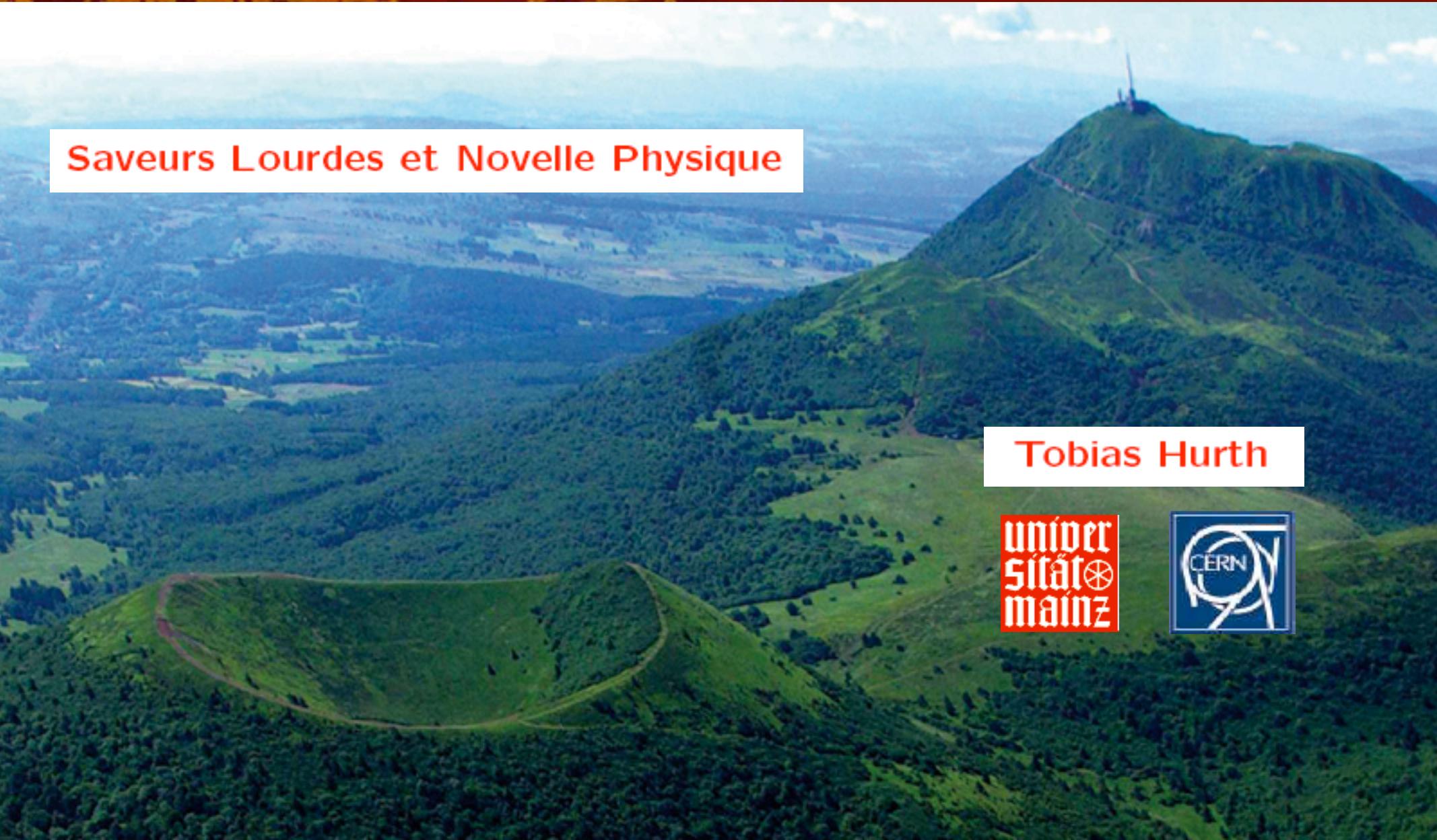




Gif 2010

Saveurs Lourdes

5 au 10 septembre 2010 - Besse-et-Saint-Anastaise



Saveurs Lourdes et Novelle Physique

Tobias Hurth



The lectures cover a selected numbers of topics in flavour physics, reflecting the flavour of the lecturer.

The focus will be on the fundamental concepts

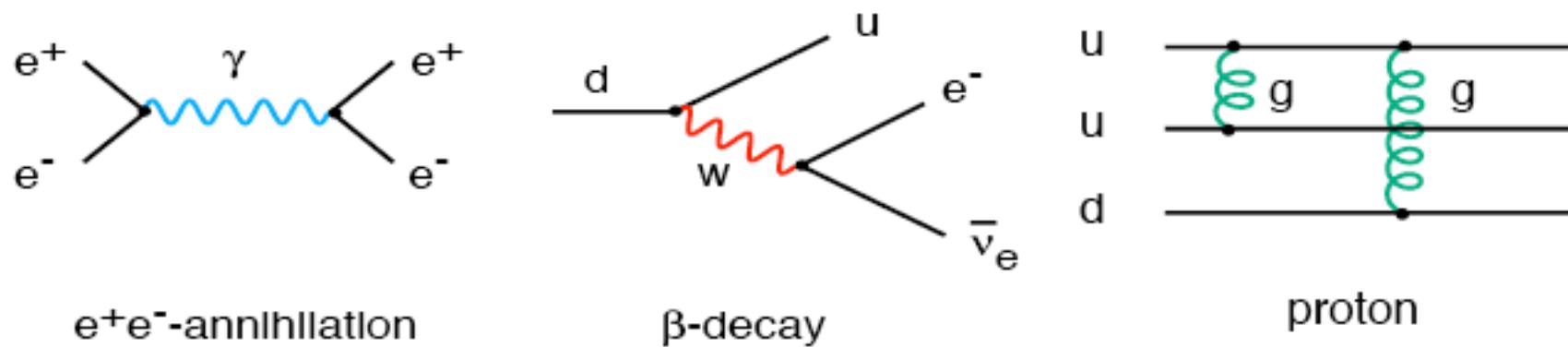
A complete coverage of the field can be found in recent books, reviews, reports and published lectures:

Plan of the talk

- Flavour problem of the SM
- Flavour problem of New Physics
- Minimal flavour violation hypothesis
- Flavour@high- p_T interplay

Prologue Standard Model of Elementary Particle Physics (SM)

- Fundamental forces in nature \Leftrightarrow Local gauge principle $U(1) \times SU(2)_L \times SU(3)$
Electromagnetism (QED) Weak interactions Strong interactions (QCD) Gravity



- Building blocks of matter:
fundamental leptons and quarks (left-handed doublets, right-handed singlets):

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L, \quad u_R, d_R, c_R, s_R, t_R, b_R$$
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \quad e_R^-, \mu_R^-, \tau_R^-, \nu_{eR}, \nu_{\mu R}, \nu_{\tau R}.$$

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

Main successes of SM:

- All gauge bosons ($J = 1$) and fundamental fermions ($J = \frac{1}{2}$) experimentally verified
- Electroweak precision measurements at LEP (CERN), SLC (SLAC), Tevatron (Fermilab) confirmed SM predictions in the gauge sector : 0.1% accuracy !

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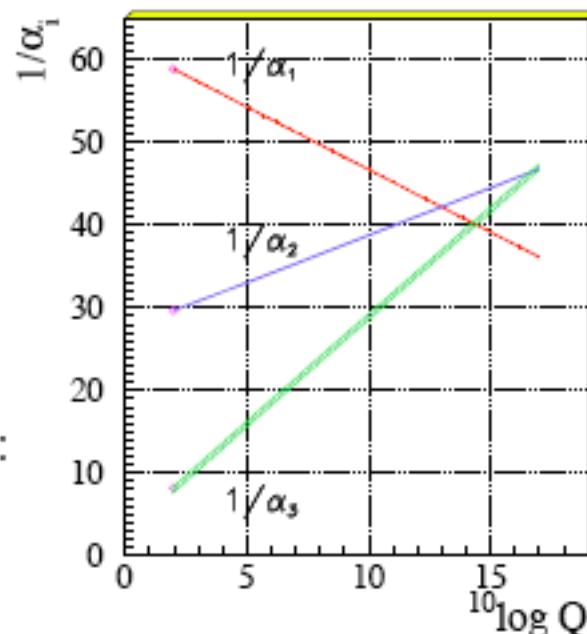
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Weaknesses of SM:

- Higgs boson not observed yet, mechanism of mass generation not confirmed yet (unitarity problem has to be solved)
- Many free parameters, mainly in the flavour sector of SM (hierarchy of masses and mixing parameters)
- Gravity not involved in unification (Planck scale)
- Unification of electromagnetic, weak and strong force.

Indications:

- quarks, leptons compatible with higher gauge symmetry:
 $U(1) \times SU(2)_L \times SU(3) \rightarrow SU(5)$ or $SU(10)$
- unification of coupling constants at higher scale

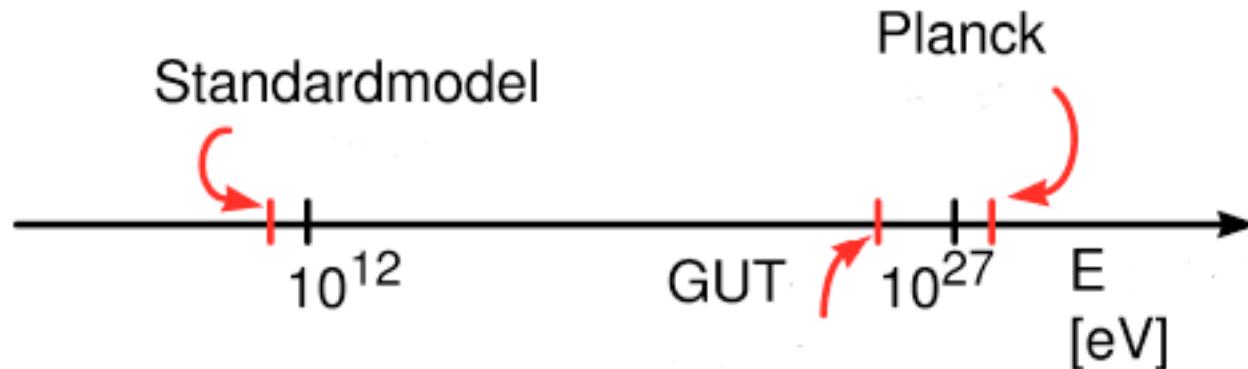


Hierarchy problem: Quantum corrections to Higgs boson mass:



$$m_H^2 \approx (m_H^2)_{\text{tree}} + 1/(16\pi^2)\Lambda_{\text{NP}}^2$$

⇒ Quadratic sensitivity to highest scale in the theory



After inclusion in larger theory: No stabilisation of the Higgs boson mass at the SM scale

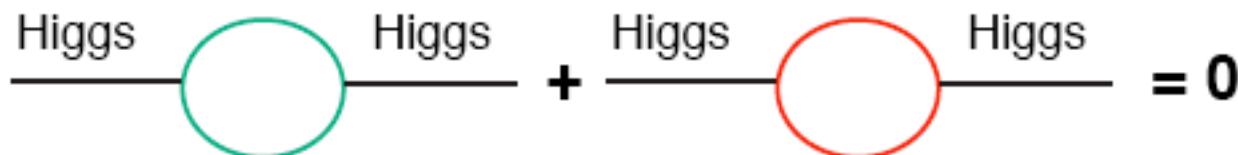
Comparison:

Photon and quark masses protected by gauge symmetry and chiral symmetry, respectively

Many solutions to the hierarchy problem on the market:

Little Higgs Models, Extra Dimensions, Supersymmetry,

- Supersymmetry offers most elegant solution for the hierarchy problem

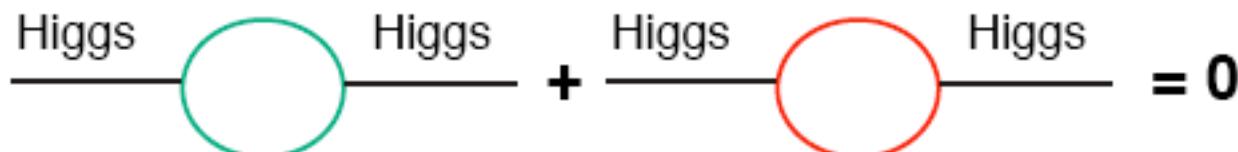


$$\delta m_H^2 \sim \Lambda_{\text{NP}}^2 \Rightarrow \delta m_H^2 \approx \log(M_{\text{stop}}/M_{\text{top}}); M_{\text{SUSY}} \leq 1 \text{ TeV}$$

- Generally to avoid fine-tuning of the Higgs mass (working hypothesis of LHC):

$$m_H^2 \approx (m_H^2)_{\text{tree}} + 1/(16\pi^2)\Lambda_{\text{NP}}^2 \Rightarrow \Lambda_{\text{NP}} \leq 4\pi m_W \approx 1 \text{ TeV}$$

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- However, electroweak precision measurements (LEP, SLC, Tevatron) naturally indicate a higher new-physics scale (parametrized by higher-dimensional operators):

Little hierarchy problem

$$\Lambda_{\text{NP}} \approx 3 - 10 \text{ TeV}$$

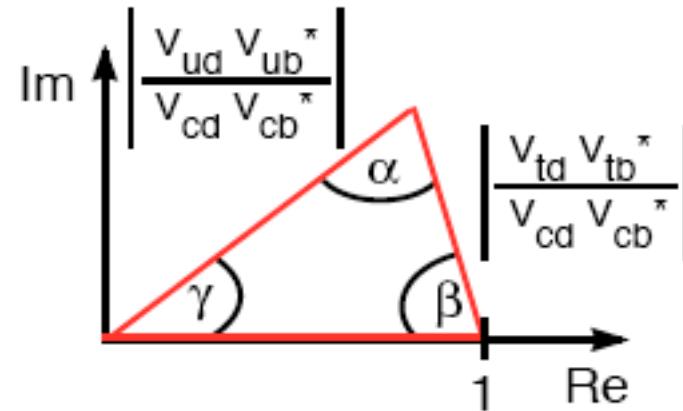
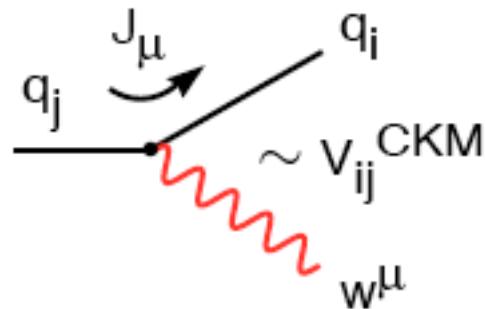
Highly nontrivial constraint on the possible new physics in the LHC reach!

- There is yet another indirect way to look for new-physics beyond SM

First status report

Flavour in the SM

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

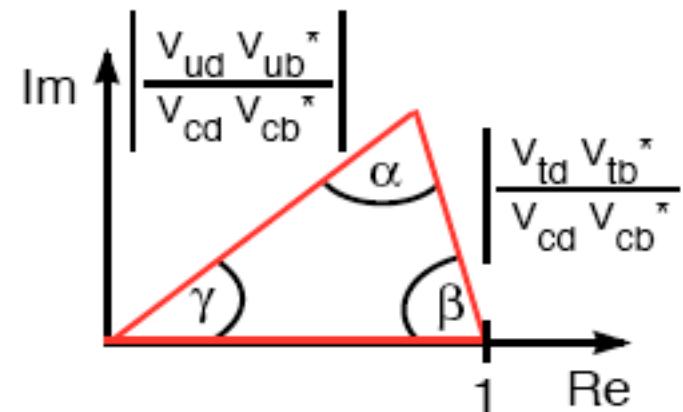
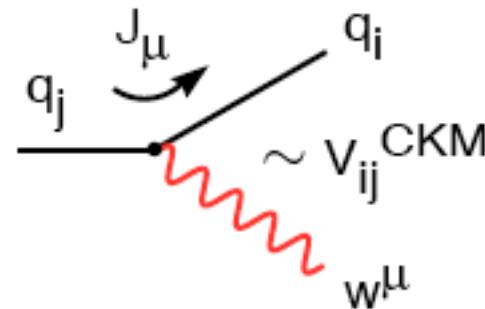


$$Im[V_{ij} V_{kl} V_{il}^* V_{kj}^*] = J_{\text{CKM}} \sum_{m,n=1}^3 \epsilon_{ikm} \epsilon_{jln} \quad J_{\text{CKM}} \sim \mathcal{O}(10^{-5})$$

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

First status report Flavour in the SM

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

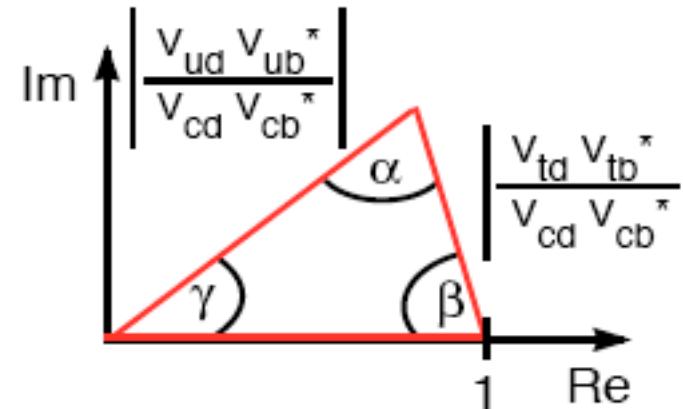
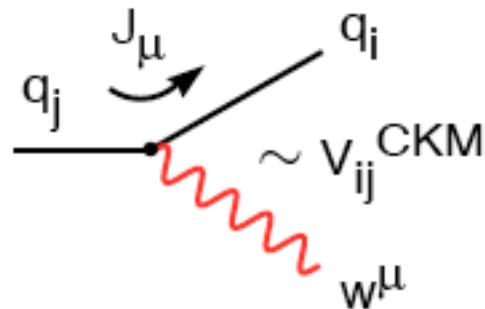
All present measurements (BaBar, Belle, CLEO, CDF, D0,...) of rare decays ($\Delta F = 1$), of mixing phenomena ($\Delta F = 2$) and of all CP violating observables at tree and loop level are consistent with the CKM theory.

Impressing success of SM and CKM theory !!

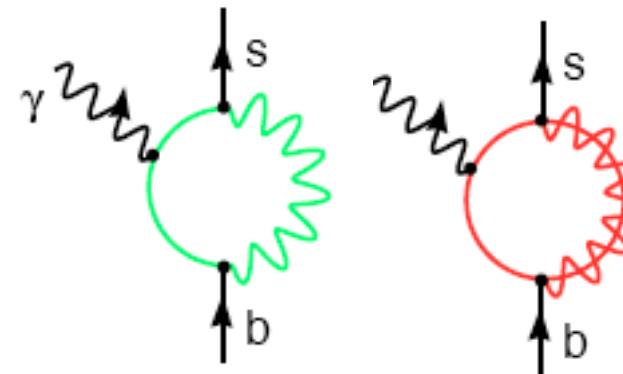
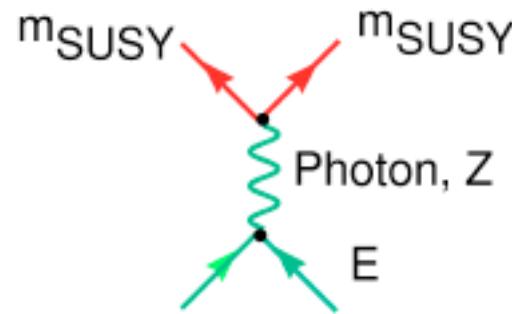
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Flavour in the SM

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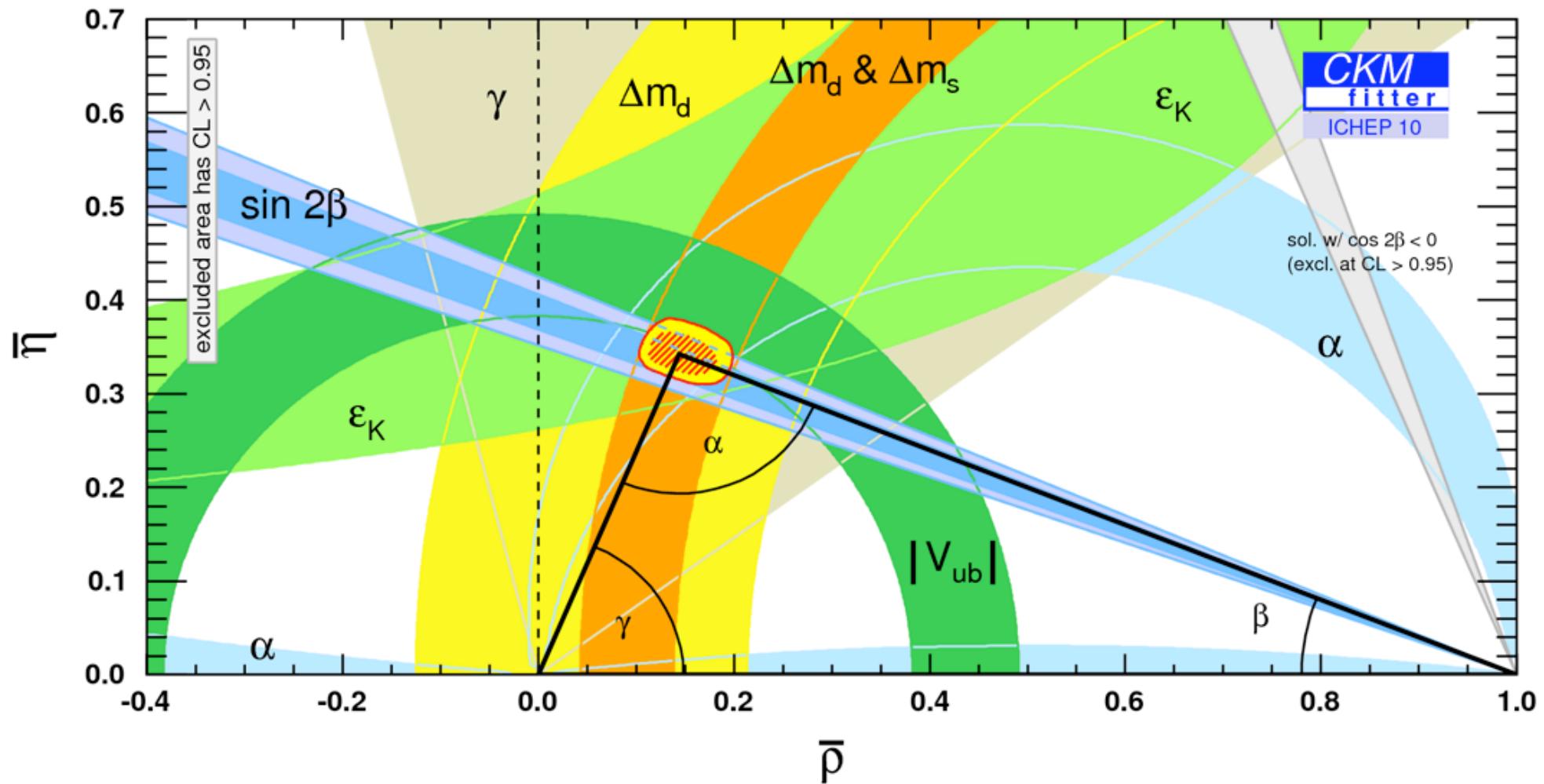
This success is somehow unexpected !!



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

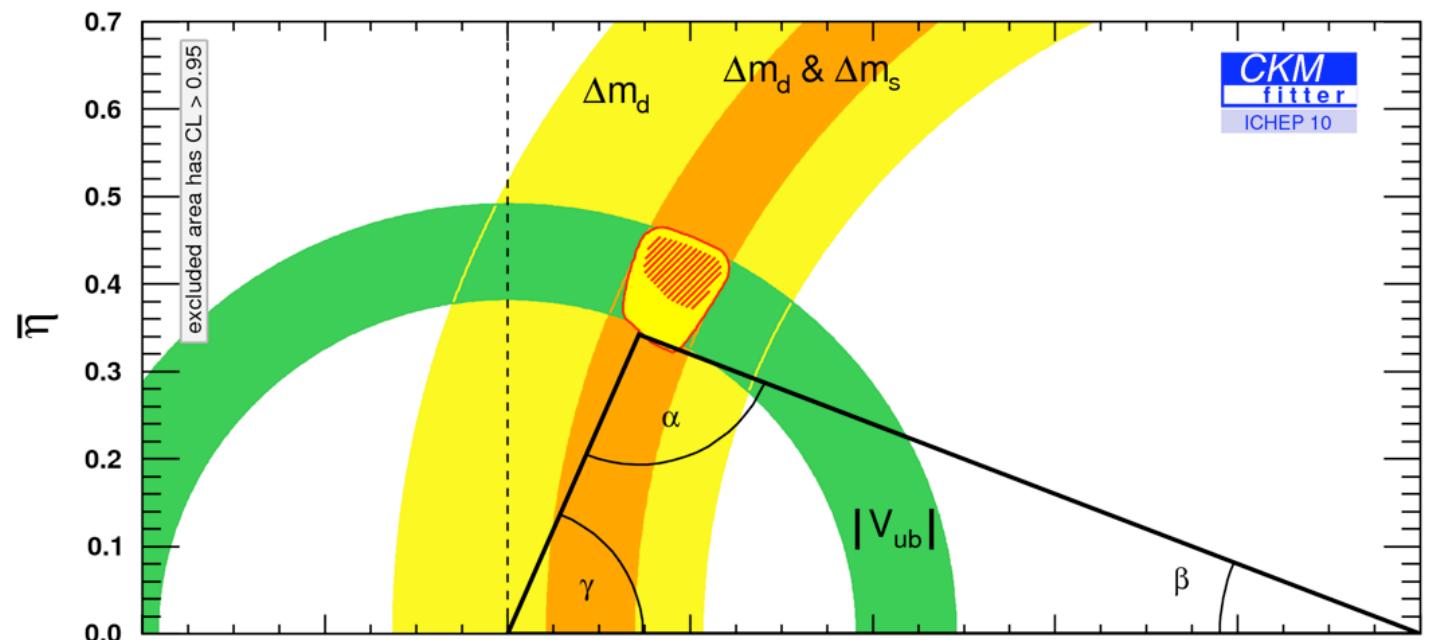
Impressing success of SM and CKM theory !!

Global fit, consistency check of the CKM theory.

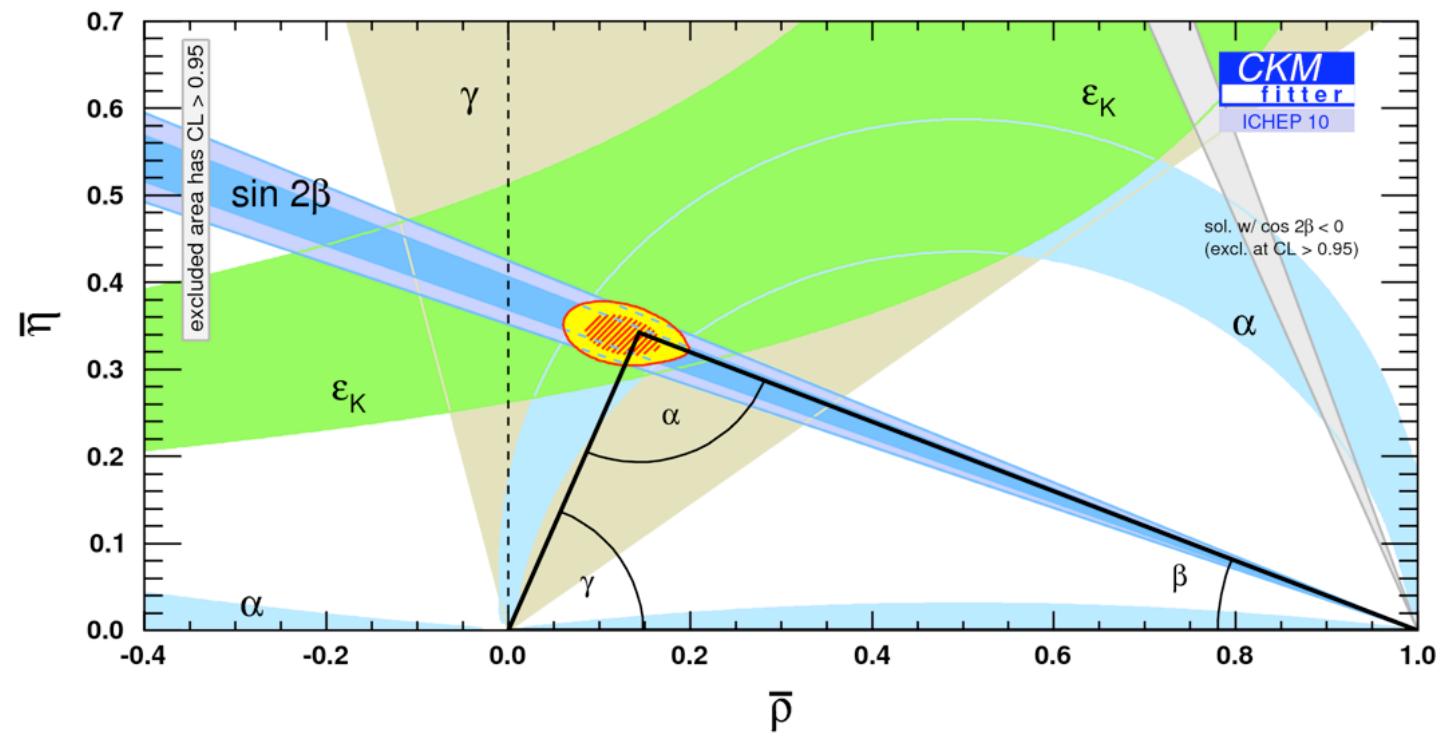


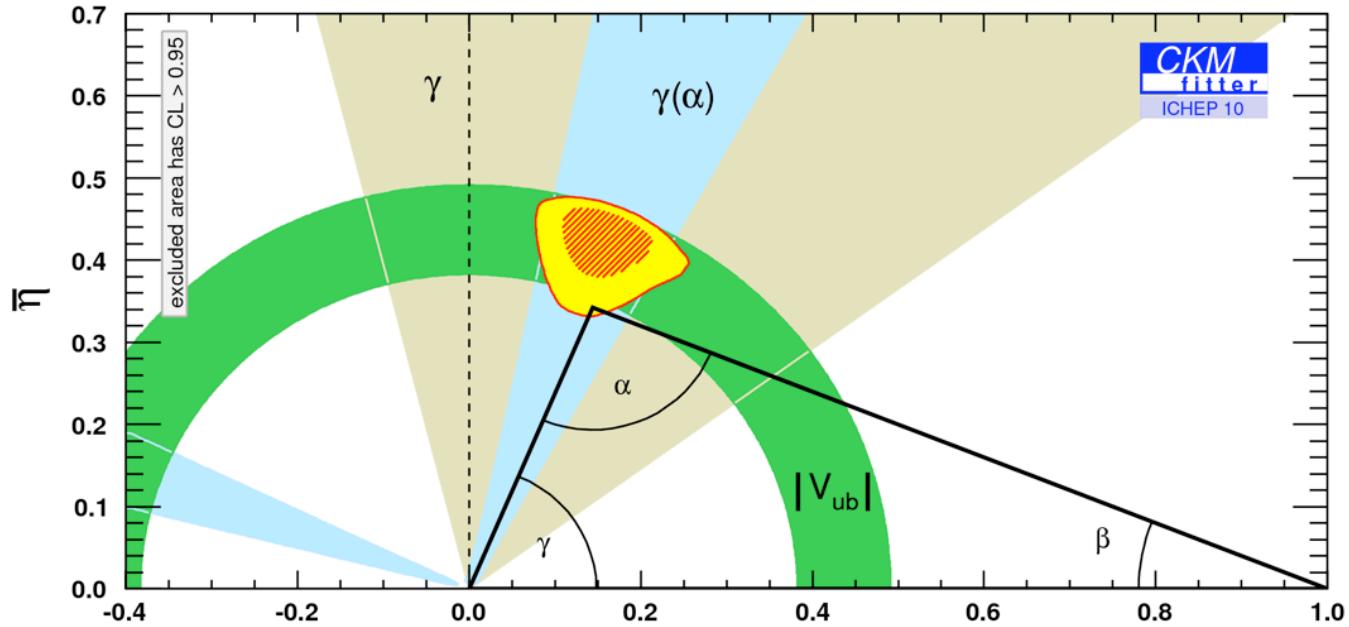
Closer Look:

CP conserving

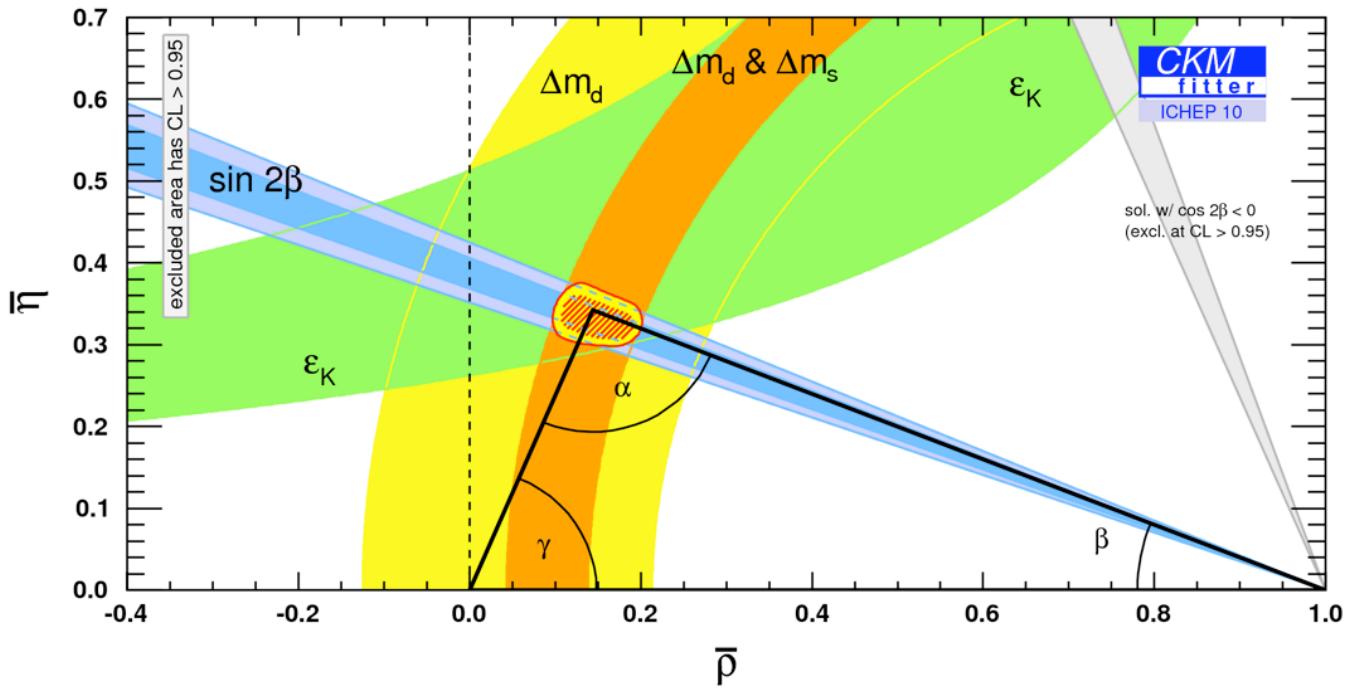


CP violating
observables



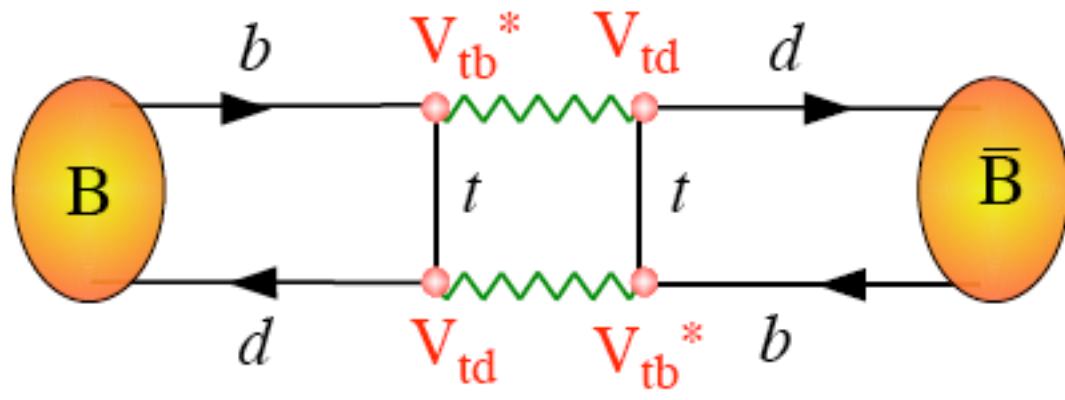
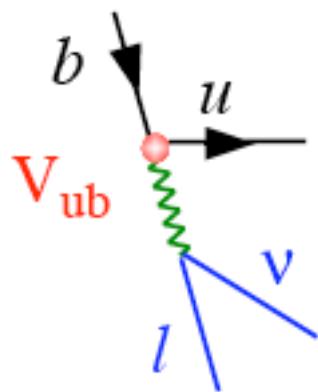


Tree processes



Loop processes

Most surprising is the consistency between the tree-level and loop-induced observables

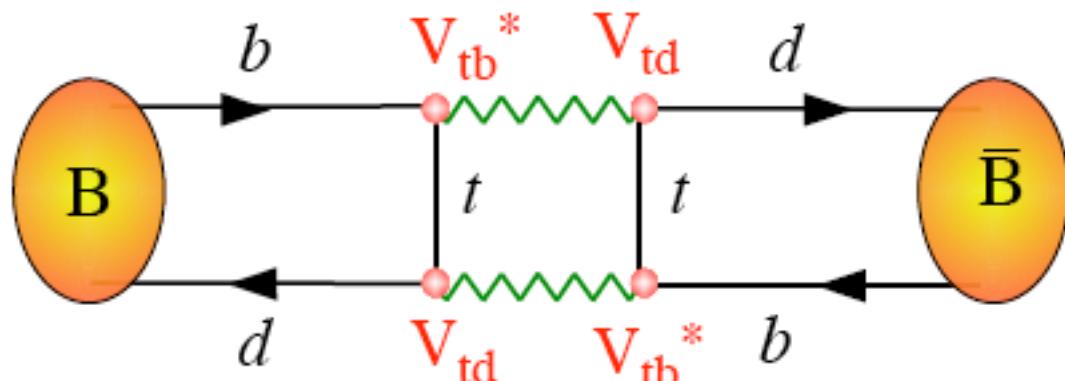
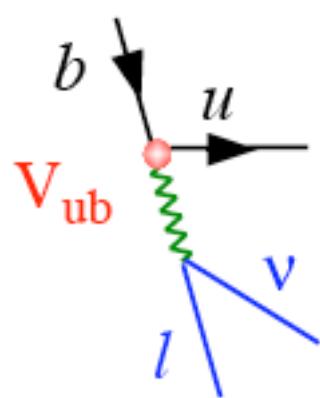


Semileptonic tree-decays versus Neutral-meson mixing $\Delta F = 2$

SM-dominated

Potentially more sensitive
to New Physics

Most surprising is the consistency between the tree-level and loop-induced observables



Semileptonic tree-decays versus Neutral-meson mixing $\Delta F = 2$

SM-dominated

Potentially more sensitive
to New Physics

There is much more data not shown in the unitarity fits which confirms the SM predictions of flavour mixing like rare decays ($\Delta F = 1$)

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

Nobel Prize 2008



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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.

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When we apply the renormalizable theory of weak interaction¹⁾ to 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 (TM) have shown²⁾ that, in the latter case, the strange interaction must be global $SU(4) \times SU(4)$ invariant as precisely as the conservation of the third component of the isospin \mathbf{I} . 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 $Q=2, -1, Q=1$ and $Q=0$ for α, β, γ and ζ , respectively, and we take the same underlying gauge group $SU_{\text{max}}(2) \times SU(3)$ and the scalar doublet field φ as those of Weinberg's original model.³⁾ Thus, hadronic parts of the Lagrangian can be divided in the following way:

$$\mathcal{L}_{\text{had}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{strong}} + \mathcal{L}^*,$$

where \mathcal{L}_{kin} is the gauge-invariant kinetic part of the quartet field, φ , so that it contains interactions with the gauge fields, A_μ , a generalized mass term of φ , which includes Yukawa couplings to φ since they contribute to the mass of φ through the spontaneous breaking of gauge symmetry, $\mathcal{L}_{\text{mass}}$ is a strong-inter-

CP-Violation in the Renormalizable Theory of Weak Interaction 653

action part which conserves \mathbf{I}_3 and therefore chiral $SU(4) \times SU(4)$ invariant,⁴⁾ We assume C - and P -invariance of $\mathcal{L}_{\text{mass}}$. The last term denotes residual interactions if they exist. Since $\mathcal{L}_{\text{mass}}$ includes couplings with φ , it has possibilities of violating CP-conservation. As is known as Higgs phenomena,⁵⁾ 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 $\mathcal{L}_{\text{mass}}$. For the mass term, however, we can eliminate such pseudoscalar parts by applying an appropriate constant gauge transformation on φ , which does not affect on $\mathcal{L}_{\text{mass}}$ due to gauge invariance.

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

- A) $4=2+2$,
- B) $4=2+1+1$,
- C) $4=1+1+1+1$,

whereas in the s.l.s., n denotes an n -dimensional representation of $SU(2)$. The present scheme of charge assignments 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 parenthesis 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 $SU_{\text{max}}(2)$ doublets and four singlets by L_μ , L_m , R_μ^0 , R_μ^1 , R_μ^2 and R_μ^3 , whose superscript $p(s)$ indicate p-like (s-like) charge states. In this case, $\mathcal{L}_{\text{mass}}$ takes, in general, the following form:

$$\mathcal{L}_{\text{mass}} = \sum_{i=1,2,3} [M_i^2 L_{\mu i} R_{\mu i}^0 + M_i^2 L_{\mu i} R_{\mu i}^1 + M_i^2 L_{\mu i} R_{\mu i}^2] + \text{h.c.},$$

$$\varphi^{\text{pm}} = \begin{pmatrix} q^+ \\ q^- \end{pmatrix}, \quad \Gamma = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \quad (1)$$

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M. Kobayashi and T. Mashkan

(i) 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

$$\begin{aligned} L_\mu &= \frac{1+\gamma}{2} \begin{pmatrix} P \\ \cos \theta \sin \theta + \sin \theta \sin \theta' \end{pmatrix}, \quad L_m = \frac{1-\gamma}{2} \begin{pmatrix} \sin^2 \theta \\ -\sin \theta \sin \theta + \cos \theta \theta' \end{pmatrix}, \\ R_\mu^0 &= \frac{1-\gamma}{2} \begin{pmatrix} \sin \theta \cdot p + \cos \theta \cdot \ell' \\ \sin \theta \cdot \ell + \cos \theta \cdot p \end{pmatrix}, \quad R_\mu^1 = \frac{1-\gamma}{2} \begin{pmatrix} \cos \theta \cdot p - \sin \theta \cdot \ell' \\ \cos \theta \cdot \ell - \sin \theta \cdot p \end{pmatrix}, \\ R_\mu^2 &= \frac{1-\gamma}{2} \begin{pmatrix} \cos \theta \cdot \ell + \sin \theta \cdot p \\ \cos \theta \cdot p - \sin \theta \cdot \ell \end{pmatrix}, \quad (2) \end{aligned}$$

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

$$\begin{aligned} \alpha^2 m_\alpha \sin \theta \sin \theta' &= m_\alpha \cos \theta \sin \ell - \alpha^2 m_\alpha \sin \gamma, \\ \alpha^2 m_\alpha \sin \theta \cos \theta' &= -m_\alpha \cos \theta \cos \ell - \alpha^2 m_\alpha \cos \gamma. \end{aligned} \quad (3)$$

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 $\sin \theta \cos \theta$ and its experimental upper bound is roughly

$$\sin \theta \cos \theta < 10^{-10}, \quad (4)$$

Thus, making an approximation of $\sin \theta \approx 0$ (the other choice $\cos \theta \approx 0$ is less critical) we obtain from Eq. (3)

$$\begin{aligned} m_\alpha/m_\varphi &\sim \tan \theta / \tan \ell, \\ m_\alpha/m_\varphi &\sim \sin \theta / \sin \ell. \end{aligned} \quad (5)$$

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 π_0/π_0 ratio of the outer kaon decay would not permit $m_\zeta > m_\varphi$. Thus, it seems difficult to reconcile the hierarchy of chiral symmetry breaking with the experimental knowledge of the semi-leptonic processes.

II) Case (B, B)

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

where M_1^0 and M_2^0 are arbitrary complex numbers. We can eliminate three Goldstone modes φ_i by putting

$$\varphi = \varphi^{\text{pm}} \begin{pmatrix} 0 \\ 1+\delta \end{pmatrix}, \quad (6)$$

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

$$\begin{aligned} \mathcal{L}_{\text{mass}} &= \varphi^{\text{pm}} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & m_3 \end{pmatrix}, \quad \varphi^{\text{pm}} = \begin{pmatrix} \varphi \\ \zeta \\ \ell \\ \ell' \end{pmatrix}. \end{aligned} \quad (7)$$

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

$$\frac{1}{2} \bar{q}_\mu A_\nu \partial^\nu A_\mu + \frac{1+\delta}{2} \varphi_\mu \Gamma. \quad (8)$$

Here, \mathcal{A}_μ is the representation matrix of $SU_{\text{max}}(2)$ for this case and explicitly given by

$$A_\mu = \frac{A_1 + i A_2}{2} = K \begin{pmatrix} 0 & U \\ 0 & 0 \end{pmatrix} K^{-1}, \quad A_\mu = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (9)$$

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

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. \quad (10)$$

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.

III) Case (A, B)

This is a rather delicate case. We denote two left doublets, one right doublet and two singlets by L_μ , L_m , R_μ^0 , R_μ^1 , respectively. The general form

CP-Violation in the Renormalizable Theory of Weak Interaction 657

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that triplet with charges $(2, 2, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{max}}(2)$ 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. (6). 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:

$$\begin{aligned} \sin \theta_1 &= -\sin \theta_1 \cos \theta_1 & -\sin \theta_1 \sin \theta_1 \\ \sin \theta_2 \cos \theta_2 &= \cos \theta_2 \cos \theta_2 & \cos \theta_2 \sin \theta_2 \\ \sin \theta_2 \sin \theta_2 &= \cos \theta_2 \sin \theta_2 & \cos \theta_2 \sin \theta_2 + \sin \theta_2 \cos \theta_2 \\ \sin \theta_3 \sin \theta_3 &= \cos \theta_3 \sin \theta_3 & \cos \theta_3 \sin \theta_3 - \cos \theta_3 \sin \theta_3 \end{aligned} \quad (11)$$

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 effect of lowest order appear only in $AS \neq 0$ semi-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, $AS=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extension of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model⁶⁾ 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.

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- E. Major and T. Mashkan, KFP-10 (preprint), April 1972.
- P. W. Higgs, Phys. Letters **12**, 130; **13**, 106, 108.
- G. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13**, 585, 1083.
- H. Georgi and S. L. Glashow, Phys. Rev. Letters **19**, 1490, 1494.

Editor

- Equation (10) should read as
- $$\begin{pmatrix} \cos \theta & -\sin \theta \cos \theta \\ \sin \theta \cos \theta & \cos^2 \theta \cos \theta \sin \theta - \sin \theta \sin \theta \sin \theta^2 \\ \sin \theta \sin \theta & \cos \theta \sin \theta \cos \theta + \cos \theta \sin \theta \sin \theta^2 \\ \cos \theta \sin \theta & \cos \theta \sin \theta \sin \theta - \cos \theta \cos \theta \sin \theta^2 \end{pmatrix}. \quad (12)$$

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:

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

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 $\Delta S \neq 0$ 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 model⁴⁾ 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 been tested at the 10% level in many cases).
- The SM does **not** describe the flavour phenomena in the lepton sector.

Flavour problem of SM

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

- Gauge principle governs the gauge sector of the SM.

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Compare for example:

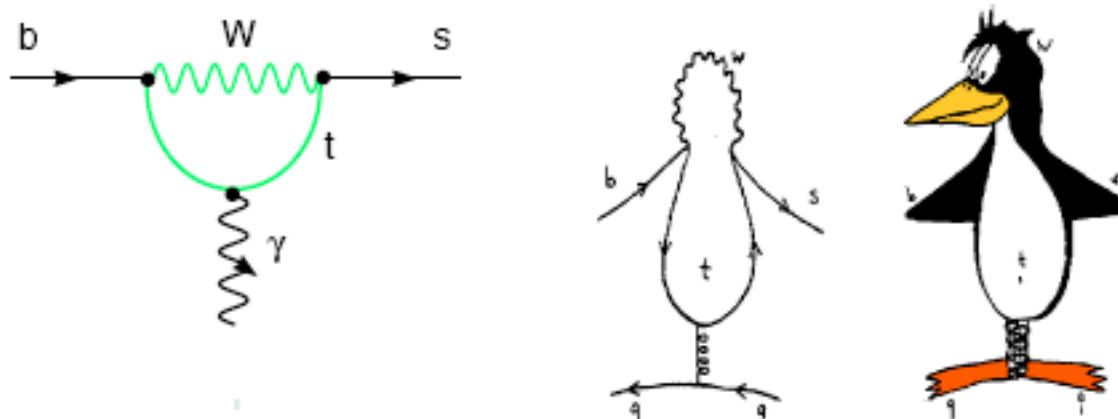
$$|V_{us}| \approx 0.2, |V_{cb}| \approx 0.04, |V_{ub}| \approx 0.004 \text{ versus } g_s \approx 1, g \approx 0.6, g' \approx 0.3$$

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 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 ?

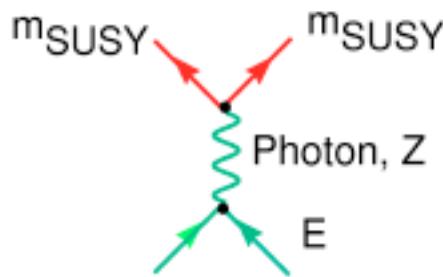
Indirect exploration of higher scales with flavour observables

- Flavour changing neutral current processes like $b \rightarrow s\gamma$ or $b \rightarrow s\ell^+\ell^-$ directly probe the SM at the one-loop level.

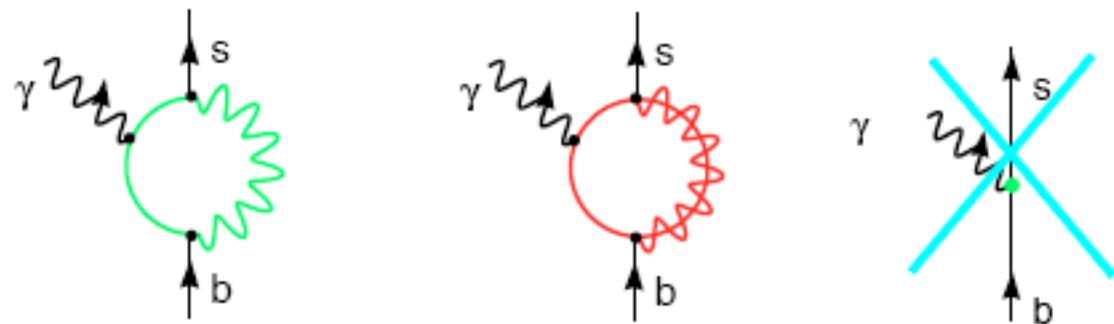


- Indirect search strategy for new degrees of freedom beyond the SM

Direct:



Indirect:



- High sensitivity for 'New Physics' (\leftrightarrow electroweak precision data, 10% \leftrightarrow 0.1%)
- Large potential for synergy and complementarity between collider (high- p_T) and flavour physics within the search for new physics

There is much more data not shown in the unitarity fits which confirms the SM predictions of flavour mixing like rare decays

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

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

VS

SM: $\mathcal{B}(B \rightarrow X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV) PRL98,022003(2007)
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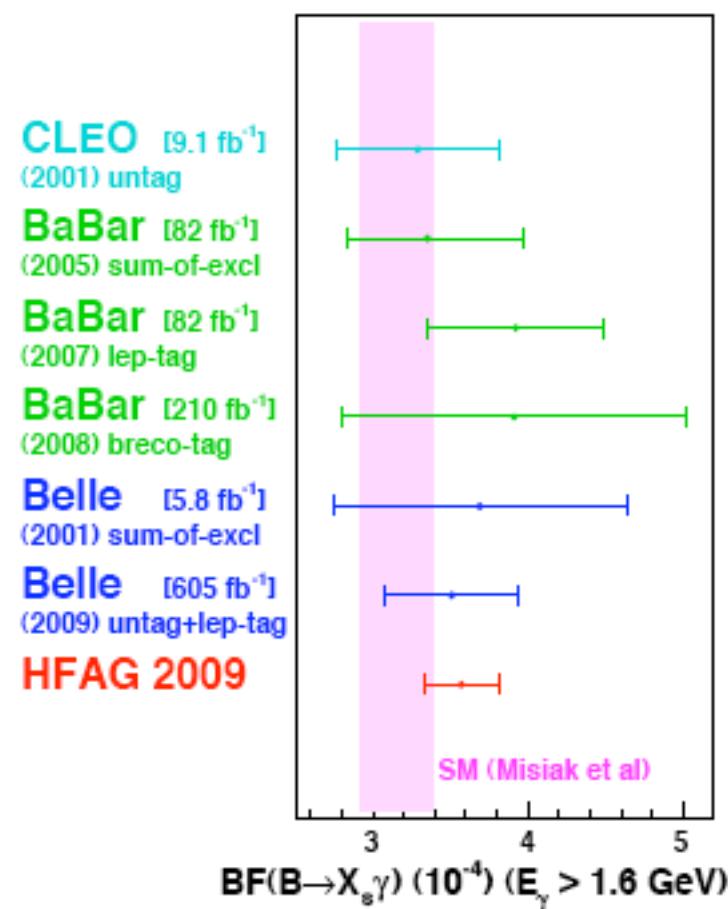
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Parameter bounds from flavour physics are model-dependent

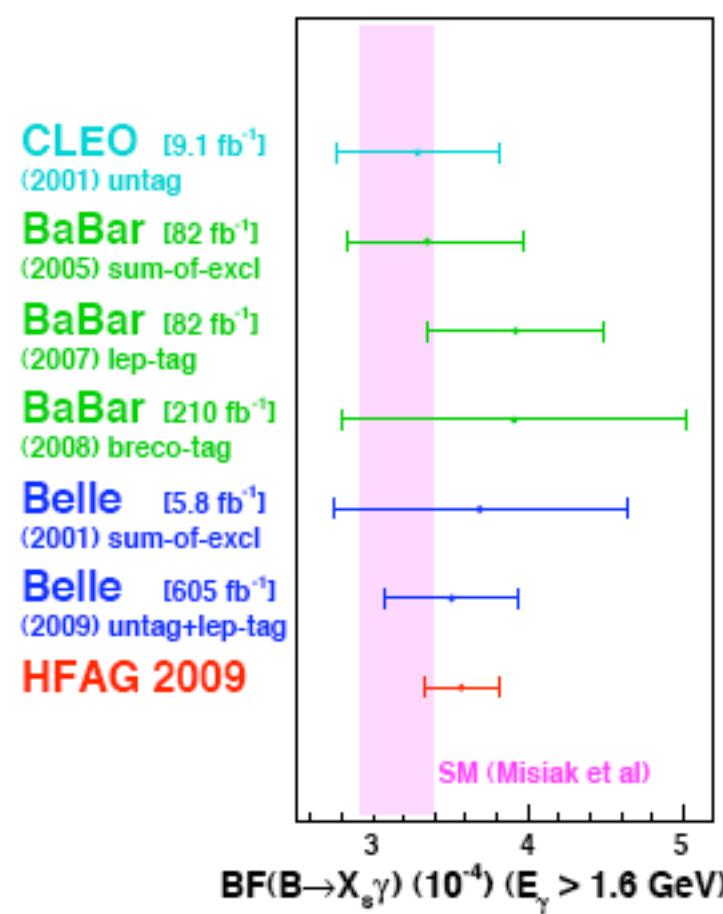
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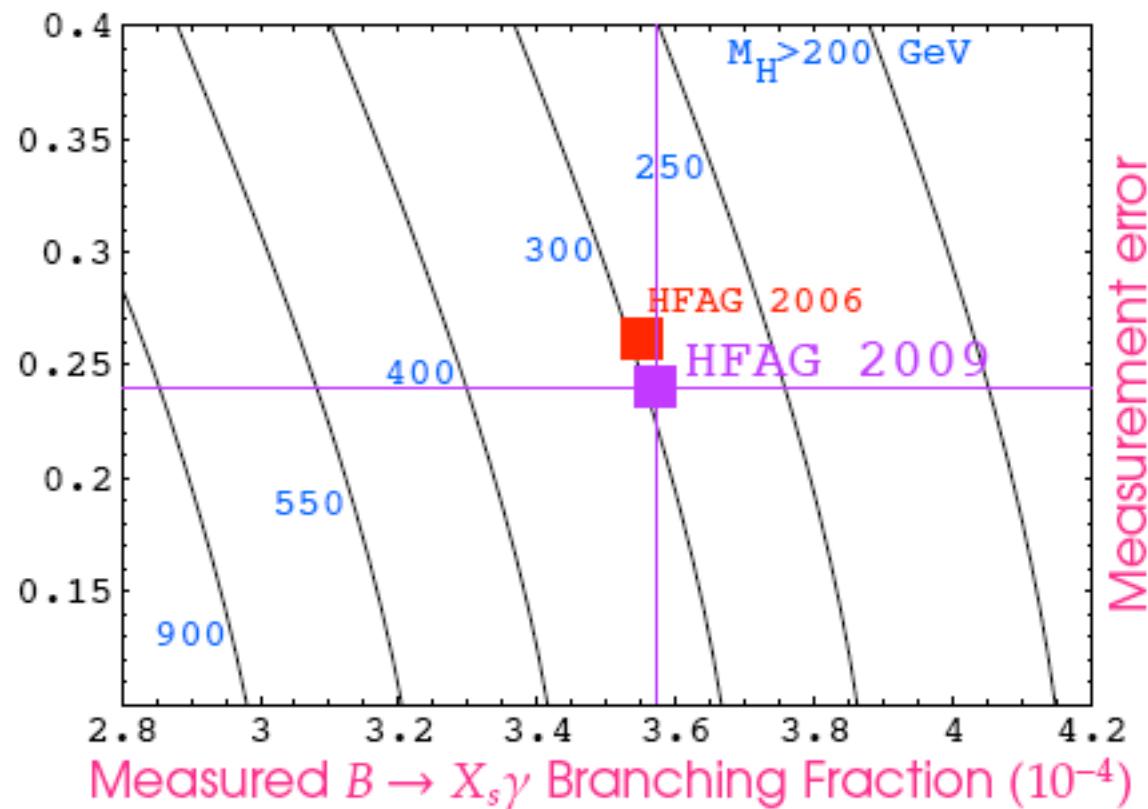
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Charged Higgs bound (2HDM)

$m_{H^+} > 300$ GeV



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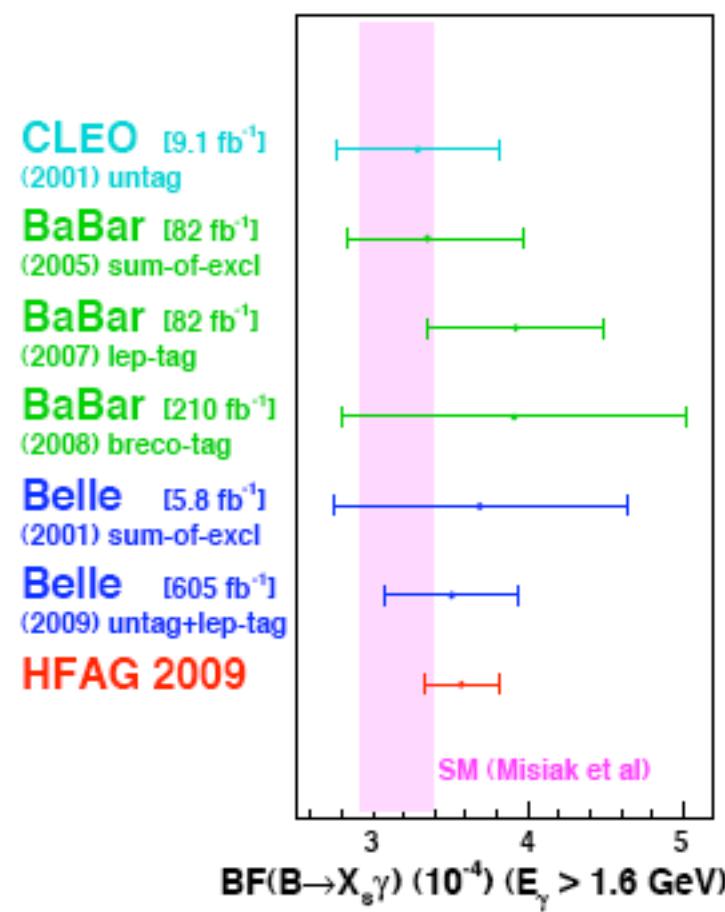
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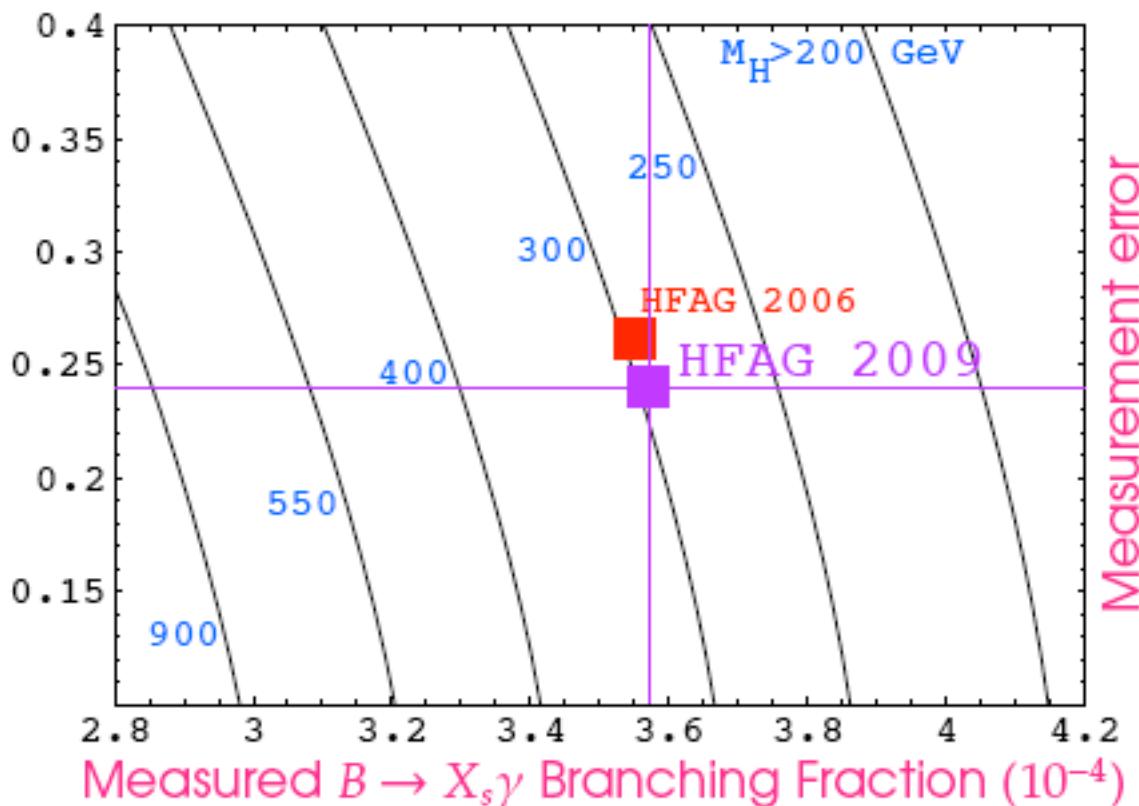
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Flavour problem of New Physics or how do FCNCs hide

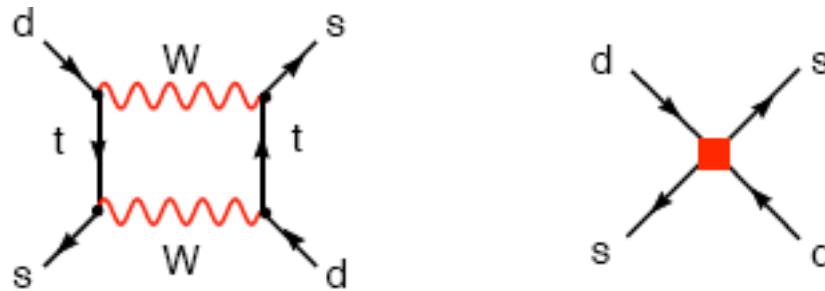
$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{NP}} \mathcal{O}_i^{(5)} + \dots$$

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

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



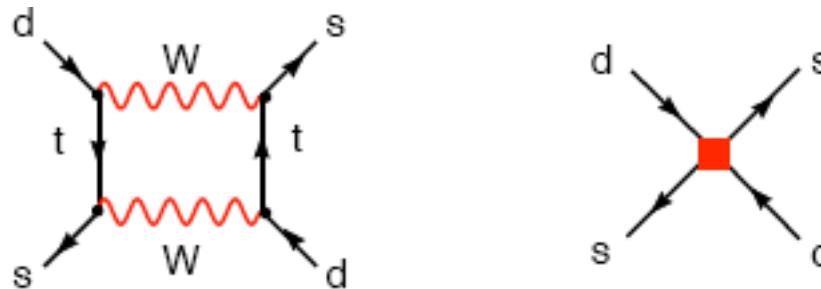
$$c^{SM}/M_W^2 \times (\bar{s}d)^2 + c^{New}/\Lambda_{NP}^2 \times (\bar{s}d)^2 \quad \Rightarrow \quad \Lambda_{NP} > 10^4 \text{ TeV}$$

(tree-level, generic new physics)

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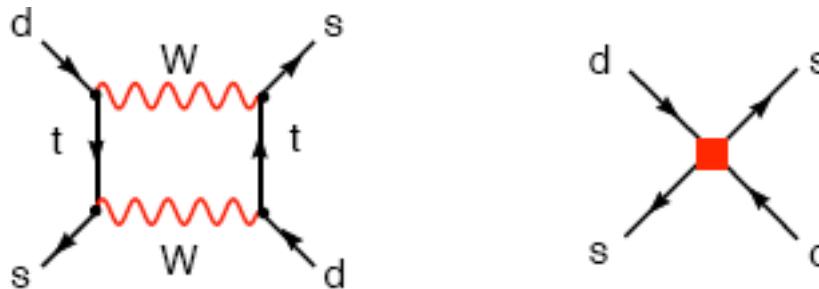
- Natural stabilisation of Higgs boson mass (hierarchy problem)
(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow \Lambda_{NP} \leq 1 \text{ TeV}$
- EW precision data \leftrightarrow little hierarchy problem $\Rightarrow \Lambda_{NP} \sim 3 - 10 \text{ TeV}$

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

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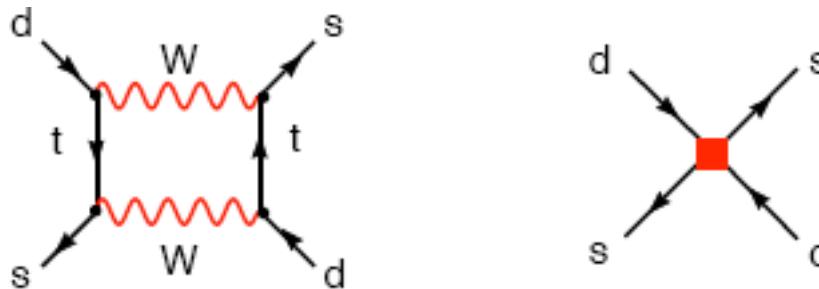
Ambiguity of new physics scale from flavour data

$$(C_{SM}^i/M_W + C_{NP}^i/\Lambda_{NP}) \times \mathcal{O}_i$$

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

This flavour problem has to be solved by any new physics scenario.

- Model-independent analysis
 - goal: overconstrain operator (Wilson) coefficients
 - but too many flavour-violating operators \Rightarrow no predictive power
 - introduce additional assumption based on our experience so far
 - Example: (Next-to-) Minimal Flavour violation
(MFV ‘flavour and CP violation as in the SM’),
might be too strong constraint from today’s point of view
- Analysis within concrete models
 - find concrete (dynamical) structures which solve the problem
 - flavour problem strong guide for model building

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

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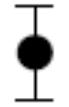
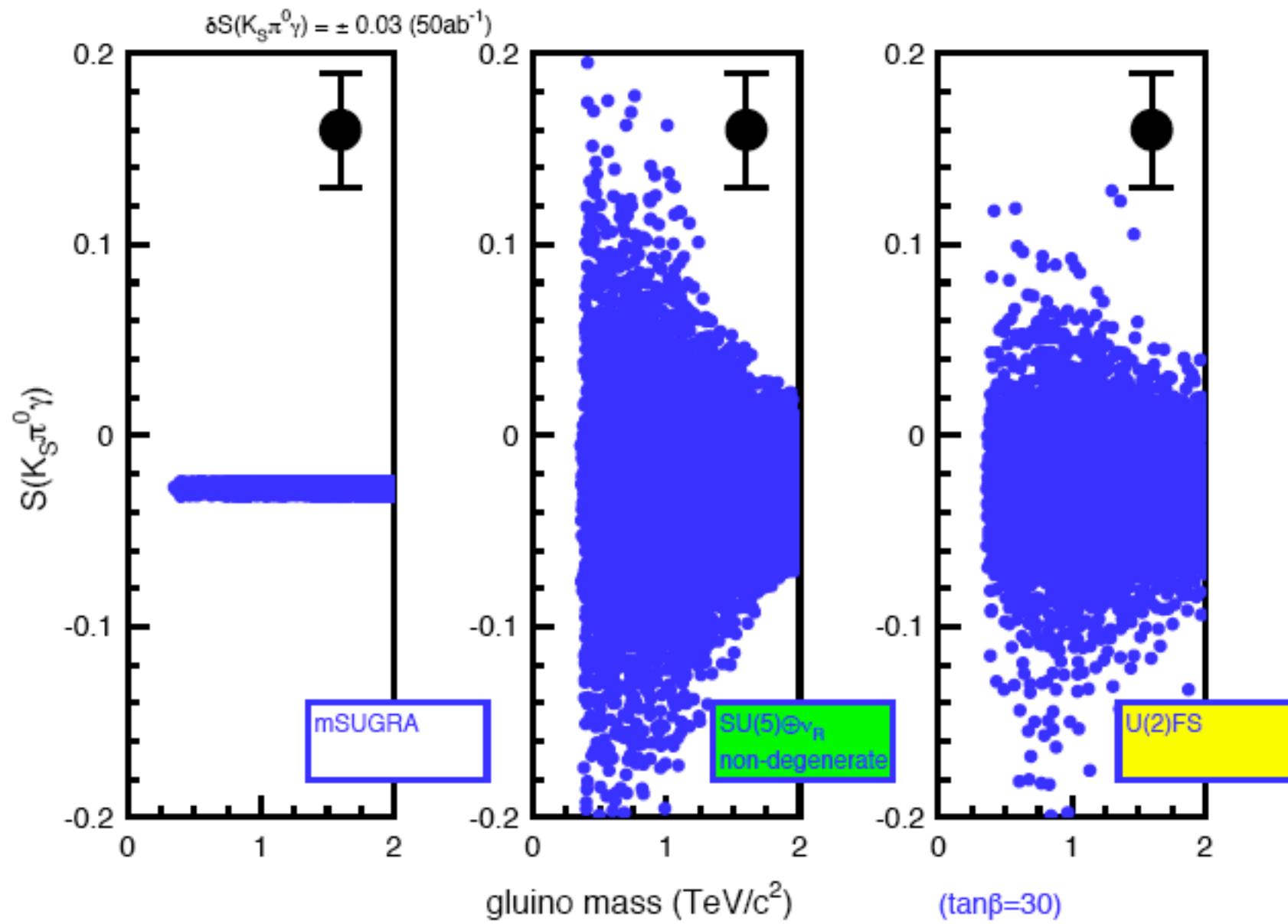
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 - Decoupling: Sfermion mass scale high
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- Dynamics of flavour \leftrightarrow mechanism of SUSY breaking
($BR(b \rightarrow s\gamma) = 0$ in exact supersymmetry)

⇒ Discrimination between various SUSY-breaking mechanism

Goto,Okada,Shindou,Tanaka,arXiv:0711.2935



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

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

Recall: SM basics

- Gauge group $G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- Fermion representations
 $Q_{Li}^I(3, 2)_{+1/6}, U_{Ri}^I(3, 1)_{+2/3}, D_{Ri}^I(3, 1)_{-1/3}, L_{Li}^I(1, 2)_{-1/2}, E_{Ri}^I(1, 1)_{-1}$

Notation: left-handed quarks, Q_L^I , $SU(3)_C$, doublets of $SU(2)_L$ and carry hypercharge $Y = +1/6$

I interaction eigenstates

$i = 1, 2, 3$ flavor index

- Spontaneous symmetry breaking

$$\phi(1, 2)_{+1/2} \quad \langle \phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad G_{\text{SM}} \rightarrow SU(3)_C \times U(1)_{\text{EM}}$$

$$\mathcal{L}_{\text{gauge}}(Q_L) = i \overline{Q_{Li}^I} \gamma_\mu \left(\partial^\mu + \frac{i}{2} g_s G_a^\mu \lambda_a + \frac{i}{2} g W_b^\mu \tau_b + \frac{i}{6} g' B^\mu \right) Q_{Li}^I$$

$$-\mathcal{L}_{\text{Yukawa}}^{\text{quarks}} = Y_{ij}^d \overline{Q_{Li}^I} \phi D_{Rj}^I + Y_{ij}^u \overline{Q_{Li}^I} \tilde{\phi} U_{Rj}^I + \text{h.c.}$$

Yukawa couplings only source of flavour violation in SM

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- Number of physical parameters in quark Yukawa couplings

$$(18 \times 2) - (9 \times 3) + 1 = 10$$

- Physical parameters:

$$6 \text{ quark masses} + (9 \text{ CKM parameters} - 5 \text{ relative phases}) = 10$$

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- **RG-invariant definition based on the flavour symmetry:**
Yukawa couplings are introduced as background values of fields
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d'Ambrosio, Giudice, Isidori, Strumia, hep-ph/0207036

Chivukula, Georgi, Phys.Lett.B188(1987)99

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MFV: All effective field operators with higher dimension
 also have to be invariant

Specific basis: $Y_D = \text{diag}(y_d, y_s, y_b)$, $Y_U = V_{CKM}^+ \times \text{diag}(y_u, y_c, y_t)$

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Specific basis: $Y_D = \text{diag}(y_d, y_s, y_b)$, $Y_U = V_{CKM}^+ \times \text{diag}(y_u, y_c, y_t)$

Typical FCNC-operator with external d-type quarks: $\overline{Q_{LL}}^i (Y_U Y_U^+)_{ij} Q_L^j \times L_L L_L$

$$\begin{aligned} \lambda_{FCij} &= (Y_U Y_U^+)_{ij} = (V_{CKM}^+ \times \text{diag}(y_u^2, y_c^2, y_t^2) \times V_{CKM})_{ij} \approx \\ &\approx (V_{CKM}^+ \times \text{diag}(0, 0, y_t^2) \times V_{CKM})_{ij} = y_t^2 \times V_{3,i}^* V_{3,j} \end{aligned}$$

Coupling λ_{FC} is the effective coupling ruling all FCNCs with external d-type quarks.

- 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

MFV predictions to be tested:

- usual CKM relations between $[b \rightarrow s] \leftrightarrow [b \rightarrow d] \leftrightarrow [s \rightarrow d]$ transitions:
-we need high-precision $b \rightarrow s$, but also $s \rightarrow d$ measurements
 $\mathcal{B}(\bar{B} \rightarrow X_d\gamma) \leftrightarrow \mathcal{B}(\bar{B} \rightarrow X_s\gamma)$, $\mathcal{B}(\bar{B} \rightarrow X_s\nu\bar{\nu}) \leftrightarrow \mathcal{B}(K \rightarrow \pi^+\nu\bar{\nu})$
- CKM phase only source of CP violation:
-phase measurements in $B \rightarrow \phi K_s$ or $\Delta M_{B_{(s/d)}}$ are not sensitive to new physics
- The usefulness of MFV-bounds/relations is obvious; **any measurement beyond those bounds indicate the existence of new flavour structures**

- In MFV models with one Higgs doublet, all FCNC processes with external d -type quarks are governed by

$$(Y_U Y_U^\dagger)_{ij} \approx y_t^2 V_{3i}^* V_{3j} \quad \text{CKM hierarchy}$$

It also allows for large $\tan\beta$ effects when additional Higgs doublets added, in particular in helicity-suppressed observables $B \rightarrow \mu\mu$, $B^\pm \rightarrow \tau^\pm\nu$

$$B \rightarrow \mu\mu \quad A_{\text{SM}} \sim m_\mu/m_b \Leftrightarrow A_{H^0, A^0} \sim \tan^3\beta$$

Spurion combination $(Y_D Y_D^\dagger)_{ij} \approx y_d^2 \delta_{ij}$ numerically important, $U(1)$

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- The MFV hypothesis is far from being verified

New spurions allowed: Next-to-MFV

Agashe, Papucci, Perez, Pijol, hep-ph/0509117 Feldmann, Mannel, hep-ph/0611095

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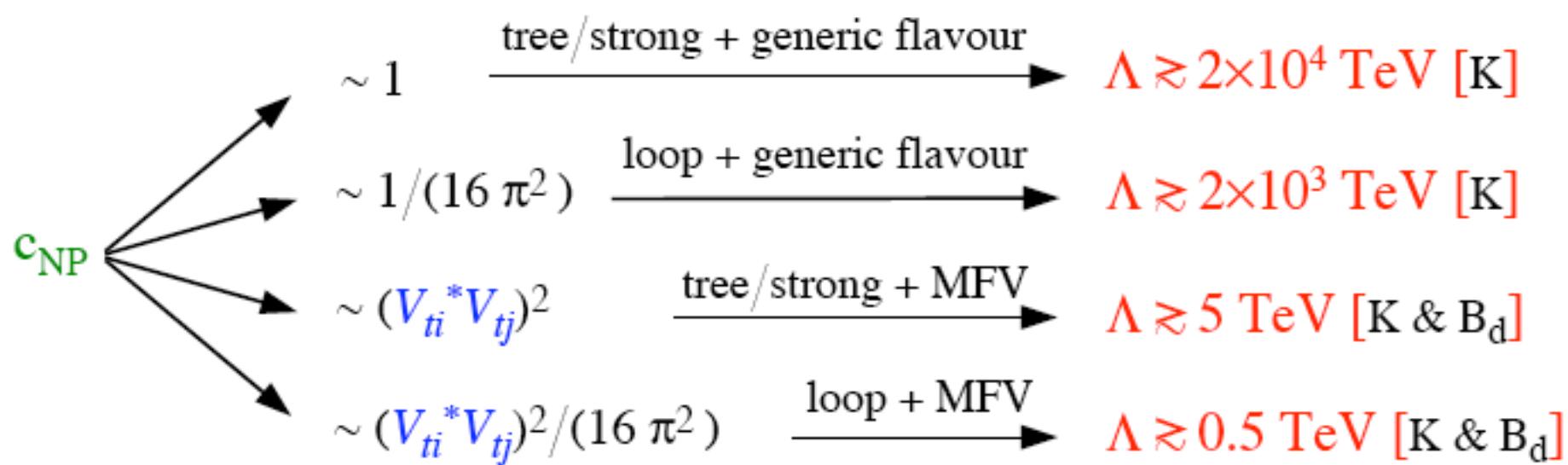
- Extension to lepton flavour possible (not unique definition, neutrino mass generation)

Cirigliano, Grinstein, Isidori, Wise, hep-ph/0507001, 0608123 Davidson, Palorini, hep-ph/0607329

Minimal flavour violation: formal solution of NP flavour problem

$$M(B_d - \bar{B}_d) \sim \frac{(V_{tb}^* V_{td})^2}{16 \pi^2 M_w^2} + \left(c_{NP} \frac{1}{\Lambda^2} \right)$$

contribution of the new heavy degrees of freedom



Courtesy of Gino Isidori

We still have to find explicit dynamical structures to realise MFV:

- Gauge-mediated supersymmetry
- $SO(10)$ GUT model with family symmetries
Dermisek,Raby,hep-ph/0507045 Straub et al.,arXiv:0707.3954
- Top-bottom- τ unification under attack of FCNC
Atmannsdorfer,Guadagnoli,Raby,Straub,arXiv:0801.4363
- Warped extra dimensions
Weiler et al.,arXiv:0709.1714
- 5DMFV \Rightarrow 4DNMFV, Randall-Sundrum
Fitzpatrick,Perez,Randall,arXiv:0710.1869
- General formalism to describe specific sequence of flavour symmetry breaking within MFV
Feldmann,Mannel,arXiv:0801.1802

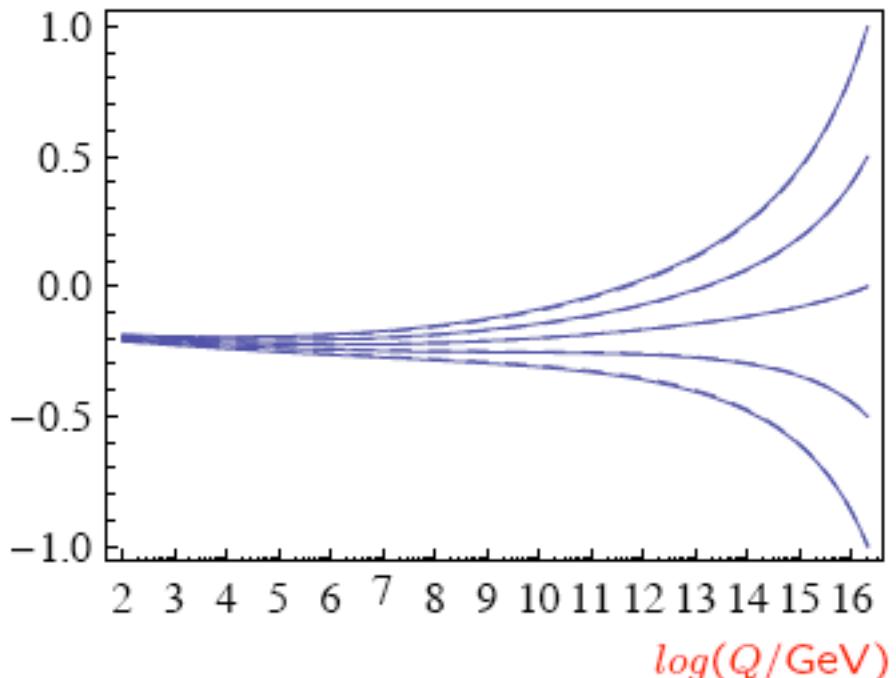
Running MFV in Supersymmetry

Paradisi,Ratz,Schieren,Simonetto,arXiv:0805.3989
Colangelo,Nikolidakis,Smith,arXiv:0807.0801

- MFV ansatz RG-invariant by construction

$$\begin{aligned}m_Q^2 &= \alpha_1 \mathbb{1} + \beta_1 Y_u^\dagger Y_u + \beta_2 Y_d^\dagger Y_d + \beta_3 Y_d^\dagger Y_d Y_u^\dagger Y_u + \beta_3 Y_u^\dagger Y_u Y_d^\dagger Y_d , \\m_u^2 &= \alpha_2 \mathbb{1} + \beta_5 Y_u Y_u^\dagger , \\m_d^2 &= \alpha_3 \mathbb{1} + \beta_6 Y_d Y_d^\dagger , \\A_u &= \alpha_4 Y_u + \beta_7 Y_u Y_d^\dagger Y_d , \\A_d &= \alpha_5 Y_d + \beta_8 Y_d Y_u^\dagger Y_u , \\A_e &= \alpha_e Y_e .\end{aligned}$$

$$\frac{\beta_1}{\alpha_1}$$



'Spurion expansion' of soft terms

- MFV coefficients β_i at low energy insensitive to their GUT boundary conditions: (gluino contribution versus Yukawa effects)
- Result: MFV-compatible change of boundary conditions at the high scale has barely any influence on the low scale spectrum. 'fixed points'

- 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

Flavour@high- p_T interplay

Can ATLAS/CMS exclude MFV ?

Can we ignore flavour when analysing possible
new physics at the electroweak scale?

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

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The poster features a blue background with a circular red outline. Inside the circle, there's a stylized illustration of a particle collision with tracks and a central interaction point. Overlaid on the image are the following text elements:

Flavour in the era of the LHC

a Workshop on the interplay of flavour and collider physics

First meeting:
CERN, November 7-10 2005

<http://mlm.home.cern.ch/mlm/FlavLHC.html>

On the right side of the poster, there are two logos: the CERN logo and a logo for "Flavour in the era of the LHC 2005". Below these are several sections of text:

- BSM signatures in BFKD physics, and their complementarity with the high-pT LHC discovery potential
- Flavour phenomena in the decays of SUSY particles
- Squark/slepton spectroscopy and family structure
- Flavour aspects of non-SUSY BSM physics
- Flavour physics in the lepton sector
- grand and EDM as BSM probes
- Flavour experiments for the next decade

Local Organizing Committee

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M. Trottolo (ISDC, Trieste)
K. Zurek (CERN, Hamburg)

5 meetings between 11/2005 and 3/2007

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

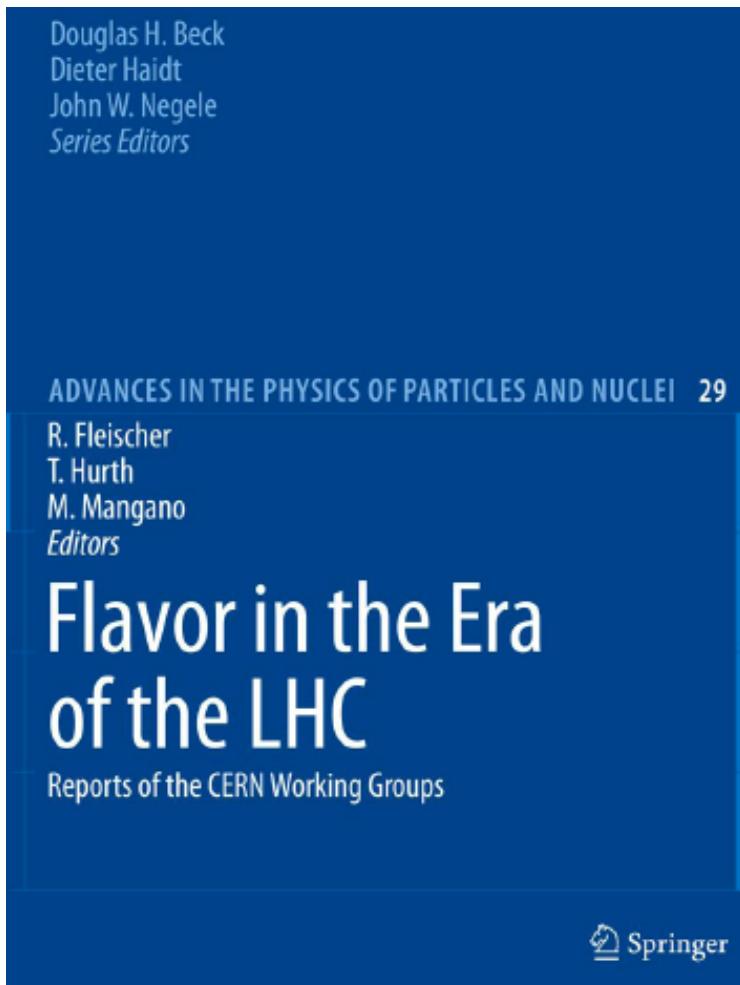
arXiv:0801.1833 [hep-ph] “B, D and K decays”

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

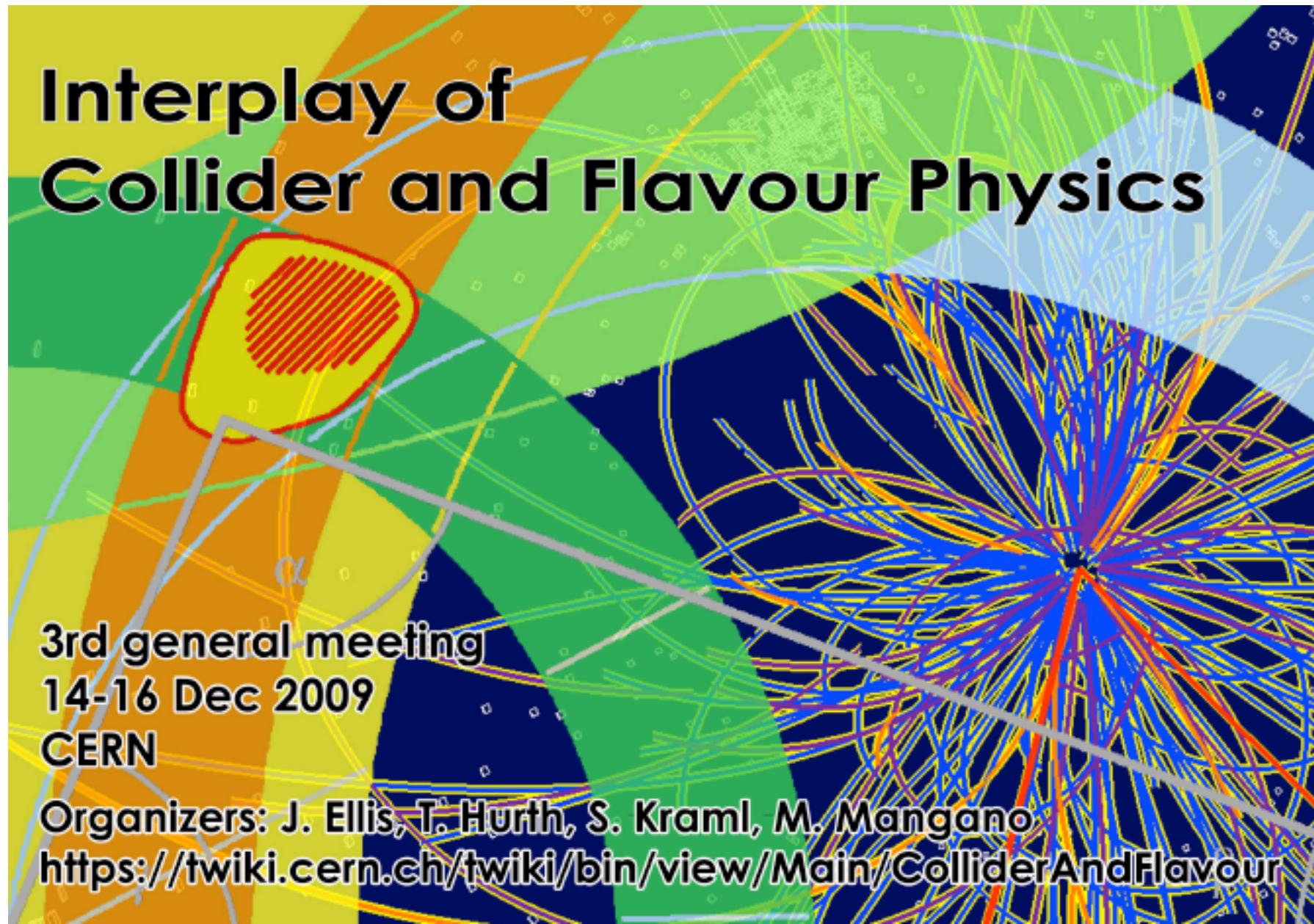
⇒ CERN workshop on the interplay of flavour and collider physics
Fleischer,Hurth,Mangano see <http://mlm.home.cern.ch/mlm/FlavLHC.html>



Reference book for flavour physics
in the LHC era

- arXiv:0801.1800 [hep-ph] “Collider aspects of flavour physics at high Q”
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Follow-up workshop



Quark flavour at ATLAS/CMS

• Probing Minimal Flavour Violation at the LHC

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

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

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

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.

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

MFV prediction for events with B' pair production:

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

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],

- Squark decays:

$$\tilde{u}_i \rightarrow u_j \tilde{\chi}_k^0, d_j \tilde{\chi}_l^+, \quad \tilde{d}_i \rightarrow d_j \tilde{\chi}_k^0, u_j \tilde{\chi}_l^-$$

with $i = 1, \dots, 6$, $j = 1, 2, 3$, $k = 1, \dots, 4$ 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 disalignment of quarks and squarks

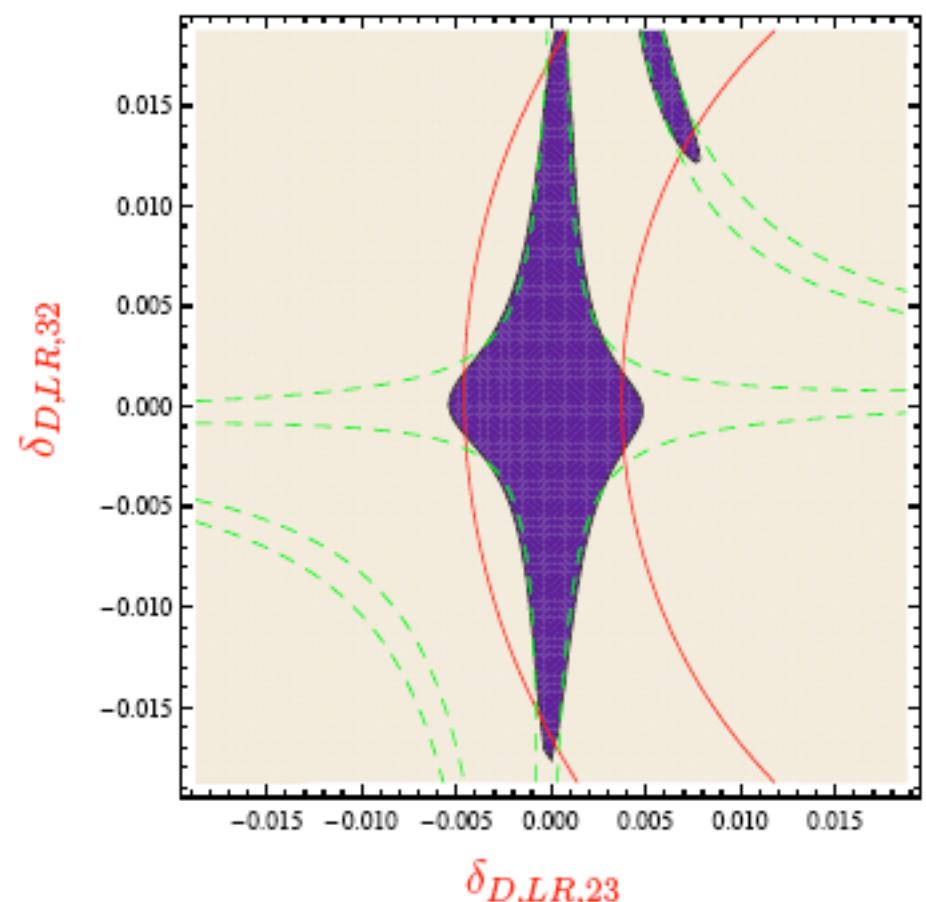
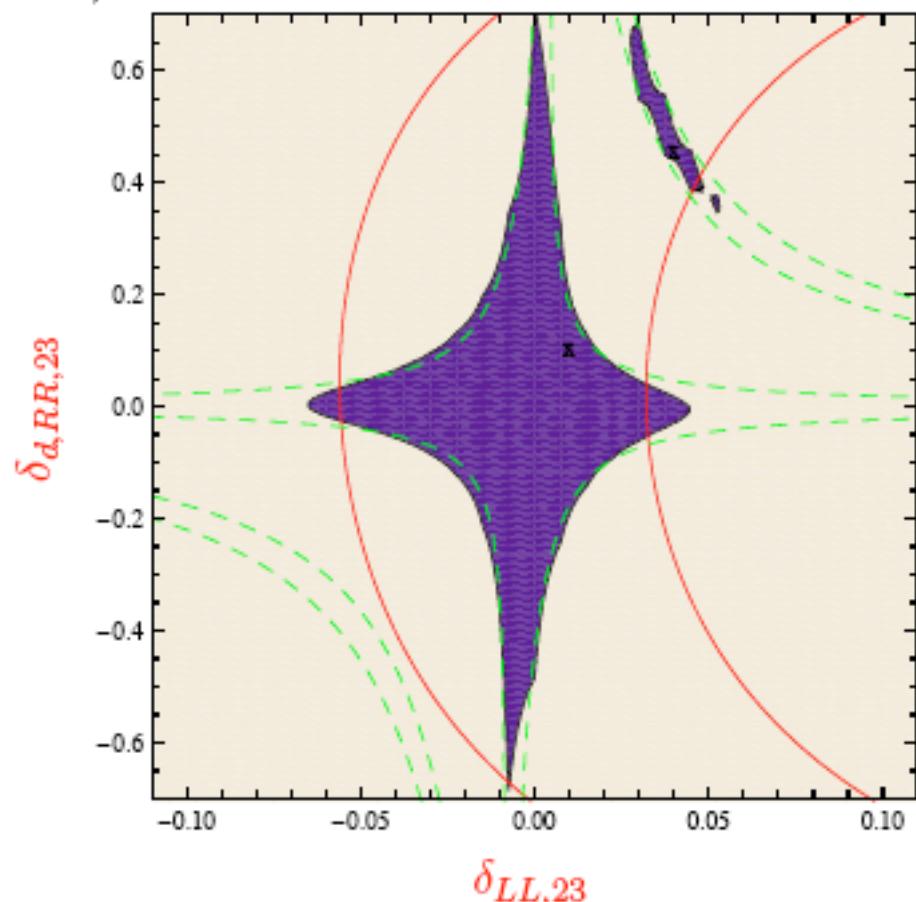
Strategy:

- Take susy benchmark points: SPS1a', γ , and I"
- Vary flavour nondiagonal parameters
(off-diagonal squark mass entries)
- Use all experimental and theoretical bounds

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⇒ 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

⇒ 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

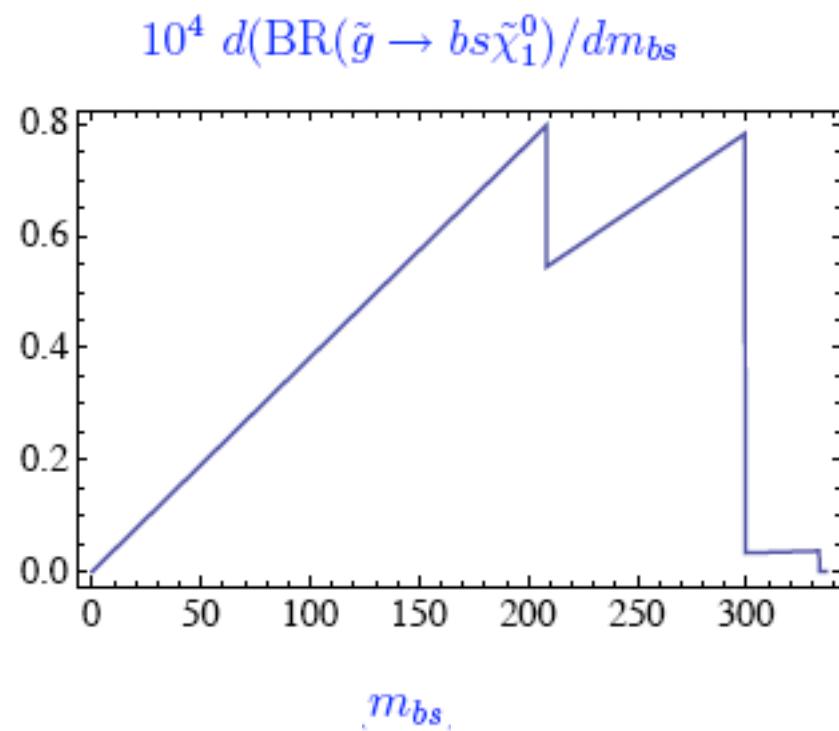
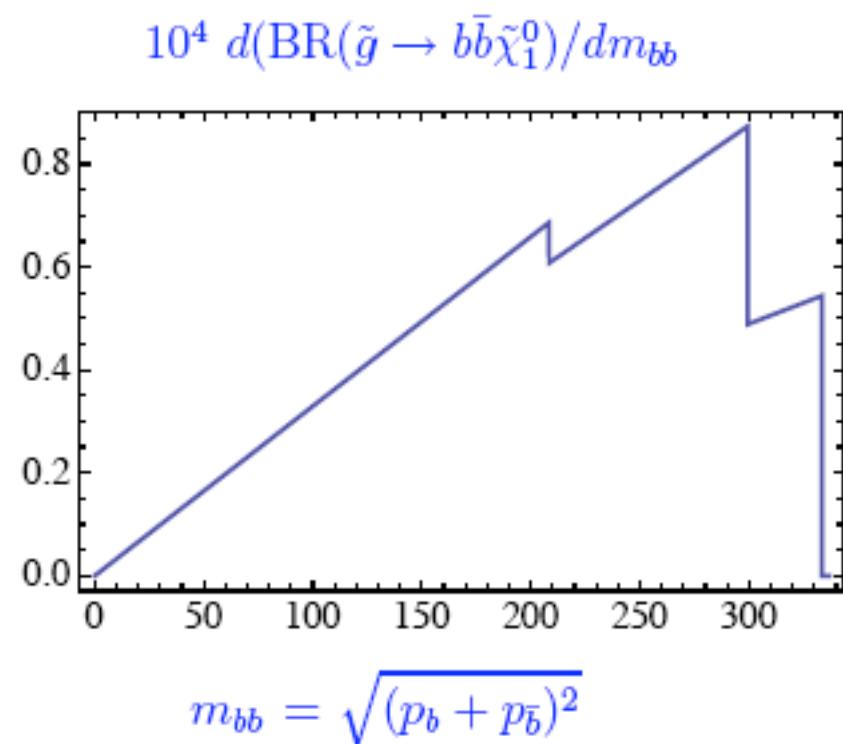
Typical results for squark and gluino decays

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: $\tilde{b}_L(\tilde{b}_R)$	$\tilde{\chi}_1^0 b$, 4.4 $\tilde{u}_1 W^-$, 27.7	$\tilde{\chi}_2^0 b$, 29.8	$\tilde{\chi}_1^- t$, 37.0	$\tilde{\chi}_1^0 s$, 36.8 $\tilde{\chi}_1^- t$, 9.6	$\tilde{\chi}_1^0 b$, 42.2	$\tilde{\chi}_2^0 b$, 10.9	
$\tilde{d}_2 \rightarrow$ I: $\tilde{b}_R(\tilde{b}_L, \tilde{s}_R)$	$\tilde{\chi}_1^0 s$, 8.0 $\tilde{\chi}_3^0 b$, 1.1 $\tilde{u}_1 W^-$, 38.9	$\tilde{\chi}_1^0 b$, 6.4 $\tilde{\chi}_4^0 b$, 1.8	$\tilde{\chi}_2^0 b$, 19.0 $\tilde{\chi}_1^- t$, 24.6	$\tilde{\chi}_1^0 b$, 2.1 $\tilde{u}_1 W^-$, 33.2	$\tilde{\chi}_2^0 b$, 27.3	$\tilde{\chi}_1^- t$, 34.6	
$\tilde{d}_4 \rightarrow$ I: $\tilde{s}_R(\tilde{s}_L, \tilde{b}_R)$	$\tilde{\chi}_1^0 s$, 9.1 $\tilde{\chi}_1^- u$, 2.1	$\tilde{\chi}_1^0 b$, 6.3 $\tilde{\chi}_1^- c$, 47.3	$\tilde{\chi}_2^0 s$, 25.3 $\tilde{u}_1 W^-$, 4.8	$\tilde{\chi}_1^0 d$, 2.3 $\tilde{\chi}_1^- c$, 3.0	$\tilde{\chi}_2^0 d$, 31.7 $\tilde{\chi}_2^- u$, 2.3	$\tilde{\chi}_1^- u$, 59.7	
$\tilde{d}_5 \rightarrow$ I: \tilde{d}_L	$\tilde{\chi}_1^0 d$, 2.3 $\tilde{\chi}_1^- c$, 2.8	$\tilde{\chi}_2^0 d$, 31.7 $\tilde{\chi}_2^- u$, 2.3	$\tilde{\chi}_1^- u$, 59.9	$\tilde{\chi}_1^0 s$, 2.2 $\tilde{\chi}_1^- c$, 58.5	$\tilde{\chi}_2^0 s$, 30.7 $\tilde{\chi}_2^- c$, 2.3	$\tilde{\chi}_1^- u$, 2.9	
$\tilde{d}_6 \rightarrow$ I: $\tilde{s}_L(\tilde{s}_R)$	$\tilde{\chi}_1^0 s$, 3.1 $\tilde{\chi}_1^- c$, 58.1	$\tilde{\chi}_2^0 s$, 30.6 $\tilde{\chi}_2^- c$, 2.4	$\tilde{\chi}_1^- u$, 2.7	$\tilde{\chi}_1^0 s$, 19.7 $\tilde{\chi}_4^0 b$, 2.9 $\tilde{g} b$, 39.8	$\tilde{\chi}_1^0 b$, 18.8 $\tilde{\chi}_2^- t$, 5.8 $\tilde{u}_1 W^-$, 5.5	$\tilde{\chi}_3^0 b$, 2.9 $\tilde{\chi}_2^- c$, 2.3 $\tilde{g} s$, 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 $\tilde{d}_3 d$, 5.9 $\tilde{d}_5 d$, 3.3	$\tilde{u}_3 u$, 5.8 $\tilde{d}_3 d$, 5.9	

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

Impact on LHC

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



Again: flavour-tagging at LHC important, but difficult

Additional information from ILC or from Superflavour factory needed !

Further observables work in progress

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



$$\chi^2 = \sum_i^{N_{const.}} \frac{(Const._i - Pred._i(MSSM))^2}{\Delta Const.^2 + \Delta Pred.^2}$$

Const. = Experimental Constraint value

Pred.(MSSM) = Predicted value for a given MSSM parameter set

MSSM Parameter in the Fit

$\tan\beta$ - ratio of vacuum expectation values

M_A - mass of the CP odd Higgs boson

A - tri-linear Higgs-stop coupling, all tri-linear couplings are set equal

μ - Higgs mixing parameter

M_{squark} - squark soft SUSY-breaking parameter; $M_{squark} = 2M_{slepton}$

Assumptions (varied to evaluate systematic):

$M_2 = 200 \text{ GeV}$, $M_3 = 300 \text{ GeV}$, $M_1 = 1/2 M_2$

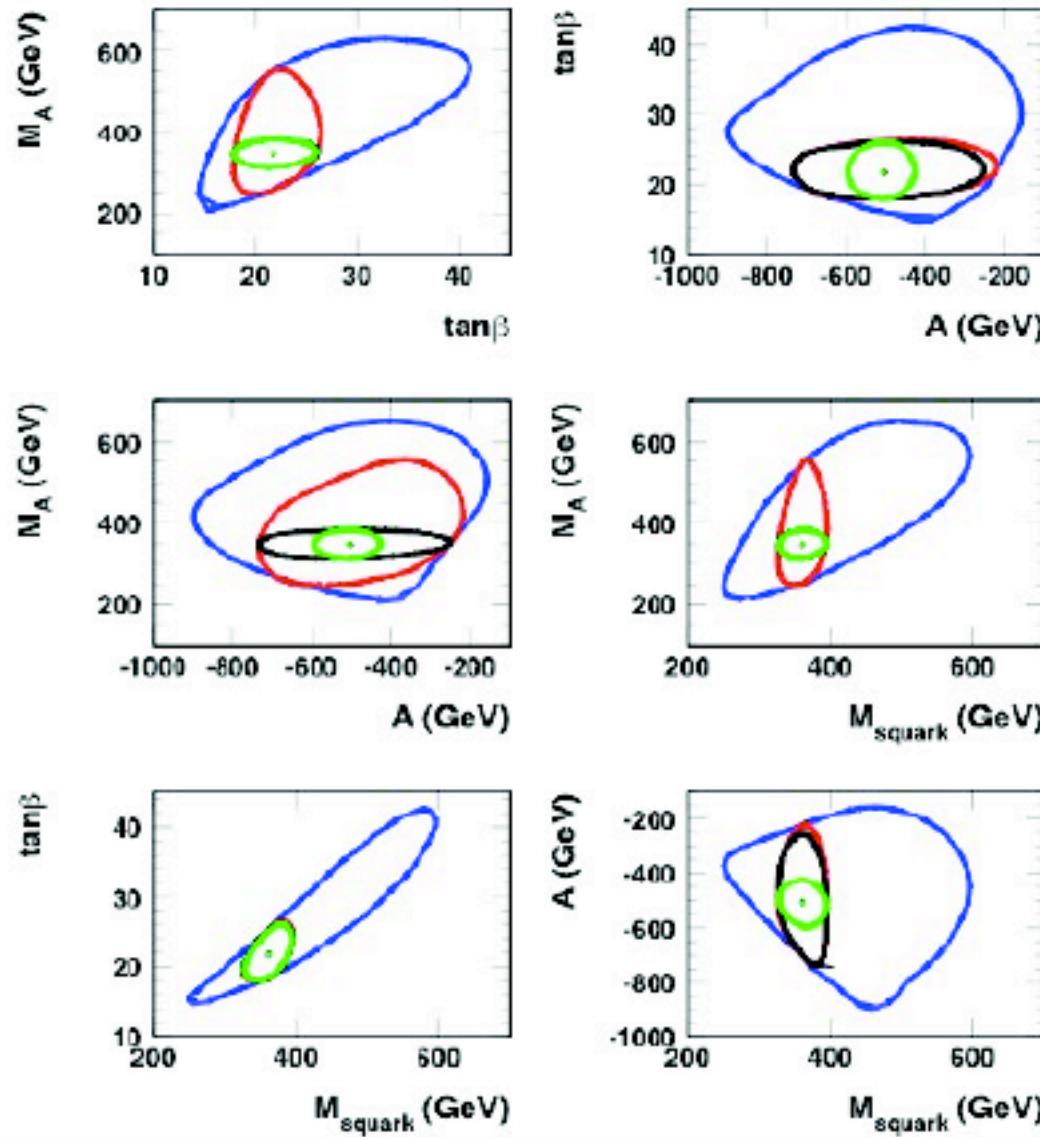
$M_{gaugino} = M_{squark}$

$M_{1,2,3}$ - Soft Susy breaking parameters in the gaugino sector

2009 reference (pessimistic) scenario:

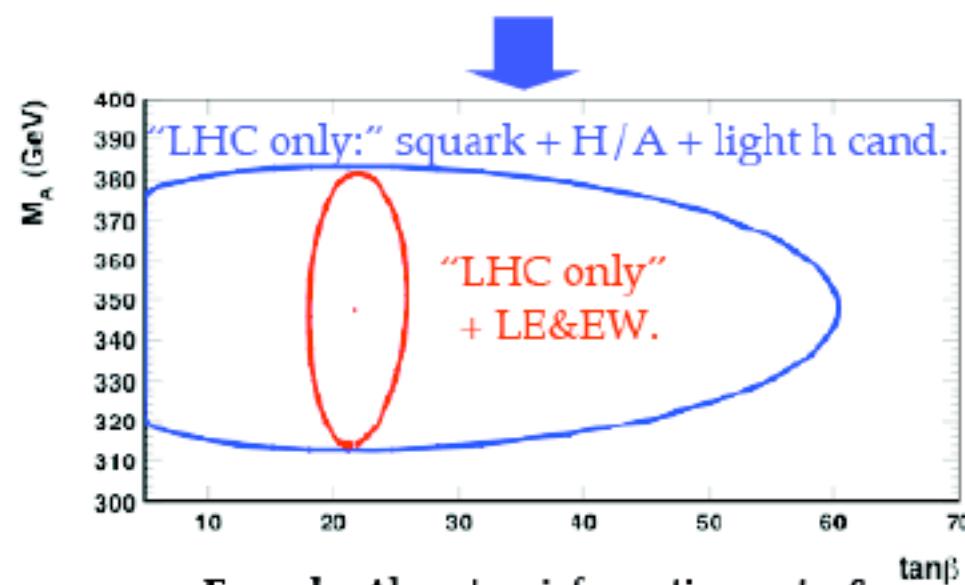
Observable	Constraint	theo. error
$R_{BR_{b \rightarrow s\gamma}}$	1.127 ± 0.1	0.1
$R_{\Delta M_s}$	0.8 ± 0.2	0.1
$BR_{b \rightarrow \mu\mu}$	$(3.5 \pm 0.35) \times 10^{-8}$	2×10^{-9}
$R_{BR_{b \rightarrow \tau\nu}}$	0.8 ± 0.2	0.1
Δa_μ	$(27.6 \pm 8.4) \times 10^{-10}$	2.0×10^{-10}
M_W^{SUSY}	$80.392 \pm 0.020 \text{ GeV}$	0.020 GeV
$\sin^2 \theta_W^{\text{SUSY}}$	0.23153 ± 0.00016	0.00016
$M_h^{\text{light}}(\text{SUSY})$	$> 114.4 \text{ GeV}$	3.0 GeV

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



- 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



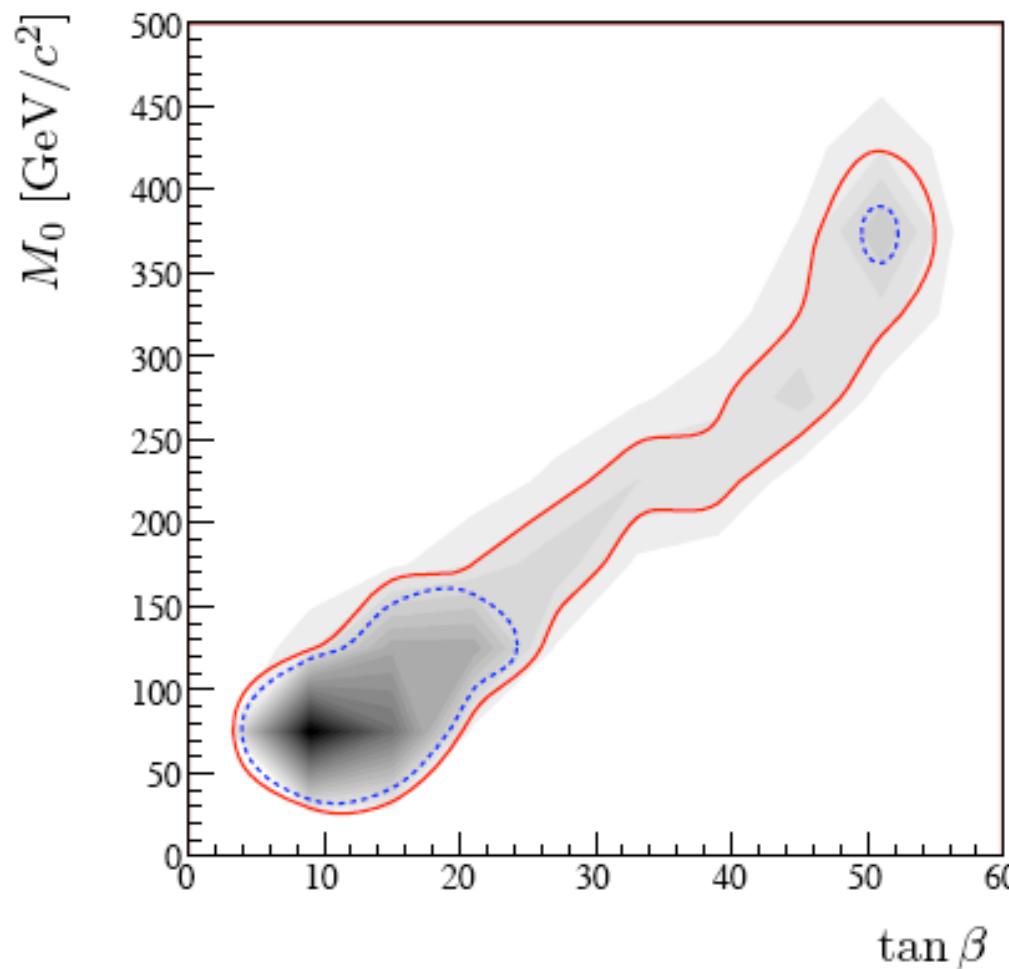
Example: Almost no information on $\tan\beta$ without external constraints. Note that a direct measurement of $\tan\beta$ is very difficult at the LHC

Illustrative Example

Flavour and dark-matter constraints in the constrained MSSM

Weiglein et al, arXiv:0707.3447

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

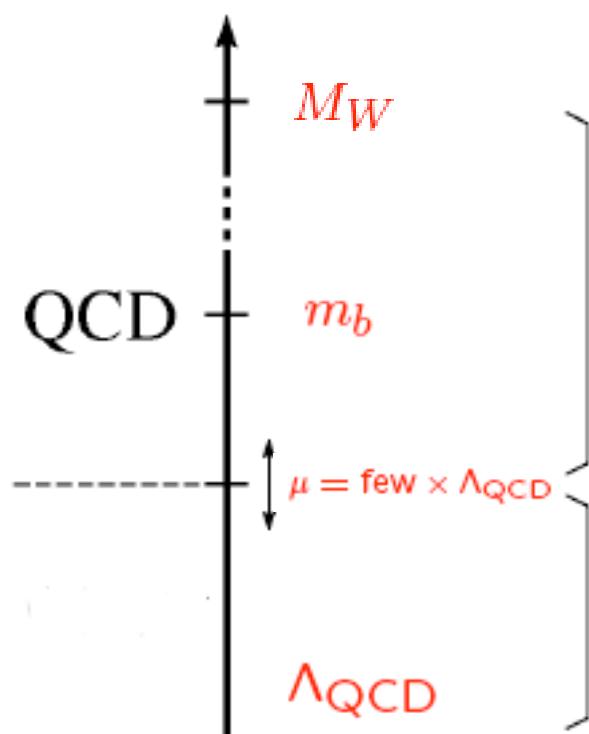


68% (dotted) and
95% (solid) CL

Constraints on the lightest Higgs boson mass

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

no restriction on m_h
imposed in the fit



QCD effects in B decays

short-distance physics
perturbative

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: $H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy}) \mathcal{O}_i(\mu)$
- $\mu^2 \approx M_{New}^2 \gg M_W^2$: 'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

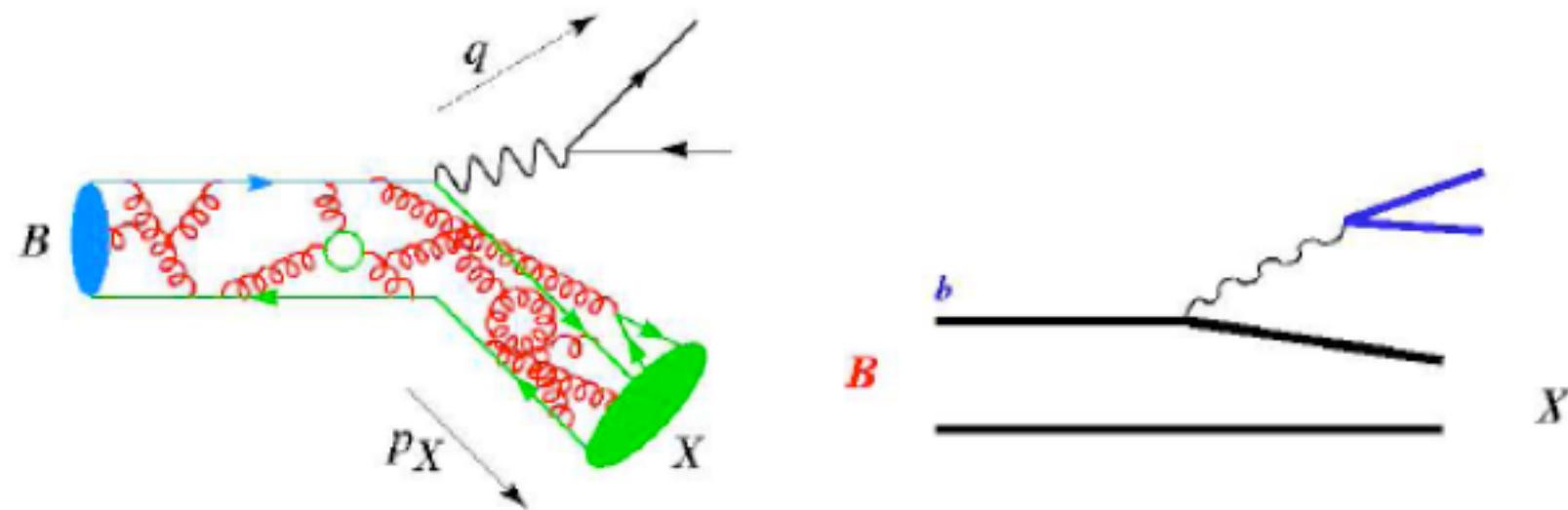
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Inclusive modes $B \rightarrow X_s \gamma$ or $B \rightarrow X_s \ell^+ \ell^-$

- Heavy mass expansion for inclusive modes:

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

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



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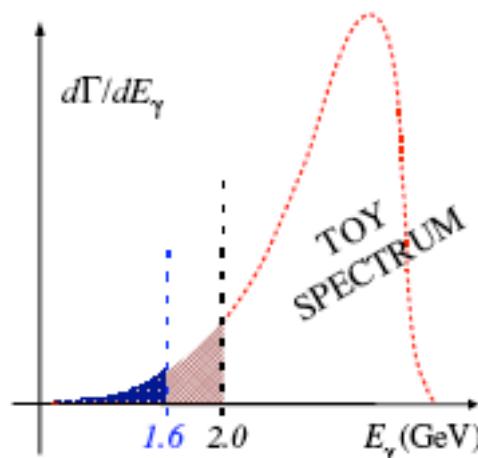
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No linear term Λ_{QCD}/m_b (perturbative contributions dominant)

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

Becher, Neubert, hep-ph/0610067



Inclusive modes $B \rightarrow X_s \gamma$ or $B \rightarrow X_s \ell^+ \ell^-$

- Heavy mass expansion for inclusive modes:

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

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

- If one goes beyond the leading operator ($\mathcal{O}_7, \mathcal{O}_9$):

breakdown of local expansion

naive estimate of non-local matrix elements leads to 5% uncertainty.

Benzke, Lee, Neubert, Paz, arXiv:1003.5012



Exclusive modes $B \rightarrow K^*\gamma$ or $B \rightarrow K^*\ell^+\ell^-$

Naive approach:

Parametrize the hadronic matrix elements in terms of form factors

How to compute the hadronic matrix elements $\mathcal{O}(m_b)$?

Exclusive modes $B \rightarrow K^*\gamma$ or $B \rightarrow K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

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

Existence of ‘non-factorizable’ strong interaction effects
which do *not* correspond to form factors

Exclusive modes $B \rightarrow K^*\gamma$ or $B \rightarrow K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

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

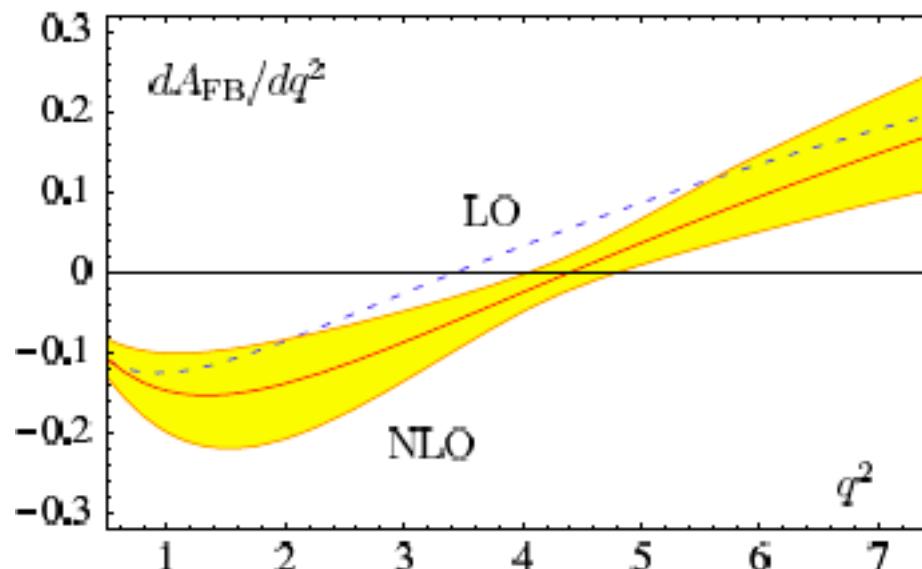
- Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors
- Relations between formfactors in large-energy limit
- Limitation: insufficient information on power-suppressed Λ/m_b terms
(breakdown of factorization: 'endpoint divergences')

Phenomenologically highly relevant issue

general strategy of LHCb to look at ratios of exclusive modes

LHCb Strategy: Focus on ratios of exclusive modes

Well-known example: Forward-Backward-Charge-Asymmetry in $B \rightarrow K^* \ell^+ \ell^-$



- In contrast to the branching ratio the zero of the FBA is almost insensitive to hadronic uncertainties. At LO the zero depends on the short-distance Wilson coefficients only:

$$q_0^2 = q_0^2(C_7, C_9), \quad q_0^2 = (3.4 + 0.6 - 0.5) \text{GeV}^2 \quad (\text{LO})$$

- NLO contribution calculated within QCD factorization approach leads to a large 30%-shift: (Beneke,Feldmann,Seidel 2001)

$$q_0^2 = (4.39 + 0.38 - 0.35) \text{GeV}^2 \quad (\text{NLO})$$

- However: Issue of unknown power corrections (Λ/m_b) !

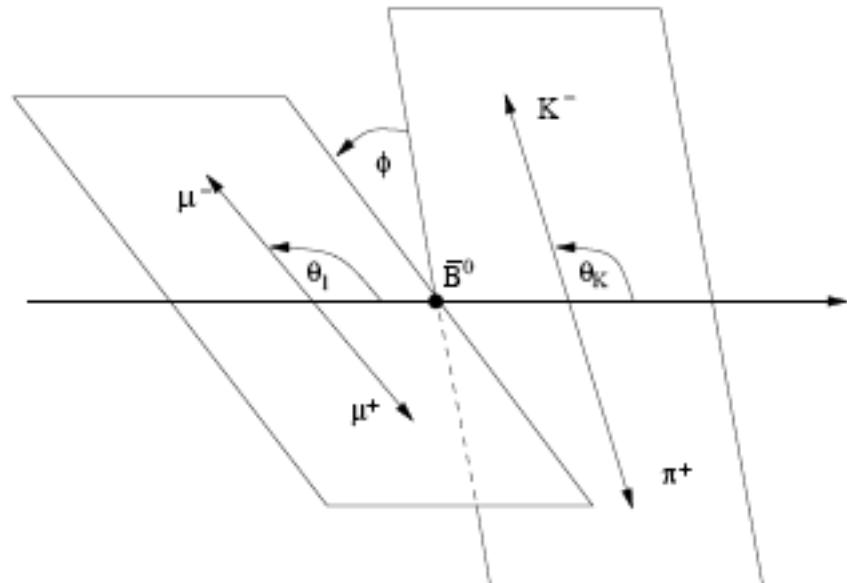
Opportunities in $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$: angular distributions

Kinematics

- Assuming the \bar{K}^* to be on the mass shell, the decay $\bar{B}^0 \rightarrow \bar{K}^{*0}(\rightarrow K^-\pi^+)\ell^+\ell^-$ 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:

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$



$$J(q^2, \theta_l, \theta_K, \phi) =$$

$$\begin{aligned}
 &= J_{1s} \sin^2 \theta_K + J_{1c} \cos^2 \theta_K + (J_{2s} \sin^2 \theta_K + J_{2c} \cos^2 \theta_K) \cos 2\theta_l + J_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
 &\quad + J_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + J_5 \sin 2\theta_K \sin \theta_l \cos \phi + (J_{6s} \sin^2 \theta_K + J_{6c} \cos^2 \theta_K) \cos \theta_l \\
 &\quad + J_7 \sin 2\theta_K \sin \theta_l \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi
 \end{aligned}$$

- LHCb statistics (10 fb^{-1} , but also already 2 fb^{-1}) allows for a full-angular fit !

In collaboration with Egede, Reece (LHCb, Imperial) Matias, Ramon (Barcelona)
JHEP 0811:032, 2008, arXiv:0807.2589 [hep-ph] and forthcoming manuscript

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

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

Form factor relations broken by α_s and Λ/m_b corrections

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

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

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

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2} \left[(C_9^{\text{eff}} \mp C_{10}) \frac{V(s)}{m_B + m_{K^*}} + \frac{2m_b}{s} (C_7^{\text{eff}} + C_7^{\text{eff}'}) T_1(s) \right]$$

$$A_{\parallel L,R} = -N\sqrt{2}(m_B^2 - m_{K^*}^2) \left[(C_9^{\text{eff}} \mp C_{10}) \frac{A_1(s)}{m_B - m_{K^*}} + \frac{2m_b}{s} (C_7^{\text{eff}} - C_7^{\text{eff}'}) T_2(s) \right]$$

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

$$A_{\perp L,R} = +\sqrt{2}Nm_B(1-\hat{s}) \left[(C_9^{\text{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} + C_7^{\text{eff}'}) \right] \xi_\perp(E_{K^*})$$

$$A_{\parallel L,R} = -\sqrt{2}Nm_B(1-\hat{s}) \left[(C_9^{\text{eff}} \mp C_{10}) + \frac{2\hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7^{\text{eff}'}) \right] \xi_\perp(E_{K^*})$$

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

Careful design of observables

- Good sensitivity to NP contributions, i.e. to $C_7^{eff'}$
- Small theoretical uncertainties
 - Dependence of soft form factors, ξ_{\perp} and ξ_{\parallel} , to be minimized !
form factors should cancel out exactly at LO, best for all s
 - unknown Λ/m_b power corrections
 $A_{\perp,\parallel,0} = A_{\perp,\parallel,0}^0 (1 + c_{\perp,\parallel,0})$ 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

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

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

Benchmark points in MSSM

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

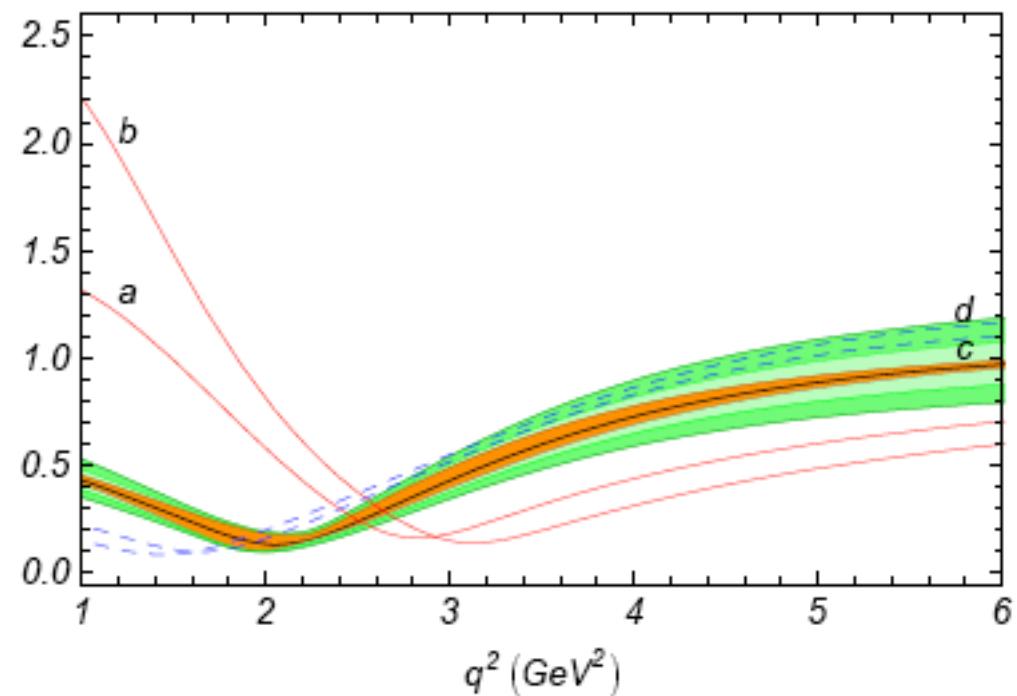
Diagonal: $\mu = M_1 = M_2 = M_{H^+} = m_{\tilde{u}_R} = 1 \text{ TeV}$ $\tan \beta = 5$

- Scenario A: $m_{\tilde{g}} = 1 \text{ TeV}$ and $m_{\tilde{d}} \in [200, 1000] \text{ GeV}$
 $-0.1 \leq (\delta_{LR}^d)_{32} \leq 0.1$
 - $m_{\tilde{g}}/m_{\tilde{d}} = 2.5, (\delta_{LR}^d)_{32} = 0.016$
 - $m_{\tilde{g}}/m_{\tilde{d}} = 4, (\delta_{LR}^d)_{32} = 0.036.$
- Scenario B: $m_{\tilde{d}} = 1 \text{ TeV}$ and $m_{\tilde{g}} \in [200, 800] \text{ GeV}$
mass insertion as in Scenario A.
 - $m_{\tilde{g}}/m_{\tilde{d}} = 0.7, (\delta_{LR}^d)_{32} = -0.004$
 - $m_{\tilde{g}}/m_{\tilde{d}} = 0.6, (\delta_{LR}^d)_{32} = -0.006.$

Check of compatibility with other constraints (B physics, ρ parameter, Higgs mass, particle searches, vacuum stability constraints)

Results

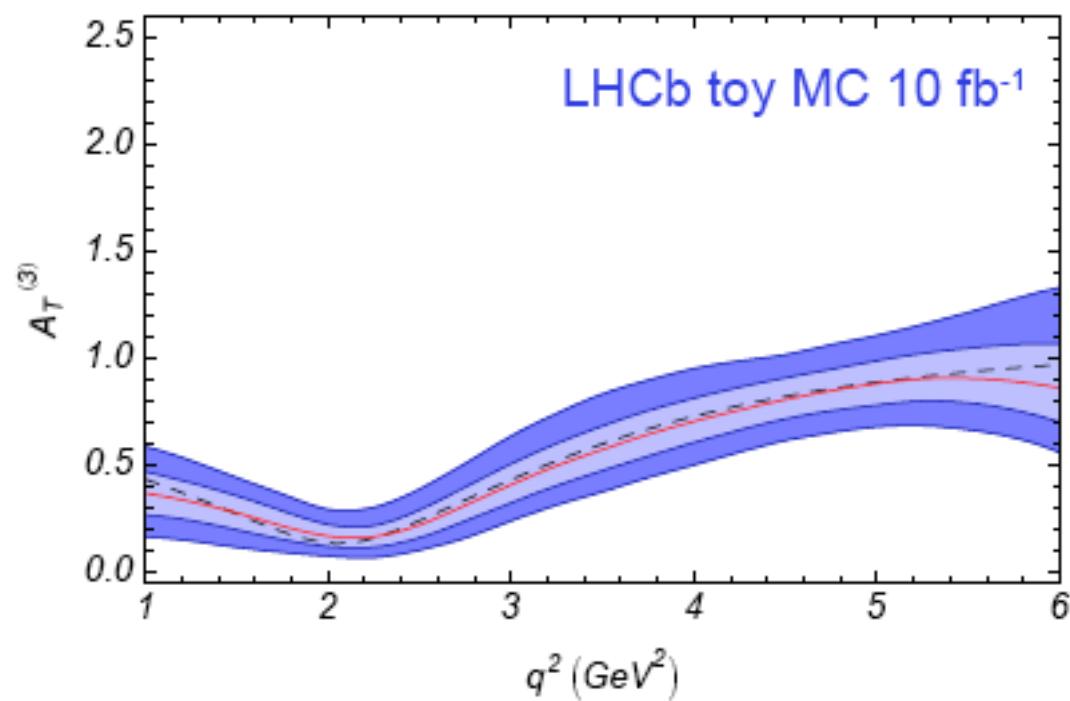
$$A_T^{(3)} = \frac{|A_{0L}A_{\parallel L}^* + A_{0R}^*A_{\parallel R}|}{\sqrt{|A_0|^2|A_{\perp}|^2}}$$



Theoretical sensitivity

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

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



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

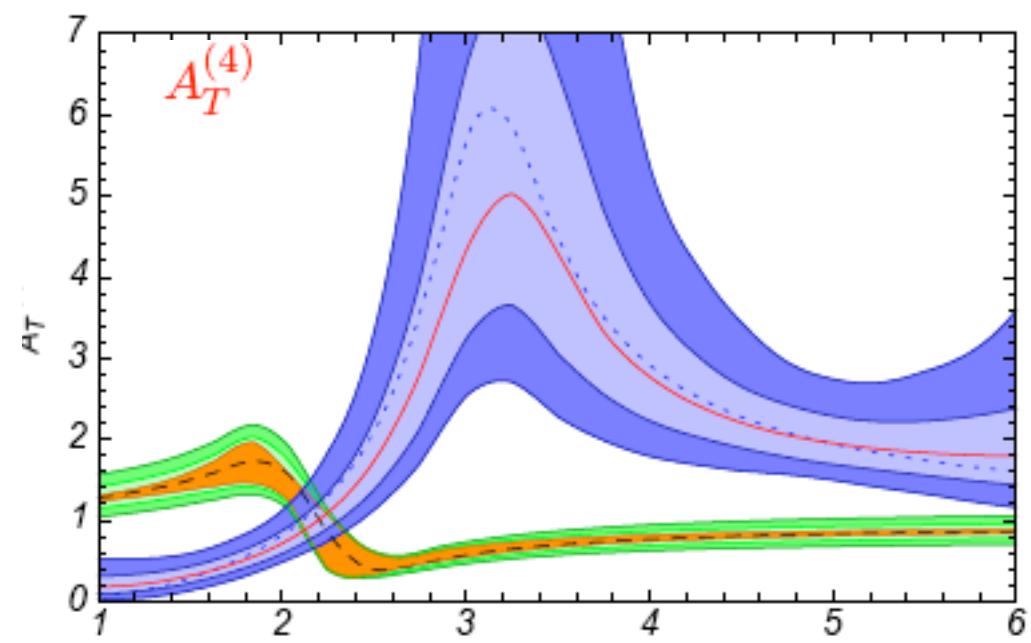
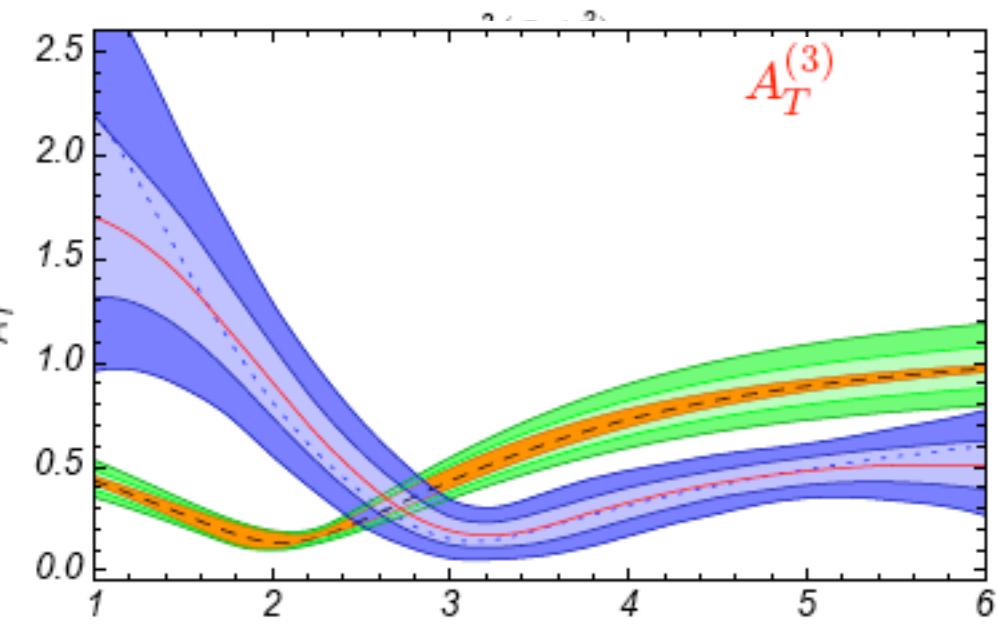
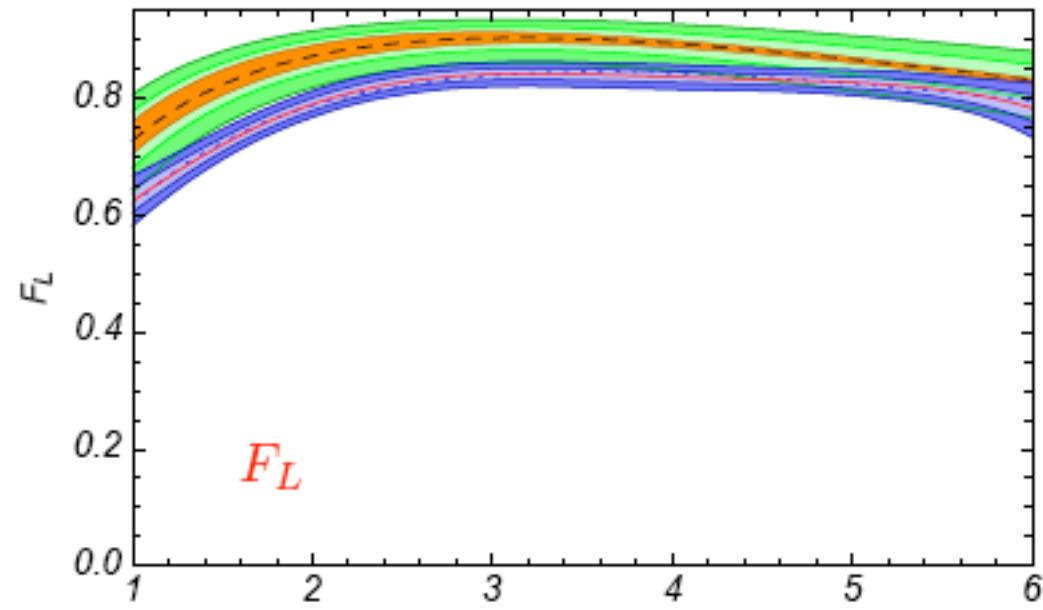
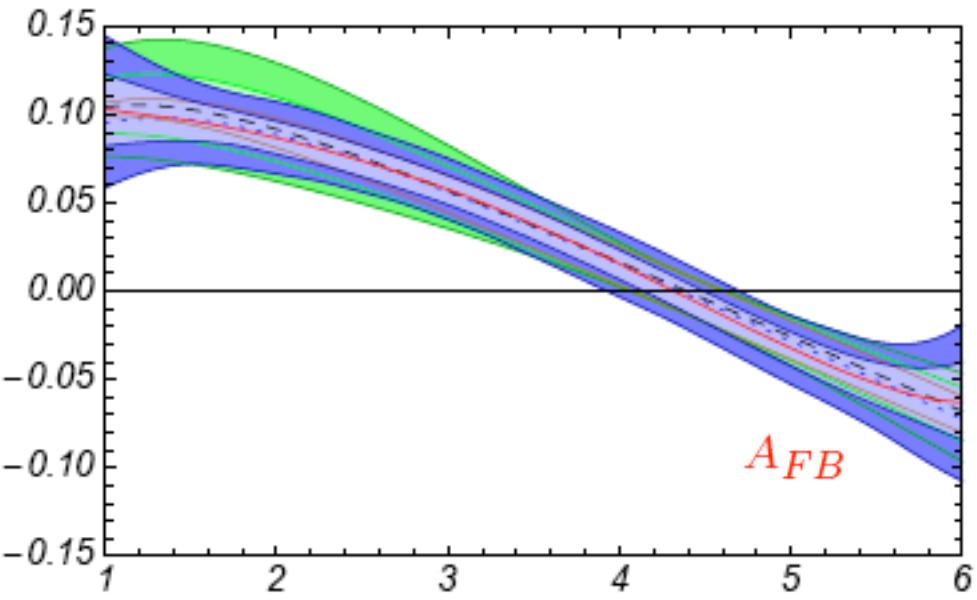
light green 1 σ

dark green 2 σ

SuperLHC/SuperB can offer more precision

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

Comparison between old and new observables



The experimental errors assuming SUSY scenario (b) with large-gluino mass and positive mass insertion, is compared to the theoretical errors assuming the SM.

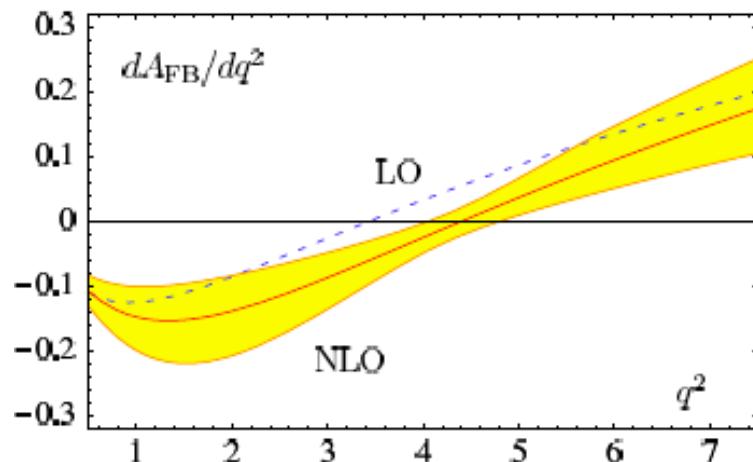
Error budget in inclusive and exclusive modes

SLHCb versus SFF Important role of Λ/m_b corrections

Measurement of inclusive modes restricted to e^+e^- machines.

(S)LHC experiments: Focus on theoretically clean exclusive modes necessary.

Well-known example: Zero of forward-backward-charge asymmetry in $b \rightarrow s\ell^+\ell^-$



Exclusive Zero:

Theoretical error: $9\% + O(\Lambda/m_b)$ uncertainty

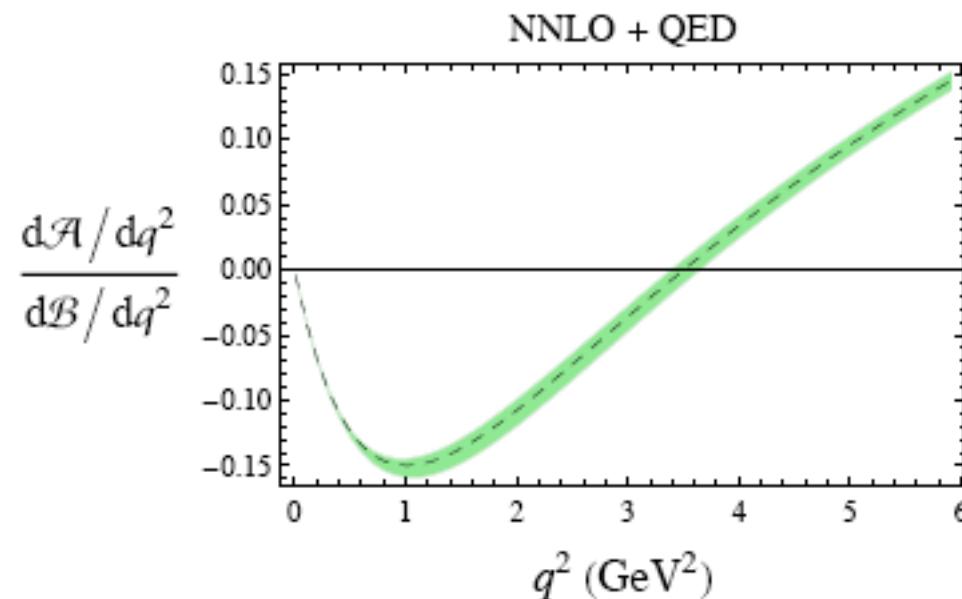
Egede,Hurth,Matias,Ramon,Reece
arXiv:0807.2589

Experimental error at SLHC: 2.1% Libby

Inclusive Zero:

Theoretical error: $O(5\%)$ Huber,Hurth,Lunghi,arXiv:0712.3009

Experimental error at SFF: 4 – 6% Browder,Cluchini,Gershon,Hazumi,Hurth,Okada,Stocchi
arXiv:0710.3799



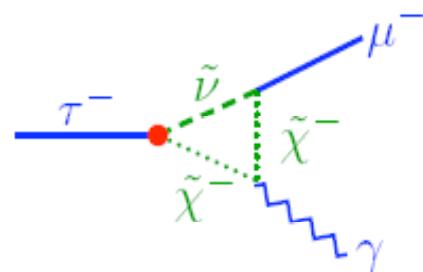
- LHCb (5 years) 10fb^{-1} : allows for wide range of analyses,
highlights: B_s mixing phase, angle γ , $B \rightarrow K^*\mu\mu$, $B_s \rightarrow \mu\mu$, $B_s \rightarrow \phi\phi$
then possibility for upgrade to 100fb^{-1}
- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:
rare kaon decays $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ and $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- Two proposals for a Super-B factory:
BELLE II at KEK and SuperB in Frascati (75ab^{-1})
Super-B is a Super Flavour factory: besides precise B measurements,
CP violation in charm, lepton flavour violating modes $\tau \rightarrow \mu\gamma, \dots$

Opportunities at a Super Flavour Factory

see JHEP 0802 (2008) 110, arXiv:0710.379

Measurement of lepton flavour violation

$\tau \rightarrow \mu\gamma$ and $\rightarrow 3\mu$



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

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

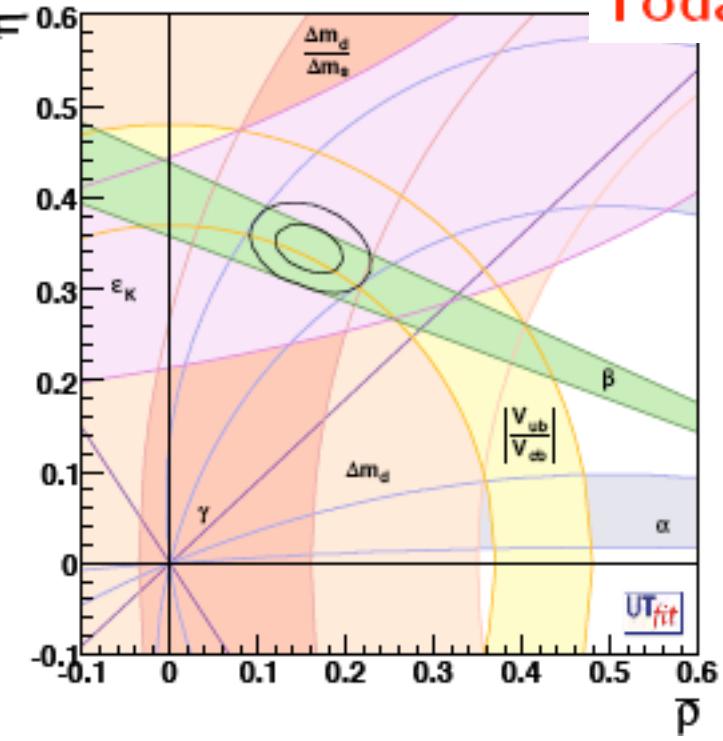
Use modes to distinguish SUSY vs LHT

Blanke et al.

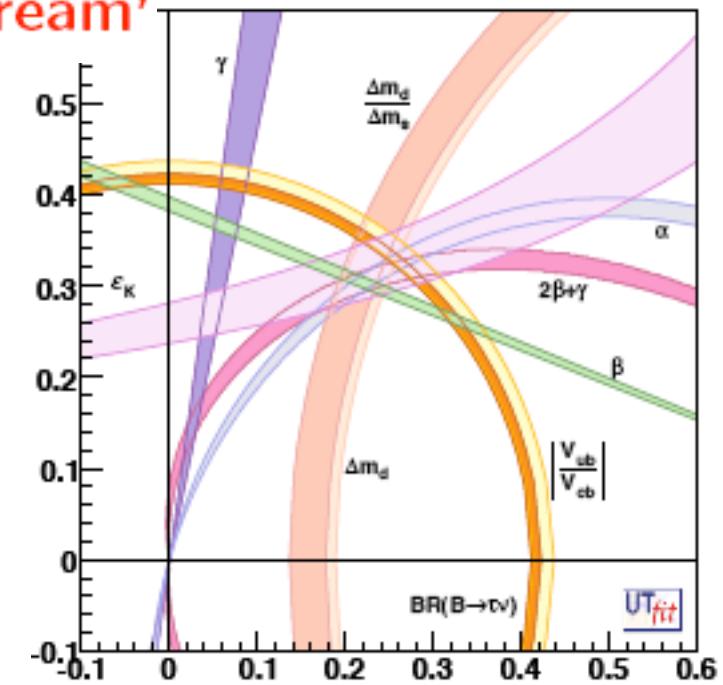
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{\mathcal{B}(\tau^- \rightarrow e^- e^+ e^-)}{\mathcal{B}(\tau \rightarrow e\gamma)}$	$0.4 \dots 2.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau \rightarrow \mu\gamma)}$	$0.4 \dots 2.3$	$\sim 2 \cdot 10^{-3}$	$0.06 \dots 0.1$
$\frac{\mathcal{B}(\tau^- \rightarrow e^- \mu^+ \mu^-)}{\mathcal{B}(\tau \rightarrow e\gamma)}$	$0.3 \dots 1.6$	$\sim 2 \cdot 10^{-3}$	$0.02 \dots 0.04$
$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- e^+ e^-)}{\mathcal{B}(\tau \rightarrow \mu\gamma)}$	$0.3 \dots 1.6$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{\mathcal{B}(\tau^- \rightarrow e^- e^+ e^-)}{\mathcal{B}(\tau^- \rightarrow e^- \mu^+ \mu^-)}$	$1.3 \dots 1.7$	~ 5	$0.3 \dots 0.5$
$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \rightarrow \mu^- e^+ e^-)}$	$1.2 \dots 1.6$	~ 0.2	$5 \dots 10$

Superflavour factory: CKM theory gets tested at 1%

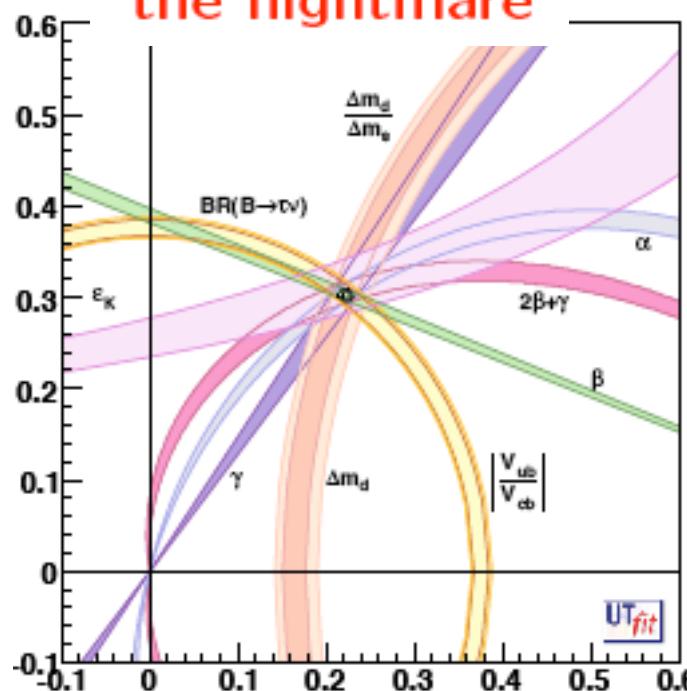
Today



'the dream'



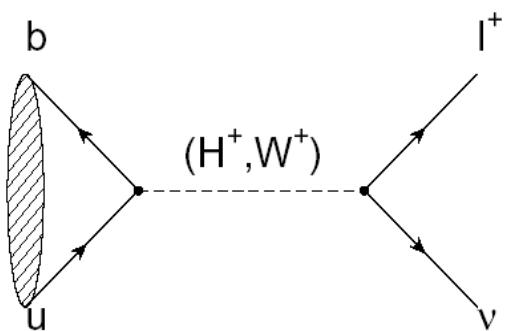
'the nightmare'



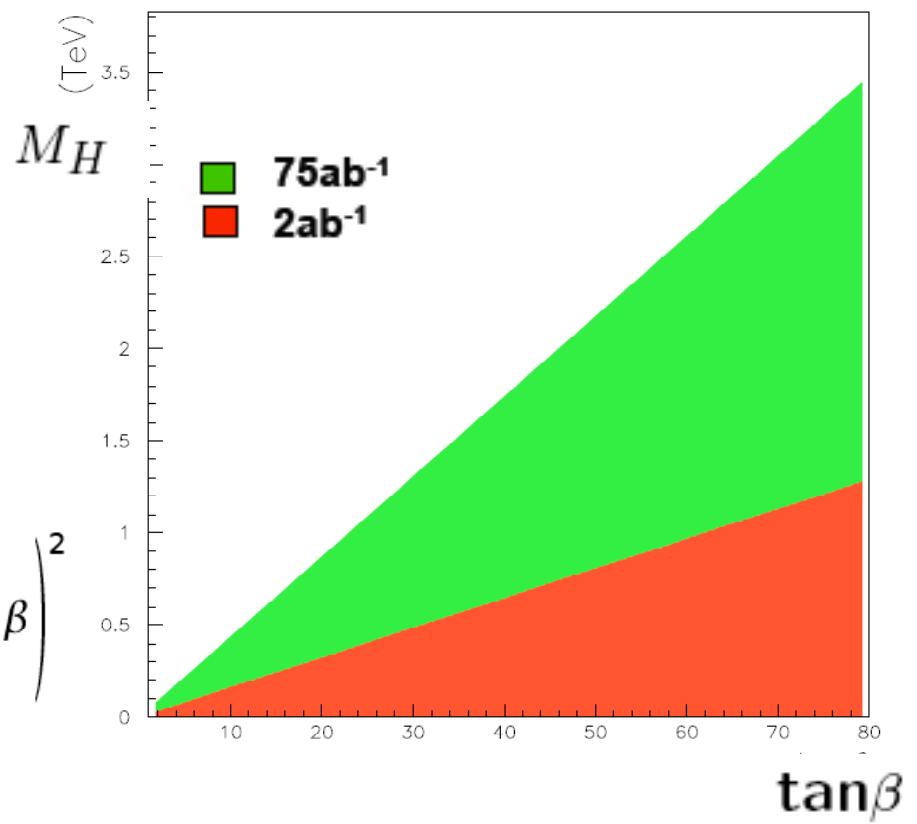
Superflavour factory: measurement of clean modes

$B \rightarrow \tau\nu$: **B factories** 20% **Super B factories** 4%

2HDM-II



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



(Assuming SM branching fraction is measured)

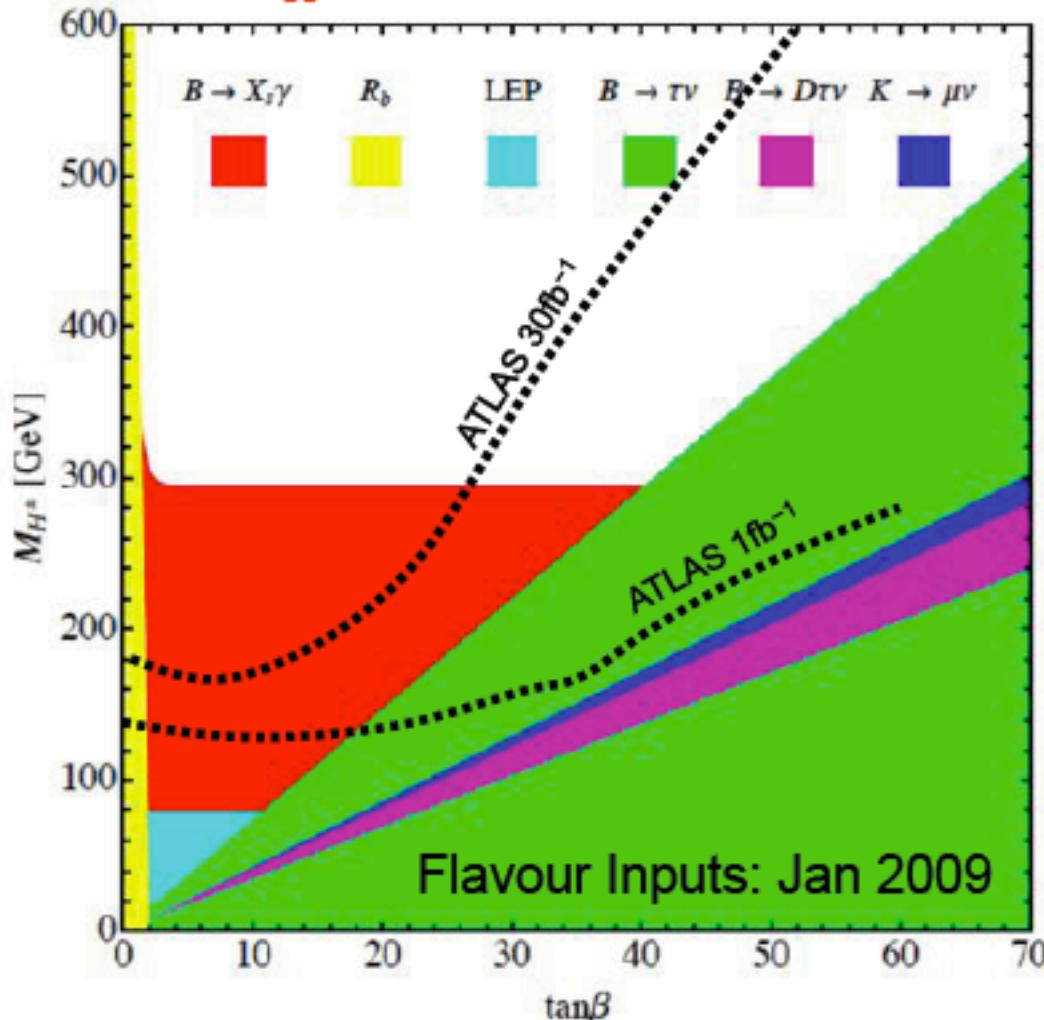
Two final remarks:

- **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)

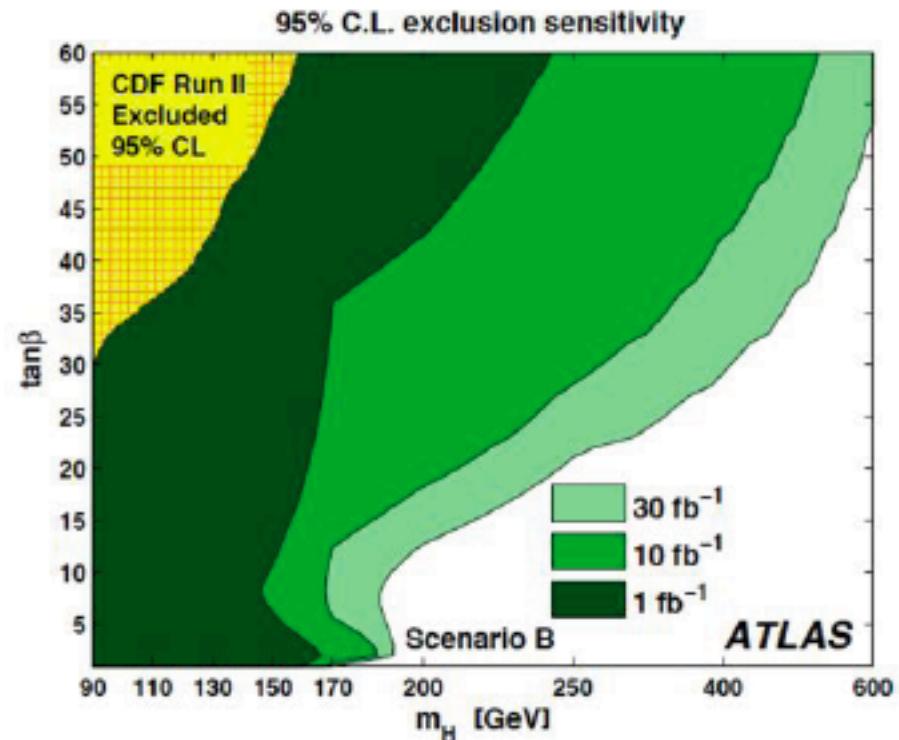
At least two of them have to do with flavour !

- LHC versus Flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



Converted constraints expected from ATLAS onto the plot by hand.



U. Haisch 0805.2141
2HDM at FPCP 2008)

Courtesy of Adrian Bevan

Anyone who keeps the ability to see beauty never grows old !

Franz Kafka