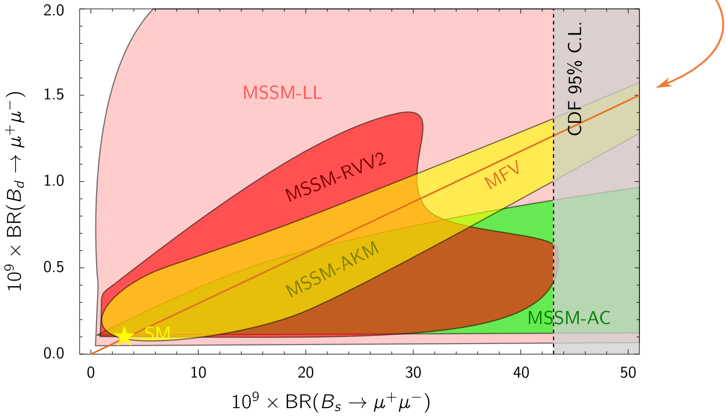

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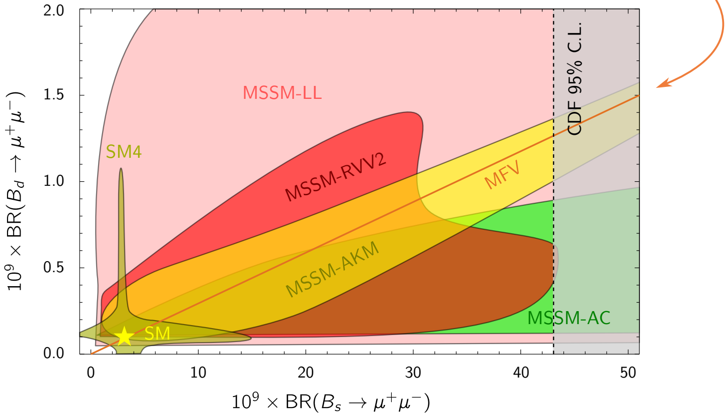
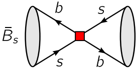


4th generation SM [Buras et al. 1002.2126] SUSY flavour models [Altmannshofer et al. 0909.1333]

New physics in B_s mixing?

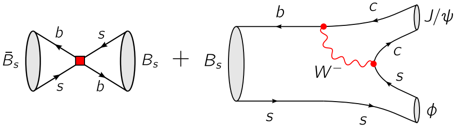
2 observables for the B_s mixing phase



$$= \frac{\Delta M_s}{2}\, e^{i(-2\beta_s+\phi_s^{\mathbf{NP}})}$$

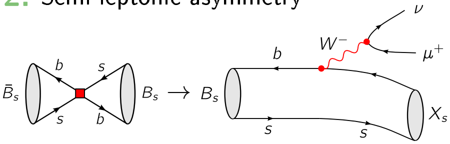
$-2\beta_s \to -1^\circ$, $\phi_s^{\mathbf{NP}} \to$?

1. Mixing-induced CP asymmetry in $B_s \to J/\psi\phi$



$$\frac{\Gamma(\bar{B}_s\to\psi\phi)-\Gamma(B_s\to\psi\phi)}{\Gamma(\bar{B}_s\to\psi\phi)+\Gamma(B_s\to\psi\phi)} = S_{\psi\phi}\sin(\Delta M_s t)$$

2. Semi-leptonic asymmetry



$$a^s_{\mathrm{SL}} \equiv \frac{\Gamma(\bar{B}_s\to l^+X)-\Gamma(B_s\to l^-X)}{\Gamma(\bar{B}_s\to l^+X)+\Gamma(B_s\to l^-X)}$$

New physics in B_s mixing?

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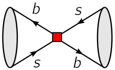
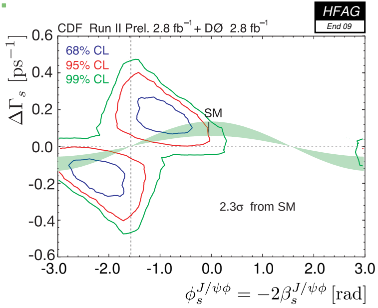
$\bar{B}_s$  $B_s = \frac{\Delta M_s}{2} \; e^{i(-2\beta_s + \phi_s^{\mathbf{NP}})}$

1.



1 year ago: 2.2σ deviation in $S_{\psi\phi}$

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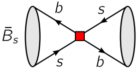

$= \frac{\Delta M_s}{2} \; e^{i(-2\beta_s+\phi_s^{\mathbf{NP}})}$

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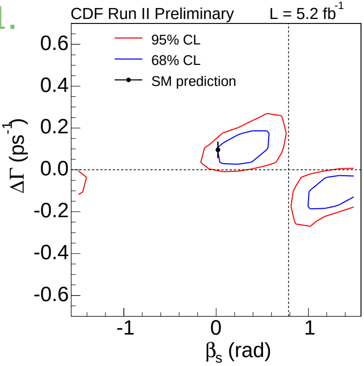

deviation in $S_{\psi\phi}$ recently dropped below 1σ

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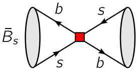

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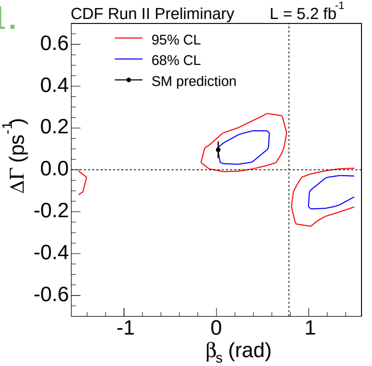

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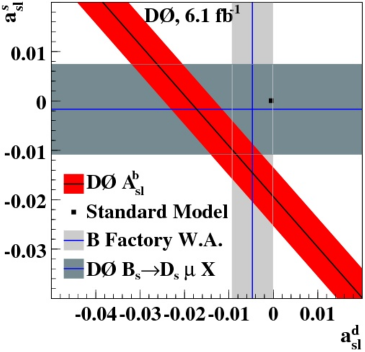
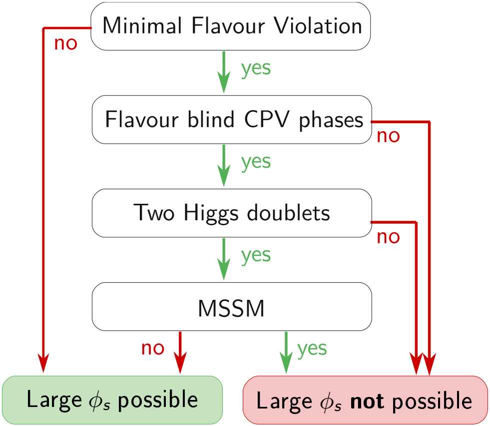
2.



3.2σ deviation in dimuon charge asymmetry at D0

Implications of a large B_s mixing phase

Which classes of models can generate a large mixing phase?



see e.g.
[Buras, Isidori, Paradisi 1007.5291]
[Lenz, Nierste & CKMfitters 1008-1593]

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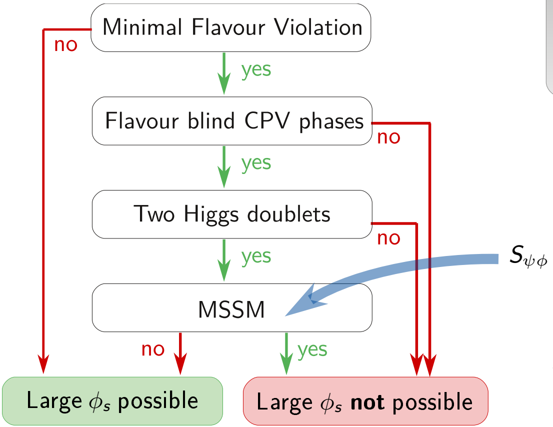
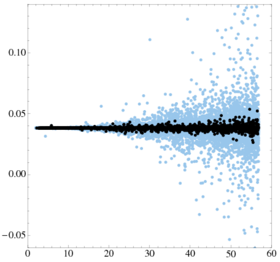
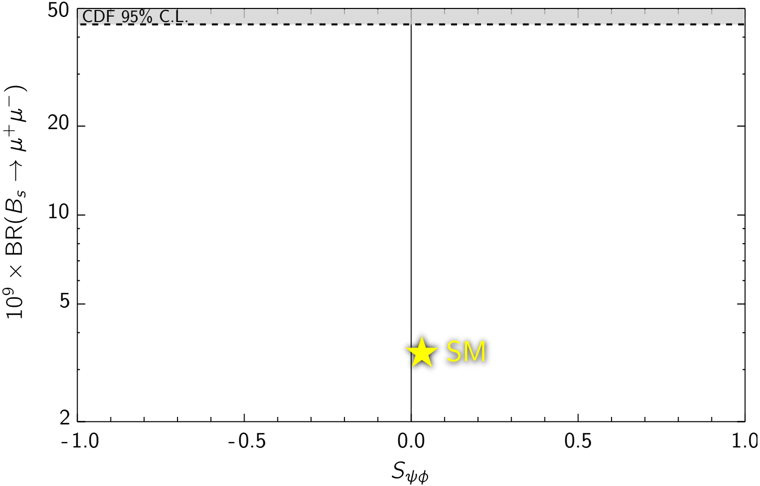


A large B_s mixing phase would rule out a large class of MFV models!



[Altmannshofer et al. 0909.1333]

Correlations between $S_{\psi\phi}$ and $B_s \to \mu^+\mu^-$



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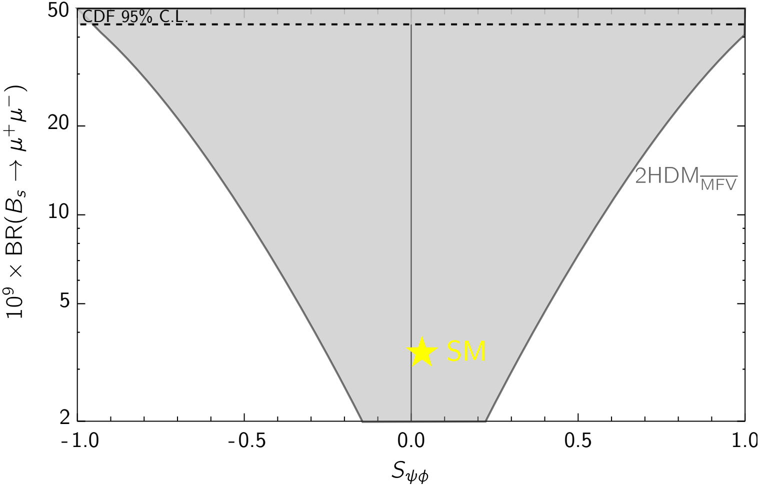

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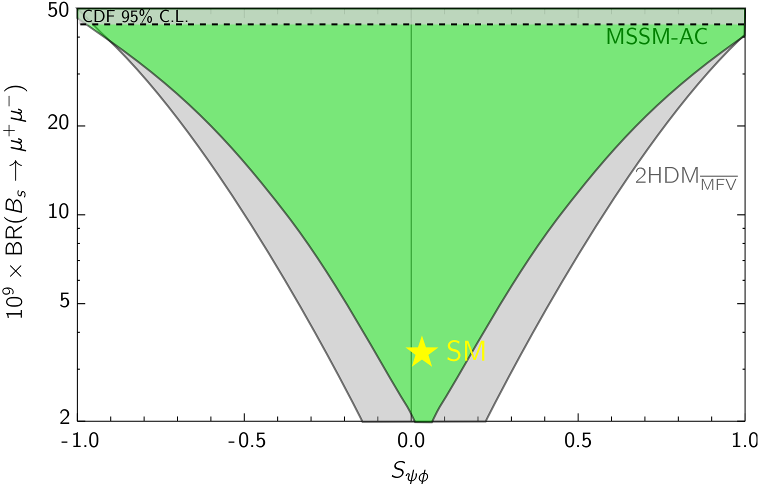

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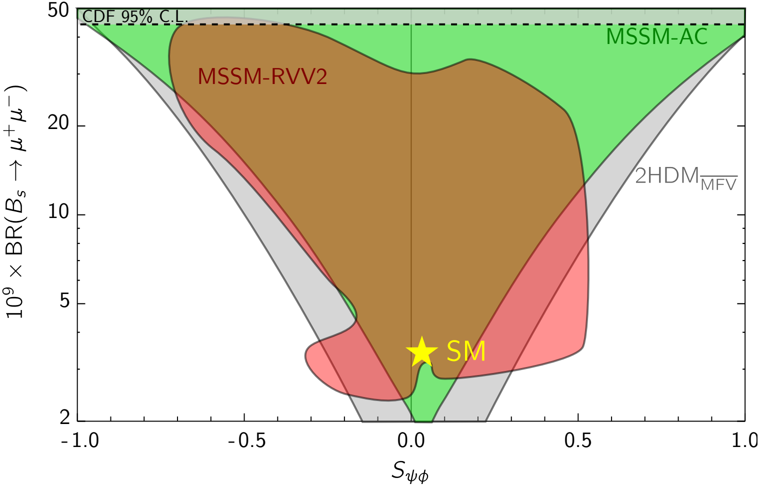

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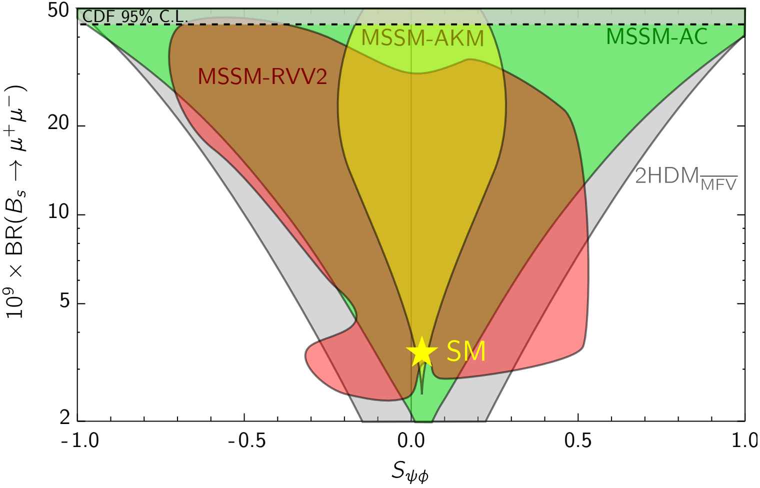

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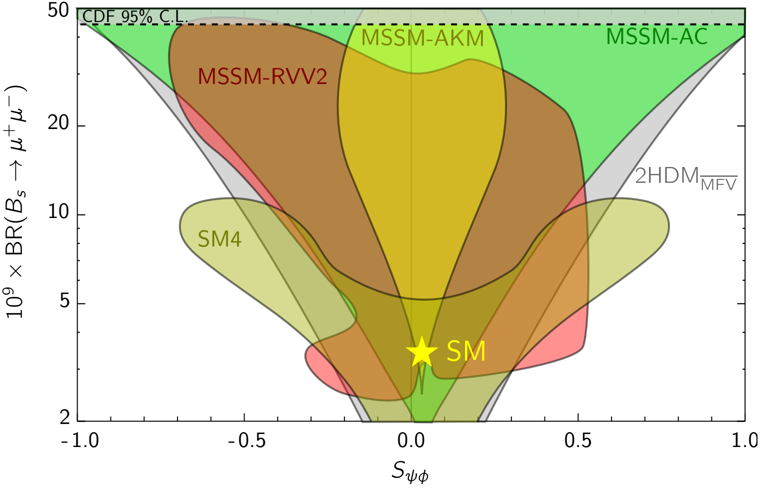

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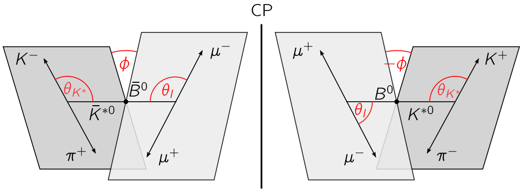
$B \to K^*(\to K\pi)\ell^+\ell^-$ offers a plethora of observables sensitive to new physics



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \sum_{i,a} I_i^{(a)}(q^2) f(\theta_l, \theta_{K^*}, \phi)$$

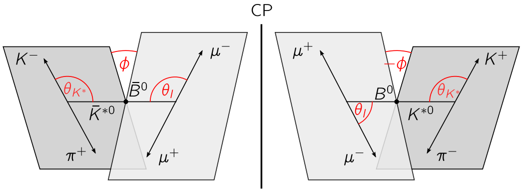
$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

CP-averaged angular coefficients
(e.g. forward-backward asymmetry)

$$A_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

CP asymmetries

$B \to K^*(\to K\pi)\ell^+\ell^-$ offers a plethora of observables sensitive to new physics



Observables requiring angular fit with

1 angle (state of the art)

- dBR/dq^2
- S_6 (A_{FB})
- S_2 (F_L)

} data from BaBar, Belle, CDF

- S_3
- A_9

} 0 in the SM
sensitive to RH currents
no data yet

2 angles (early LHC)

- S_5
- A_7

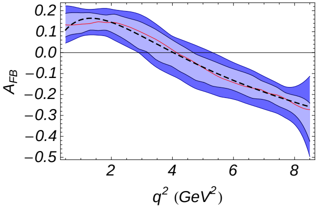
all **3 angles**

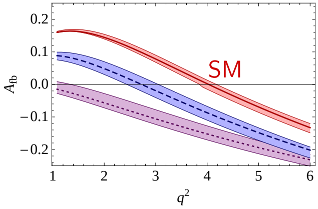
- S_4
- A_8

$B \to K^* \ell^+ \ell^-$: LHC sensitivity

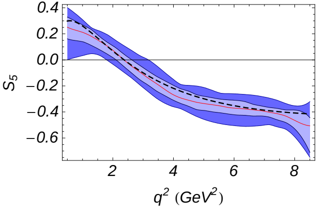
Sensitivity to 2 example MSSM scenarios at LHCb with 2 fb^{-1}

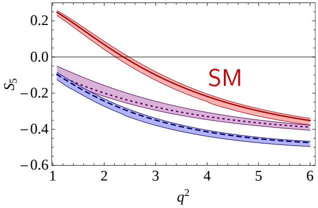
A_{FB}





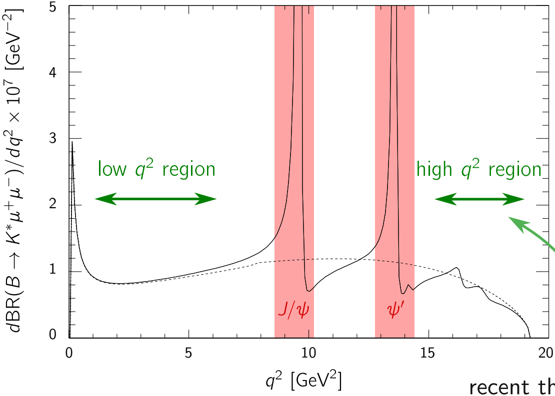
S_5





[Bharucha, Reece, 1002.4310] [Altmannshofer, Ball, Bharucha, Buras, Straub, DS, 0811.1214]

$B \to K^*\ell^+\ell^-$: low vs. high q^2



recent theory improvements

[Beylich, Buchalla, Feldmann 1101.5118]
see also [Bobeth et al. 1006.5013]

⇒ both regions under reasonable theoretical control and phenomenologically complementary

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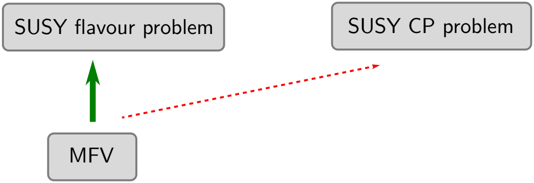
Effective Minimal Flavour Violation

If weak scale SUSY exists, why didn't it show up in flavour & CPV?



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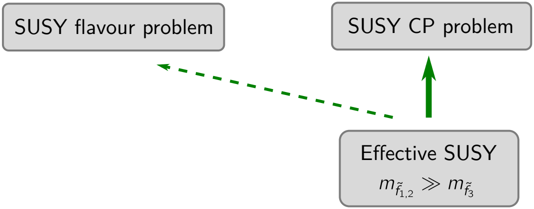

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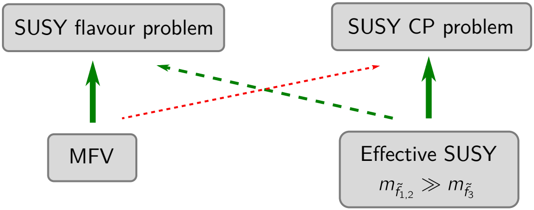


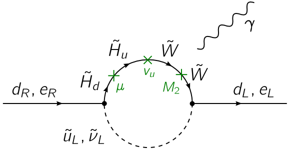
"Effective MFV"

- all sfermions except stops and left-handed sbottom are heavy
- squark mass matrices aligned with up-type Yukawa matrix
- large flavour-blind **CPV phases allowed**

[Barbieri, Bertuzzo, Farina, Lodone, Zhuridov 1011.0730; Barbieri, Lodone, DS 1102.0726]

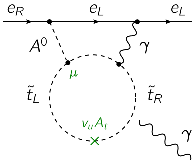
Flavour blind phases lead to contributions to electric dipole moments.

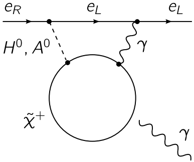
$$\text{Exp.:} \qquad |d_e| < 1.6\times10^{-27}\ e\,\text{cm}\,, \qquad |d_n| < 2.9\times10^{-26}\ e\,\text{cm}$$



1-loop contributions **suppressed** by heavy 1st generation sfermions

$$m_{\tilde{\nu}} > 4.0\ \text{TeV} \ \times (\sin\phi_\mu \tan\beta)^{\frac{1}{2}}$$
$$m_{\tilde{u}} > 2.7\ \text{TeV} \ \times (\sin\phi_\mu \tan\beta)^{\frac{1}{2}}$$



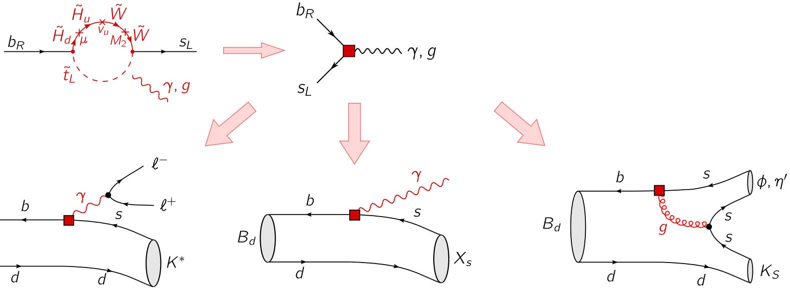


2-loop contributions lead to effects in the ballpark of the experimental bound

CP asymmetries in EMFV

CP violating contributions to dipole operators not suppressed by 1st/2nd generation sfermion masses

e.g.



A_7, A_8 in $B \to K^* \ell^+ \ell^-$

Direct CP asymmetry in $B \to X_s \gamma$

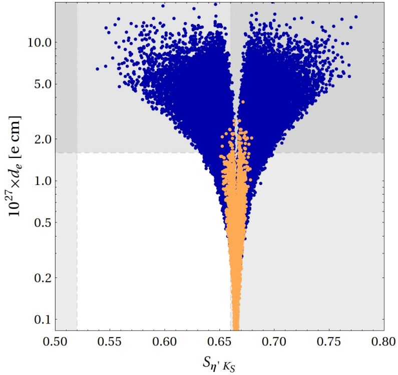
Mixing-induced CP as. in $B \to (\phi, \eta') K_S$

Only accessible at (Super) B factories!

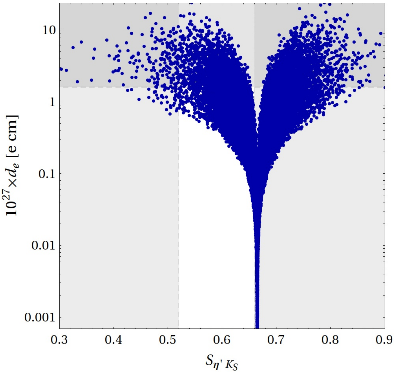
EMFV results I

Electron EDM vs. $S_{\eta' K_S}$, scanning over ...

phase of μ



phase of trilinear couplings



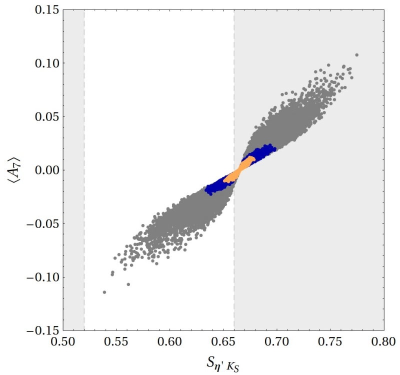
$\tan\beta < 10$, $m_{\tilde{f}_3} \in [200, 700]$ GeV

[Barbieri, Lodone, DS 1102.0726]

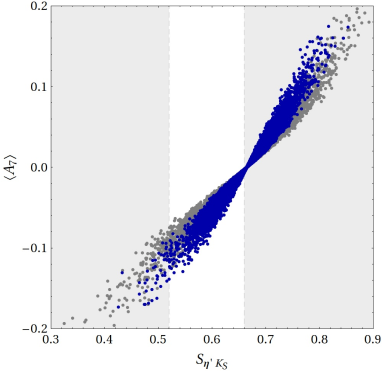
EMFV results II

CP asymmetry A_7 in $B \to K^* \ell^+ \ell^-$ vs. $S_{\eta' K_S}$, scanning over ...

phase of μ



phase of trilinear couplings



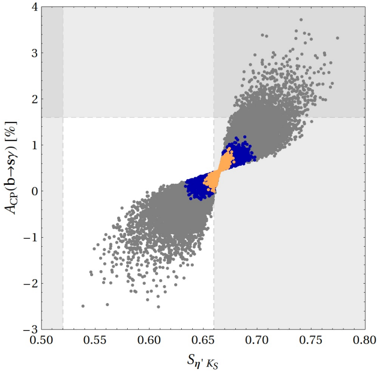
$\tan\beta < 10$, $m_{\tilde{f}_3} \in [200, 700]$ GeV

[Barbieri, Lodone, DS 1102.0726]

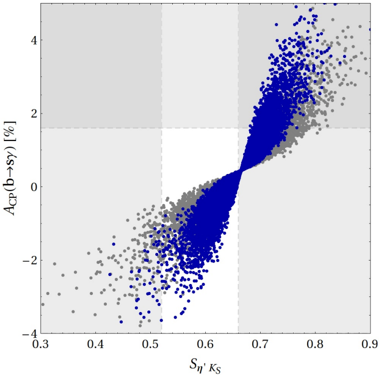
EMFV results III

CP asymmetry in $B \to X_s\gamma$ vs. $S_{\eta' K_S}$, scanning over ...

phase of μ



phase of trilinear couplings



NB: SM theory uncertainty possibly large [Benzke et al. 1012.3167]

Conclusions

1. Flavour physics offers a unique way to look for new physics.
Exciting results should be expected already in the first LHC run, including (but not limited to)

- $B_{s,d} \to \mu^+\mu^-$
- the B_s mixing phase
- $B \to K^*\ell^+\ell^-$

2. MFV combined with hierarchical sfermions can solve the SUSY flavour and CP problems.
It leads to interesting signatures in

- electric dipole moments
- CP asymmetries in B physics accessible at Super B factories

PS There are many other interesting probes of NP in the flavour sector!

K physics, D physics, lepton flavour violation, top FCNCs, ...