Heavy Flavor Theory

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- Introduction
- Future prospects (general considerations)
- Selected examples (within SUSY models)
- More exotic models and observables
- Conclusions

Introduction

Despite all its successes, the SM is likely to be an *effective theory*, i.e. the limit (*in the experimentally accessible range of energies and effective couplings*) of a more fundamental theory, with new degrees of freedom

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We need to search for New Physics

[*with a broad spectrum perspective given the lack of NP signal so far...*]

⬇

Twofold role of Flavor Physics

[= *study of flavor-changing and CPV phenomena, of both quarks and leptons*]

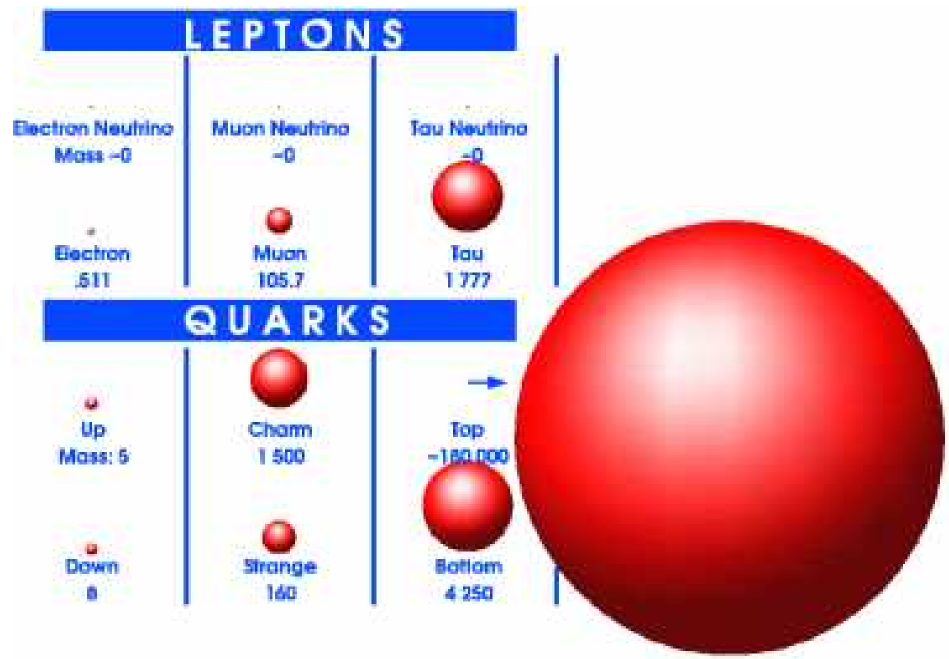
- Identify symmetries and symmetry-breaking patterns beyond those present in the SM

- Indirect probe of physics at energy scales not directly accessible at accelerators

Introduction

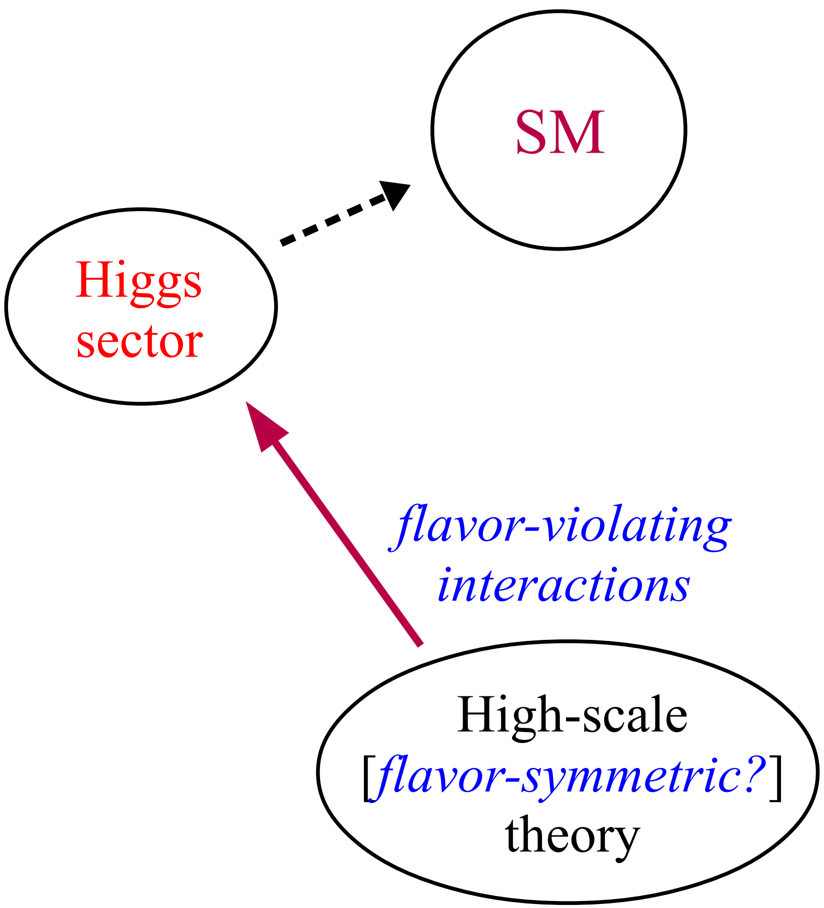
<u>Twofold role of Flavor Physics</u>

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM



<u>The observed pattern of fermion masses angles does not seem to be accidental:</u>

- *What determines the observed pattern of quark & lepton mass matrices?*



▶ Introduction

Twofold role of Flavor Physics

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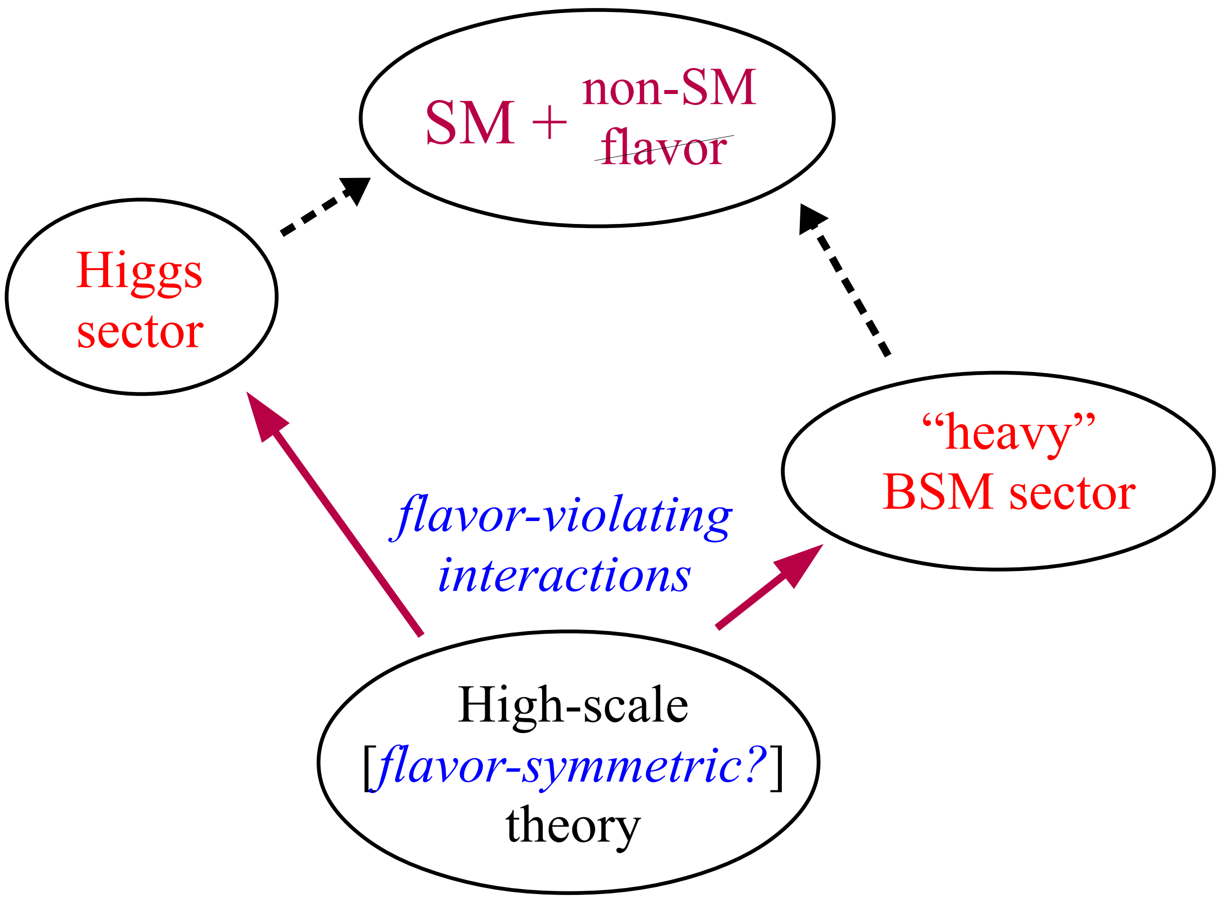


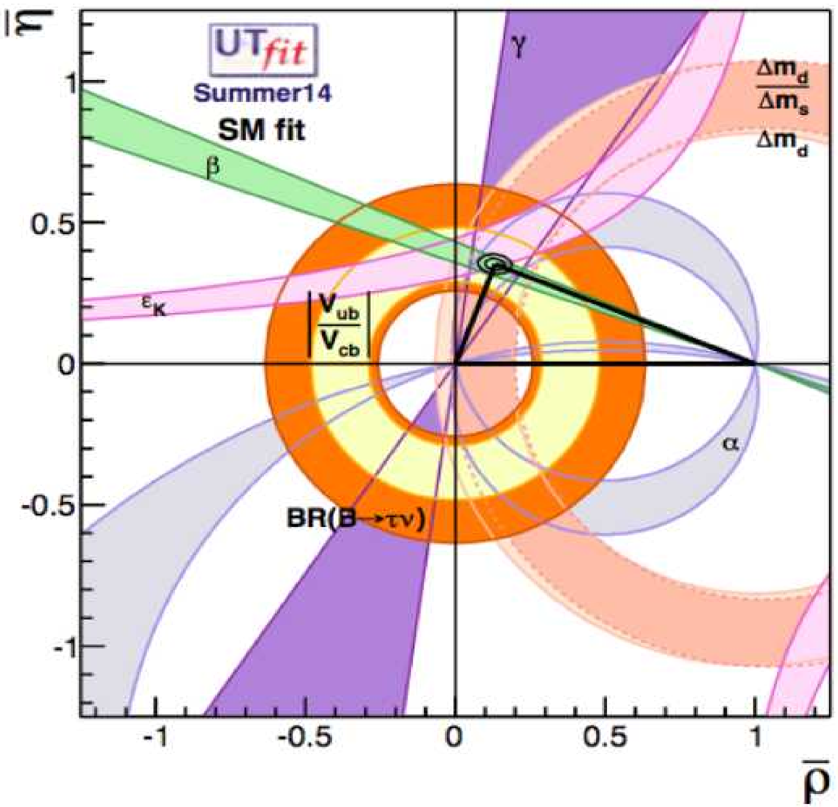
Two key open questions:

- *Are there other sources of flavor symmetry breaking?*
- *What determines the observed pattern of quark & lepton mass matrices?*

- *Are there other sources of flavor symmetry breaking (beside the SM Yukawa couplings)?*

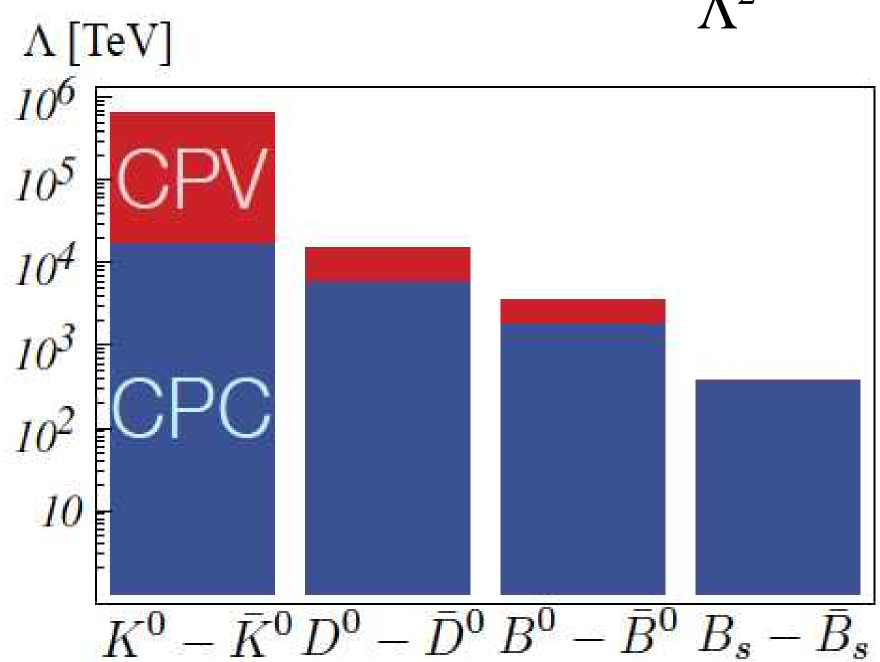
- *What determines the observed pattern of quark & lepton mass matrices?*

That's the question addressed by precision measurements (& searches) of flavor-changing processes of quarks & charged-leptons → So far everything seems to fit well with the SM→ Strong limits on NP



→

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2} O_{\Delta F=2}$$



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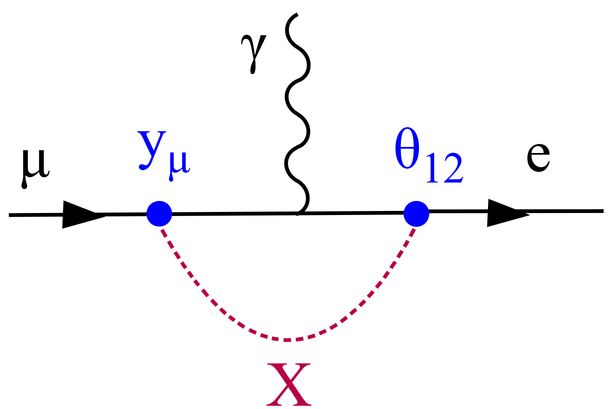

$$BR(\mu\to e\gamma)^{exp} < 5.7\times 10^{-13}$$

MEG '13

$$M_X \gtrsim 200 \text{ TeV}$$

Either NP is very heavy...

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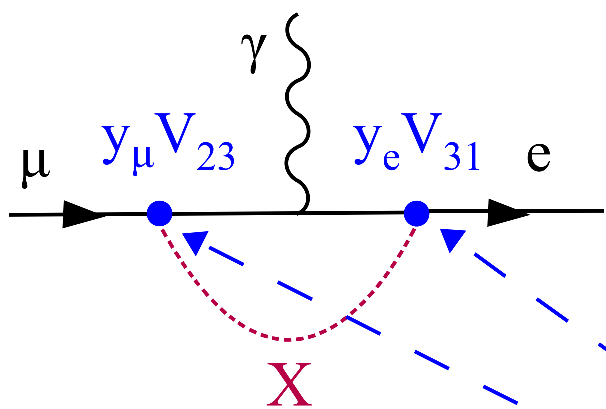

$BR(\mu \to e\gamma)^{exp} < 5.7\times10^{-13}$

MEG '13

$M_X \gtrsim 10$ GeV

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

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↓

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

There is still a wide (*possibly interesting...*)
region of NP parameter space
(*both in masses and couplings*)
that is waiting to be explored yet...

▶ *Future prospects* [General considerations]

General decomposition of flavor-violating observables:

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{M_{NP}^2} \right]$$

A_0: trivial kinematical factors

c_{SM}, c_{NP}: (dimensionless) effective couplings

M_{NP}: effective mass (scale) of NP

decomposition that holds for *<u>both</u>* *forbidden processes*
(e.g.: $\tau \to 3\mu$, where $c_{SM} \approx 0$)
and precision measurements
(e.g.: $B_s \to \mu\mu$, where $c_{SM} \neq 0$)

- <u>For statistically limited measurements</u>, the sensitivity to the NP mass grows as $\sigma(M_{NP}) \sim 1/N^{1/4} \to$ <u>Luminosity matters !</u>

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E.g.: If $c_{NP} \sim c_{SM}$ [*electroweak-MFV-like*] => 10% precision $\leftrightarrow$ $M_{NP} \sim 250$ GeV

Decreasing the error to 2% (~30 x statistics) => 250 GeV $\to$ 600 GeV
$\sigma(c_{NP}) \to 0.2 \times \sigma(c_{NP})$

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- For statistically limited measurements, the sensitivity to the NP mass grows as $\sigma(M_{NP}) \sim 1/N^{1/4}$ → Luminosity matters !

- The interest of a given flavor obs. depends on the magnitude of c_{SM} vs. c_{NP} and on the theoretical error of c_{SM} => concentrate on clean & rare processes

Future prospects [General considerations: LFV]

After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting (*and potentially rewarding*) search in the flavor sector.

Despite this is not the main focus of experiments at HL-LHC, there is one channel that can be searched for at the LHC and should not be forgotten: $\tau \to 3\mu$

$\tau \to \mu\mu\mu$ limits (90 % CL)	
BaBar(FC)	3.3×10^{-8}
Belle(FC)	2.1×10^{-8}
LHCb(CLs)	4.6×10^{-8}
HFAG(CLs)	1.2×10^{-8}

← $3\,\mathrm{fb}^{-1}$ update (LHCb)

M. Chraszcz [TAU 2014]

Given the strong limit from $\mu \to e\gamma$ and $\mu \to e$ conversion, in realistic models (*SUSY like*) $\tau \to 3\mu$ is expected below 10^{-10}, but it may be higher in more exotic frameworks.

Interesting complementarity with $h \to \tau\mu$
($h \to \tau\mu$ is *more sensitive than* $\tau \to 3\mu$ *only if* $\tau \to 3\mu$ *is Higgs-mediated*)

Future prospects [General considerations: The quark sector]

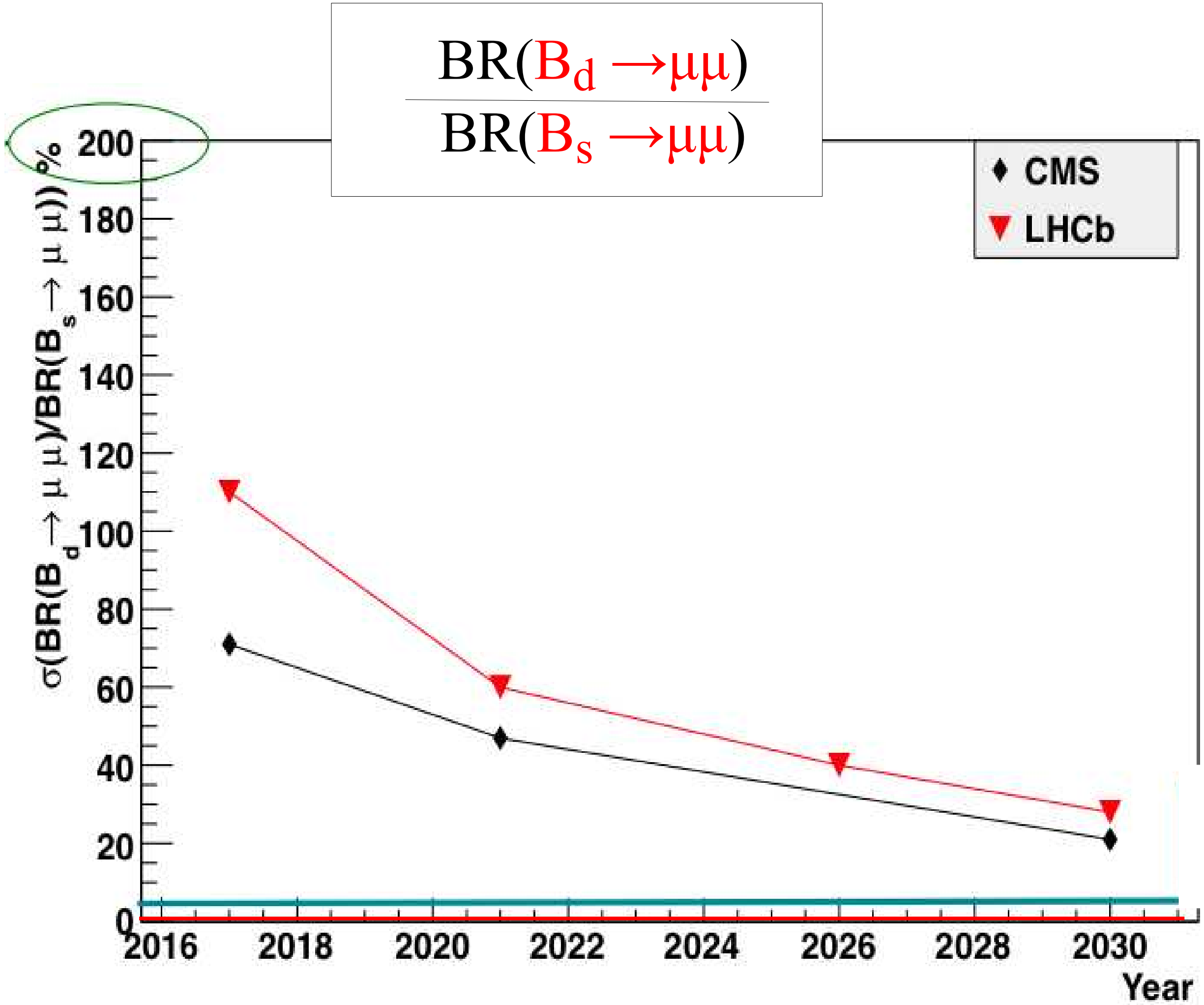
- Several "*SM null tests*" possible also in the quark sector ($B \to \mu e$, $B^+ \to \pi^- \mu^+ \mu^+$, …): same virtues as $\tau \to 3\mu$ (*but less motivated in most "natural" models*)
- In many CPV and FCNC measurements the main limitation is provided by TH errors. However, there is a limited but very interesting set of observables where the th. erorr is far from being dominant.
- Still significant room for improvements in all purely-leptonic or semi-leptonic modes (↔ key role of Lattice)

"Minimalistic" list of the key (low-energy) flavor-physics observables relevant for the HL-LHC that are not TH-error dominated:

- γ [from tree: $B \to DK$, …]
- $B_{s,d} \to l^+l^-$
- ϕ_s [CPV in B_s mixing]
- $B \to K^{(*)} l^+l^-$ [*selected diff. observables*]
- CPV in charm [*selected observables*]
- Time-dep. CPV in semi-leptonic B decays

▶ *Future prospects* [General considerations: The quark sector]

Example of B-physics observable that will NOT be dominated by the TH error for a long time...:



TH error (now): 5%

↓

TH error (2030): ~1%

▶ *Future prospects* [General considerations: The quark sector]

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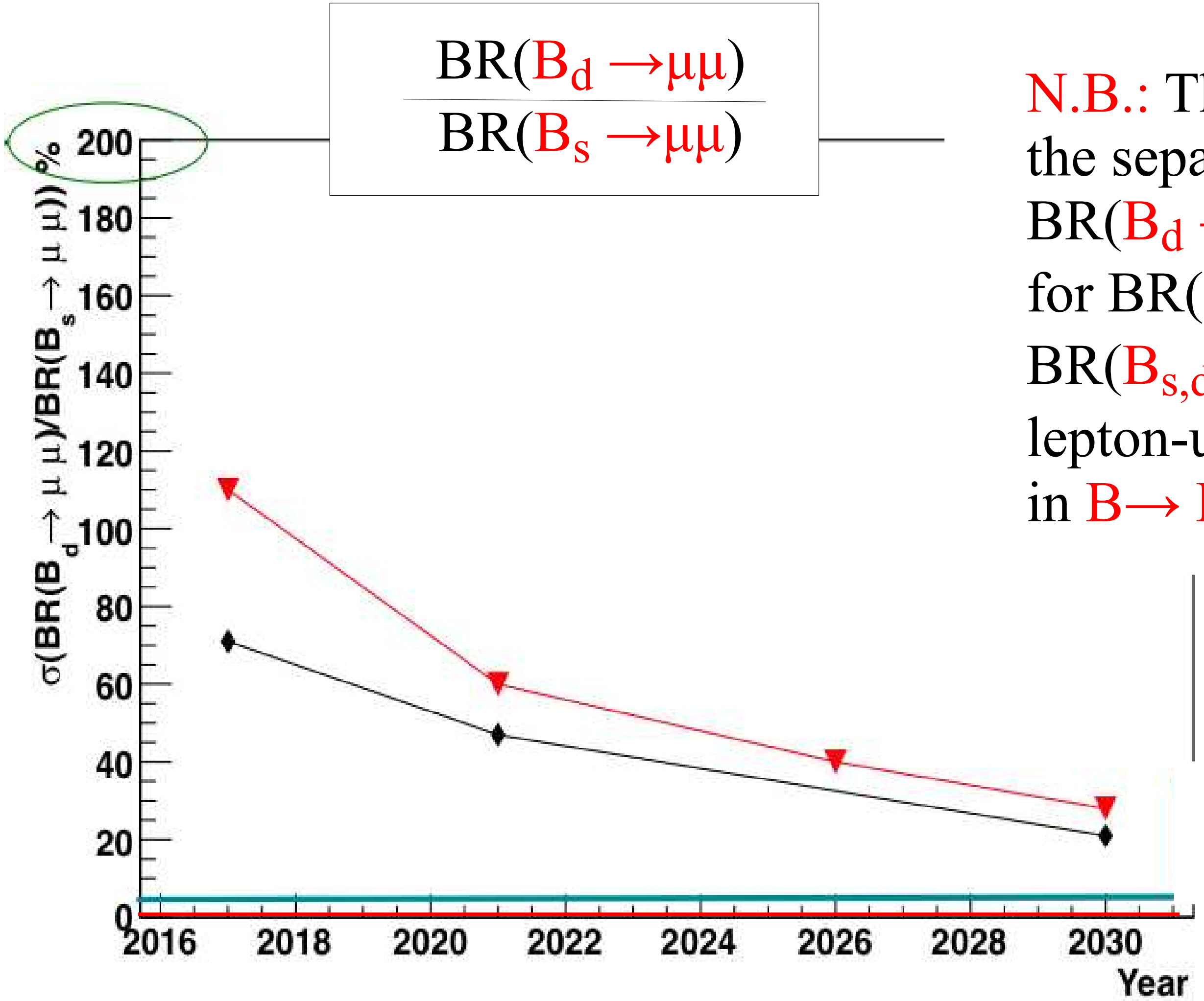


N.B.: The same is true for the separate predictions of $BR(B_d \to \mu\mu)$ & $BR(B_s \to \mu\mu)$, for $BR(B_{s,d} \to \tau\tau)$ and $BR(B_{s,d} \to ee)$ for the lepton-universality ratios in $B \to K^* ll$, etc...

TH error (now): 5%

↓

TH error (2030): ~1%

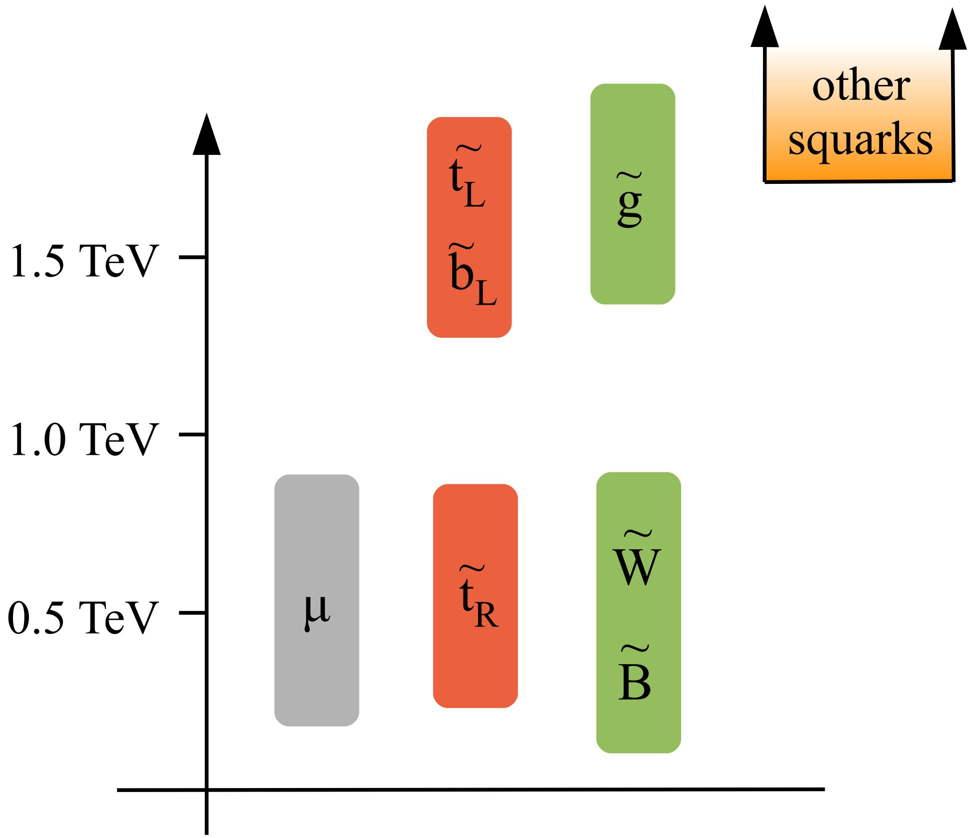
Selected examples [in the SUSY context]

Despite the absence of signals, SUSY remains our best candidate for a UV completion of the SM not far from the TeV scale:

- Weakly coupled theory + light Higgs (*125 is well the SUSY region...*) + dark-matter & unification
- Some tuning in m_h is unavoidable: *do we really care if the fine-tuning is ~1% ?*

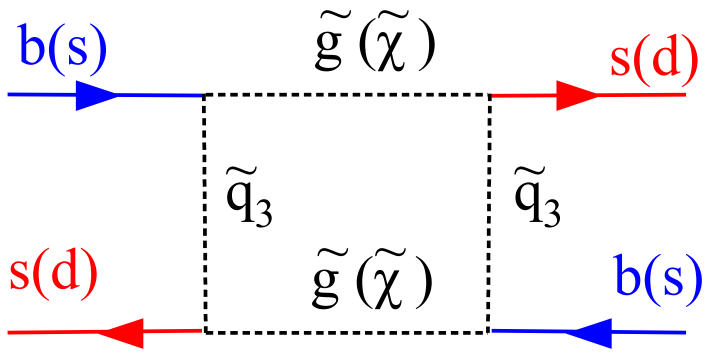
Most of the low-scale SUSY virtues are maintained if we assume a flavor non-trivial spectrum →

- 3^{rd} gen. squarks + Higgsinos key ingredients in the m_h tuning
- splitting the 3^{rd} family can easily be motivated in flavor models

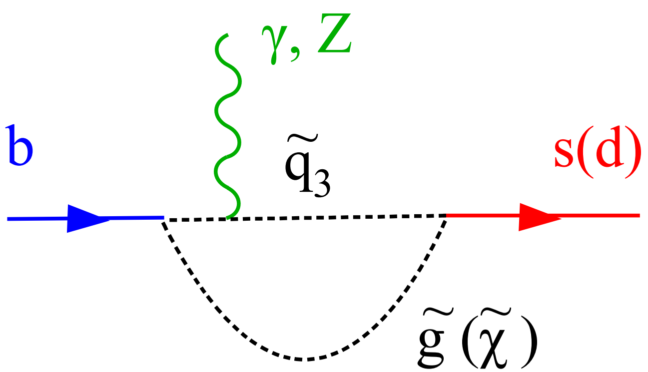


Selected examples [in the SUSY context]

- LHC experiments have started to directly explore this scenario & possible variations (e.g: *mini-spilt…*).
- In this context, flavor physics plays a key role [non-trivial flavor structure] → BSM effects mediated by 3rd gen. squarks & leptons:



Possible "visible" [~ 5-20%] effects in
- CPV in K mixing (ε_K)
- CPV in $B_{s,d}$ mixing ($\phi_{s,d}$)

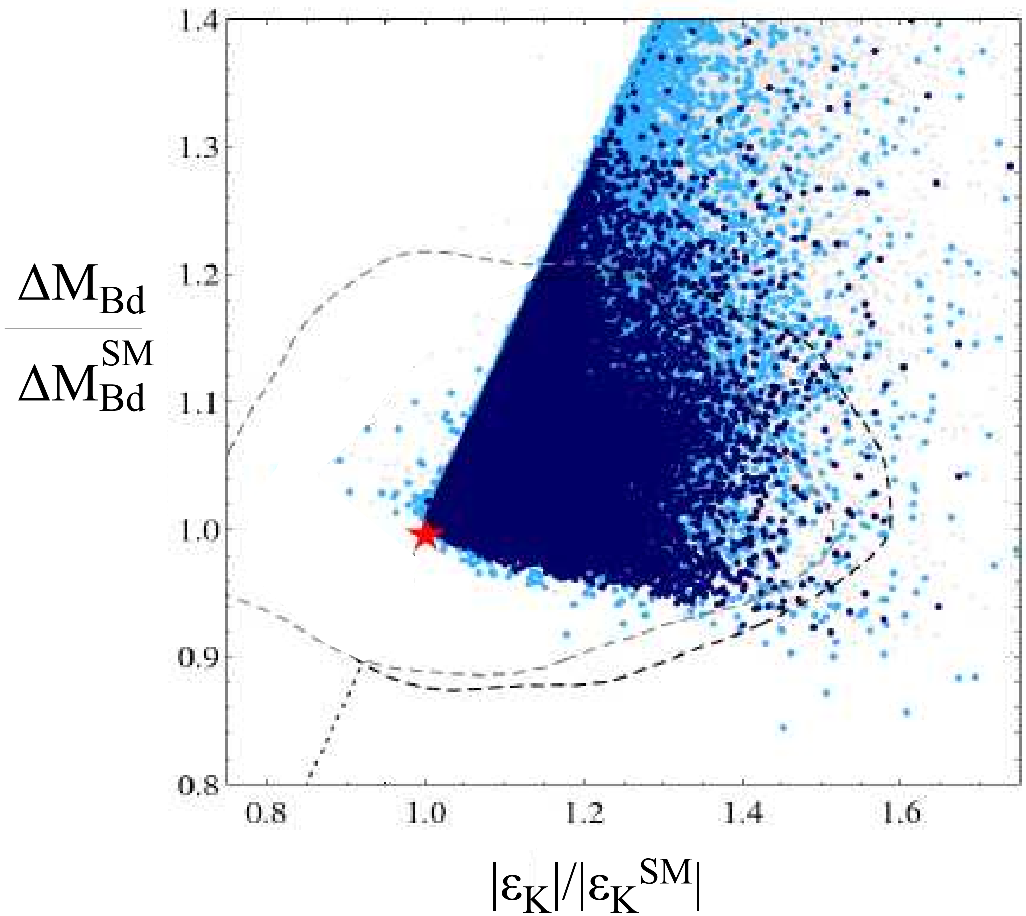


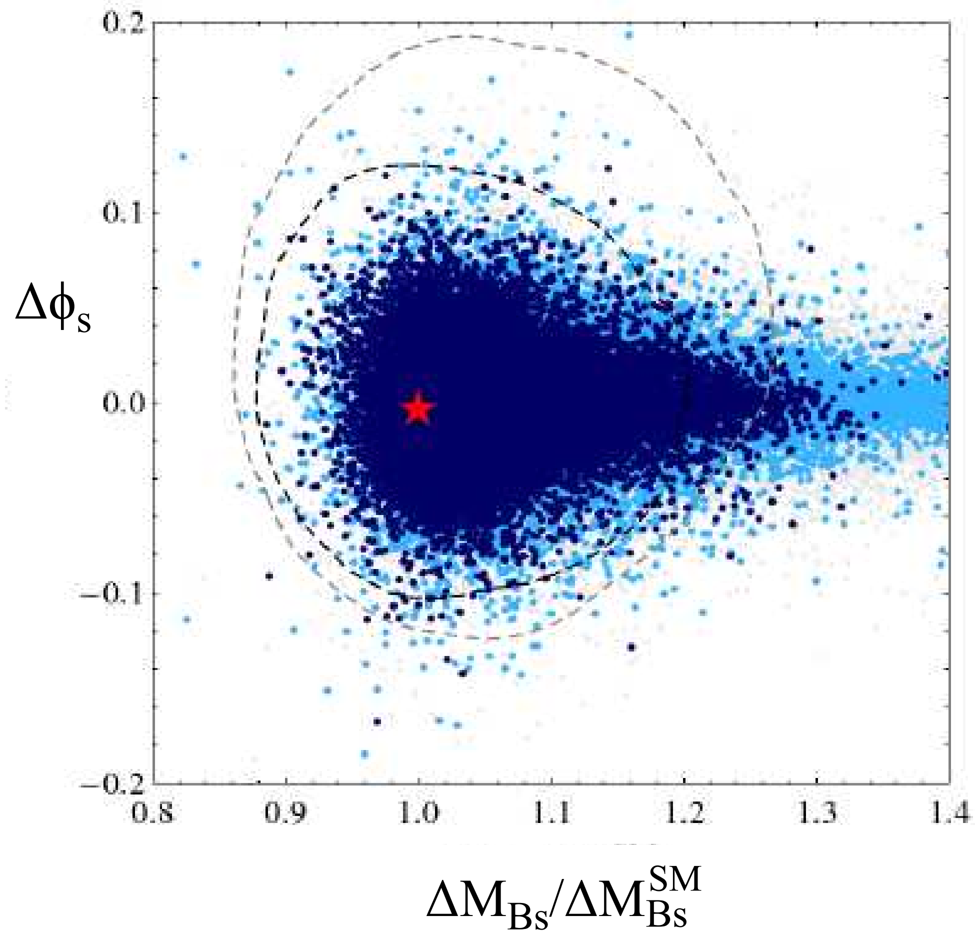
Possible "visible" [~ 5-20%] effects in
- Rare B decays ($B_s \to \mu\mu$, $B_s \to K^*\mu\mu$)

Example I: *Meson mixing in "Natural SUSY" with* U(2)^3 *flavor symm.*

Barbieri, Buttazzo, Sala, Straub, '14

Points allowed by present CMS/ATLAS data:





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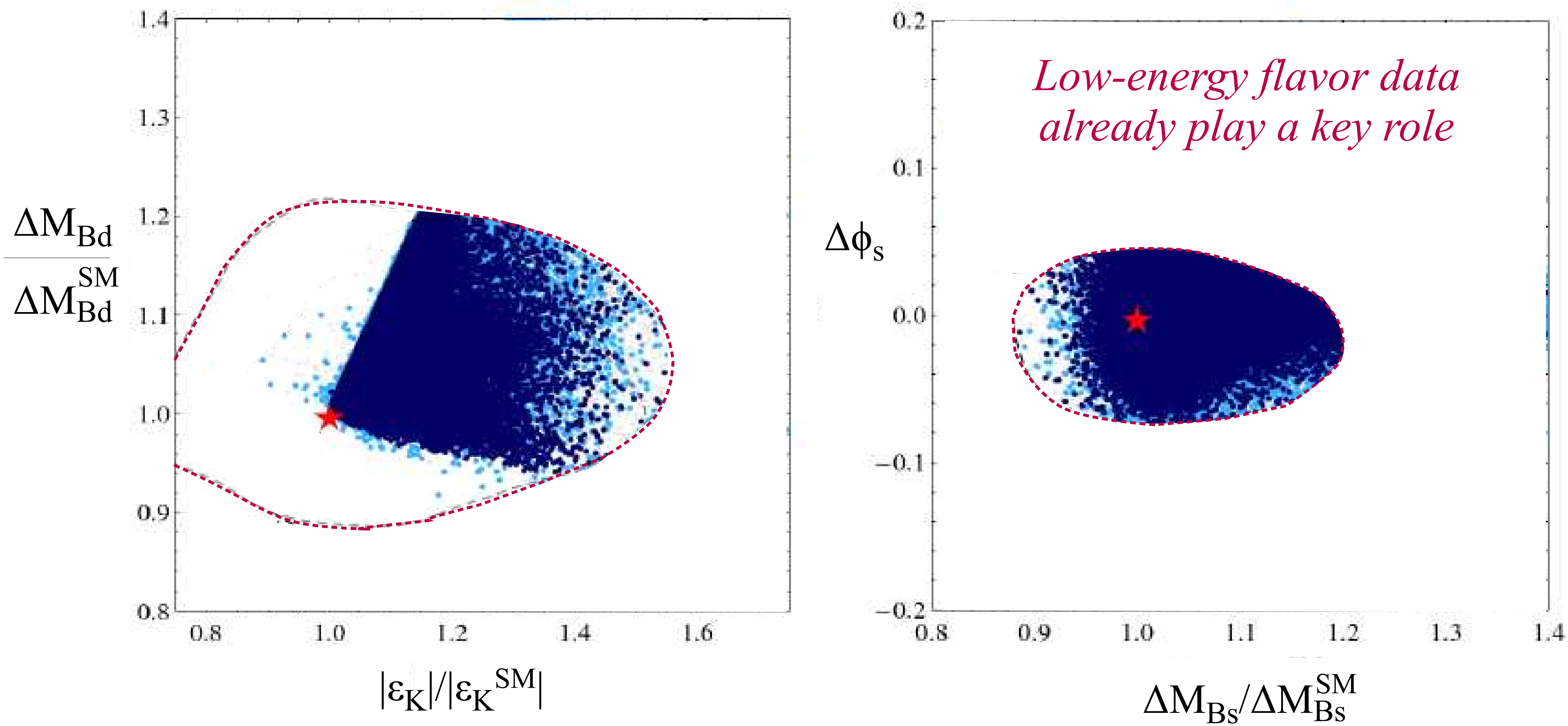
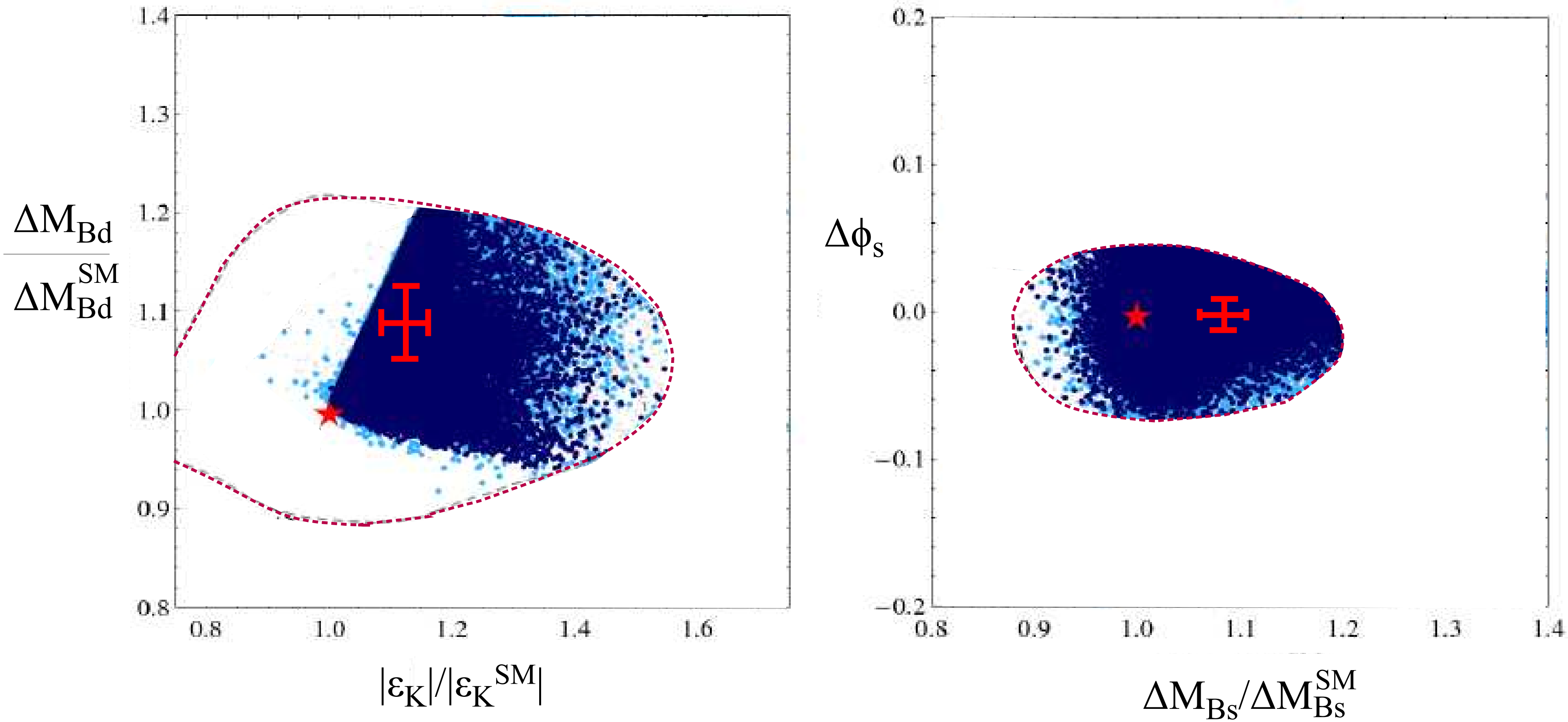
Barbieri, Buttazzo, Sala, Straub, '14

Points allowed by present CMS/ATLAS data + present flavor data



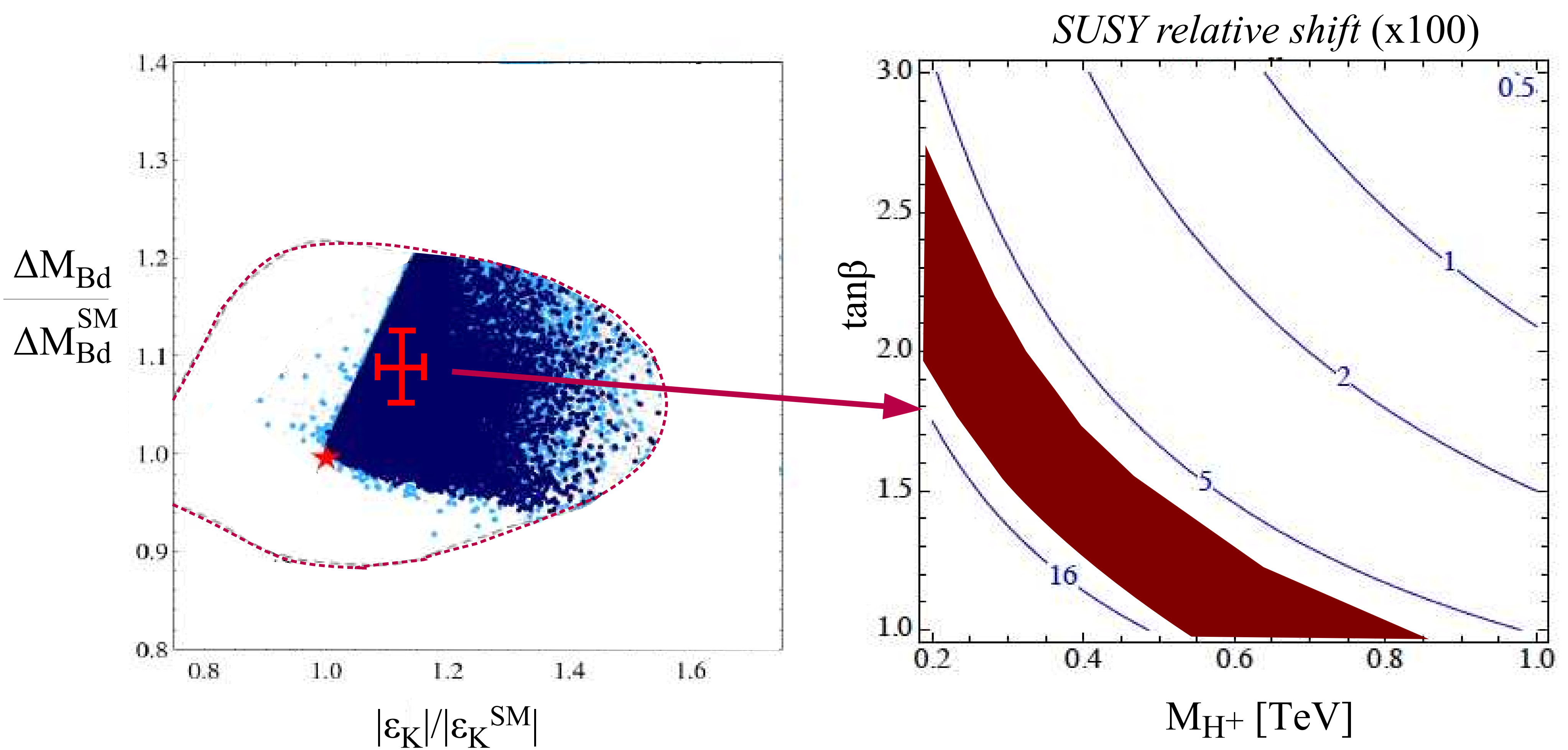
Example I: *Meson mixing in "Natural SUSY" with* U(2)^3 *flavor symm.*

Future precision expected in the HL-LHC era
[*personal estimate, taking into account also progress from Lattice-QCD & Belle-II*]



Example I: *Meson mixing in "Natural SUSY" with* $U(2)^3$ *flavor symm.*

Future precision expected in the HL-LHC era
→ full complementarity with the high-p_T program
[*combining flavor and high-p_T data essential to "decode" the NP model*]

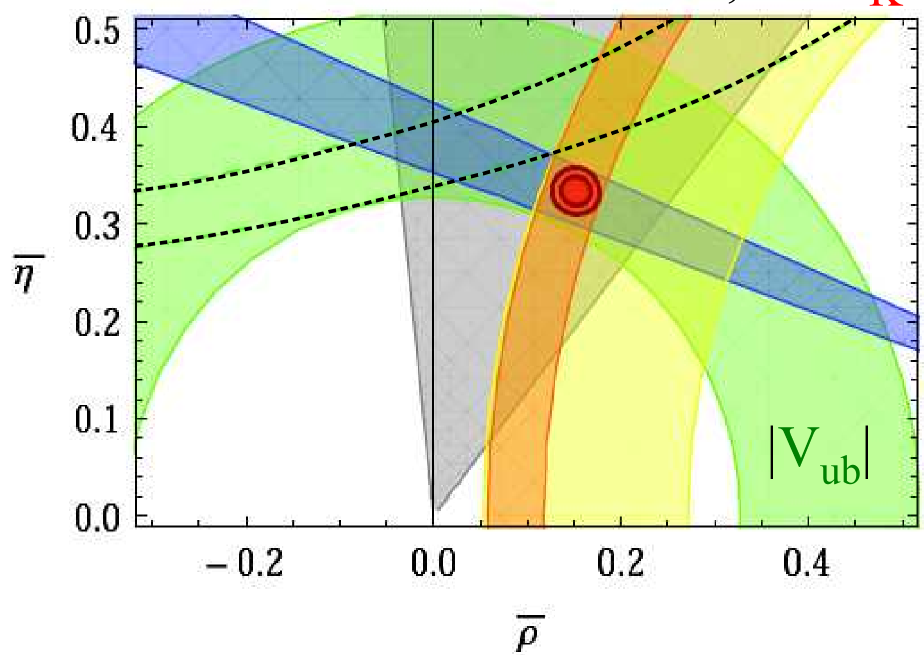


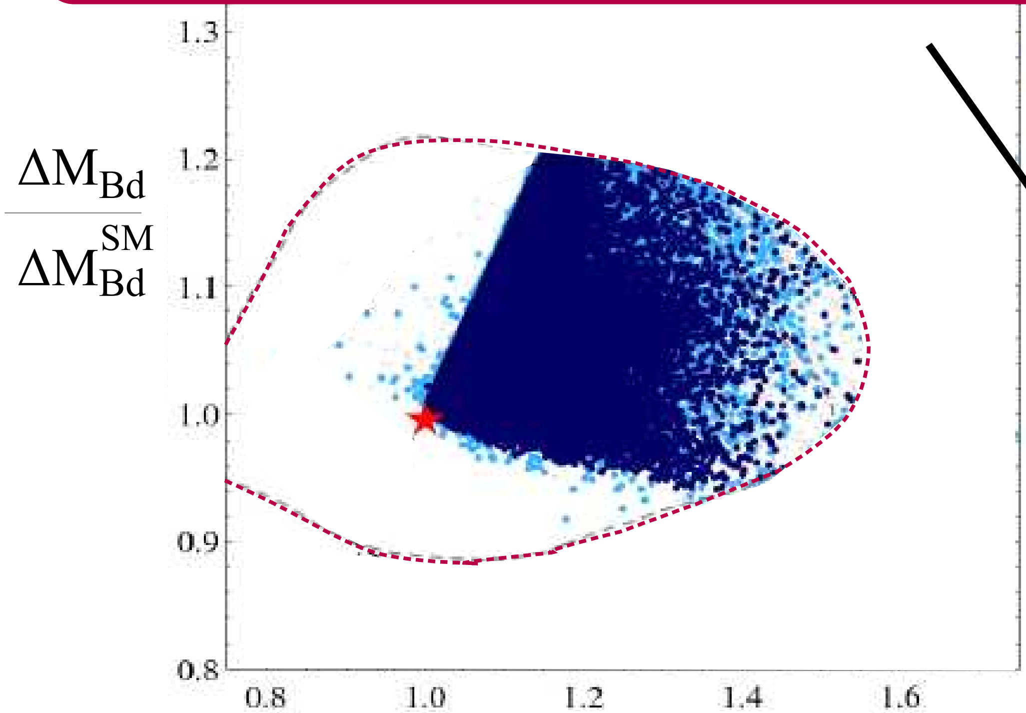
Example I: *Meson mixing in "Natural SUSY" with $U(2)^3$ flavor symm.*

N.B.: There is already a (weak) evidence of a (positive) non-standard contribution to ε_K

In order to clarify the picture we need a more clean determination of $|V_{ub}|$ & γ

SM fit, no ε_K





Beside ϕ_s, key role played by the future improvement on γ in the HL-LHC phase [→ next talk]

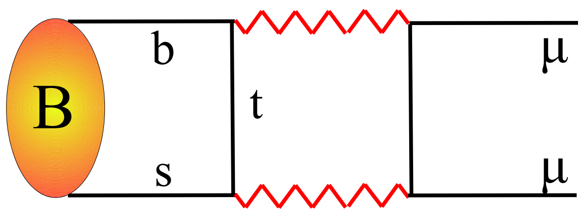
N.B.: a positive contribution to ε_K is a general feature of MFV-like SUSY models [*light stops* and/or *charged H*]

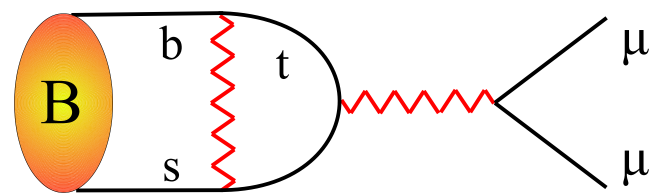
Example II: $B_{s,d} \to \mu\mu$ & SUSY

These modes are a unique source of information about flavor physics beyond the SM:

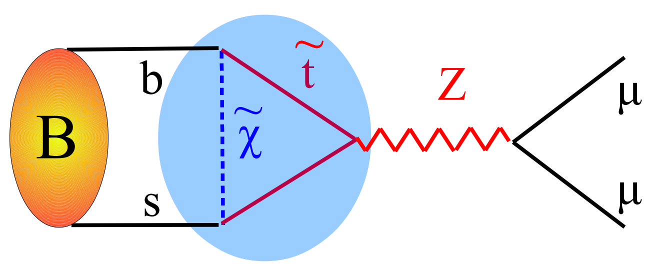
- theoretically very clean (virtually no long-distance contributions)
- particularly sensitive to FCNC *scalar currents* and FCNC *Z penguins*

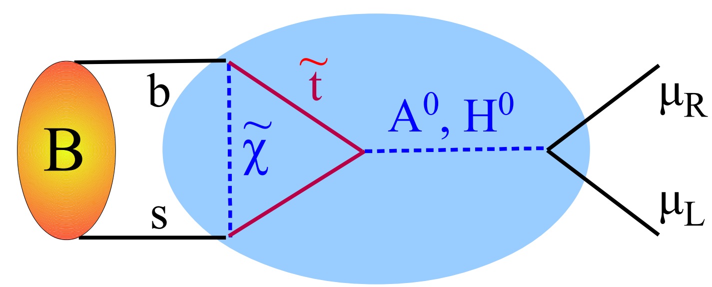
Leading SM diagrams (unitary gauge):





Possible non-SM contributions:





Relevant for BR = O(SM)

Possible large enhancement (e.g. SUSY @ large tanβ)

Example II: $B_{s,d} \to \mu\mu$ & SUSY

Recent developments both on the theory and on the experimental side:

$$\overline{BR}_{s,SM} = (3.66 \pm 0.23)\times 10^{-9}$$

(time-integrated average)

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser '13
+
progress from Lattice QCD

$$\overline{BR}_{s}^{(exp)} = (2.8 \pm 0.7)\times 10^{-9}$$

LHCb + CMS '13

$$BR_{d,SM} = (1.06 \pm 0.09)\times 10^{-10}$$

$$BR_{d}^{(exp)} = (3.9 \pm 1.5)\times 10^{-10}$$

An overall th. error below 5% is definitely within the reach in the next few years

At this stage there is perfect compatibility, but we are only at the beginning...

Example II: $B_{s,d} \to \mu\mu$ & SUSY

$\overline{BR}_{s,SM} = (3.66 \pm 0.23)\times 10^{-9}$

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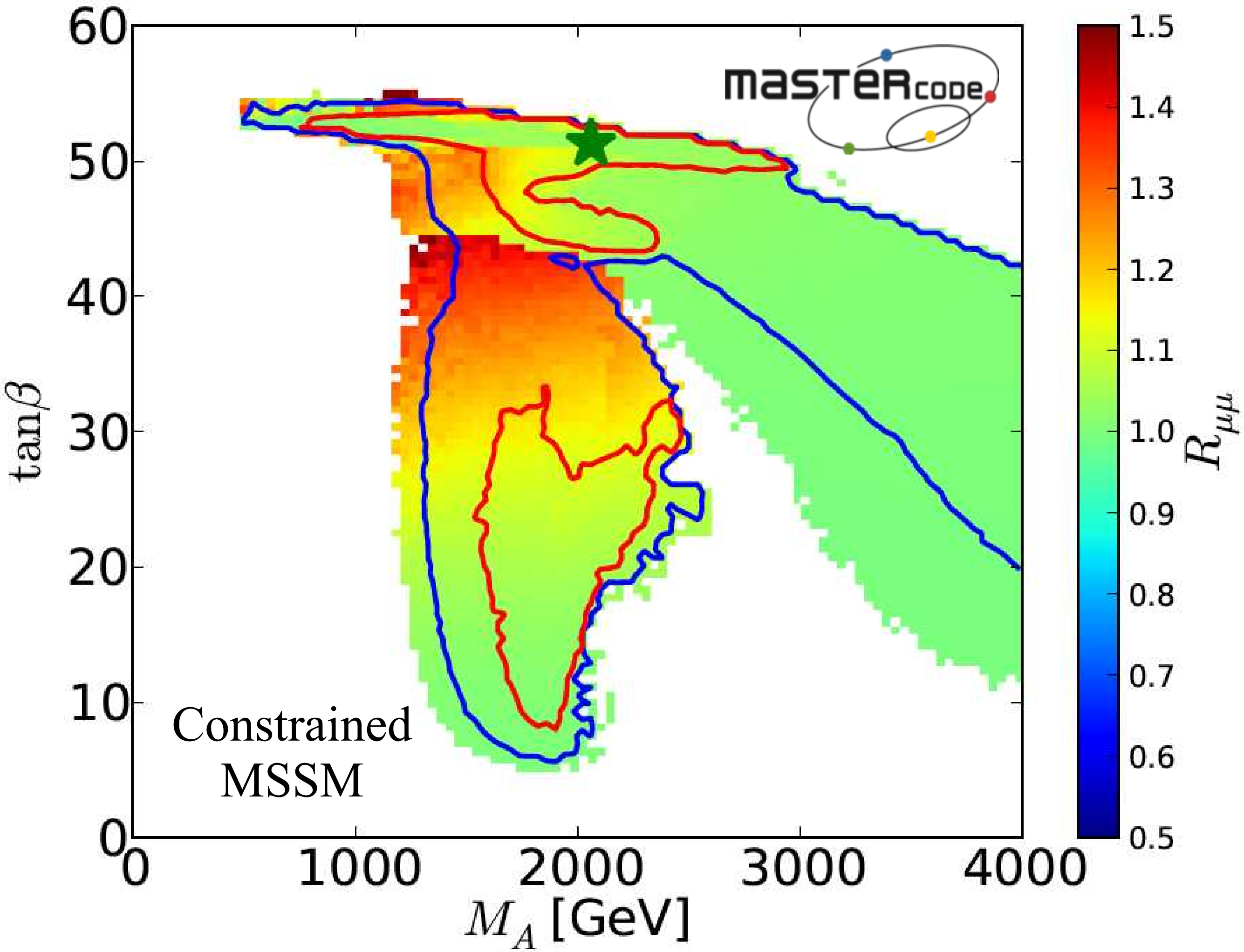

The possible large effects occurring in the MSSM at large tanβ are ruled out...

...but more precision on this mode can still provide very valuable infos

Buchmueller *et al.* [Mastercode]
Mahmoudi *et al.* [SuperIso]
Roszkowski *et al.* '12
Haisch & Mahmoudi '12
Althmanshofer *et al.* '13
…

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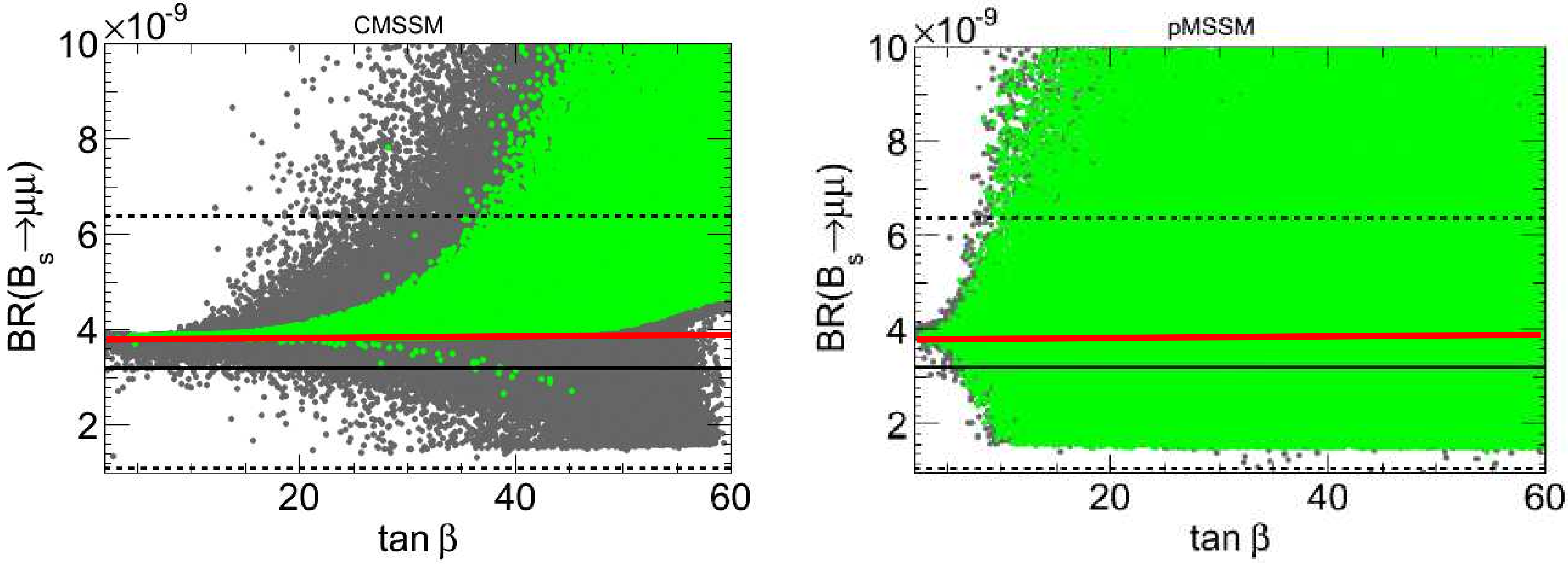


Arbey *et al.* '12

More exotic models and observables

Absence of clean New Physics signals so far

⬇

Need to search for NP with a broad-spectrum perspective
beyond the "usual suspects", both in terms of models (*SUSY*, *MFV*, ...)
and in terms of observables (ε_K, ϕ_s, $B \to \mu\mu$, ...)

⬇

Long-list of potentially interesting of flavor-changing observables
that could be significantly improved in the HL-LHC era.

E.g: $B_s \to \tau\mu$ [↔ lepto-quark models (renewed interest)]

$B,D \to X + \mu\nu \to \mu\mu + \mu\nu$ [↔ exotic light new particles]

⋮

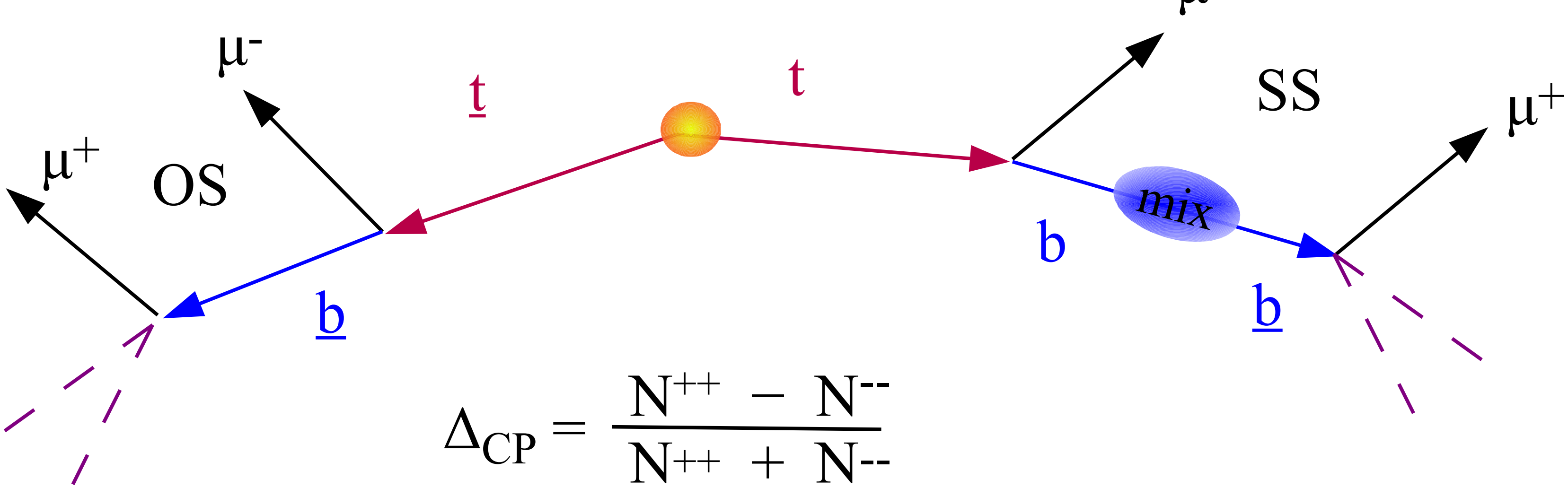
- More exotic models and observables

<u>A less-obvious example:</u> Top-tagged B-physics

The large number of top pairs expected at the HL-LHC open the possibility of new studies in b physics (especially CPV studies) using "*top-tagged b decays*"

Gedalia *et al.* '13

E.g.:



$$\Delta_{CP} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Clean CPV observable, expected to be very small ($< 10^{-4}$) in the SM.

Not competitive with "standard" probes of CPV in B-meson mixing, but sensitive also to other NP effects (<u>direct & indirect CVP in any step of the decay chain</u>: t, b & c decays)

Semi-realistic estimate [Gedalia *et al.* '13]: $\sigma(\Delta_{CP}) \sim 5.0\ (1.4) \times 10^{-4}$ with 300 (3000) fb^{-1}

Conclusions

- Flavor-changing transitions represent a "unique window" on BSM physics. *There is still a lot to learn & explore in the HL-LHC phase.*

- The "Usual Suspects" (ε_K, ϕ_s, $B \to \mu\mu$, ...) may already hide NP signals @ 10% level in well-motivated models (e.g. "natural SUSY") → need combined th+exp precision at the few% level → possible only @ HL-LHC (significant improvement both in the precision on the rare modes + quality of CKM fits)

- The HL-LHC program will also allow us to significantly improve the searches for more exotic channels ($\tau \to 3\mu$, "top-tagged B-physics", $B \to \tau\mu$, & *many additional channels not covered in this talk...*) that provide invaluable tools for unbiased searches of NP.