Heavy Flavours:

low energy precision and high energy collisions

Tobias Hurth

LPSC Grenoble, 17.12.2009

Plan of the talk

Flavour in the SM

Flavour problem of New Physics

Flavour@high-p_T interplay

Concrete examples of new physics search

Flavour Physics within the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge}(A_i, \psi_i) + \mathcal{L}_{Higgs}(\Phi, \psi_i, v)$$

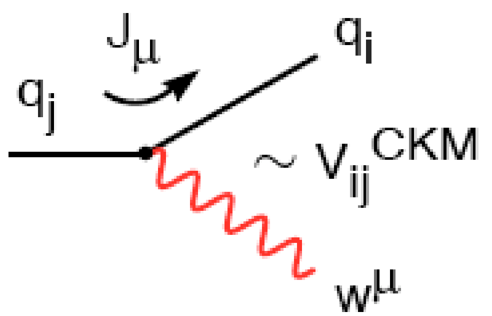
- Electroweak precision data (SLC,LEP, Tevatron) mainly confirmed SM predictions within the gauge sector.

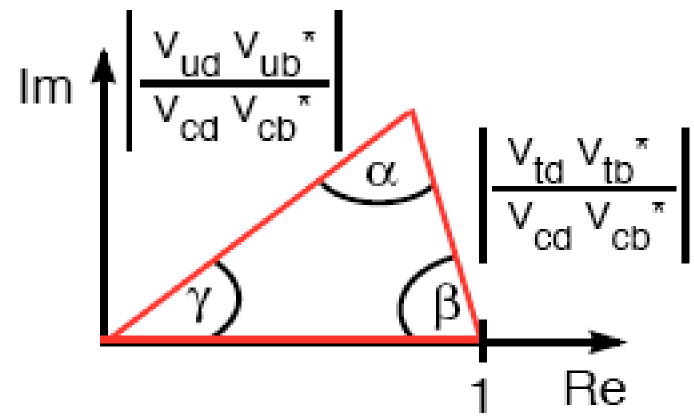
- Scalar Higgs particle Φ not found yet: mechanism of mass generation is an open issue.

- Flavour sector: testing the SM beyond the gauge interactions

Flavour physics is that part of the SM which differentiates between the three families of fundamental fermions.

CKM mechanism of flavour mixing and CP violation: V_{CKM}, J_{CKM}

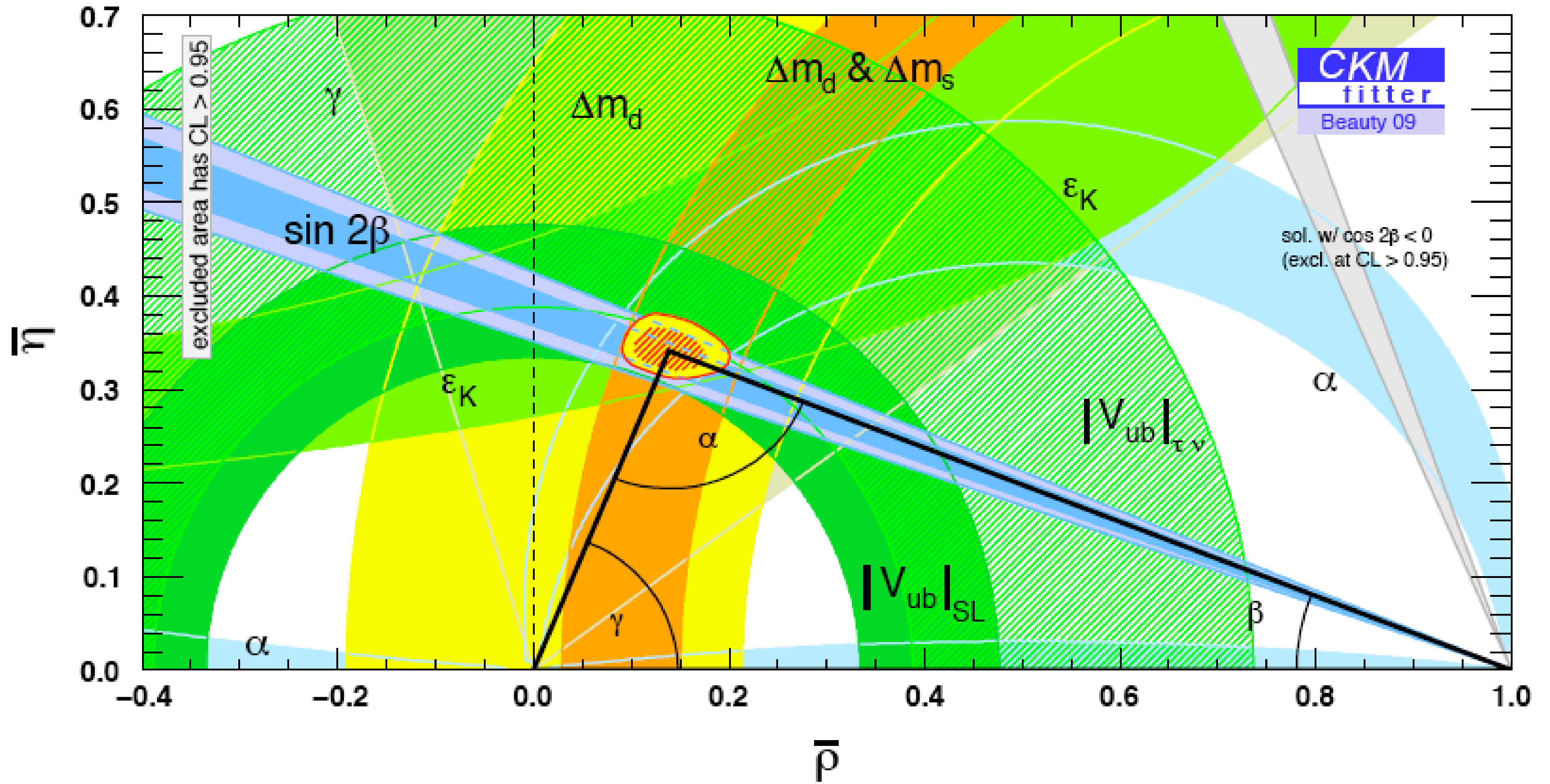




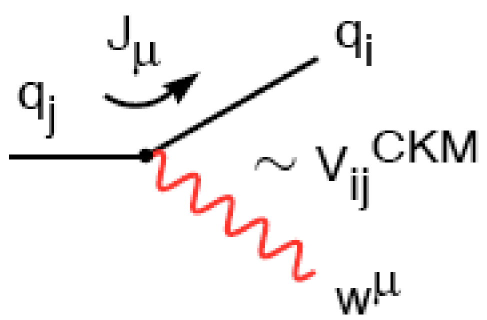
$$Im[V_{ij}\, V_{kl}\, V^*_{il}\, V^*_{kj}] = J_{\text{CKM}} \sum_{m,n=1}^{3} \epsilon_{ikm}\, \epsilon_{jln} \qquad J_{\text{CKM}} \sim \mathcal{O}(10^{-5})$$

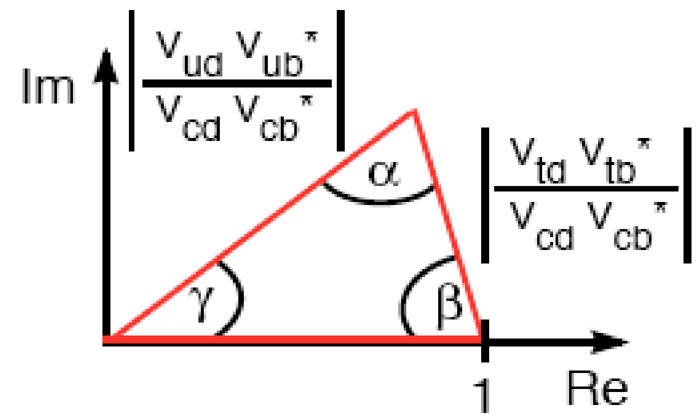
All present measurements (BaBar, Belle, CLEO, CDF, D0,....)
of rare decays ($\Delta F = 1$),
of mixing phenomena ($\Delta F = 2$) and
of all CP violating observables at tree and loop level
are consistent with the CKM theory.

Impressing success of SM and CKM theory !!

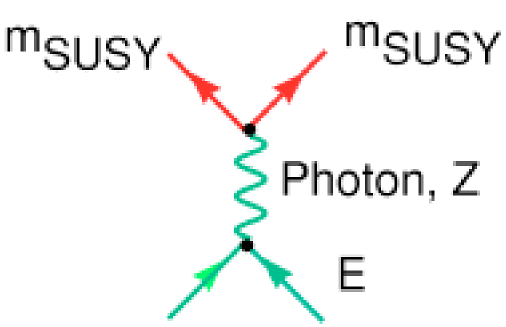

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
–0.4
–0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\bar{\eta}$
$\bar{\rho}$
excluded area has CL > 0.95
γ
Δm_d
Δm_d & Δm_s
CKM
fitter
Beauty 09
ε_K
sin 2β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
ε_K
α
α
$|V_{ub}|_{\tau\nu}$
$|V_{ub}|_{SL}$
γ
β
α

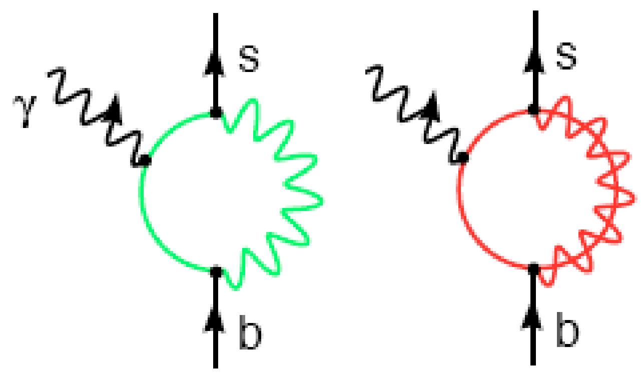
CKM mechanism of flavour mixing and CP violation: V_{CKM}, J_{CKM}





This success is somehow unexpected !!





Flavour-changing-neutral-currents as loop-induced processes are highly-sensitive probes for possible new degrees of freedom

Impressing success of SM and CKM theory !!

From left, Yoichiro Nambu, Makoto Kobayashi and Toshihide Masukawa, who shared the Nobel Prize in Physics on Tuesday

Nobel Prize 2008

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1] to the hadron system, we have some limitations on the hadron model. It is well known that there exists, in the case of the triplet model, a difficulty of the strangeness changing neutral current and that the quartet model is free from this difficulty. Furthermore, Maki and one of the present authors (T.M.) have shown[2] that, in the latter case, the strong interaction must be chiral $SU(4)\times SU(4)$ invariant as precisely as the conservation of the third component of the iso-spin I_3. In addition to these arguments, for the theory to be realistic, CP-violating interactions should be incorporated in a gauge invariant way. This requirement will impose further limitations on the hadron model and the CP-violating interaction itself. The purpose of the present paper is to investigate this problem. In the following, it will be shown that in the case of the above-mentioned quartet model, we cannot make a CP-violating interaction without introducing any other new fields when we require the following conditions: a) The mass of the fourth member of the quartet, which we will call ζ, is sufficiently large, b) the model should be consistent with our well-established knowledge of the semi-leptonic processes. After that some possible ways of bringing CP-violation into the theory will be discussed.

We consider the quartet model with a charge assignment of Q, $Q-1$, $Q-1$ and Q for p, n, λ and ζ, respectively, and we take the same underlying gauge group $SU_{weak}(2)\times U(1)$ and the scalar doublet field φ as those of Weinberg's original model.[1] Then, hadronic parts of the Lagrangian can be divided in the following way:

$$\mathcal{L}_{had}=\mathcal{L}_{kin}+\mathcal{L}_{mass}+\mathcal{L}_{strong}+\mathcal{L}',$$

where $\mathcal{L}_{kin}$ is the gauge-invariant kinetic part of the quartet field, q, so that it contains interactions with the gauge fields. $\mathcal{L}_{mass}$ is a generalized mass term of q, which includes Yukawa couplings to φ since they contribute to the mass of q through the spontaneous breaking of gauge symmetry. $\mathcal{L}_{strong}$ is a strong-interaction part which conserves I_3 and therefore chiral $SU(4)\times SU(4)$ invariant.[2] We assume C- and P-invariance of $\mathcal{L}_{strong}$. The last term denotes residual interaction parts if they exist. Since $\mathcal{L}_{mass}$ includes couplings with φ, it has possibilities of violating CP-conservation. As is known as Higgs phenomena,[3] three massless components of φ can be absorbed into the massive gauge fields and eliminated from the Lagrangian. Even after this has been done, both scalar and pseudoscalar parts remain in $\mathcal{L}_{mass}$. For the mass term, however, we can eliminate such pseudoscalar parts by applying an appropriate constant gauge transformation on q, which does not affect on $\mathcal{L}_{strong}$ due to gauge invariance.

Now we consider possible ways of assigning the quartet field to representations of the $SU_{weak}(2)$. Since this group is commutative with the Lorentz transformation, the left and right components of the quartet field, which are respectively defined as $q_L=\frac{1}{2}(1+\gamma_5)q$ and $q_R=\frac{1}{2}(1-\gamma_5)q$, do not mix each other under the gauge transformation. Then, each component has three possibilities:

A) $\mathbf{4}=\mathbf{2}+\mathbf{2}$,

B) $\mathbf{4}=\mathbf{2}+\mathbf{1}+\mathbf{1}$,

C) $\mathbf{4}=\mathbf{1}+\mathbf{1}+\mathbf{1}+\mathbf{1}$,

where on the r.h.s., $\mathbf{n}$ denotes an n-dimensional representation of $SU(2)$. The present scheme of charge assignment of the quartet does not permit representations of $n\geq 3$. As a result, we have nine possibilities which we will denote by (A, A), (A, B), ---, where the former (latter) in the parentheses indicates the transformation properties of the left (right) component. Since all members of the quartet should take part in the weak interaction, and size of the strangeness changing neutral current is bounded experimentally to a very small value, the cases of (B, C), (C, B) and (C, C) should be abandoned. The models of (B, A) and (C, A) are equivalent to those of (A, B) and (A, C), respectively, except relative signs between vector and axial vector parts of the weak current. Since g_A/g_V ratios are measured only for composite states, this difference of the relative signs would be reduced to a dynamical problem of the composite system. So, we investigate in detail the cases of (A, A), (A, B), (A, C) and (B, B).

i) Case (A, C)

This is the most natural choice in the quartet model. Let us denote two ($SU_{weak}(2)$) doublets and four singlets by L_{1L}, L_{2L}, $R_1^{(p)}$, $R_2^{(p)}$, $R_1^{(n)}$ and $R_2^{(n)}$, where superscript $p(n)$ indicates p-like (n-like) charge states. In this case, $\mathcal{L}_{mass}$ takes, in general, the following form:

$$\mathcal{L}_{mass}=\sum_{i,j=1,2}[M_{ij}^{(p)}\bar{L}_{iL}\varphi R_j^{(p)}+M_{ij}^{(n)}\bar{L}_{iL}\varepsilon\varphi^* R_j^{(n)}]+\text{h.c.},$$

$$\varphi^*=\begin{pmatrix}\varphi^-\\ \bar{\varphi}^0\end{pmatrix},\qquad \varepsilon=\begin{pmatrix}0&1\\ -1&0\end{pmatrix},\qquad (1)$$

where $M_{ij}^{(p)}$ and $M_{ij}^{(n)}$ are arbitrary complex numbers. We can eliminate three Goldstone modes χ_i by putting

$$\varphi=e^{i\lambda\cdot\chi}\begin{pmatrix}0\\ l+\sigma\end{pmatrix},\qquad (2)$$

where l is a vacuum expectation value of φ^0 and σ is a massive scalar field. Thereafter, performing a diagonalization of the remaining mass term, we obtain

$$\mathcal{L}_{mass}=\bar{q}mq\left(1+\frac{\sigma}{l}\right),$$

$$m=\begin{pmatrix}m_p&0&0&0\\ 0&m_n&0&0\\ 0&0&m_\zeta&0\\ 0&0&0&m_\lambda\end{pmatrix},\qquad q=\begin{pmatrix}p\\ n\\ \zeta\\ \lambda\end{pmatrix}.\qquad (3)$$

Then, the interaction with the gauge field in $\mathcal{L}_{kin}$ is expressed as

$$\sum_{i=1}^{3}A_\mu^i\bar{q}\Lambda_i\gamma_\mu\frac{1+\gamma_5}{2}q.\qquad (4)$$

Here, Λ_i is the representation matrix of $SU_{weak}(2)$ for this case and explicitly given by

$$\Lambda_+=\frac{\Lambda_1+i\Lambda_2}{2}=K\begin{pmatrix}0&U\\ 0&0\end{pmatrix}K^{-1},\quad \Lambda_3=\begin{pmatrix}1&0&0&0\\ 0&1&0&0\\ 0&0&-1&0\\ 0&0&0&-1\end{pmatrix},\quad K=\begin{pmatrix}1&0&0&0\\ 0&0&1&0\\ 0&1&0&0\\ 0&0&0&1\end{pmatrix},\qquad (5)$$

where U is a 2×2 unitary matrix. Here and hereafter we neglect the gauge field corresponding to $U(1)$ which is irrelevant to our discussion. With an appropriate phase convention of the quartet field we can take U as

$$U=\begin{pmatrix}\cos\theta&\sin\theta\\ -\sin\theta&\cos\theta\end{pmatrix}.\qquad (6)$$

Therefore, if $\mathcal{L}'=0$, no CP-violations occur in this case. It should be noted, however, that this argument does not hold when we introduce one more fermion doublet with the same charge assignment. This is because all phases of elements of a 3×3 unitary matrix cannot be absorbed into the phase convention of six fields. This possibility of CP-violation will be discussed later on.

ii) Case (A, B)

This is a rather delicate case. We denote two left doublets, one right doublet and two singlets by L_{1L}, L_{2L}, R_R, $R_1^{(p)}$ and $R_1^{(n)}$, respectively. The general form

of $\mathcal{L}_{mass}$ is given by

$$\mathcal{L}_{mass}=\sum_{i=1,2}[m_i\bar{L}_{iL}R_R+M_i^{(p)}\bar{L}_{iL}\varphi R_1^{(p)}+M_i^{(n)}\bar{L}_{iL}\varepsilon\varphi^*R_1^{(n)}]+\text{h.c.},$$

where m_i, $M_i^{(p)}$ and $M_i^{(n)}$ are arbitrary complex numbers. After diagonalization of mass terms (in this case, the CP-odd part of coupling with σ does not disappear in general) each multiplet can be expressed as follows:

$$L_{pL}=\frac{1+\gamma_5}{2}\begin{pmatrix}p\\ \cos\theta e^{i\alpha}n+\sin\theta e^{i\beta}\lambda\end{pmatrix},\qquad L_{\zeta L}=\frac{1+\gamma_5}{2}\begin{pmatrix}e^{i\gamma}\zeta\\ -\sin\theta e^{i\alpha}n+\cos\theta e^{i\beta}\lambda\end{pmatrix},$$

$$R_R=\frac{1-\gamma_5}{2}\begin{pmatrix}\sin\xi\cdot p+\cos\xi\cdot\zeta\\ \sin\eta\cdot n+\cos\eta\cdot\lambda\end{pmatrix},\qquad R_1^{(p)}=\frac{1-\gamma_5}{2}(\cos\xi\cdot p-\sin\xi\cdot\zeta),$$

$$R_1^{(n)}=\frac{1-\gamma_5}{2}(\cos\eta\cdot n-\sin\eta\cdot\lambda),\qquad (7)$$

where phase factors α, β and γ satisfy two relations with the masses of the quartet:

$$e^{i\gamma}m_\zeta\sin\theta\cos\xi=m_\lambda\cos\theta\sin\xi-e^{i\alpha}m_n\sin\eta,$$

$$e^{i\gamma}m_\zeta\cos\theta\cos\xi=-m_\lambda\sin\theta\cos\xi+e^{i\beta}m_n\cos\eta.\qquad (8)$$

Owing to the presence of phase factors, there exists a possibility of CP-violation also through the weak current. However, the strangeness changing neutral current is proportional to $\sin\eta\cos\eta$ and its experimental upper bound is roughly

$$\sin\eta\cos\eta\lesssim 10^{-3\sim-4}.\qquad (9)$$

Thus, making an approximation of $\sin\eta\sim 0$ (the other choice $\cos\eta\sim 0$ is less critical) we obtain from Eq. (8)

$$m_\zeta/m_p\sim\cot\theta\cdot\tan\xi,$$

$$m_\zeta/m_\lambda\sim\sin\xi/\sin\theta.\qquad (10)$$

We have no low-lying particle with a quantum number corresponding to ζ, so that m_ζ, which is a measure of chiral $SU(4)\times SU(4)$ breaking, should be sufficiently large compared to the masses of the other members. However, the present experimental results on the g_A/g_V ratios of the octet baryon β-decay would not permit $\sin\xi\gg\sin\theta$. Thus, it seems difficult to reconcile the hierarchy of chiral symmetry breaking with the experimental knowledge of the semileptonic processes.

iii) Case (B, B)

As a previous one, in this case also, occurrence of CP-violation is possible, but in order to suppress $|\Delta S|=1$ neutral currents, coefficients of the axial-vector part of $\Delta S=0$ and $|\Delta S|=1$ weak currents must take signs opposite to each other. This contradicts again the experiments on the baryon β-decay.

iv) Case (A, A)

In a similar way, we can show that no CP-violation occurs in this case as far as $\mathcal{L}'=0$. Furthermore this model would reduce to an exactly $U(4)$ symmetric one.

Summarizing the above results, we have no realistic models in the quartet scheme as far as $\mathcal{L}'=0$. Now we consider some examples of CP-violation through $\mathcal{L}'$. Hereafter we will consider only the case of (A, C). The first one is to introduce another scalar doublet field ϕ. Then, we may consider an interaction with this new field

$$\mathcal{L}'=\bar{q}\boldsymbol{\phi}C\frac{1-\gamma_5}{2}q+\text{h.c.},\qquad (11)$$

$$\boldsymbol{\phi}=\begin{pmatrix}\bar{\phi}^0&\phi^+&0&0\\ -\phi^-&\phi^0&0&0\\ 0&0&\bar{\phi}^0&\phi^+\\ 0&0&-\phi^-&\phi^0\end{pmatrix},\qquad C=\begin{pmatrix}c_{11}&0&c_{12}&0\\ 0&d_{11}&0&d_{12}\\ c_{21}&0&c_{22}&0\\ 0&d_{21}&0&d_{22}\end{pmatrix},$$

where c_{ij} and d_{ij} are arbitrary complex numbers. Since we have already made use of the gauge transformation to get rid of the CP-odd part from the quartet mass term, there remains no such arbitrariness. Furthermore, we note that an arbitrariness of the phase of ϕ cannot absorb all the phases of c_{ij} and d_{ij}. So, this interaction can cause a CP-violation.

Another one is a possibility associated with the strong interaction. Let us consider a scalar (pseudoscalar) field S which mediates the strong interaction. For the interaction to be renormalizable and $SU_{weak}(2)$ invariant, it must belong to a $(4, 4^*)+(4^*, 4)$ representation of chiral $SU(4)\times SU(4)$ and interact with q through scalar and pseudoscalar couplings. It also interacts with φ and possible renormalizable forms are given as follows:

$$\text{tr}\{G_1S^+\boldsymbol{\varphi}\}+\text{h.c.},$$

$$\text{tr}\{G_2S^+\boldsymbol{\varphi}G_2\boldsymbol{\varphi}^+S\}+\text{h.c.},$$

$$\text{tr}\{G_3'S^+\boldsymbol{\varphi}G_3'S^+\boldsymbol{\varphi}\}+\text{h.c.},\qquad (12)$$

with

$$\boldsymbol{\varphi}=\begin{pmatrix}\bar{\varphi}^0&\varphi^+&0&0\\ -\varphi^-&\varphi^0&0&0\\ 0&0&\bar{\varphi}^0&\varphi^+\\ 0&0&-\varphi^-&\varphi^0\end{pmatrix},$$

where G_i is a 4×4 complex matrix and we have used a 4×4 matrix representation for S. It is easy to see that these interaction terms can violate CP-conservation.

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{weak}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix}\cos\theta_1&-\sin\theta_1\cos\theta_3&-\sin\theta_1\sin\theta_3\\ \sin\theta_1\cos\theta_2&\cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3e^{i\delta}&\cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3e^{i\delta}\\ \sin\theta_1\sin\theta_2&\cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3e^{i\delta}&\cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3e^{i\delta}\end{pmatrix}\qquad (13)$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq 0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extensions of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one of them. We can easily see that CP-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

1) S. Weinberg, Phys. Rev. Letters 19 (1967), 1264; 27 (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters 12 (1964), 132; 13 (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters 13 (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters 28 (1972), 1494.

Errata

Equation (13) should read as

$$\begin{pmatrix}\cos\theta_1&-\sin\theta_1\cos\theta_3&-\sin\theta_1\sin\theta_3\\ \sin\theta_1\cos\theta_2&\cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3e^{i\delta}&\cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3e^{i\delta}\\ \sin\theta_1\sin\theta_2&\cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3e^{i\delta}&\cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3e^{i\delta}\end{pmatrix}.\qquad (13)$$

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extensions of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one of them. We can easily see that CP-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

1) S. Weinberg, Phys. Rev. Letters **19** (1967), 1264; **27** (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13** (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1494.

Errata:

Equation (13) should read as

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

However,....

- CKM mechanism is the dominating effect for CP violation and flavour mixing in the quark sector;

  but there is still room for sizable new effects and new flavour structures (the flavour sector has only be tested at the 10% level in many cases).

- The SM does not describe the flavour phenomena in the lepton sector.

However,...

- CKM mechanism is the dominating effect for CP violation and flavour mixing in the quark sector;

  but there is still room for sizable new effects and new flavour structures (the flavour sector has only be tested at the 10% level in many cases).

- The SM does not describe the flavour phenomena in the lepton sector.

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge}(A_i, \psi_i) + \mathcal{L}_{Higgs}(\Phi, \psi_i, v)$$

- Gauge principle governs the gauge sector of the SM.

- No guiding principle in the flavour sector:

  CKM mechanism (3 Yukawa SM couplings) provides a phenomenological descripton of quark flavour processes, but leaves significant hierarchy of quark masses and mixing parameters unexplained.

Many open fundamental questions of particle physics are related to flavour :

- How many families of fundamental fermions are there ?
- How are neutrino and quark masses and mixing angles are generated ?
- Do there exist new sources of flavour and CP violation ?
- Is there CP violation in the QCD gauge sector ?
- Relations between the flavour structure in the lepton and quark sector ?

Flavour problem of New Physics

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \dots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}
- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\, d)^2 \qquad \Rightarrow \quad \Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$$

(tree-level, generic new physics)

Flavour problem of New Physics

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{NP}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}
- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\,d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\,d)^2 + c^{New}/\Lambda_{NP}^2 \times (\bar{s}\,d)^2 \qquad \Rightarrow \quad \Lambda_{NP} > 10^4\,\text{TeV}$$

(tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)

(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow \Lambda_{NP} \leq 1\text{TeV}$

- EW precision data $\leftrightarrow$ little hierarchy problem $\Rightarrow \Lambda_{NP} \sim 3 - 10\text{TeV}$

Possible New Physics at the TeV scale has to have a very non-generic flavour structure

Flavour problem of New Physics

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}

- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\, d)^2 \qquad \Rightarrow \quad \Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$$

(tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)

  (i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow \Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$

- EW precision data $\leftrightarrow$ little hierarchy problem $\Rightarrow \Lambda_{\mathrm{NP}} \sim 3 - 10\mathrm{TeV}$

Ambiguity of new physics scale from flavour data

$$(\, C^i_{\mathrm{SM}}/M_W + C^i_{\mathrm{NP}}\,/\Lambda_{\mathrm{NP}}\,) \times \mathcal{O}_i$$

Minimal flavour violation hypothesis

- SM gauge interactions are universal in quark flavour space:

  flavour symmetry $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

- Symmetry is only broken by the Yukawa couplings Y_U and Y_D responsible for the quark masses

- Any new physics model in which all flavour- and CP-violating interactions can be linked to the known Yukawa couplings is MFV

- RG-invariant definition based on the flavour symmetry:
  Yukawa couplings are introduced as background values of fields (spurions) transforming under the flavour group

  d'Ambrosio,Giudice,Isidori,Strumia,hep-ph/0207036 Chivukula,Georgi,Phys.Lett.B188(1987)99

Minimal flavour violation hypothesis

- SM gauge interactions are universal in quark flavour space:

  flavour symmetry $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

- Symmetry is only broken by the Yukawa couplings Y_U and Y_D responsible for the quark masses

- Any new physics model in which all flavour- and CP-violating interactions can be linked to the known Yukawa couplings is MFV

- RG-invariant definition based on the flavour symmetry:
  Yukawa couplings are introduced as background values of fields (spurions) transforming under the flavour group

  d'Ambrosio,Giudice,Isidori,Strumia,hep-ph/0207036 Chivukula,Georgi,Phys.Lett.B188(1987)99

- MFV implies model-independent relations between FCNC processes

  $\Delta F = 2$ UTfit,arXiv:0707.0636 $\Delta F = 1$ H.,Isidori,Kamenik,Mescia,arXiv:0807.5039

  Best $\Delta F = 1$ candidates $B_{d,s} \to \ell^+\ell^-$ and $K_{u,d} \to \pi\nu\bar{\nu}$

- The usefulness of MFV-bounds/relations is obvious; any measurement beyond those bounds indicate the existence of new flavour structures

- In MFV CKM phase only source of CP violation:
  all phase measurements are not sensitive to new physics

- In MFV models with one Higgs doublet, all FCNC processes with external d-type quarks are governed by $(Y_U Y_U^\dagger)_{ij} \approx y_t^2 V_{3i}^* V_{3j}$ CKM hierarchy

- The MFV hypothesis is far from being verified

  New spurions allowed: Next-to-MFV

MFV as a substitute for R-parity

Nikolidakis,Smith,arXiv:0710.3129

- Surprisingly, MFV sufficient to forbid a too fast proton decay
- MFV hypothesis applied to R-parity violating terms: spurion expansion lead to suppression by neutrino masses and light-fermion masses
- Proton decay could be very close to present bounds

Example: Supersymmetry

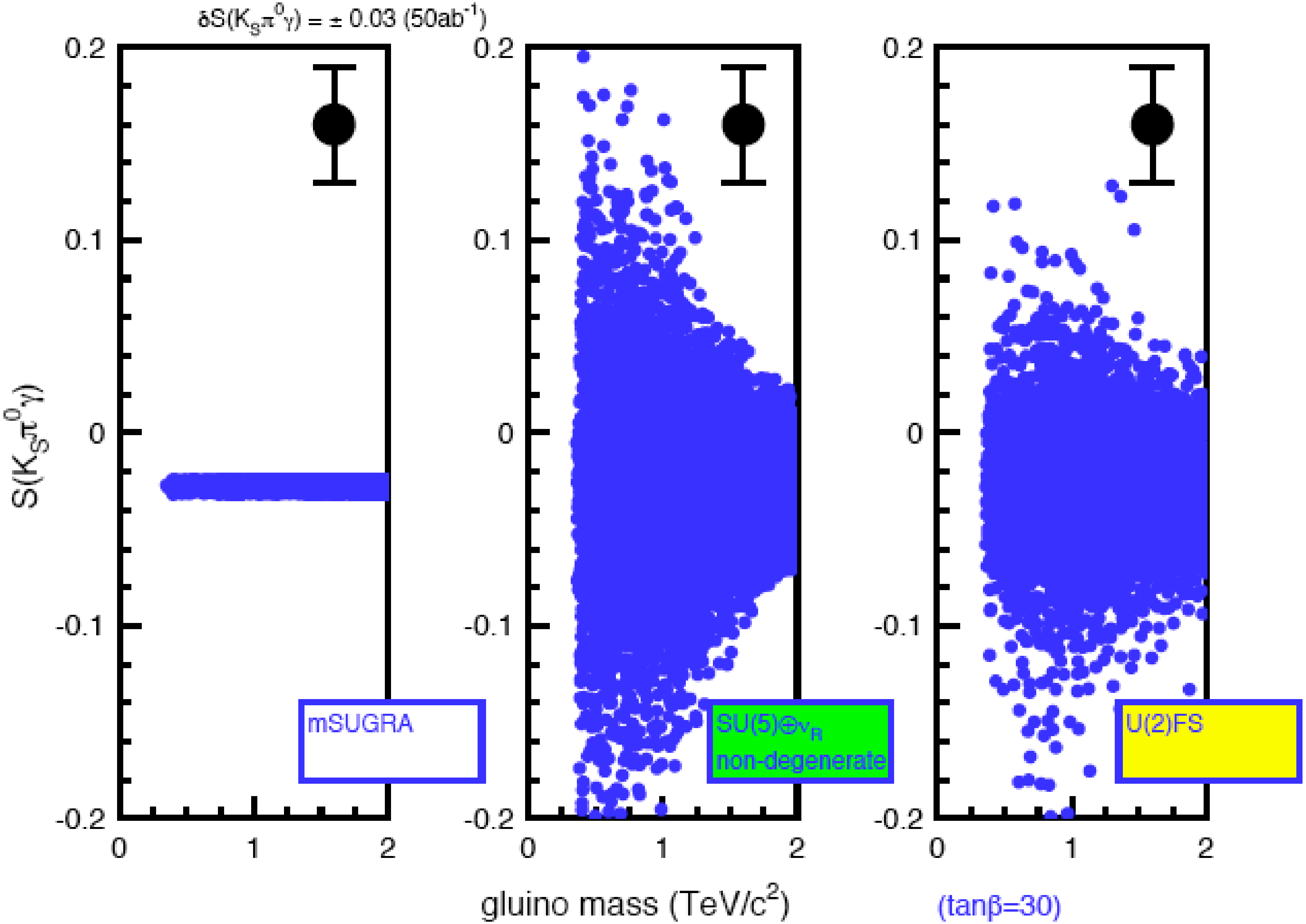
- In the general MSSM too many contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix

- Possible solutions:
  - Decoupling: Sfermion mass scale high
    (i.e. split supersymmetry)
  - Super-GIM: Sfermion masses almost degenerate
    (i.e. gauge-mediated supersymmetry breaking)
  - Alignment: Sfermion mixing suppressed

- Dynamics of flavour $\leftrightarrow$ mechanism of SUSY breaking
  ($BR(b \to s\gamma) = 0$ in exact supersymmetry)

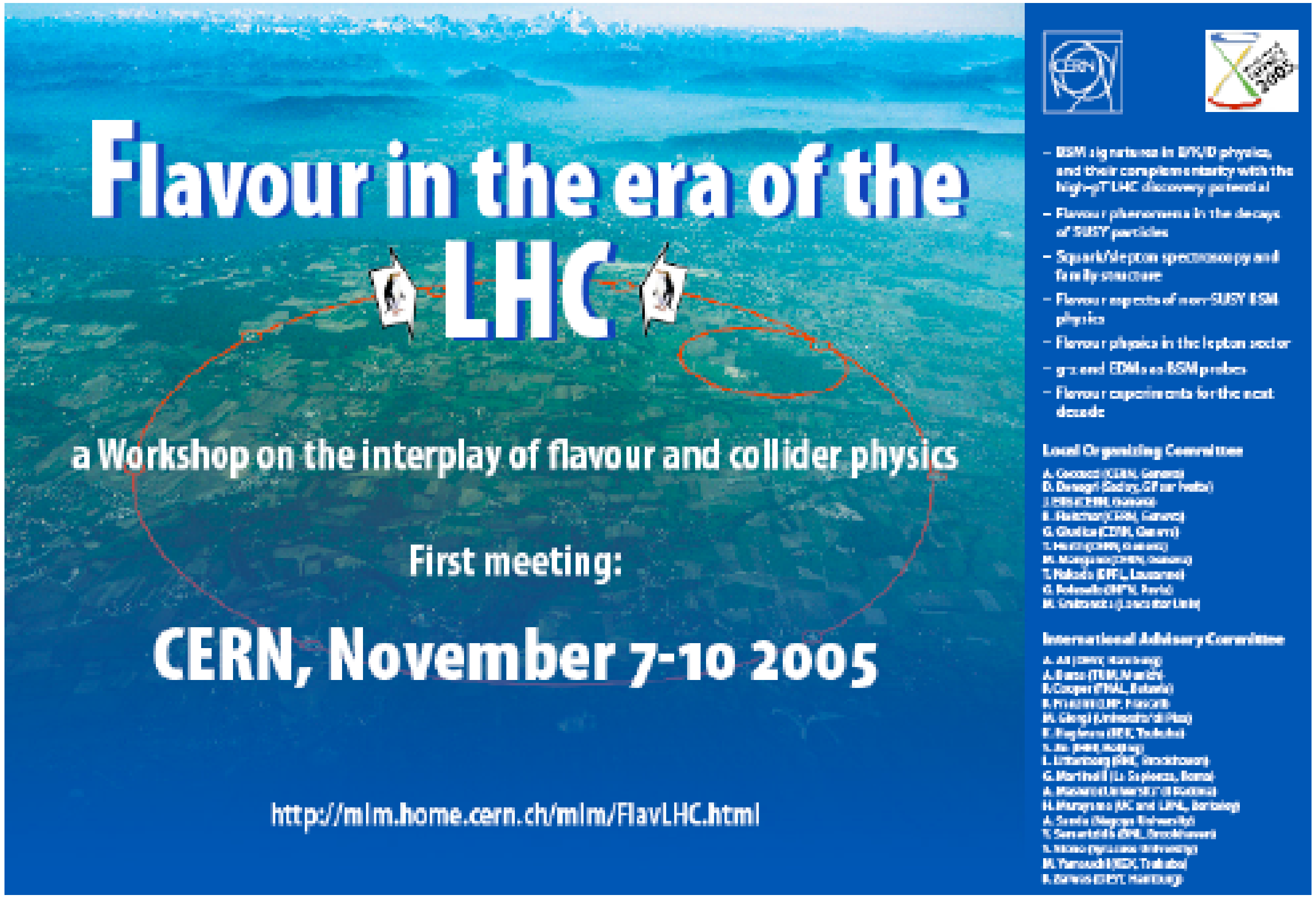
⇒ Discrimination between various SUSY-breaking mechanism

Goto,Okada,Shindou,Tanaka,arXiv:0711.2935



Expected Super-B sensitivity ($50ab^{-1}$)

⇒ CERN workshop on the interplay of flavour and collider physics
Fleischer,Hurth,Mangano see http://mlm.home.cern.ch/mlm/FlavLHC.html



5 meetings between 11/2005 and 3/2007

arXiv:0801.1800 [hep-ph] "Collider aspects of flavour physics at high Q"

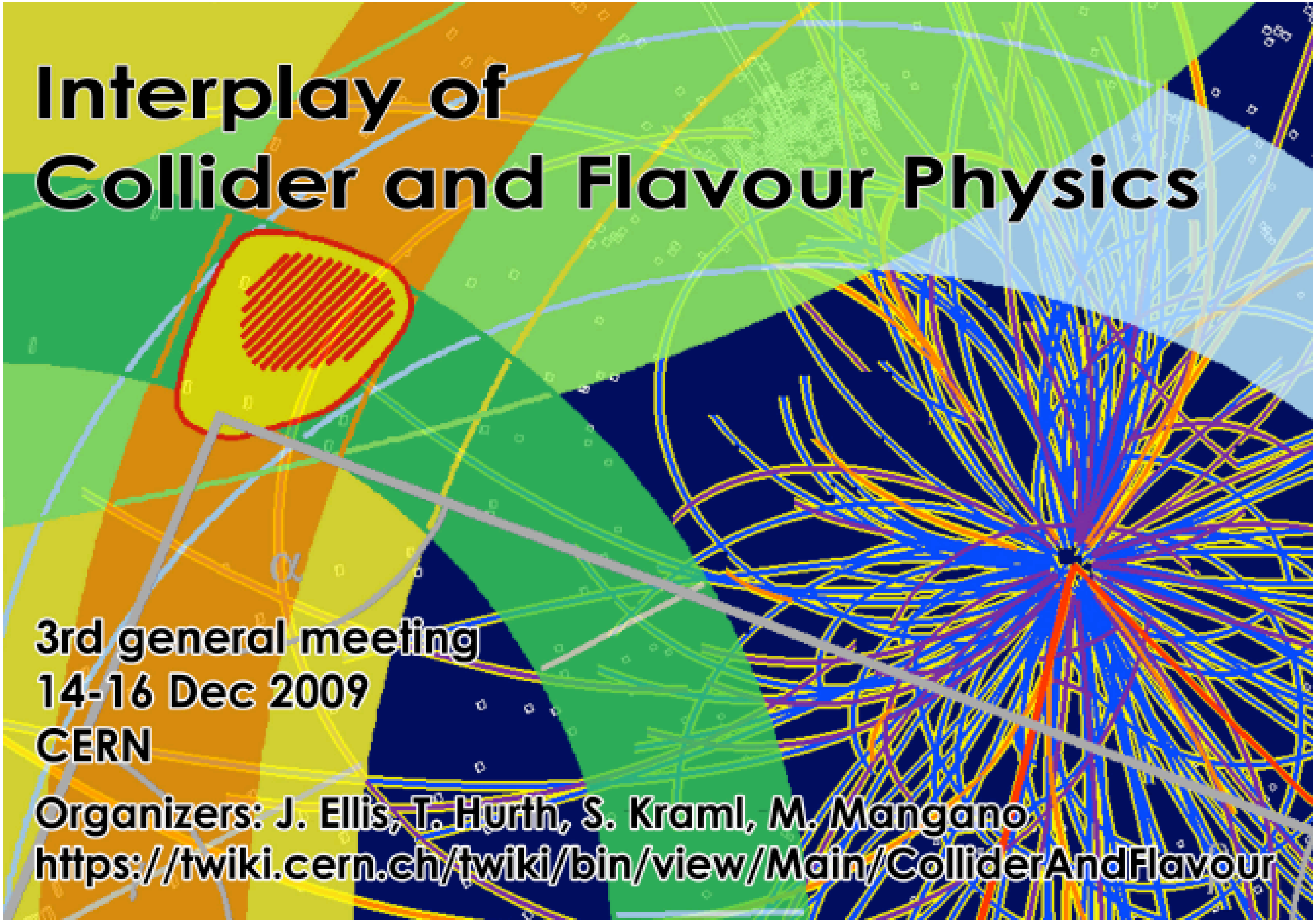
arXiv:0801.1833 [hep-ph] "B, D and K decays"

arXiv:0801.1826 [hep-ph] "Flavour physics of leptons and dipole moments"

published in EPJC 57 (2008) 1-492

and in Advances in the Physics of Particles and Nuclei, Vol 29, 480p, 2009

Follow-up workshop



Flavour@high-p_T interplay   some spotlights

Correlations of high-p_T and flavour physics

How can flavour data help to interprete high-p_T physics ?

What can ATLAS/CMS tell us about flavour ?

Can ATLAS/CMS exclude MFV ?

Can we ignore flavour when analysing possible

new physics at the electroweak scale?

Flavour constraints in the cMSSM

Ronga et al., arXiv:0801.1833

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

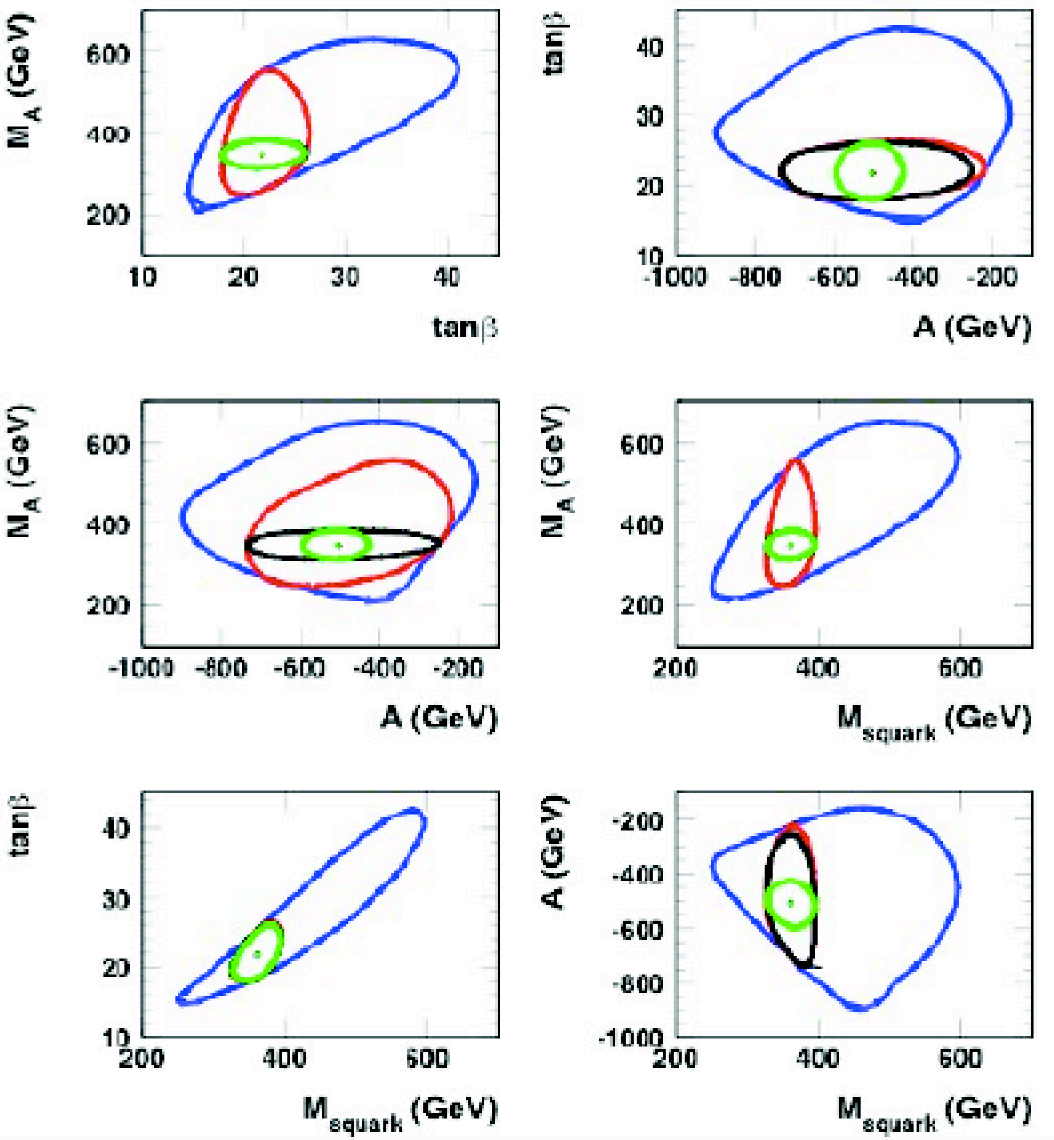
"Master Layer"
steers communication between the individual calculations / codes

"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)

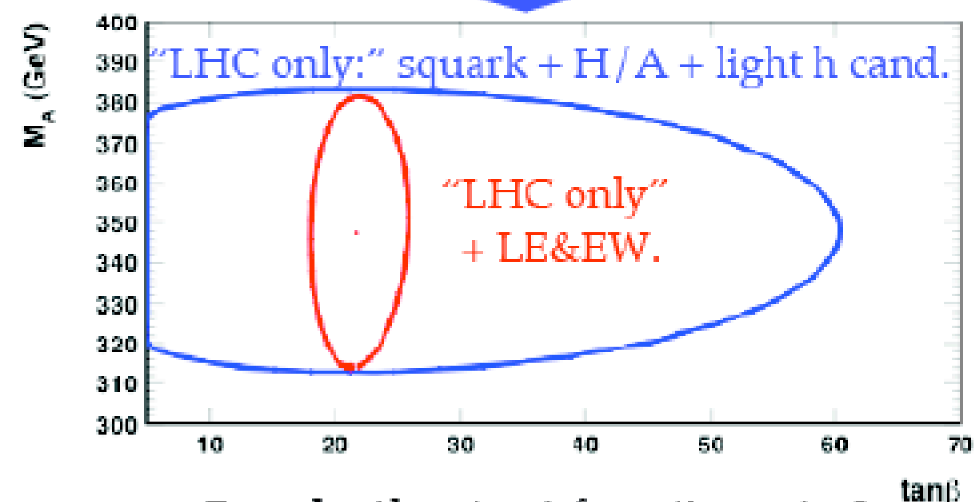
"other observables"
e.g. cosmology constraints
NOT yet included but on to-do-list

Courtesy of Oliver Buchmüller



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



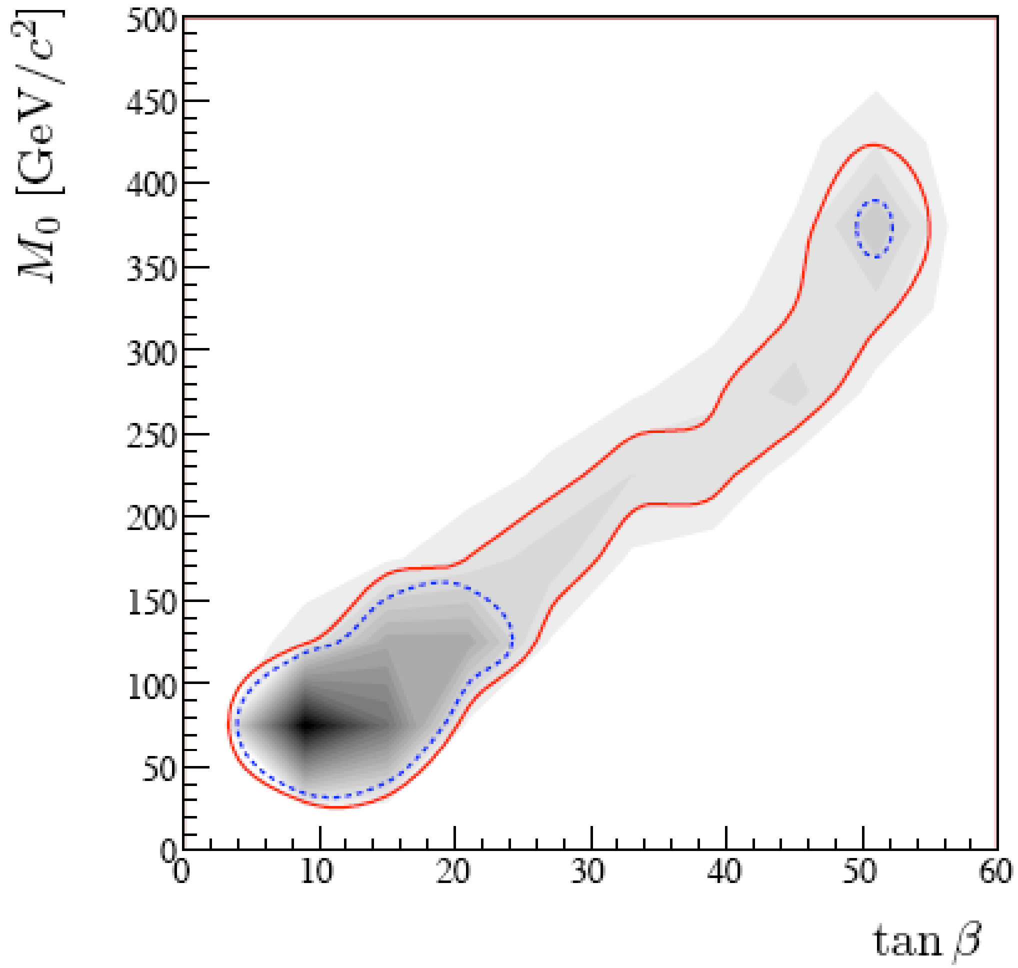
Example: Almost no information on tanβ without external constraints. Note that a direct measurement of tanβ is very difficult at the LHC

Illustrative Example

More flavour constraints in the cMSSM

Weiglein et al,arXiv:0707.3447
Update Weiglein et al.,arXiv:0907.5568

Multi-parameter χ^2 fit for all CMSSM parameters, $M_0, M_{1/2}, A_0, \tan\beta$



68% (dotted) and

95% (solid) CL

$(g-2)_\mu$, $b \to s\gamma$, Ω_{CDM}

Constraints on the lightest Higgs boson mass

$$m_h^{\rm CMSSM} = 110^{+8}_{-10}\ (\rm exp.) \pm 3\ (\rm theo.)\ GeV/c^2$$

no restriction on m_h imposed in the fit

Quark flavour at ATLAS/CMS

- **Probing Minimal Flavour Violation at the LHC**

Grossman, Nir, Thaler, Volansky, Zupan, arXiv:0706.1845

To an accuracy of $\mathcal{O}(0.05)$

$$V_{\rm LHC}^{\rm CKM} = \begin{pmatrix} 1 & 0.23 & 0 \\ -0.23 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

New particles (i.e. heavy vector-like quarks) that couple to the SM quarks decay to either 3rd generation quark, or to non-3rd generation quark, but not to both.

If ATLAS/CMS measures $BR(q_3) \sim BR(q_{1,2})$ then this excludes MFV.

MFV prediction for events with B' pair production:

$$\frac{\Gamma(B'\overline{B'} \to X q_{1,2} q_3)}{\Gamma(B'\overline{B'} \to X q_{1,2} q_{1,2}) + \Gamma(B'\overline{B'} \to X q_3 q_3)} \lesssim 10^{-3}$$

Flavour tagging efficiencies are crucial.

Quark flavour at ATLAS/CMS II

- **Flavour-violating squark and gluino decays** — Hurth,Porod,hep-ph/0311075 arXiv:0904.4574 [hep-ph], to appear in JHEP

  - Squark decays: $\tilde{u}_i \to u_j \tilde{\chi}_k^0 \,,\, d_j \tilde{\chi}_l^+ \qquad \tilde{d}_i \to d_j \tilde{\chi}_k^0 \,,\, u_j \tilde{\chi}_l^-$

    with $i = 1,..,6$, $j = 1,2,3$, $k = 1,..,4$ and $l = 1,2$.

  - These tree decays are governed by the same mixing matrices as the contributions to flavour violating low-energy observables

  - In the unconstrained MSSM new contributions to flavour violation
    - CKM-induced contributions from H^+, χ^+ exchanges
    - flavour mixing in the sfermion mass matrix

  - Possible disalignement of quarks and squarks

Strategy:

- Take susy benchmark points: SPS1a',γ, and I''
- Vary flavour nondiagonal parameters

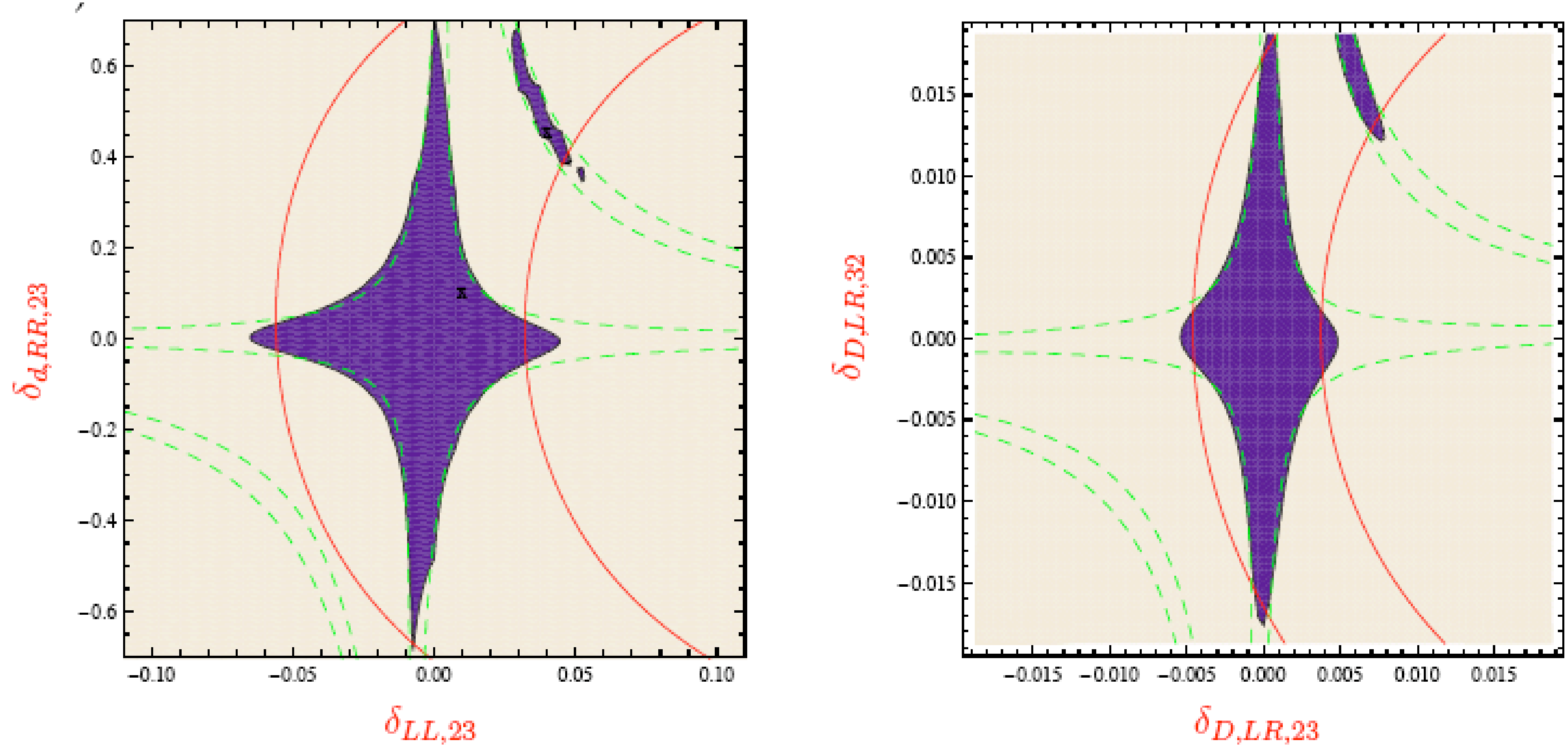
  (off-diagonal squark mass entries)
- Use all experimental and theoretical bounds

Strategy:

- Take susy benchmark points: SPS1a',γ, and I''
- Vary flavour nondiagonal parameters

  (off-diagonal squark mass entries)
- Use all experimental and theoretical bounds

$\Rightarrow$ Bounds on δ parameters



($b \rightarrow s\gamma$ red lines, ΔM_{B_s} magenta)

Strategy:

- Take susy benchmark points: SPS1a',γ, and I"
- Vary flavour nondiagonal parameters

  (off-diagonal squark mass entries)
- Use all experimental and theoretical bounds

$\Rightarrow$ Information on flavour-violating tree decays

- Flavour-violating squark and gluino decays can be typically of order of 10%,

  - consistent with the present flavour data.

  - common feature for a couple of SUSY benchmark points like SPS1a',γ, and I''

  - even 40% possible for large new physics contributions

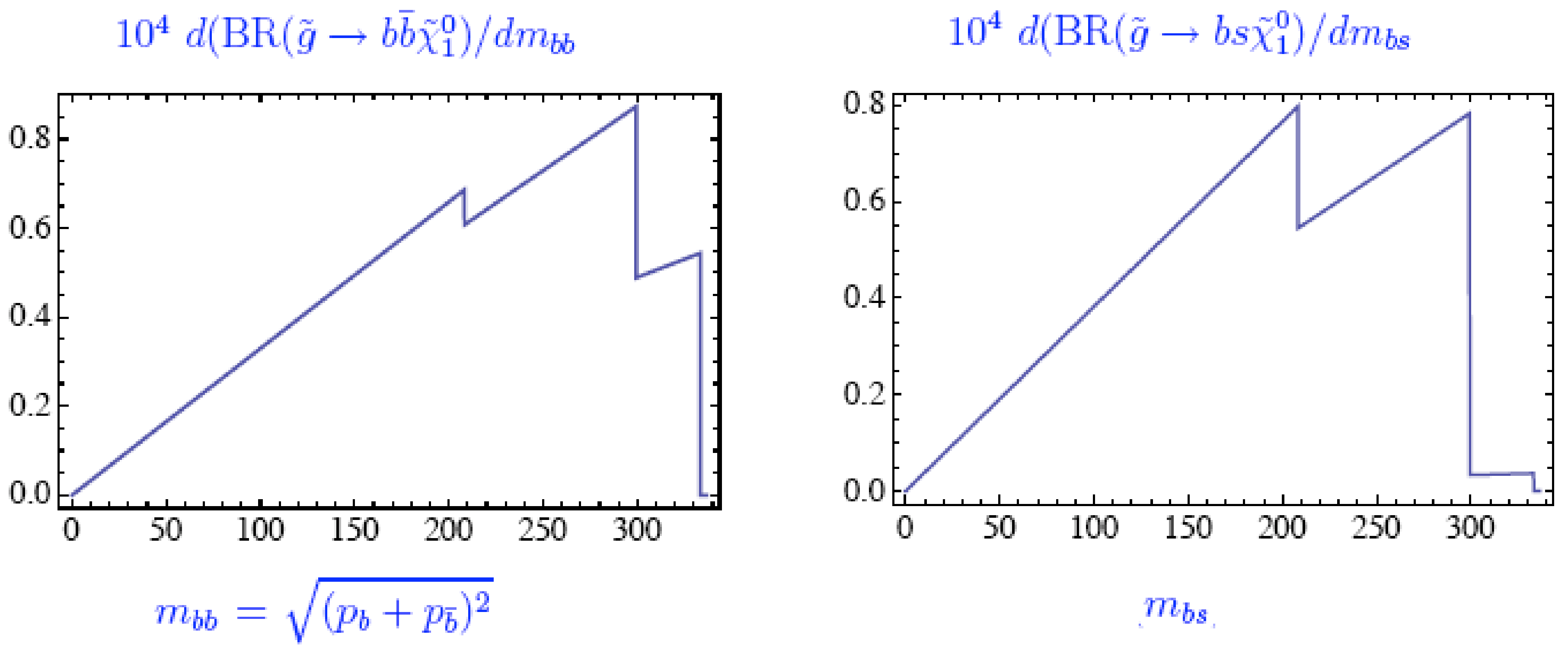
Typical results for squark and gluino decays

decaying particle	final states and corresponding branching ratios in % for.					
	I. $\delta_{LL,23} = 0.01, \delta_{D,RR23} = 0.1$			II. $\delta_{LL,23} = 0.04, \delta_{D,RR23} = 0.45$		
$\tilde{d}_1 \rightarrow$ I: $\tilde{b}_L(\tilde{b}_R)$	$\tilde{\chi}^0_1 b$, 4.4 $\tilde{u}_1 W^-$, 27.7	$\tilde{\chi}^0_2 b$, 29.8	$\tilde{\chi}^-_1 t$, 37.0	$\tilde{\chi}^0_1 s$, 36.8 $\tilde{\chi}^-_1 t$, 9.6	$\tilde{\chi}^0_1 b$, 42.2	$\tilde{\chi}^0_2 b$, 10.9
$\tilde{d}_2 \rightarrow$ I: $\tilde{b}_R(\tilde{b}_L, \tilde{s}_R)$	$\tilde{\chi}^0_1 s$, 8.0 $\tilde{\chi}^0_3 b$, 1.1 $\tilde{u}_1 W^-$, 38.9	$\tilde{\chi}^0_1 b$, 6.4 $\tilde{\chi}^0_4 b$, 1.8	$\tilde{\chi}^0_2 b$, 19.0 $\tilde{\chi}^-_1 t$, 24.6	$\tilde{\chi}^0_1 b$, 2.1 $\tilde{u}_1 W^-$, 33.2	$\tilde{\chi}^0_2 b$, 27.3	$\tilde{\chi}^-_1 t$, 34.6
$\tilde{d}_4 \rightarrow$ I: $\tilde{s}_R(\tilde{s}_L, \tilde{b}_R)$	$\tilde{\chi}^0_1 s$, 9.1 $\tilde{\chi}^-_1 u$, 2.1	$\tilde{\chi}^0_1 b$, 6.3 $\tilde{\chi}^-_1 c$, 47.3	$\tilde{\chi}^0_2 s$, 25.3 $\tilde{u}_1 W^-$, 4.8	$\tilde{\chi}^0_1 d$, 2.3 $\tilde{\chi}^-_1 c$, 3.0	$\tilde{\chi}^0_2 d$, 31.7 $\tilde{\chi}^-_2 u$, 2.3	$\tilde{\chi}^-_1 u$, 59.7
$\tilde{d}_5 \rightarrow$ I: $\tilde{d}_L$	$\tilde{\chi}^0_1 d$, 2.3 $\tilde{\chi}^-_1 c$, 2.8	$\tilde{\chi}^0_2 d$, 31.7 $\tilde{\chi}^-_2 u$, 2.3	$\tilde{\chi}^-_1 u$, 59.9	$\tilde{\chi}^0_1 s$, 2.2 $\tilde{\chi}^-_1 c$, 58.5	$\tilde{\chi}^0_2 s$, 30.7 $\tilde{\chi}^-_2 c$, 2.3	$\tilde{\chi}^-_1 u$, 2.9
$\tilde{d}_6 \rightarrow$ I: $\tilde{s}_L(\tilde{s}_R)$	$\tilde{\chi}^0_1 s$, 3.1 $\tilde{\chi}^-_1 c$, 58.1	$\tilde{\chi}^0_2 s$, 30.6 $\tilde{\chi}^-_2 c$, 2.4	$\tilde{\chi}^-_1 u$, 2.7	$\tilde{\chi}^0_1 s$, 19.7 $\tilde{\chi}^0_4 b$, 2.9 $\tilde{g} b$, 39.8	$\tilde{\chi}^0_1 b$, 18.8 $\tilde{\chi}^-_2 t$, 5.8 $\tilde{u}_1 W^-$, 5.5	$\tilde{\chi}^0_3 b$, 2.9 $\tilde{g} s$, 2.2
$\tilde{g} \rightarrow$	$\tilde{u}_1 t$, 19.2 $\tilde{u}_4 u$, 4.2 $\tilde{d}_1 s$, 1.4 $\tilde{d}_2 s$, 6.3 $\tilde{d}_4 s$, 2.3	$\tilde{u}_2 c$, 8.2 $\tilde{u}_5 c$, 4.2 $\tilde{d}_1 b$, 20.6 $\tilde{d}_2 b$, 9.0 $\tilde{d}_4 b$, 1.3	$\tilde{u}_3 u$, 8.3 $\tilde{d}_3 d$, 8.3 $\tilde{d}_6 s$, 2.8	$\tilde{u}_1 t$, 13.5 $\tilde{u}_4 c$, 2.6 $\tilde{d}_1 s$, 21.1 $\tilde{d}_2 b$, 14.0 $\tilde{d}_4 d$, 2.3	$\tilde{u}_2 c$, 5.8 $\tilde{u}_5 u$, 2.6 $\tilde{d}_1 b$, 22.7 $\tilde{d}_5 d$, 3.3	$\tilde{u}_3 u$, 5.8 $\tilde{d}_3 d$, 5.9

II: $\tilde{d}_1 \simeq \tilde{b}_R, \tilde{s}_R(\tilde{b}_L)$, $\tilde{d}_6 \simeq \tilde{s}_R, \tilde{b}_R(\tilde{b}_L)$, $\tilde{d}_2 \simeq \tilde{b}_L$, $\tilde{d}_3 \simeq \tilde{d}_R$, $\tilde{d}_4 \simeq \tilde{d}_L$ and $\tilde{d}_5 \simeq \tilde{s}_L$

Impact on LHC

This can complicate determination of sparticle masses: $\tilde{g} \longrightarrow b\tilde{b}_j \longrightarrow b\bar{b}\tilde{\chi}_k^0$



Again: flavour-tagging at LHC important, but difficult

Additional information from ILC or from Superflavour factory needed !

Concrete examples of new physics search:

Separation of new physics and hadronic effects

Challenge for our understanding of QCD

Opportunity for (Super-) B factories: Inclusive $B \to X_s \gamma$

"spokesperson" of our collaboration of 17 persons: M. Misiak

Opportunity for LHCb (restriction to exclusive modes): $B \to K^* \ell^+ \ell^-$

in collaboration with Egede, Reece (LHCb,Imperial) and Matias, Ramon (Barcelona)

JHEP 0811:032,2008, arXiv:0807.2589 [hep-ph] and forthcoming manuscript

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: $H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy})\ \mathcal{O}_i(\mu)$

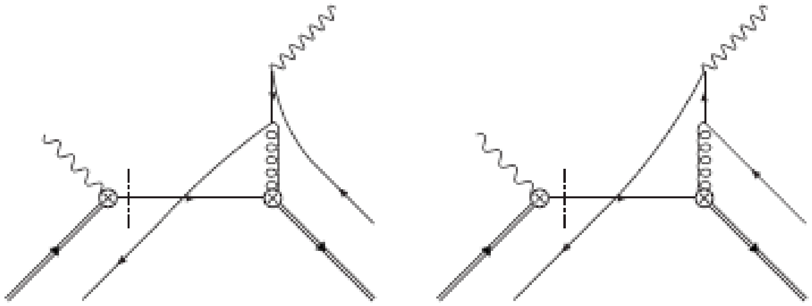
- Heavy mass expansion for inclusive modes: (in general restricted to e^+e^-)

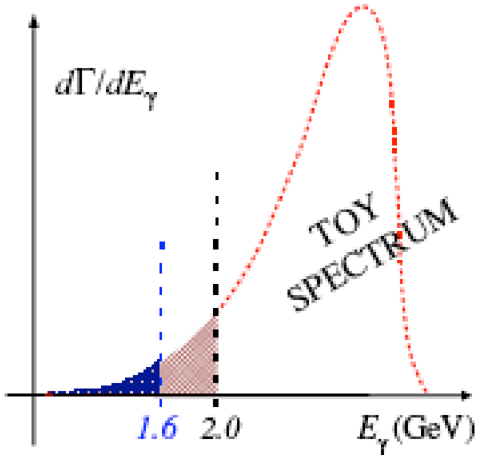
$$\Gamma(\bar{B} \to X_s\gamma) \stackrel{m_b\to\infty}{\longrightarrow} \Gamma(b \to X_s^{parton}\gamma)\,, \quad \Delta^{nonpert.} \sim \Lambda_{QCD}^2/m_b^2$$

No linear term Λ_{QCD}/m_b (perturbative contributions dominant)

– More sensitivities to nonperturbative physics due to kinematical cuts: shape functions; multiscale OPE (SCET) with $\Delta = m_b - 2E_\gamma^0$

– Breakdown of local expansion: class of nonlocal power corrections identified; naive estimates lead to 5% uncertainty.





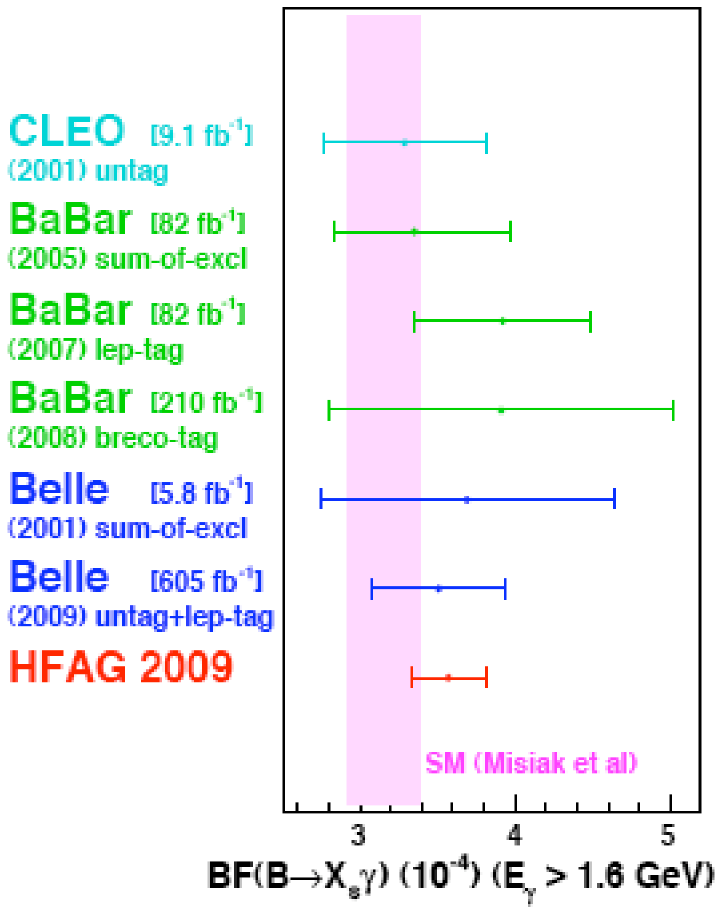
Status of the inclusive mode $\bar{B} \to X_s\gamma$

HFAG: $\mathcal{B}(B \to X_s\gamma) = (3.57 \pm 0.24) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

VS

SM: $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

NNLO calculation by M.Misiak, T.H. et al.
PRL98,022003(2007)



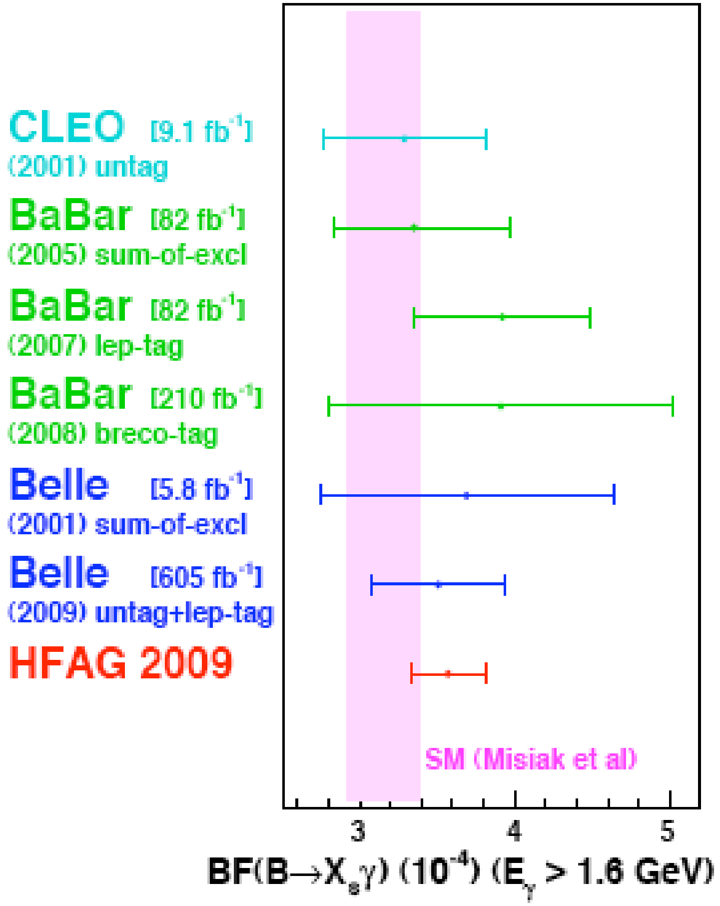
Status of the inclusive mode $\bar{B} \to X_s\gamma$

HFAG: $\mathcal{B}(B \to X_s\gamma) = (3.57 \pm 0.24) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

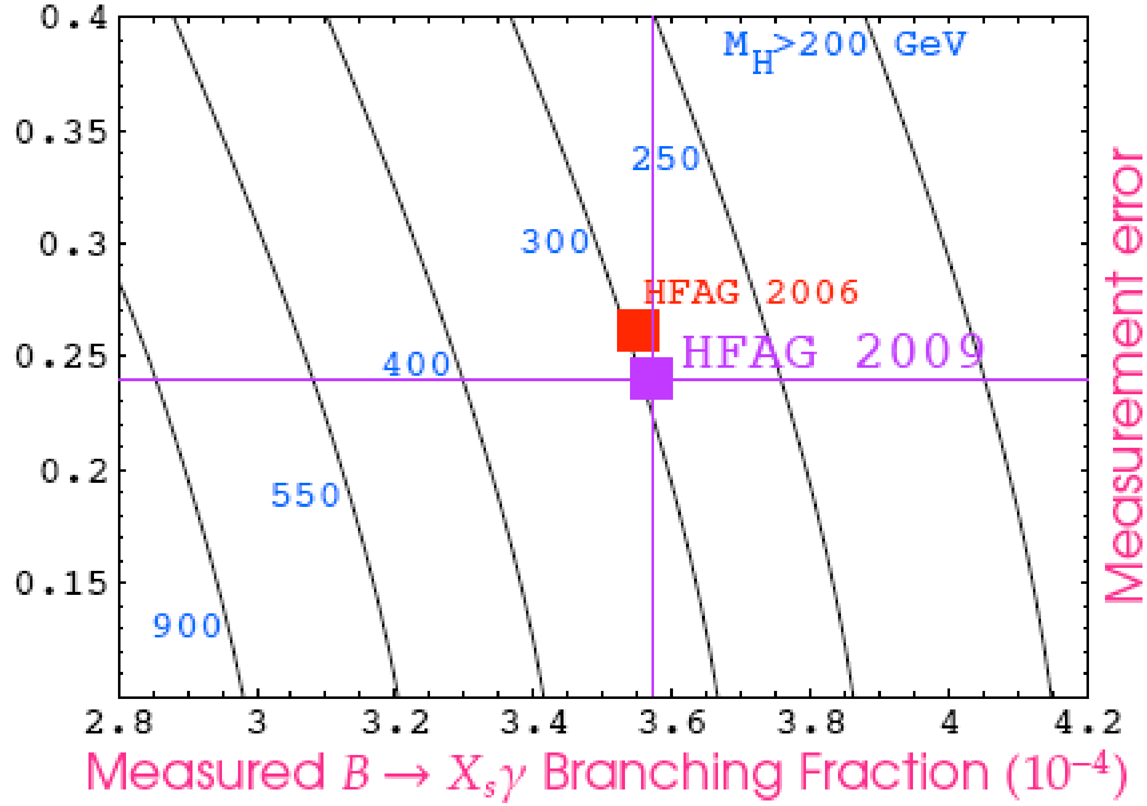
VS

SM: $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

NNLO calculation by M.Misiak, T.H. et al.
PRL98,022003(2007)



Charged Higgs bound (2HDM)
$m_{H^+} > 300$ GeV



Courtesy of Mikihiko Nakao

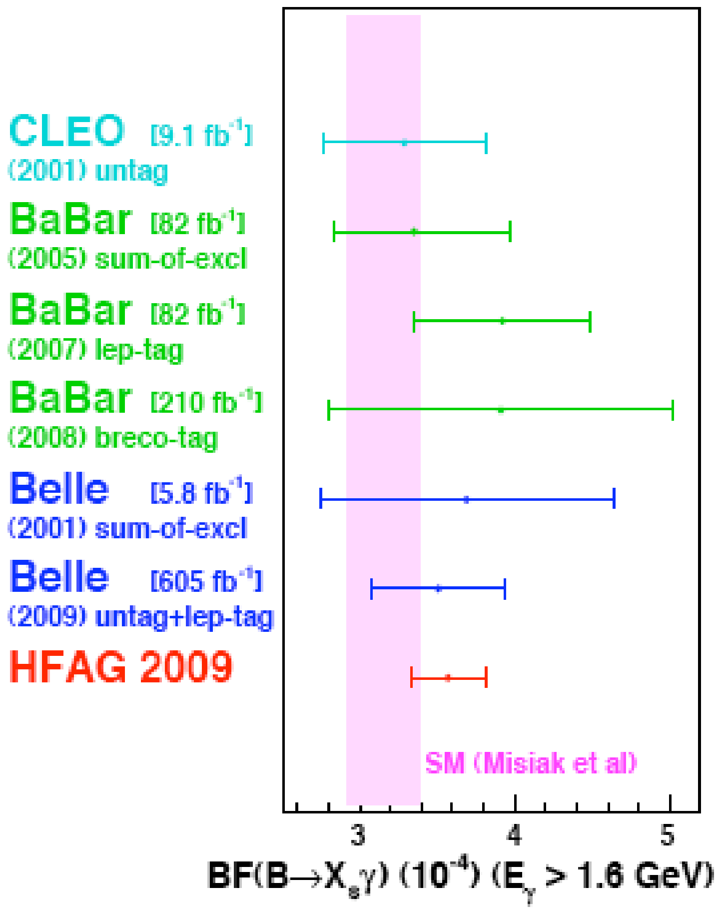
Status of the inclusive mode $\bar{B} \to X_s\gamma$

HFAG: $\mathcal{B}(B \to X_s\gamma) = (3.57 \pm 0.24) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

VS

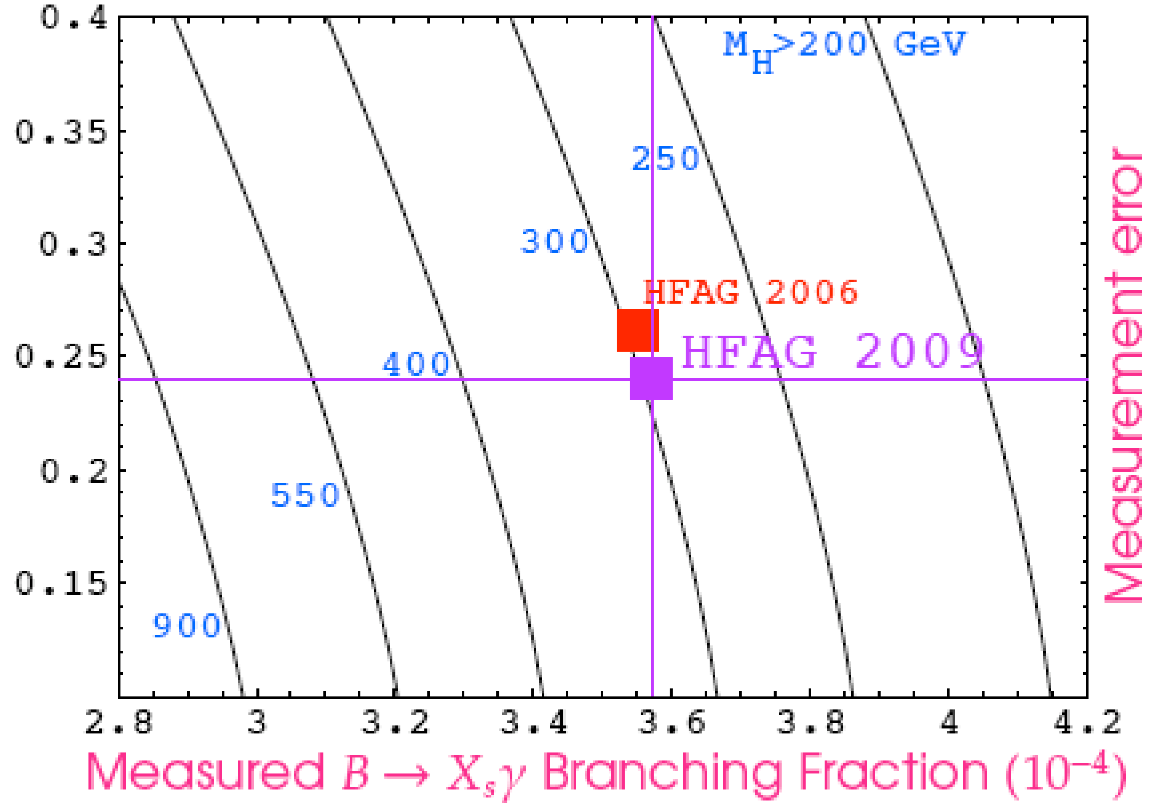
SM: $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

NNLO calculation by M.Misiak, T.H. et al.
PRL98,022003(2007)



Charged Higgs bound (2HDM)

$m_{H^+} > 300$ GeV



Parameter bounds from flavour physics are model-dependent

- Exclusive mode $B \to K^* \ell^+ \ell^-$

Factorization formulae based on soft-collinear effective theory (SCET):

for $B \to K^*$ formfactors

$$F_i = H_i \xi^P(E) + \phi_B \otimes T_i \otimes \phi^P_{K^*} + O(\Lambda/m_b)$$

for the decay amplitudes

$$\mathcal{T}_a^{(i)} = C_a^{(i)} \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

– Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors

– Relations between formfactors in large-energy limit

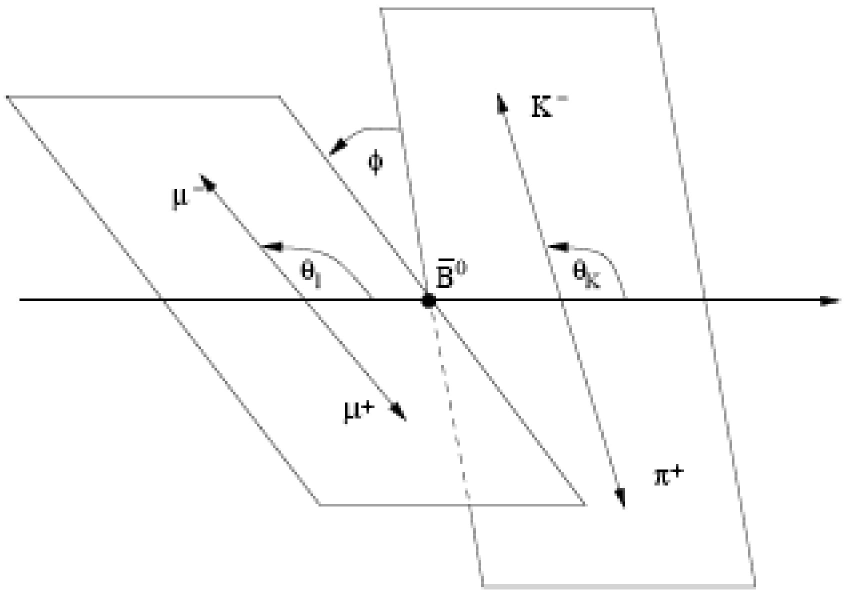
– Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

Phenomenologically highly relevant issue

general strategy of LHCb to look at ratios of exclusive modes

Angular analysis of $B \to K^* \ell^+ \ell^-$

Assuming the $\bar{K}^*$ to be on the mass shell, the decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-$ described by the lepton-pair invariant mass, s, and the three angles θ_l, θ_{K^*}, ϕ.



After summing over the spins of the final particles:

$$\frac{d^4\Gamma_{\overline{B}_d}}{dq^2\, d\theta_l\, d\theta_K\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_K, \phi) \sin\theta_l \sin\theta_K$$

$$I = I_1 + I_2 \cos 2\theta_l + I_3 \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_l \cos\phi + I_5 \sin\theta_l \cos\phi + I_6 \cos\theta_l$$
$$+ I_7 \sin\theta_l \sin\phi + I_8 \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_l \sin 2\phi.$$

LHCb statistics $(10\,fb^{-1},\ \succ 2\,fb^{-1})$ allows for a full angular fit!

Theoretical framework

- Effective Hamiltonian describing the quark transition $b \to s\ell^+\ell^-$:

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} [C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)]$$

- Hadronic matrix element parametrized in terms of $B \to K^*$ form factors:

- Crucial input: In the $m_B \to \infty$ and $E_{K^*} \to \infty$ limit

  7 form factors $(A_i(s)/T_i(s)/V(s))$ reduce to 2 univeral form factors $(\xi_\perp, \xi_\parallel)$

  Form factor relations broken by α_s and Λ/m_b corrections

  (Charles,Le Yaouanc,Oliver,Pène,Raynal 1999)

- Large Energy Effective Theory $\Rightarrow$ QCD factorization/SCET

  (IR structure of QCD)

- Above results are valid in the kinematic region in which

$$E_{K^*} \simeq \frac{m_B}{2}\left(1 - \frac{s}{m_B^2} + \frac{m_{K^*}^2}{m_B^2}\right)$$ is large.

We restrict our analysis to the dilepton mass region $s \in [1\text{GeV}^2, 6\text{GeV}^2]$

K^* spin amplitudes in the heavy quark and large energy limit

$$A_{\perp,\parallel} = (H_{+1} \mp H_{-1})/\sqrt{2}, \quad A_0 = H_0$$

$$\begin{aligned}
A_{\perp L,R} &= N\sqrt{2}\lambda^{1/2}\left[(C_9^{\rm eff} \mp C_{10})\frac{V(s)}{m_B + m_{K^*}} + \frac{2m_b}{s}(C_7^{\rm eff} + C_7^{\rm eff\prime})T_1(s)\right] \\
A_{\parallel L,R} &= -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left[(C_9^{\rm eff} \mp C_{10})\frac{A_1(s)}{m_B - m_{K^*}} + \frac{2m_b}{s}(C_7^{\rm eff} - C_7^{\rm eff\prime})T_2(s)\right] \\
A_{0L,R} &= -\frac{N}{2m_{K^*}\sqrt{s}}\left[(C_9^{\rm eff} \mp C_{10})\left\{(m_B^2 - m_{K^*}^2 - s)(m_B + m_{K^*})A_1(s) - \lambda\frac{A_2(s)}{m_B + m_{K^*}}\right\}\right. \\
&\quad \left. + 2m_b(C_7^{\rm eff} - C_7^{\rm eff\prime})\left\{(m_B^2 + 3m_{K^*}^2 - s)T_2(s) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(s)\right\}\right]
\end{aligned}$$

$$\begin{aligned}
A_{\perp L,R} &= +\sqrt{2}Nm_B(1-\hat{s})\left[(C_9^{\rm eff} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}}(C_7^{\rm eff} + C_7^{\rm eff\prime})\right]\xi_\perp(E_{K^*}) \\
A_{\parallel L,R} &= -\sqrt{2}Nm_B(1-\hat{s})\left[(C_9^{\rm eff} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}}(C_7^{\rm eff} - C_7^{\rm eff\prime})\right]\xi_\perp(E_{K^*}) \\
A_{0L,R} &= -\frac{Nm_B}{2\hat{m}_{K^*}\sqrt{\hat{s}}}(1-\hat{s})^2\left[(C_9^{\rm eff} \mp C_{10}) + 2\hat{m}_b(C_7^{\rm eff} - C_7^{\rm eff\prime})\right]\xi_\parallel(E_{K^*})
\end{aligned}$$

Careful design of observables

- Good sensitivity to NP contribitions, i.e. to $C_7^{eff'}$
- Small theoretical uncertainties
  - Dependence of soft form factors, $\xi_\perp$ and $\xi_\parallel$, to be minimized !
    form factors should cancel out exactly at LO, best for all s
  - unknown Λ/m_b power corrections
    $A_{\perp,\parallel,0} = A^0_{\perp,\parallel,0}\left(1 + c_{\perp,\parallel,0}\right)$ vary c_i in a range of $\pm$10% and also of $\pm$5%
  - Scale dependence of NLO result
  - Input parameters
- Good experimental resolution

New observables

$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} \qquad A_T^{(3)} = \frac{|A_{0L} A^*_{\parallel L} + A^*_{0R} A_{\parallel R}|}{\sqrt{|A_0|^2 |A_\perp|^2}}$$

$$A_T^{(4)} = \frac{|A_{0L} A^*_{\perp L} - A^*_{0R} A_{\perp R}|}{|A^*_{0L} A_{\parallel L} + A_{0R} A^*_{\parallel R}|}$$

Next step: design of observables sensitive to other new physics operators

(see also Buras et al. 2008)

Phenomenological analysis

Analysis of SM and models with additional right handed currents ($C_7^{eff'}$)

Specific model:

MSSM with non-minimal flavour violation in the down squark sector

4 benchmark points

Diagonal: $\mu = M_1 = M_2 = M_{H^+} = m_{\tilde{u}_R} = 1$ TeV $\tan\beta = 5$

- Scenario A: $m_{\tilde{g}} = 1$ TeV and $m_{\tilde{d}} \in [200, 1000]$ GeV

  $-0.1 \leq (\delta^d_{LR})_{32} \leq 0.1$

  a) $m_{\tilde{g}}/m_{\tilde{d}} = 2.5$, $(\delta^d_{LR})_{32} = 0.016$

  b) $m_{\tilde{g}}/m_{\tilde{d}} = 4$, $(\delta^d_{LR})_{32} = 0.036$.

- Scenario B: $m_{\tilde{d}} = 1$ TeV and $m_{\tilde{g}} \in [200, 800]$ GeV

  mass insertion as in Scenario A.

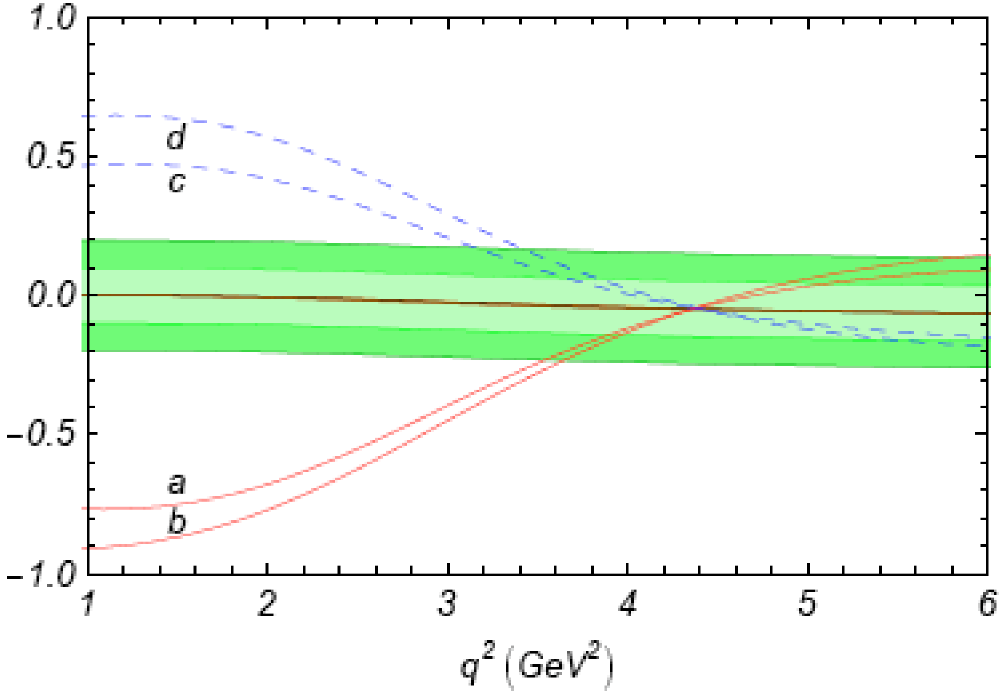
  c) $m_{\tilde{g}}/m_{\tilde{d}} = 0.7$, $(\delta^d_{LR})_{32} = -0.004$

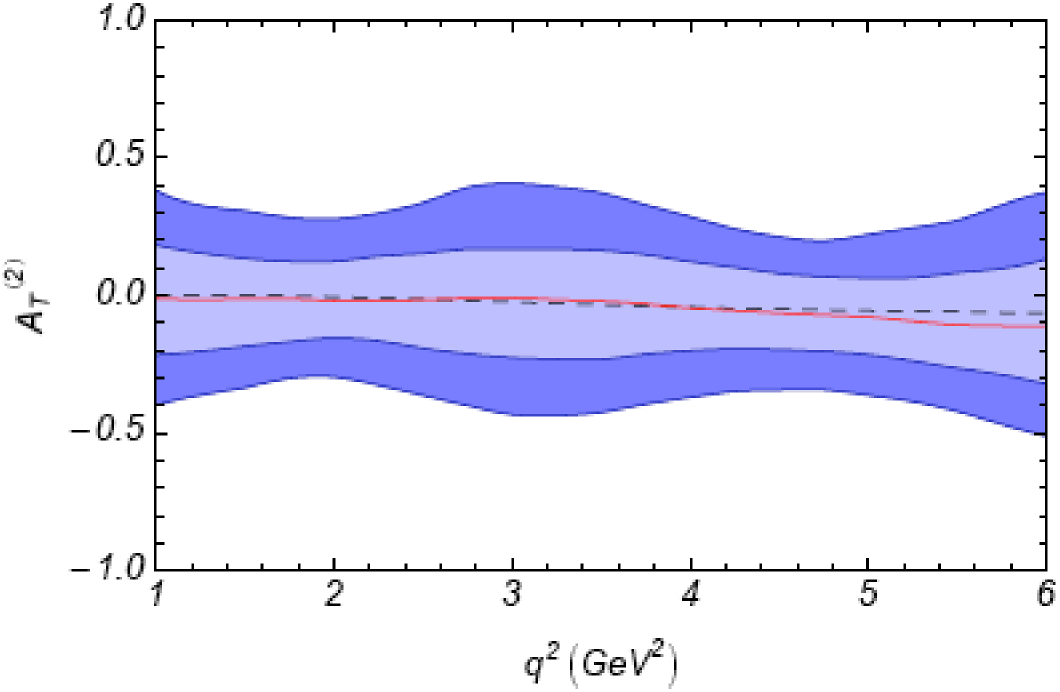
  d) $m_{\tilde{g}}/m_{\tilde{d}} = 0.6$, $(\delta^d_{LR})_{32} = -0.006$.

Check of compatibility with other constraints (B physics,ρ parameter,

Higgs mass, particle searches, vacuum stability constraints

Results $A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$





Theoretical sensitivity

light green $\pm 5\% \Lambda/m_b$

dark green $\pm 10\% \Lambda/m_b$

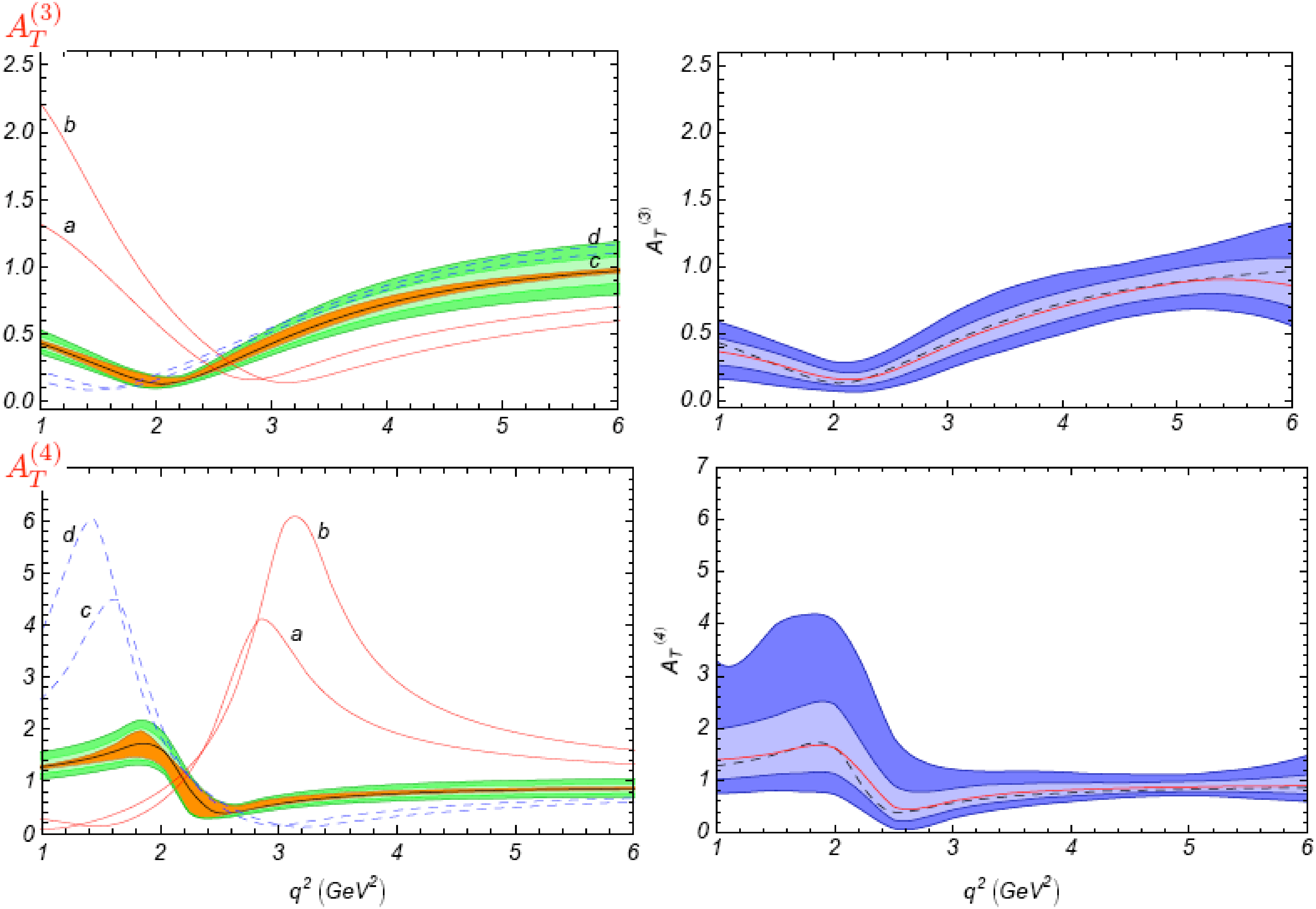
Experimental sensitivity $(10 fb^{-1})$

light green 1 σ

dark green 2 σ

Remark: SuperLHCB/SuperB can offer more precision

Crucial: theoretical status of Λ/m_b corrections has to be improved



$A_T^{(3)}$
b
a
d
c
$A_T^{(3)}$
$A_T^{(4)}$
d
c
b
a
$A_T^{(4)}$
q^2 (GeV^2)
q^2 (GeV^2)

Future opportunities

- LHCb (5 years) 10fb^{-1}: allows for wide range of analyses,

  highlights: B_s mixing phase, angle γ, $B \to K^* \mu\mu$, $B_s \to \mu\mu$,$B_s \to \phi\phi$

  then possibility for upgrade to 100fb^{-1}

- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:

  rare kaon decays $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- Two proposals for a Super-B factory:

  SuperKEKB (50ab^{-1}), SuperB (75ab^{-1})

  Super-B is a Super Flavour factory: besides precise B measurements, CP violation in charm, lepton flavour violating modes $\tau \to \mu\gamma$,...

Future opportunities

- LHCb (5 years) $10 fb^{-1}$: allows for wide range of analyses,

  highlights: B_s mixing phase, angle γ, $B \to K^* \mu\mu$, $B_s \to \mu\mu$, $B_s \to \phi\phi$

  then possibility for upgrade to $100 fb^{-1}$

- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:

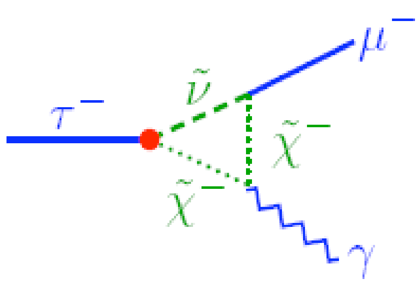
  rare kaon decays $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- Two proposals for a Super-B factory:

  SuperKEKB ($50 ab^{-1}$), SuperB ($75 ab^{-1}$)

  Super-B is a Super Flavour factory: besides precise B measurements, CP violation in charm, lepton flavour violating modes $\tau \to \mu\gamma$,...

$\tau \to \mu\gamma$ and 3μ



$$\text{BR}(l_j^- \to l_i^- \gamma)|_{\text{SM}_R} \approx (m_\nu / M_W)^2 \sim \mathcal{O}(10^{-54})$$

Process	Expected 90%CL upper limited	4σ Discovery Reach
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}	5×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}	8.8×10^{-10}

Future opportunities

- LHCb (5 years) 10fb^{-1}: allows for wide range of analyses,

  highlights: B_s mixing phase, angle γ, $B \to K^* \mu\mu$, $B_s \to \mu\mu$,$B_s \to \phi\phi$

  then possibility for upgrade to 100fb^{-1}

- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:

  rare kaon decays $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- Two proposals for a Super-B factory:

  SuperKEKB (50ab^{-1}), SuperB (75ab^{-1})

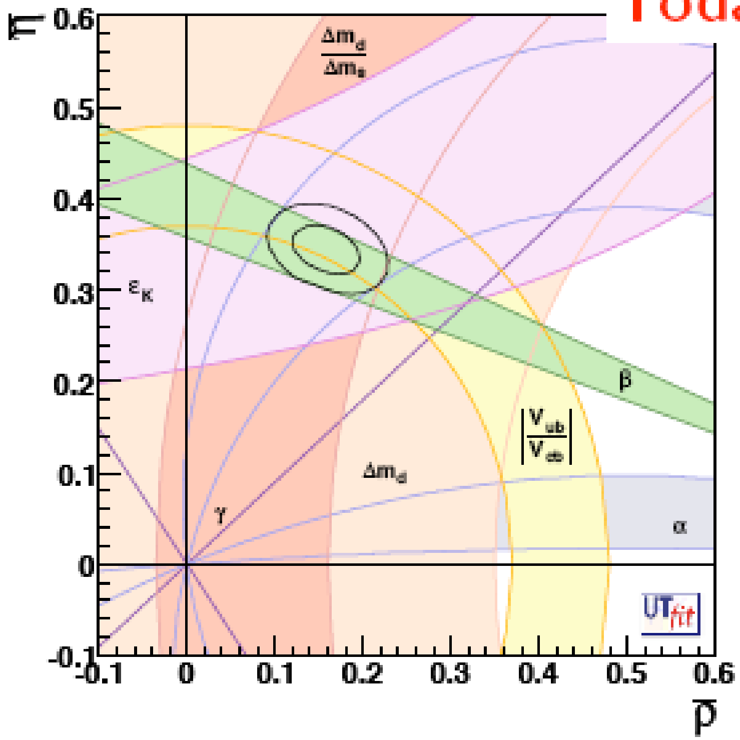
  Super-B is a Super Flavour factory: besides precise B measurements, CP violation in charm, lepton flavour violating modes $\tau \to \mu\gamma$,...

Use $\mu\gamma$/3l to distinguish SUSY vs. LHT.

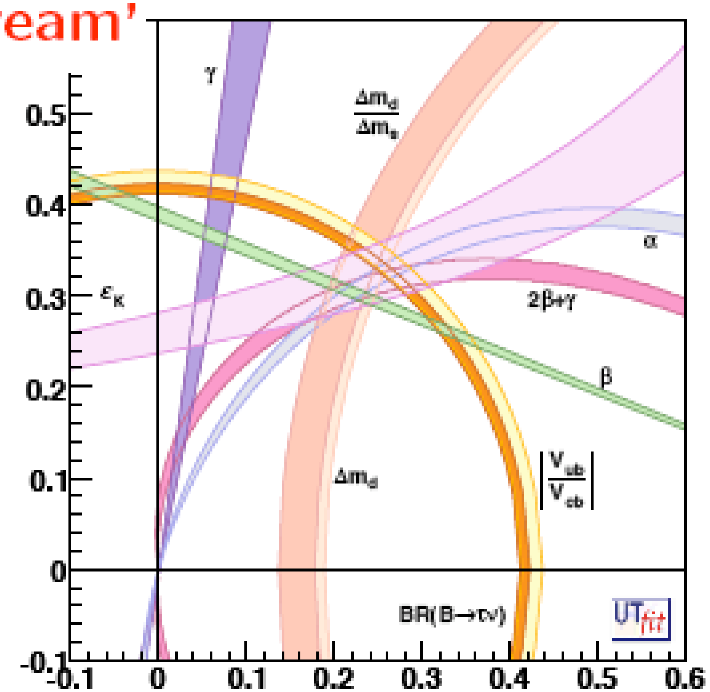
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{\mathcal{B}(\tau^-\to e^-e^+e^-)}{\mathcal{B}(\tau\to e\gamma)}$	$0.4\ldots2.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{\mathcal{B}(\tau^-\to\mu^-\mu^+\mu^-)}{\mathcal{B}(\tau\to\mu\gamma)}$	$0.4\ldots2.3$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{\mathcal{B}(\tau^-\to e^-\mu^+\mu^-)}{\mathcal{B}(\tau\to e\gamma)}$	$0.3\ldots1.6$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{\mathcal{B}(\tau^-\to\mu^-e^+e^-)}{\mathcal{B}(\tau\to\mu\gamma)}$	$0.3\ldots1.6$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{\mathcal{B}(\tau^-\to e^-e^+e^-)}{\mathcal{B}(\tau^-\to e^-\mu^+\mu^-)}$	$1.3\ldots1.7$	~ 5	$0.3\ldots0.5$
$\frac{\mathcal{B}(\tau^-\to\mu^-\mu^+\mu^-)}{\mathcal{B}(\tau^-\to\mu^-e^+e^-)}$	$1.2\ldots1.6$	~ 0.2	$5\ldots10$

Superflavour factory: CKM theory gets tested at 1%

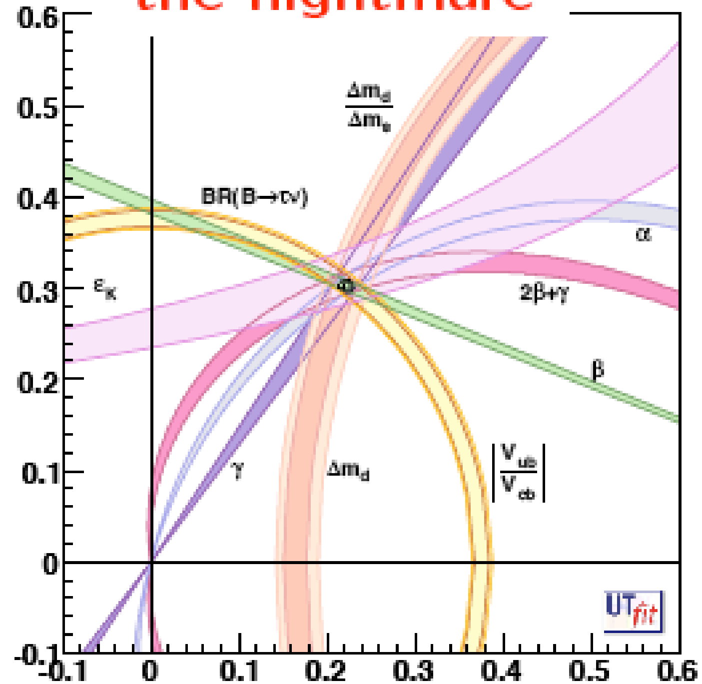
Today



'the dream'



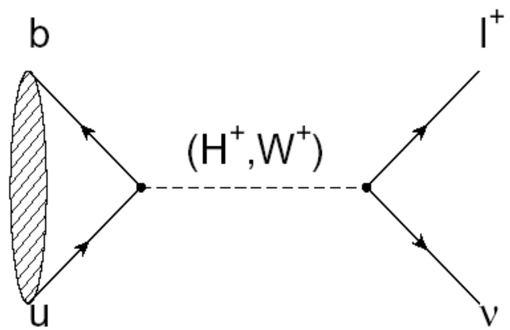
'the nightmare'



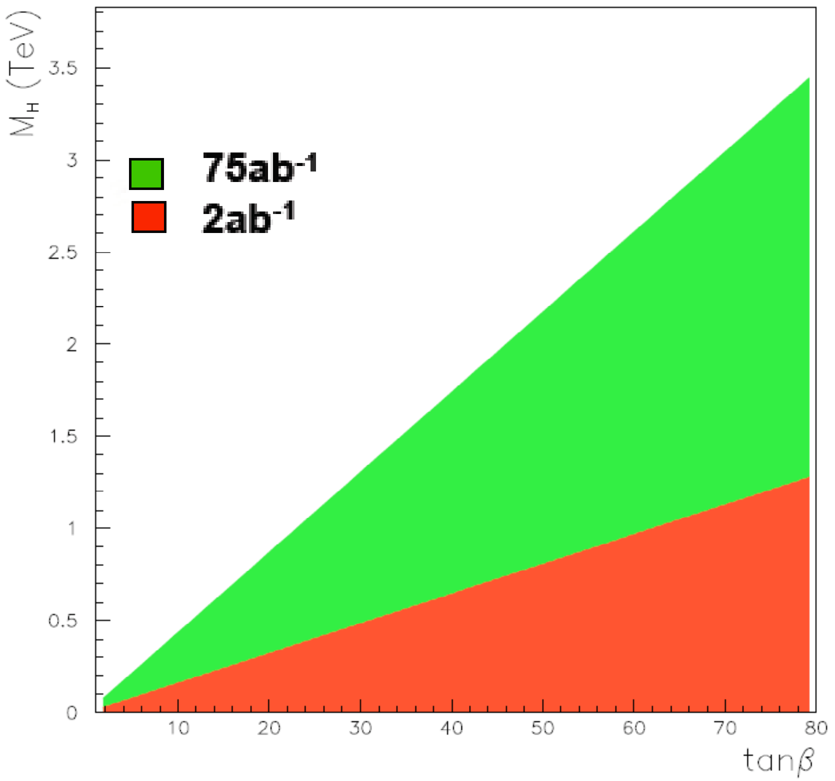
Superflavour factory: measurement of clean modes

$B \to \tau\nu$: B factories 20% Super B factories 4%

2HDM-II



$$\mathrm{BR}(B\to\tau\nu)=\mathrm{BR}_{SM}(B\to\tau\nu)\left(1-\frac{m_B^2}{M_H^2}\tan^2\beta\right)^2$$



(Assuming SM branching fraction is measured)

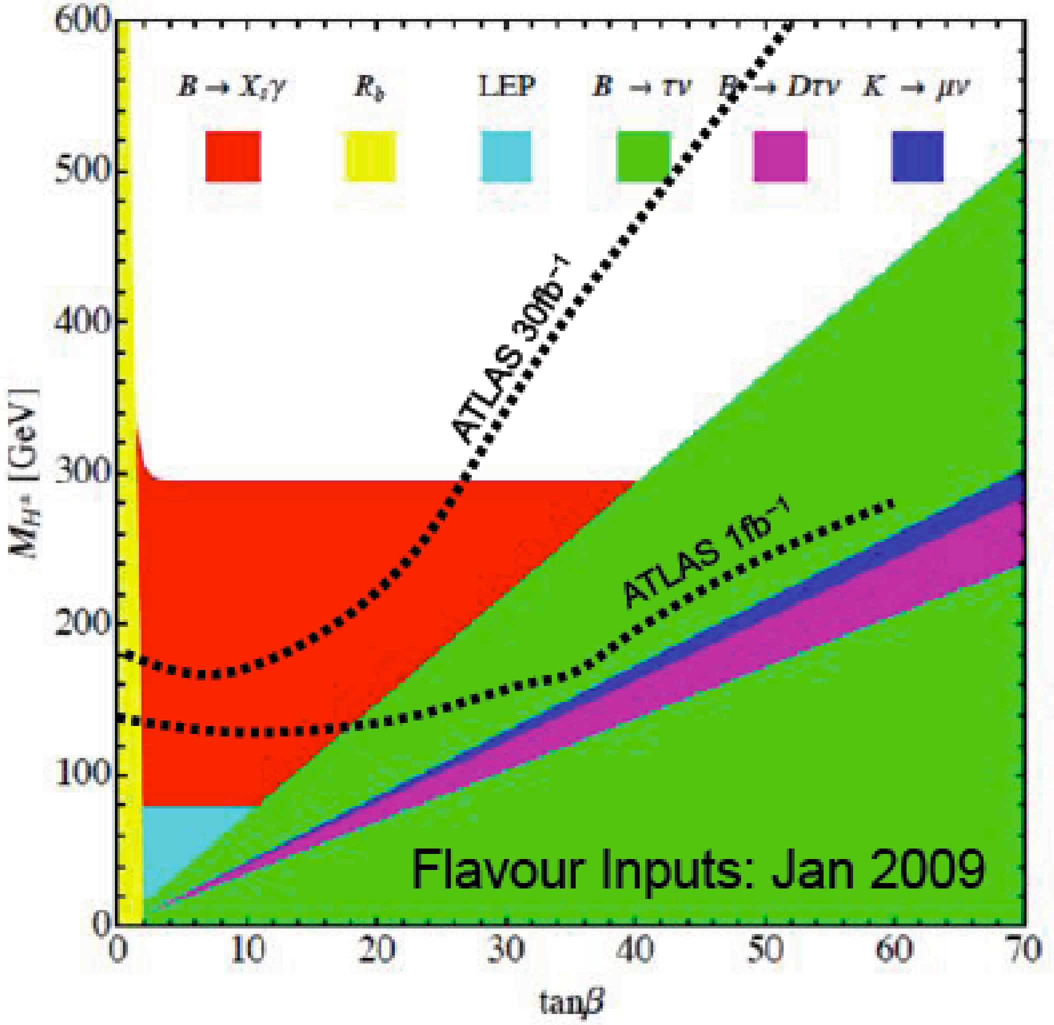
Two final remarks:

- **Experimental evidence beyond SM:**
  - Dark matter (visible matter accounts for only 4% of the Universe)
  - Neutrino masses (Dirac or Majorana masses ?)
  - Baryon asymmetry of the Universe (new sources of CP violation needed)

At least two of them have to do with flavour !

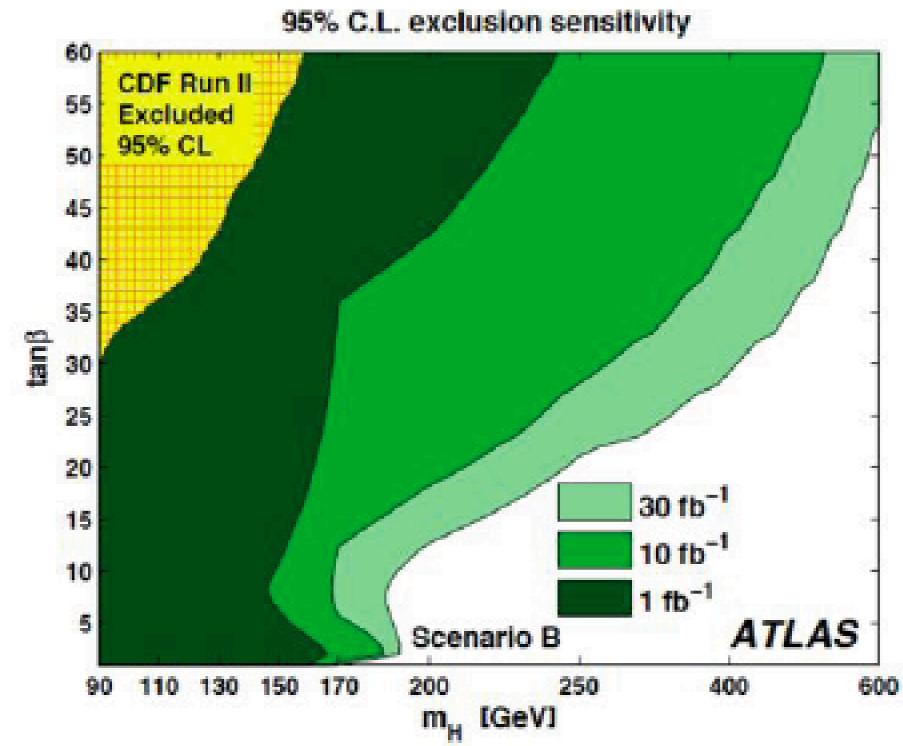
- LHC versus Flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



U. Haisch 0805.2141
2HDM at FPCP 2008)

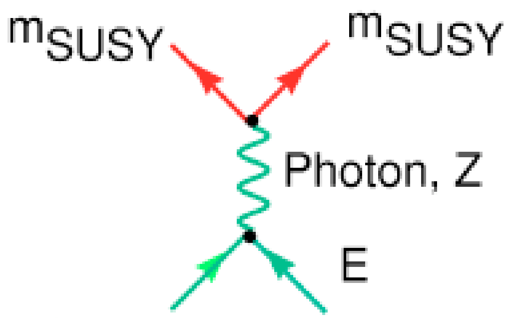
Converted constraints expected from ATLAS onto the plot by hand.

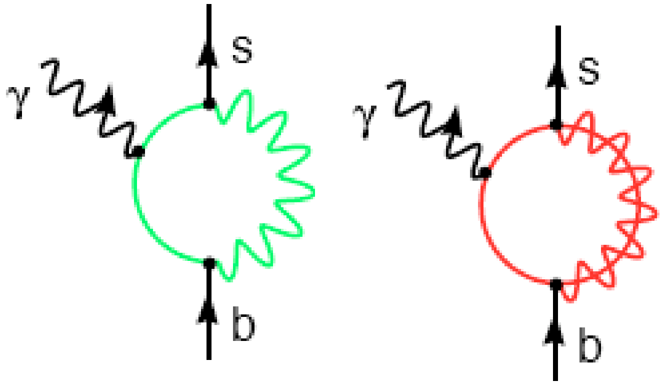


Courtesy of Adrian Bevan

Flavour@high-p_T

Immense potential for synergy and complementarity between high-p_T and flavour physics within the search for new physics





Why?

The indirect information will be most valuable when the general nature of new physics will be identified in the direct search, especially when the mass scale of the new physics will be fixed.

$$(\, C^i_{\mathsf{SM}}/M_W + C^i_{\mathsf{NP}}\,/\Lambda_{\mathsf{NP}}\,)\times \mathcal{O}_i$$