



PASCOS | 2012

Mérida, México June 3rd - 8th

PLENARY SPEAKERS INCLUDE

Nathan Berkovits, Alberto Casas, Daniel Chung, Laura Covi, Mirjam Cvetič, Abdelhak Djouadi, Jens Erler, Pavel Fileviez Pérez, Paul Frampton, Paolo Gondolo, André de Gouvêa, Steen Hannestad, Jonathan Heckman, Tobias Hurth, Jihn E. Kim, Manfred Lindner, Alessandro Melchiorri, Peter Mezsaros, Pran Nath, Stefano Profumo, Stuart Raby, Andreas Ringwald, Gary Shiu, Günther Sigl, Peter Tandy, José Valle, Dirk Zerwas.

International Advisory Committee

Jonathan Bagger, Wilfried Buchmüller, Paul Frampton, John F. Gunion, Jihn E. Kim, Robert C. Myers, Pran Nath, Stuart Raby, Durga P. Roy, Joseph Silk, Michael T. Vaughn, Kameshwar C. Wali

Local Organizing Committee

Adnan Bashir, David Delepine, Francisco Larios, Oscar Loaliza, Axel de la Macorra, Myriam Mondragón (Chair), Lukas Nellen, Sarita Sahu, Humberto Salazar, Liliانا Velasco-Sevilla.

18th International Symposium on Particles, Strings and Cosmology

www.fisica.unam.mx/pascos2012

CONTACT

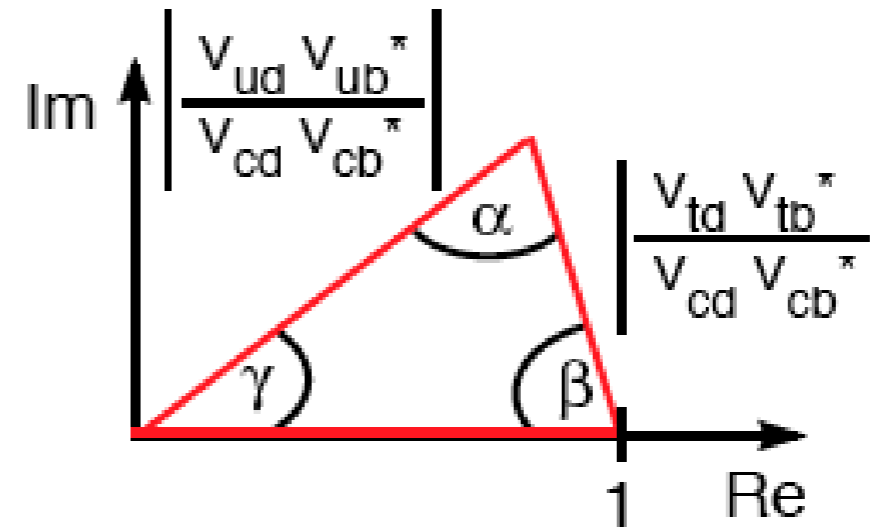
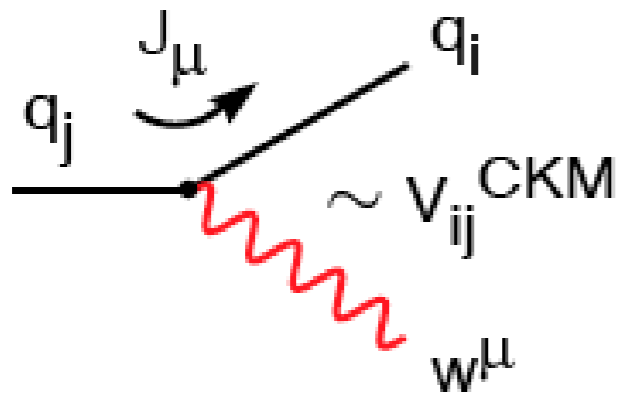
email: pascos2012@pegaso.fisica.unam.mx

Dr. Myriam Mondragón
Instituto de Física, UNAM
Apdo Postal 20-364
México 01000 D.F. México
Tel: +52 55 5622 5167, 5020
Fax: +52 55 5622 5015



Flavour in the SM

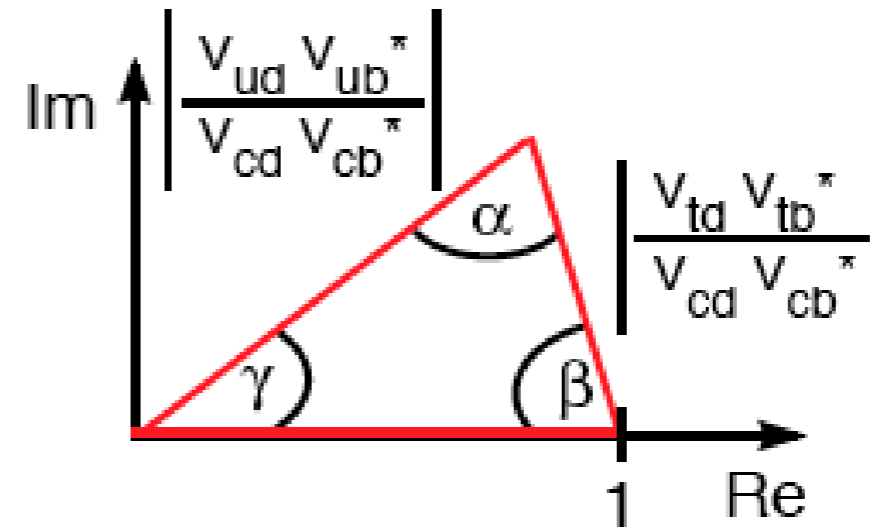
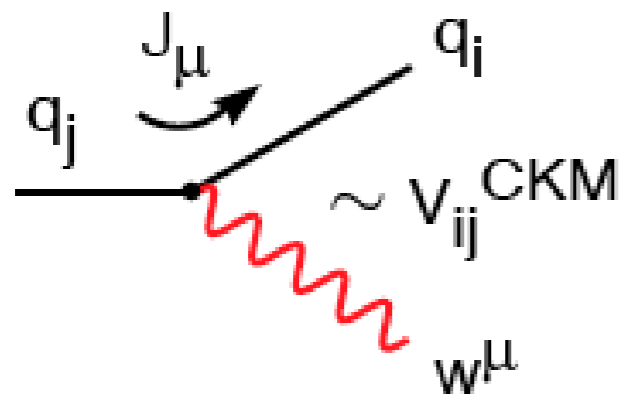
CKM mechanism of flavour mixing and CP violation: V_{CKM} , J_{CKM}



$$\text{Im}[V_{ij} V_{kl} V_{il}^* V_{kj}^*] = J_{CKM} \sum_{m,n=1}^3 \epsilon_{ikm} \epsilon_{jln}$$

$$J_{CKM} \sim \mathcal{O}(10^{-5})$$

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



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

Status of flavour physics in the pre-LHC(b) era:

All measurements (Babar, Belle, Cleo, CDF, DO, ...)

of rare decays ($\Delta F = 1$),

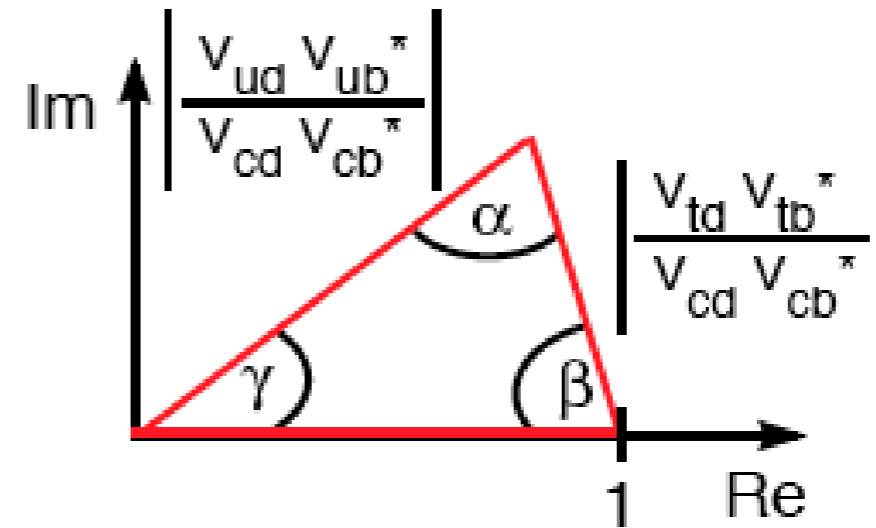
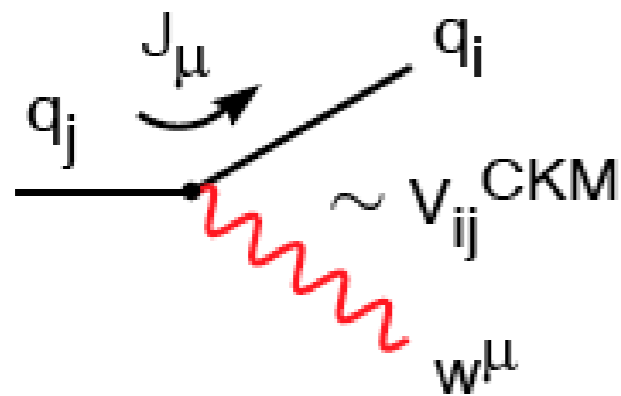
of mixing phenomena ($\Delta F = 2$) and

of all CP violating observables at tree and loop level

have been consistent with the CKM theory.

Impressing success of SM and CKM theory !!

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



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

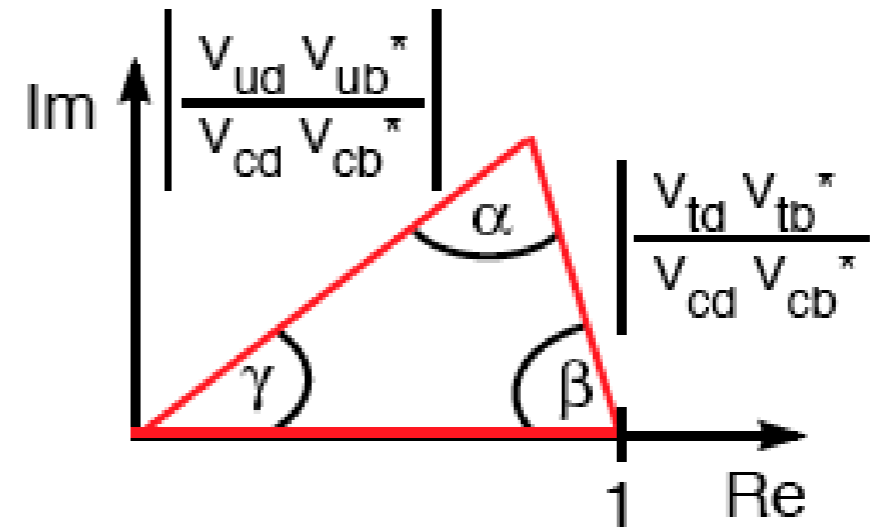
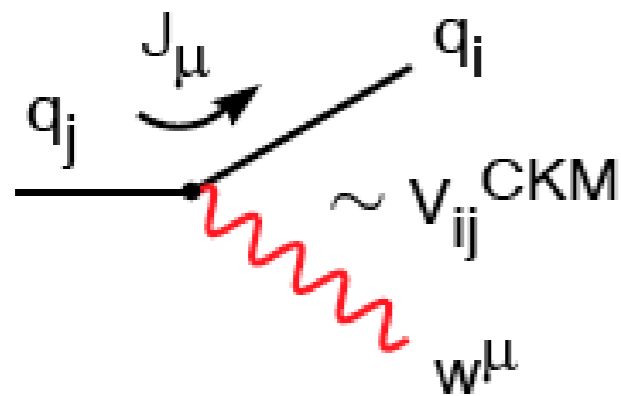
Status of flavour physics in the pre-LHC(b) era:

Of course there have been so-called puzzles, tensions, anomalies in the flavour data at the $1, 2, \text{ or } 3\sigma$ level.

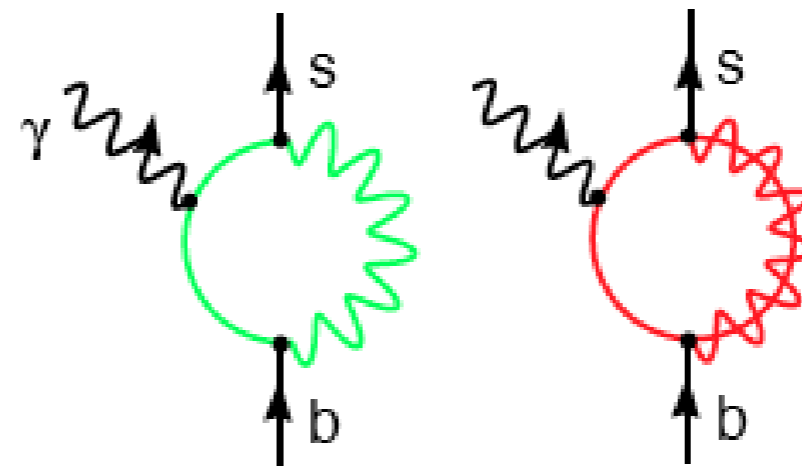
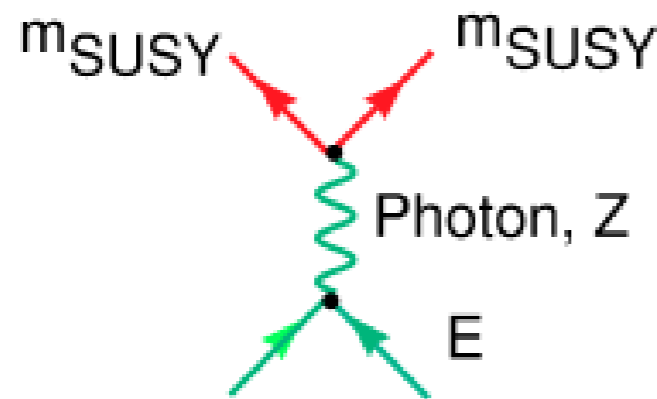
For example: Tension between $\mathcal{B}(B \rightarrow \tau \nu)$ and $\sin \beta$.
 Mixing phase in $B_s - \bar{B}_s$ mixing

Impressing success of SM and CKM theory !!

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



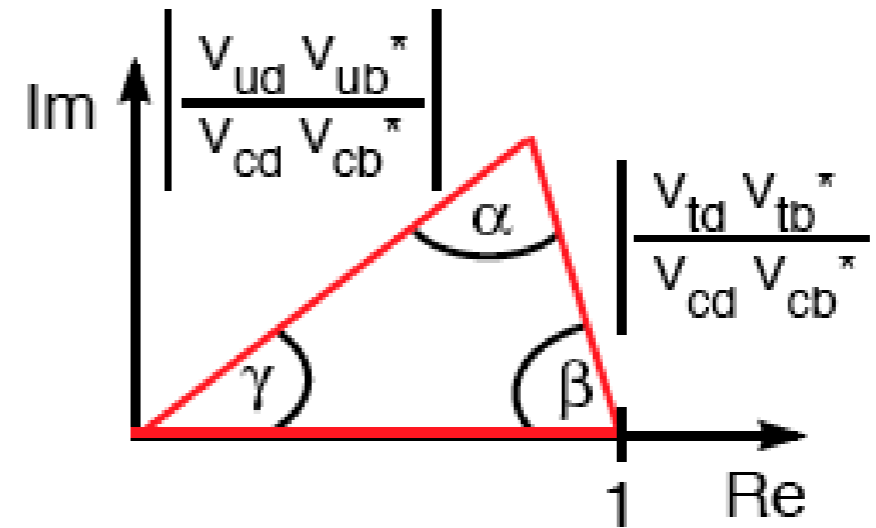
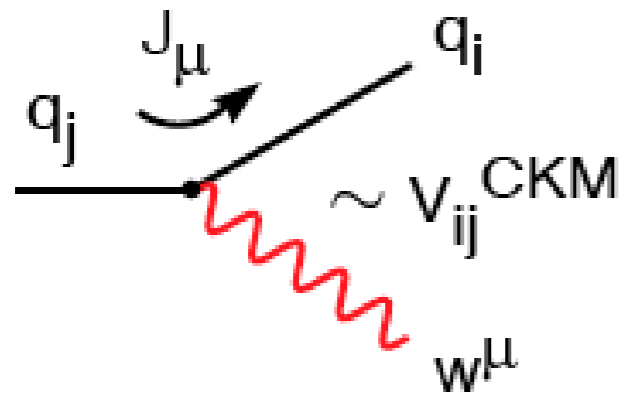
This success is somehow unexpected !!



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 !!

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



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

LHC(b) has not changed this, in contrary !!

All measurements (Babar, Belle, Cleo, CDF, DO, **LHC(b),...**)

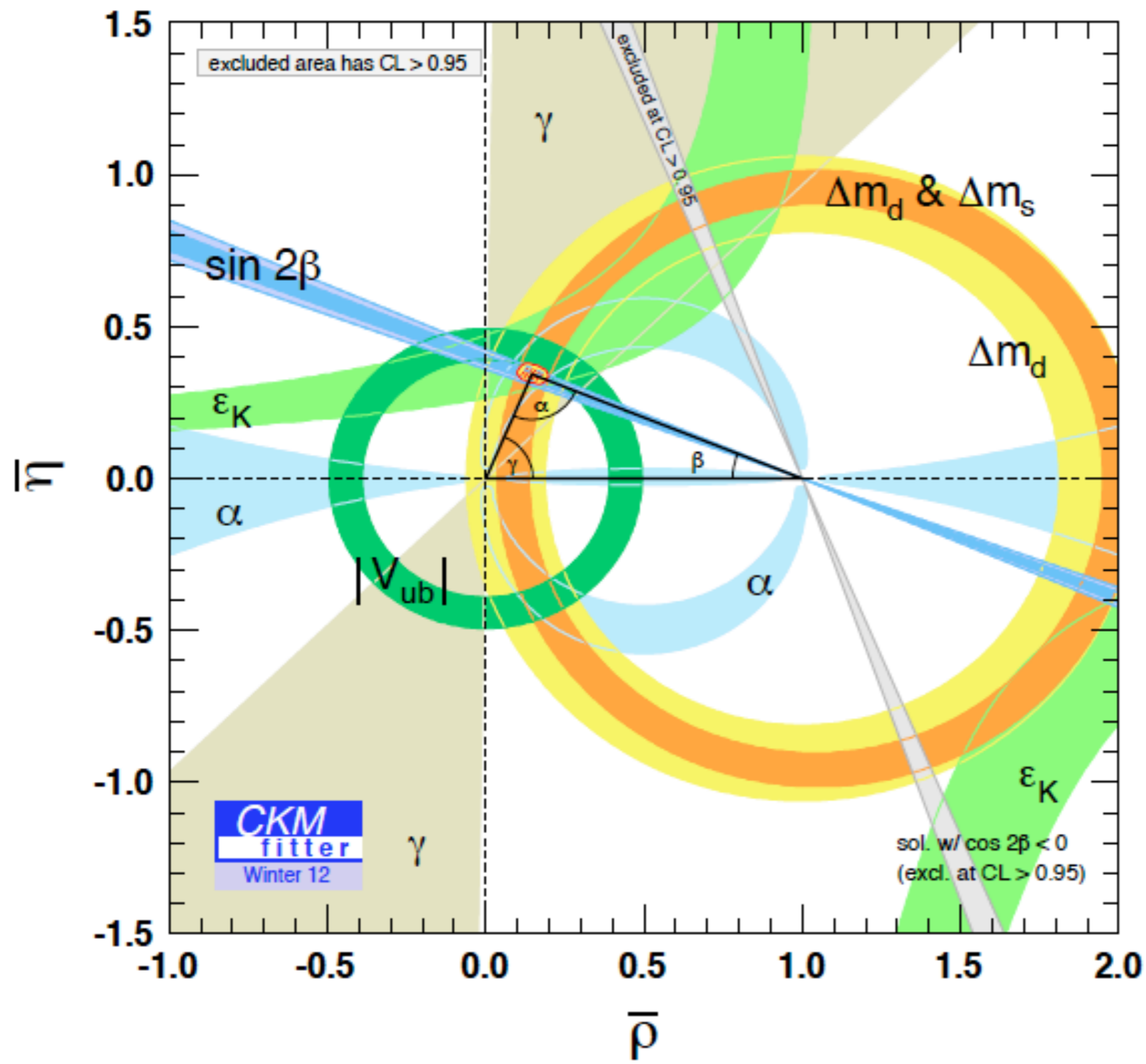
of rare decays ($\Delta F = 1$),

of mixing phenomena ($\Delta F = 2$) and

of all CP violating observables at tree and loop level

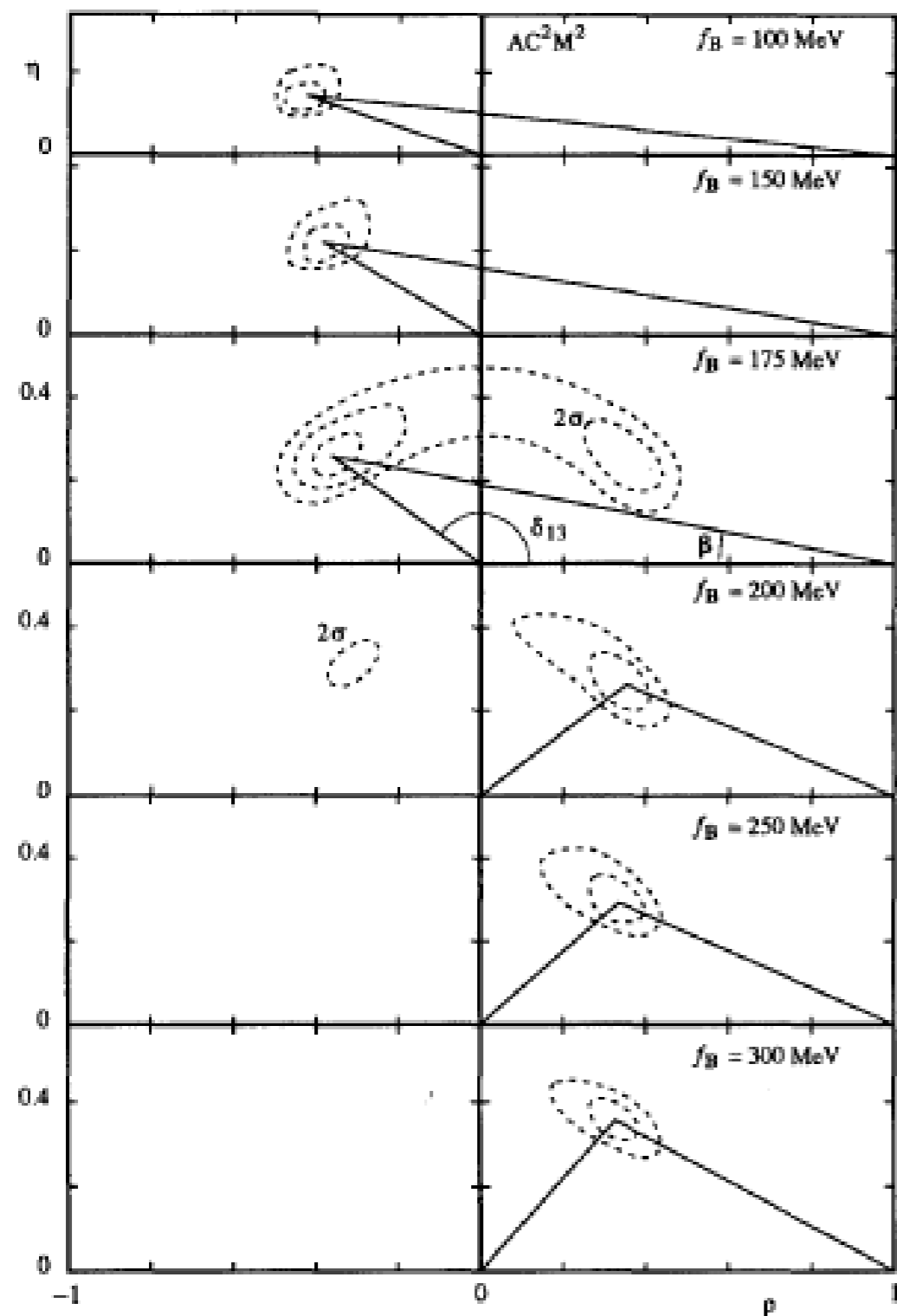
are consistent with the CKM theory.

Impressing success of SM and CKM theory !!



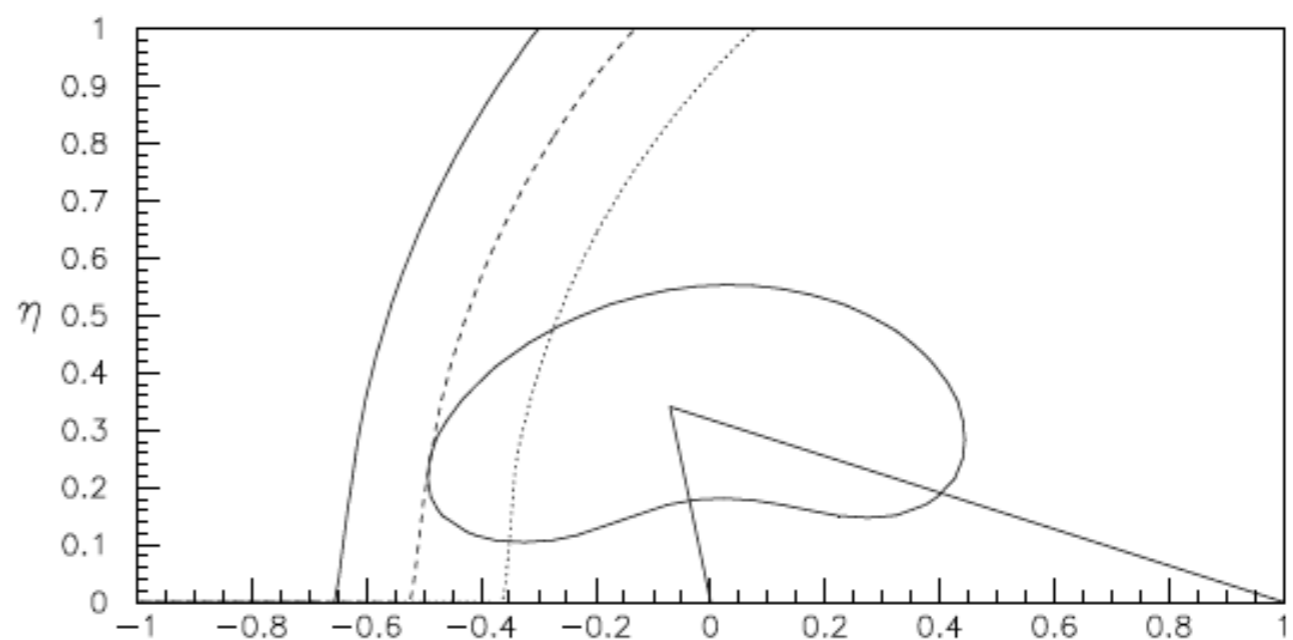
Global fit,
 consistency check
 of
 the CKM theory.

For comparison; some historical CKM fits

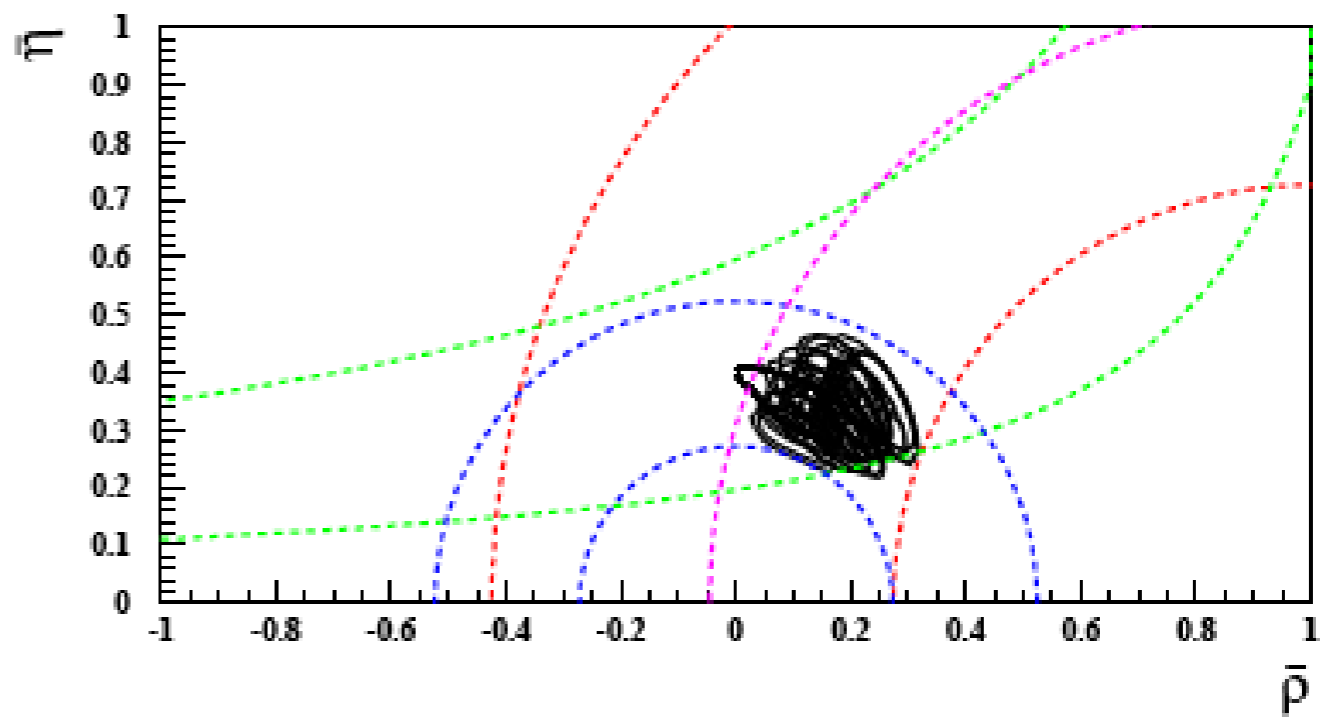


Schmidtler, Schubert 1992

$$f_{B_d} = 180 \pm 50 \text{ MeV}, \quad B_{B_d} = 1.0 \pm 0.2, \quad B_K = 0.8 \pm 0.2$$

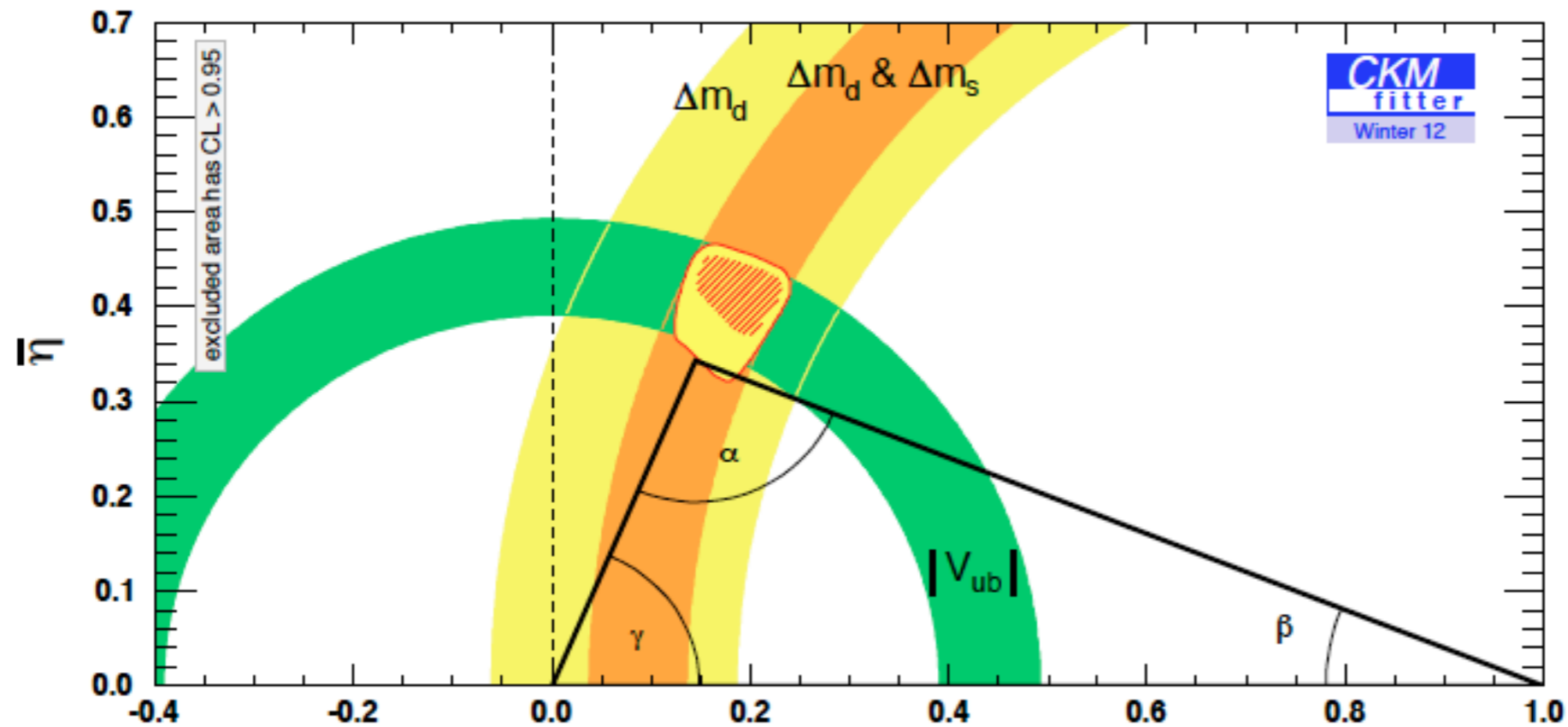


Ali, London 1995

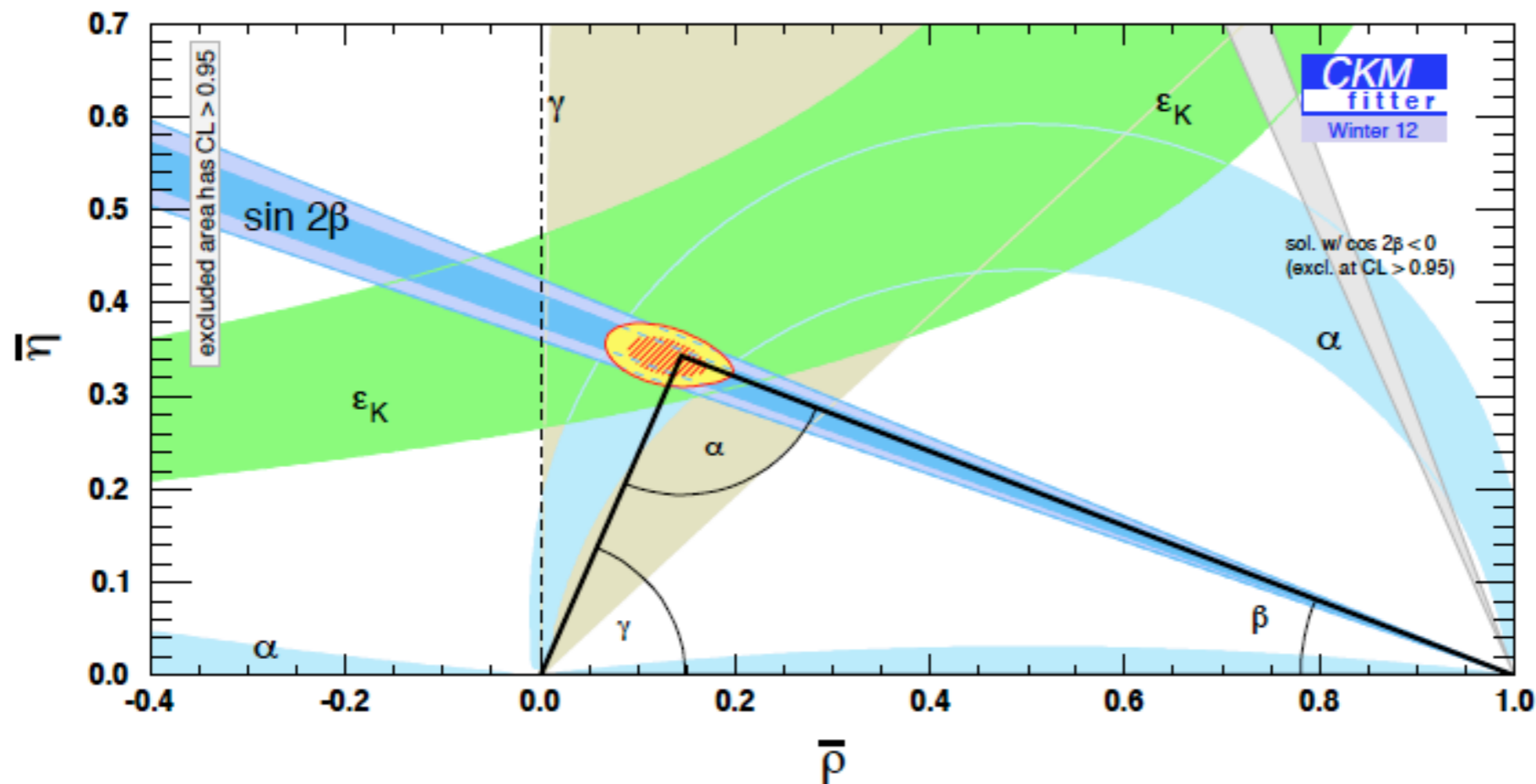


Placzynski, Schune 1999

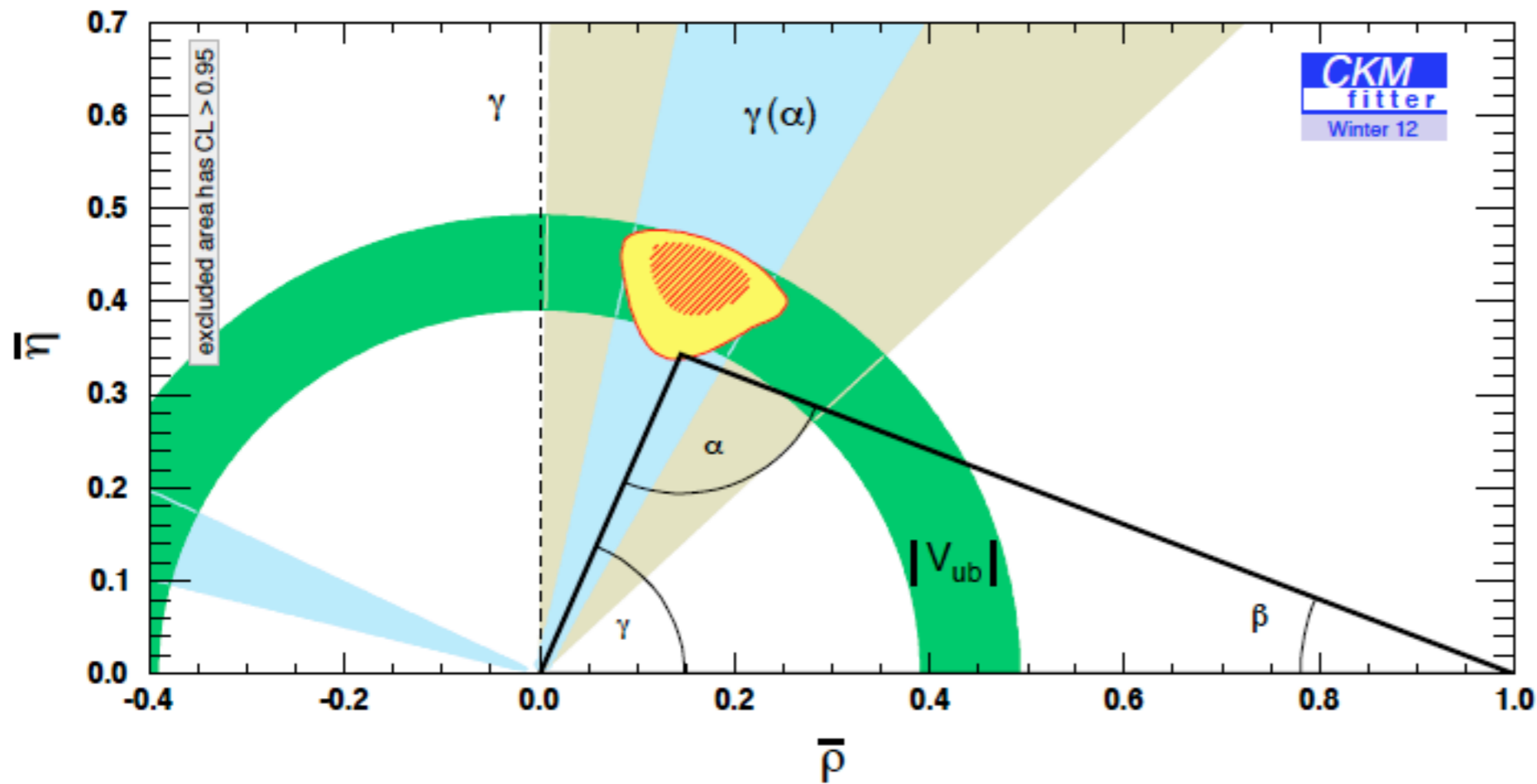
Closer Look:



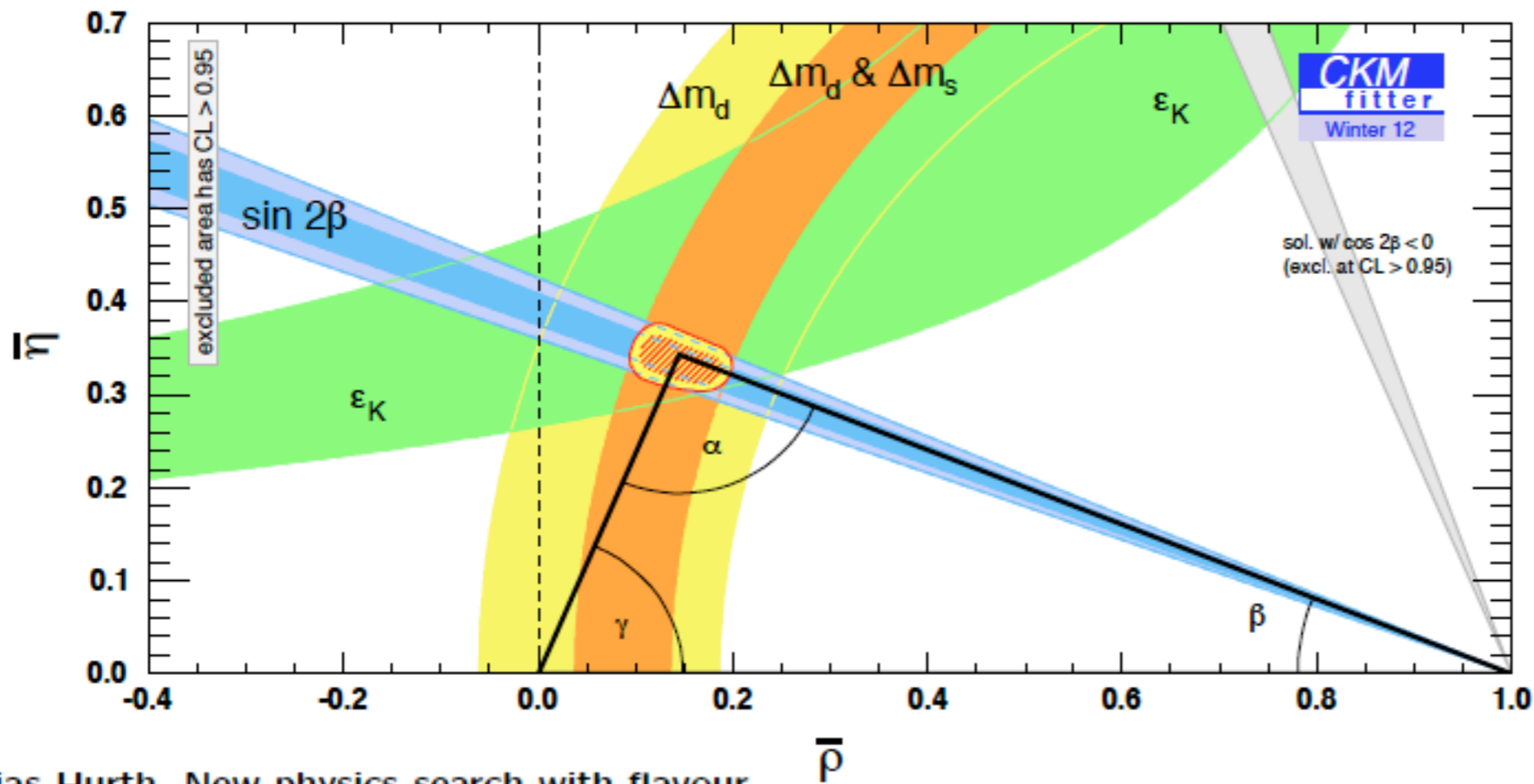
CP conserving



CP violating
observables

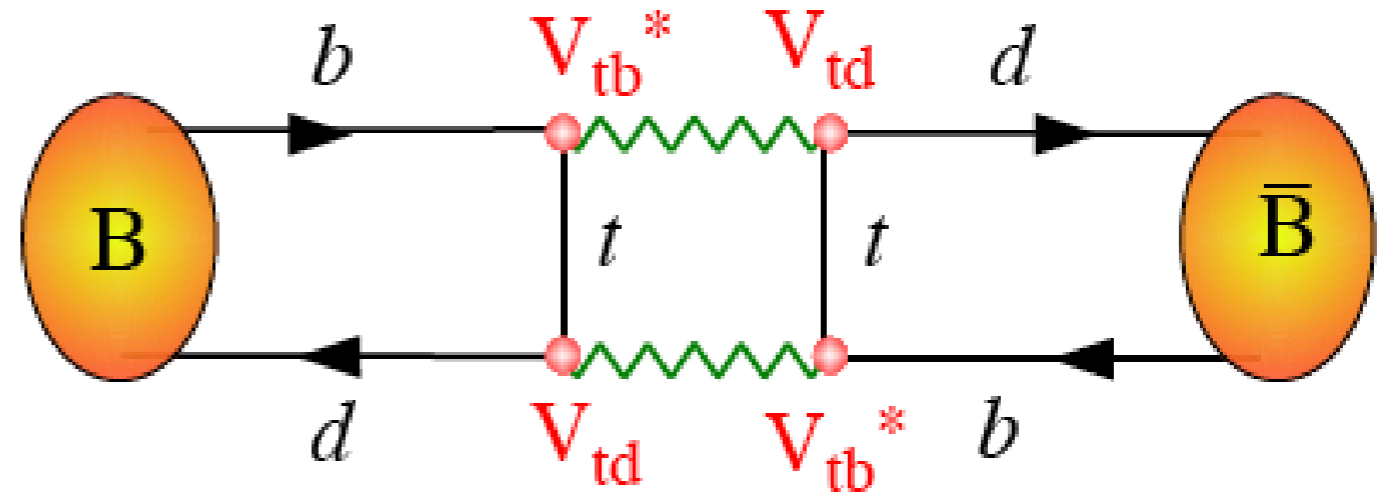
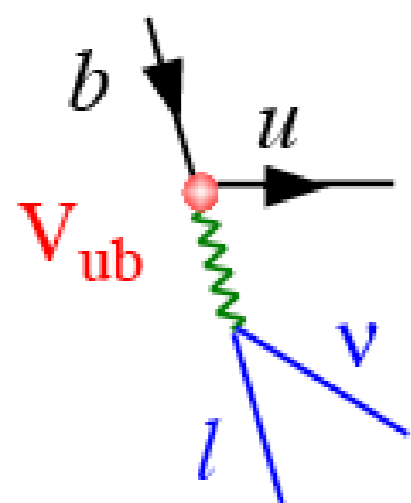


Tree processes



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

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

Nobel Prize 2008

652



Progress of Theoretical Physics 49 (1973) 652

***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.

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KIKUYAKI and Toshihide MANKAWA

Department of Physics, Kyoto University, Kyoto

Received September 1, 1973

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 present scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

When we apply the renormalizable theory of weak interaction¹⁾ 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 shown²⁾ 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 isospin 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 ψ, ψ, ψ and ζ , respectively, and we take the same underlying gauge group $SU_{weak}(2) \times SU(1)$ and the scalar doublet field ϕ as those of Weinberg's original model.³⁾ 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, ψ , so that it contains interactions with the gauge fields, \mathcal{L}_{mass} is a generalized mass term of ψ , which includes Yukawa couplings to ϕ since they contribute to the mass of ψ through the spontaneous breaking of gauge symmetry, \mathcal{L}_{strong} is a strong-inter-

action part which conserves I_3 and therefore chiral $SU(4) \times SU(4)$ invariant.⁴⁾ We assume C and P invariance of \mathcal{L}_{strong} . The last term denotes residual interaction parts if they exist. Since \mathcal{L}_{strong} includes couplings with ψ , it has possibilities of violating CP-conservation. As is known as Higgs phenomena,⁵⁾ these 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}_{strong} . For the mass term, however, we can eliminate such pseudoscalar parts by applying an appropriate constant gauge transformation on ψ , 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 $\psi_L = \frac{1}{2}(1+i\gamma_5)\psi$ and $\psi_R = \frac{1}{2}(1-i\gamma_5)\psi$, 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) $4 = 1+1+1+1$,

where on the r.h.s., 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_V/g_A 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) .

1) 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 $L_1, L_2, R_1^+, R_2^+, R_3^+$ and R_4^+ , whose superscript $\rho(\sigma)$ indicates ρ -like (σ -like) charge states. In this case, \mathcal{L}_{mass} takes, in general, the following form:

$$\mathcal{L}_{mass} = \sum_{i,j=1}^4 [M_{ij}^+ L_{1i} R_j^+ + M_{ij}^0 L_{2i} R_j^0] + h.c.,$$

$$\psi^L = \begin{pmatrix} \psi^+ \\ \psi^0 \end{pmatrix}, \quad \psi^R = \begin{pmatrix} \psi^+ \\ -\psi^0 \end{pmatrix} \quad (1)$$

652

M. Kikuyaki and T. Mankawa

1a) 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

$$\mathcal{L}' = \frac{1}{2} \bar{\psi} \phi \psi + h.c., \quad (11)$$

$$\psi = \begin{pmatrix} \bar{\psi}^+ & \psi^+ & 0 & 0 \\ -\psi^0 & \psi^0 & 0 & 0 \\ 0 & 0 & \bar{\psi}^+ & \psi^+ \\ 0 & 0 & -\psi^0 & \psi^0 \end{pmatrix}, \quad \phi = \begin{pmatrix} c_1 & 0 & c_2 & 0 \\ 0 & d_1 & 0 & d_2 \\ c_3 & 0 & c_4 & 0 \\ 0 & d_3 & 0 & d_4 \end{pmatrix}$$

where c_i and d_i 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_i and d_i . 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 ψ through scalar and pseudoscalar couplings. It also interacts with ψ and possible renormalizable terms are given as follows:

$$\begin{aligned} & \text{tr}(G_1 S^2 \psi) + h.c., \\ & \text{tr}(G_2 S^2 \psi G_3 \psi^* S) + h.c., \\ & \text{tr}(G_4 S^2 \psi G_5 S^* \psi) + h.c., \end{aligned} \quad (12)$$

with

$$G = \begin{pmatrix} g^+ & g^+ & 0 & 0 \\ -g^0 & g^0 & 0 & 0 \\ 0 & 0 & g^+ & g^+ \\ 0 & 0 & -g^0 & g^0 \end{pmatrix},$$

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-con-

where M_{ij}^+ and M_{ij}^0 are arbitrary complex numbers. We can eliminate three Goldstone modes ϕ_i by writing

$$\phi = \rho^{1/2} \begin{pmatrix} \theta \\ \chi + \phi \end{pmatrix} \quad (2)$$

where ρ is a vacuum expectation value of ρ^2 and θ is a massive scalar field. Thereafter, performing a diagonalization of the remaining mass term, we obtain

$$\mathcal{L}_{mass} = \frac{1}{2} \bar{\psi} m \psi \left(1 + \frac{\theta}{f} \right),$$

$$m = \begin{pmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{pmatrix}, \quad \psi = \begin{pmatrix} \psi^+ \\ \psi^0 \\ \psi^+ \\ \psi^0 \end{pmatrix} \quad (3)$$

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

$$\frac{1}{2} A_i^+ \bar{\psi} \gamma_5 A_i \psi + \frac{1+i\gamma_5}{2} \psi. \quad (4)$$

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

$$A_i = \frac{A_i + A_i^*}{2} = K \begin{pmatrix} 0 & U \\ 0 & 0 \end{pmatrix} K^{-1}, \quad A_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (5)$$

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

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

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.

1b) Case (A, B)

This is a rather delicate case. We denote two left doublets, one right doublet and two singlets by L_1, L_2, R_1, R_2^0 and R_3^0 , respectively. The general form

Next we consider a 6plet model, another interesting model of CP-violation. Suppose that triplet with charges $(2, 2, 2, Q-1, Q-1, Q-1)$ 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 we pointed out in this case we cannot absorb all phases of matrix elements into the phase convention and we take, for example, the following expression:

$$\begin{pmatrix} \cos \theta_1 & -\sin \theta_1 \cos \theta_2 & -\sin \theta_1 \sin \theta_2 \\ \sin \theta_1 \cos \theta_2 & \cos \theta_1 \cos \theta_2 \cos \theta_3 - \sin \theta_1 \sin \theta_2 \theta_3^2 & \cos \theta_1 \cos \theta_2 \sin \theta_3 + \sin \theta_1 \cos \theta_2 \theta_3^2 \\ \sin \theta_1 \sin \theta_2 & \cos \theta_1 \sin \theta_2 \cos \theta_3 + \cos \theta_1 \sin \theta_2 \theta_3^2 & \cos \theta_1 \sin \theta_2 \sin \theta_3 - \cos \theta_1 \sin \theta_2 \theta_3^2 \end{pmatrix} \quad (13)$$

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 $g^2=0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher orders with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and para-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 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.

References

- 1) S. Weinberg, Phys. Rev. Letters **18** (1967), 1840; **21** (1971), 848.
- 2) S. Maki and T. Mankawa, KIPP-140 (preprint), April 1973.
- 3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 506.
- 4) S. Ghoshal, C. S. Hagen and T. W. Eubank, Phys. Rev. Letters **18** (1964), 383.
- 5) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1594.

Equation

Equation (13) should read as

$$\begin{pmatrix} \cos \theta_1 & -\sin \theta_1 \cos \theta_2 & -\sin \theta_1 \sin \theta_2 \\ \sin \theta_1 \cos \theta_2 & \cos \theta_1 \cos \theta_2 \cos \theta_3 - \sin \theta_1 \sin \theta_2 \theta_3^2 & \cos \theta_1 \cos \theta_2 \sin \theta_3 + \sin \theta_1 \cos \theta_2 \theta_3^2 \\ \sin \theta_1 \sin \theta_2 & \cos \theta_1 \sin \theta_2 \cos \theta_3 + \cos \theta_1 \sin \theta_2 \theta_3^2 & \cos \theta_1 \sin \theta_2 \sin \theta_3 - \cos \theta_1 \sin \theta_2 \theta_3^2 \end{pmatrix} \quad (13)$$

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:

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

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.

Erratum

Errata:

Equation (13) should read as

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

However,...

- CKM mechanism is **the dominating effect** for CP violation and flavour mixing in the quark sector;
but there is still room for **sizeable 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**.

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.

- No guiding principle in the flavour sector:

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

Compare for example:

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

Possible solutions to the SM flavour problem

- Approximate symmetries (Froggatt -Nielsen)
- Geometry in extra dimensions (Randall-Sundrum)

$$\Lambda_{\text{Flavour}} > \Lambda_{\text{NP}} ?$$

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 ?

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)

Flavour problem of New Physics

How do FCNCs hide ?

Ambiguity of new physics scale from flavour data

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

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

Ambiguity of new physics scale from flavour data

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

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

Ambiguity of new physics scale from flavour data

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

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

- 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)

- 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 $\Rightarrow \Lambda_{NP} \sim 3 - 10 \text{ TeV}$

Ambiguity of new physics scale from flavour data

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

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

- 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)

- 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

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

Ambiguity of new physics scale from flavour data

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

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

- 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)

- 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 $\Rightarrow \Lambda_{NP} \sim 3 - 10 \text{ TeV}$

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.

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

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**
($BR(b \rightarrow s\gamma) = 0$ in exact supersymmetry)

Parameter bounds from flavour physics are model-dependent

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

HFAG: $\mathcal{B}(B \rightarrow X_s \gamma) = (3.55 \pm 0.24) \times 10^{-4}$ (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\(2007\)](#)

NNLL calculation by Misiak et al.
(collaboration of 17 theorists)

CLEO [9.1 fb⁻¹]
(2001) untag

BaBar [82 fb⁻¹]
(2005) sum-of-excl

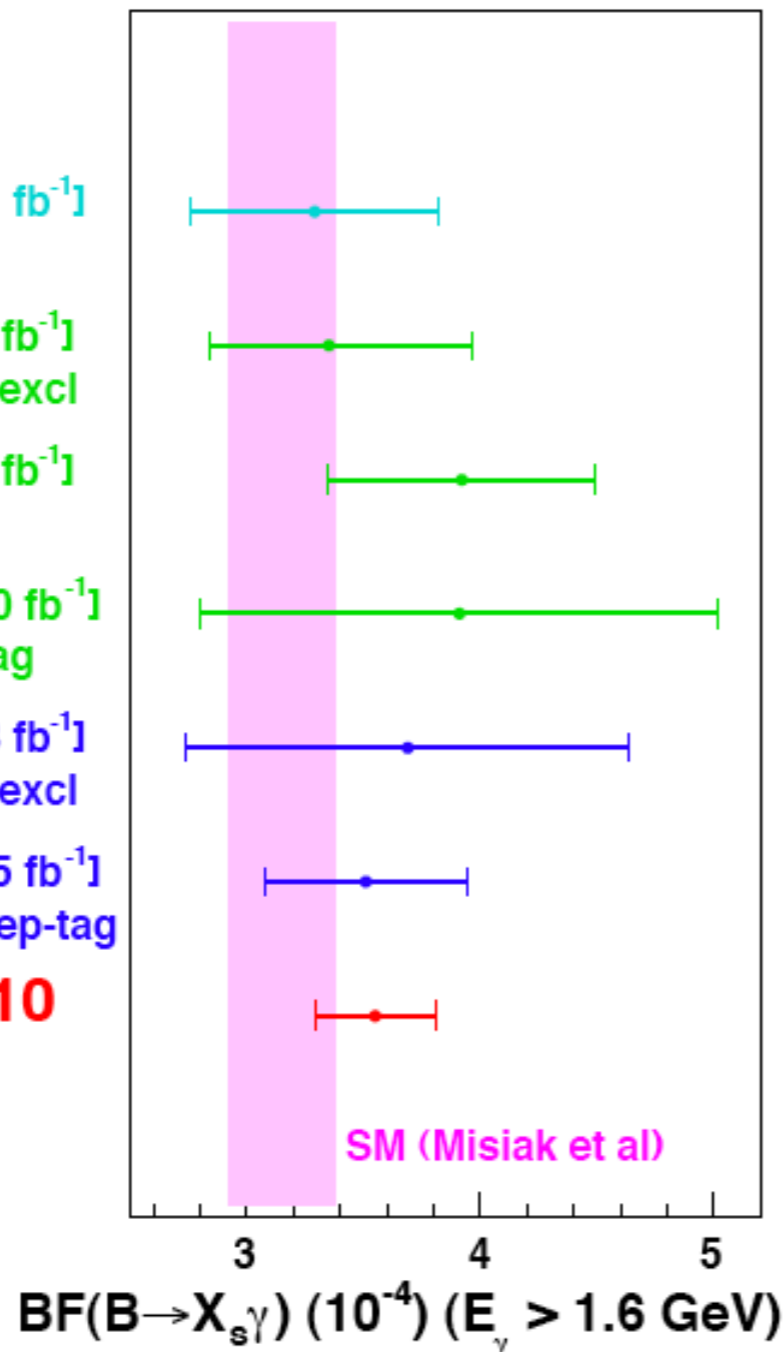
BaBar [82 fb⁻¹]
(2006) lep-tag

BaBar [210 fb⁻¹]
(2008) breco-tag

Belle [5.8 fb⁻¹]
(2001) sum-of-excl

Belle [605 fb⁻¹]
(2009) untag+lep-tag

HFAG 2010



Parameter bounds from flavour physics are model-dependent

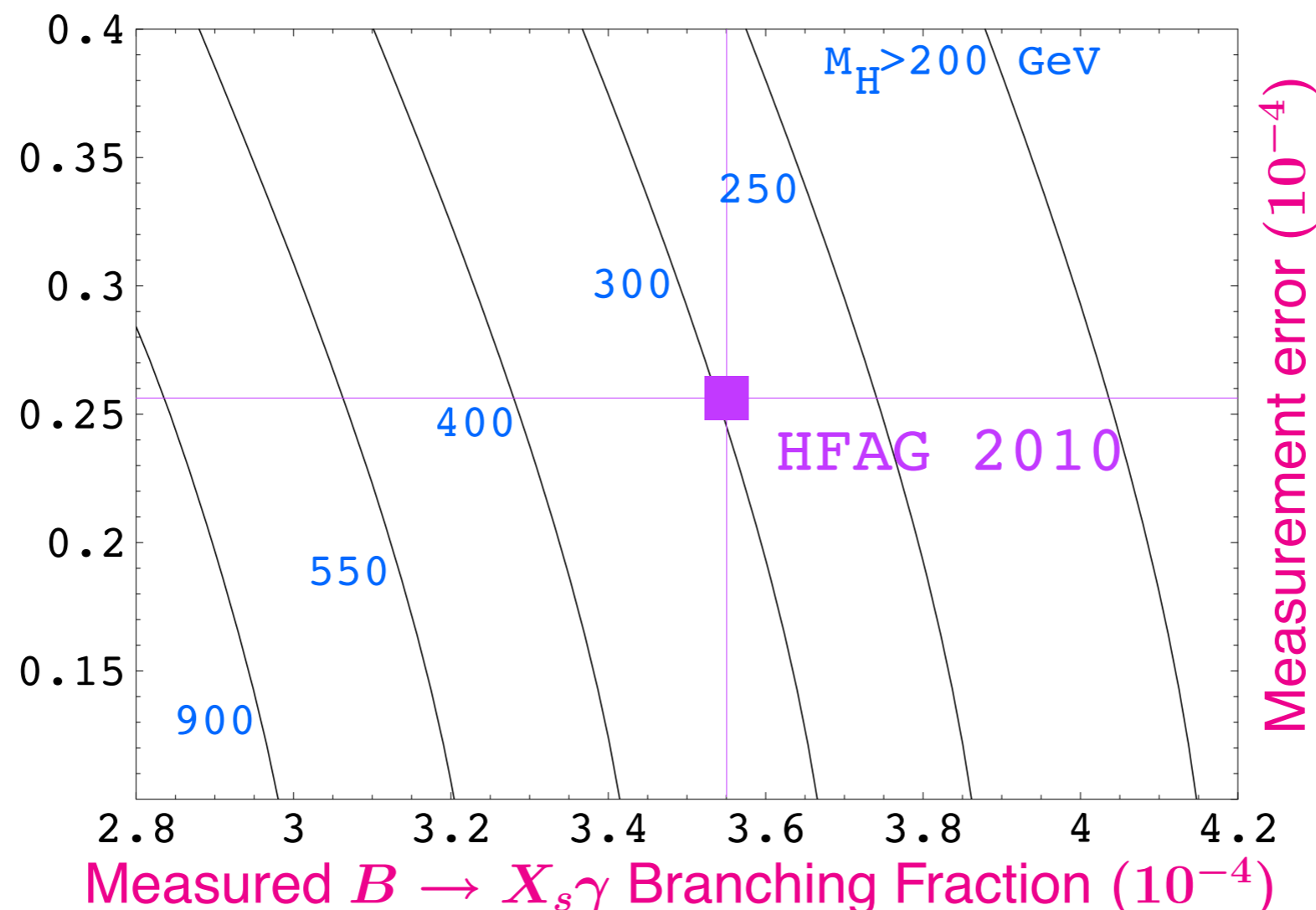
Status of the inclusive mode $\bar{B} \rightarrow X_s \gamma$

HFAG: $\mathcal{B}(B \rightarrow X_s \gamma) = (3.55 \pm 0.24) \times 10^{-4}$ (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)

Bound on charged Higgs mass in Two-Higgs-Doublet model



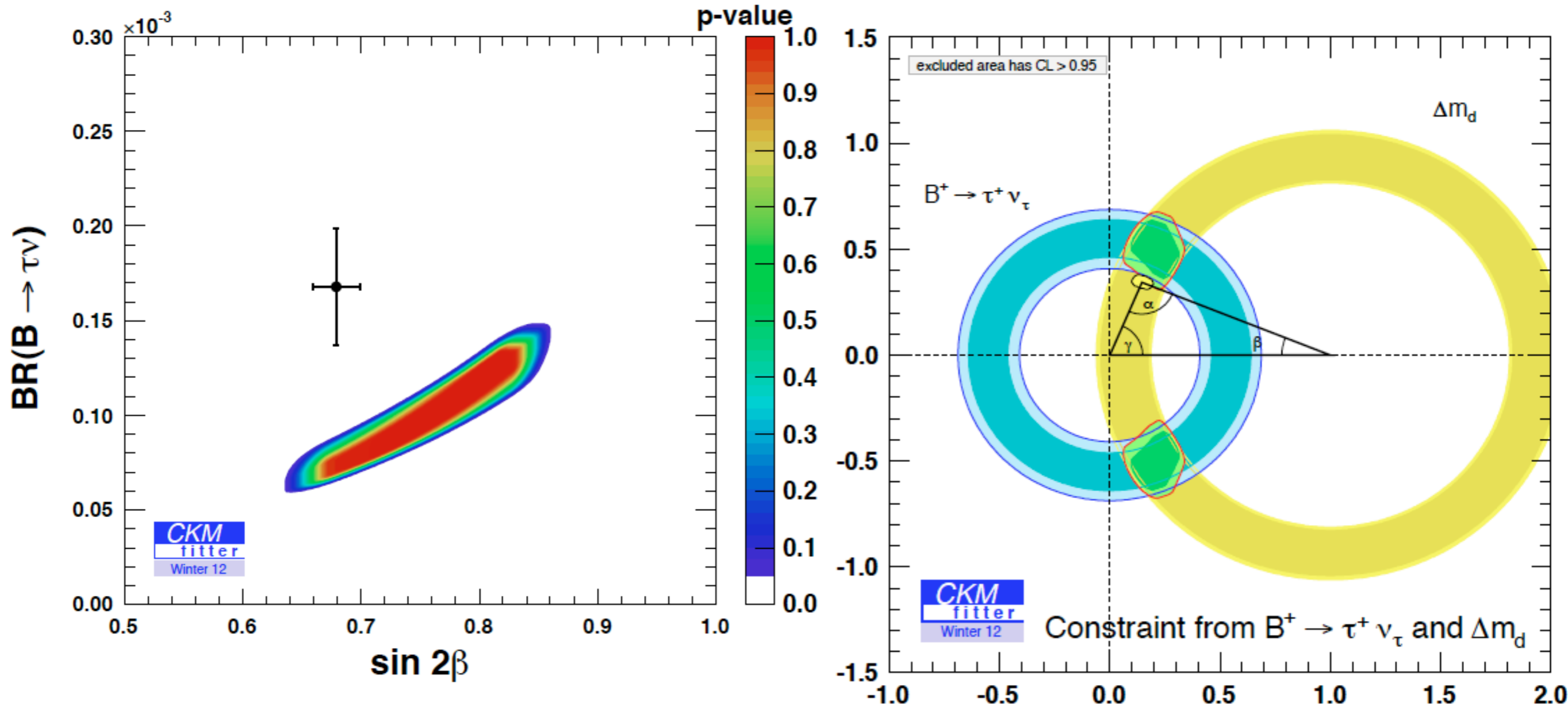
Courtesy of Mikihiro Nakao

Status report in view of the latest LHCb data

$\mathcal{B}(B \rightarrow \tau\nu)$ versus $\sin\beta$ in the CKM-fit

Specific correlation between $\mathcal{B}(B \rightarrow \tau\nu)$ and $\sin\beta$

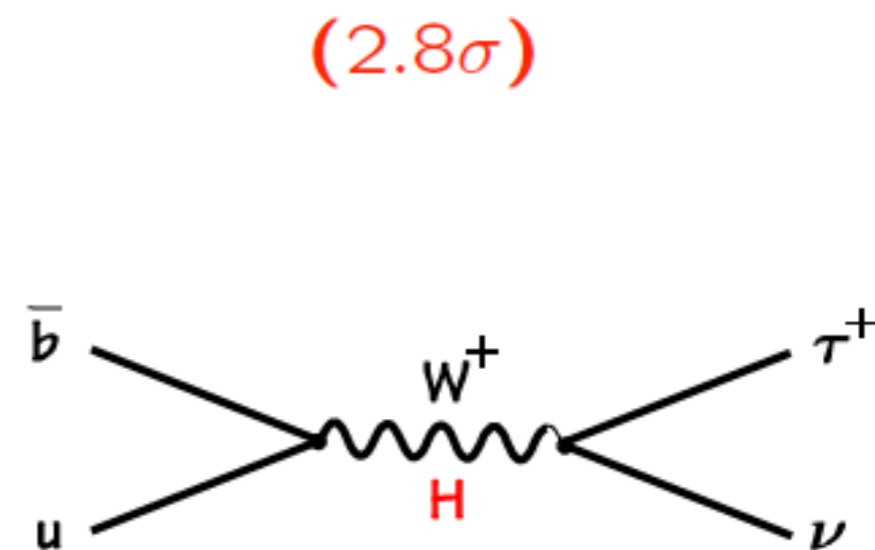
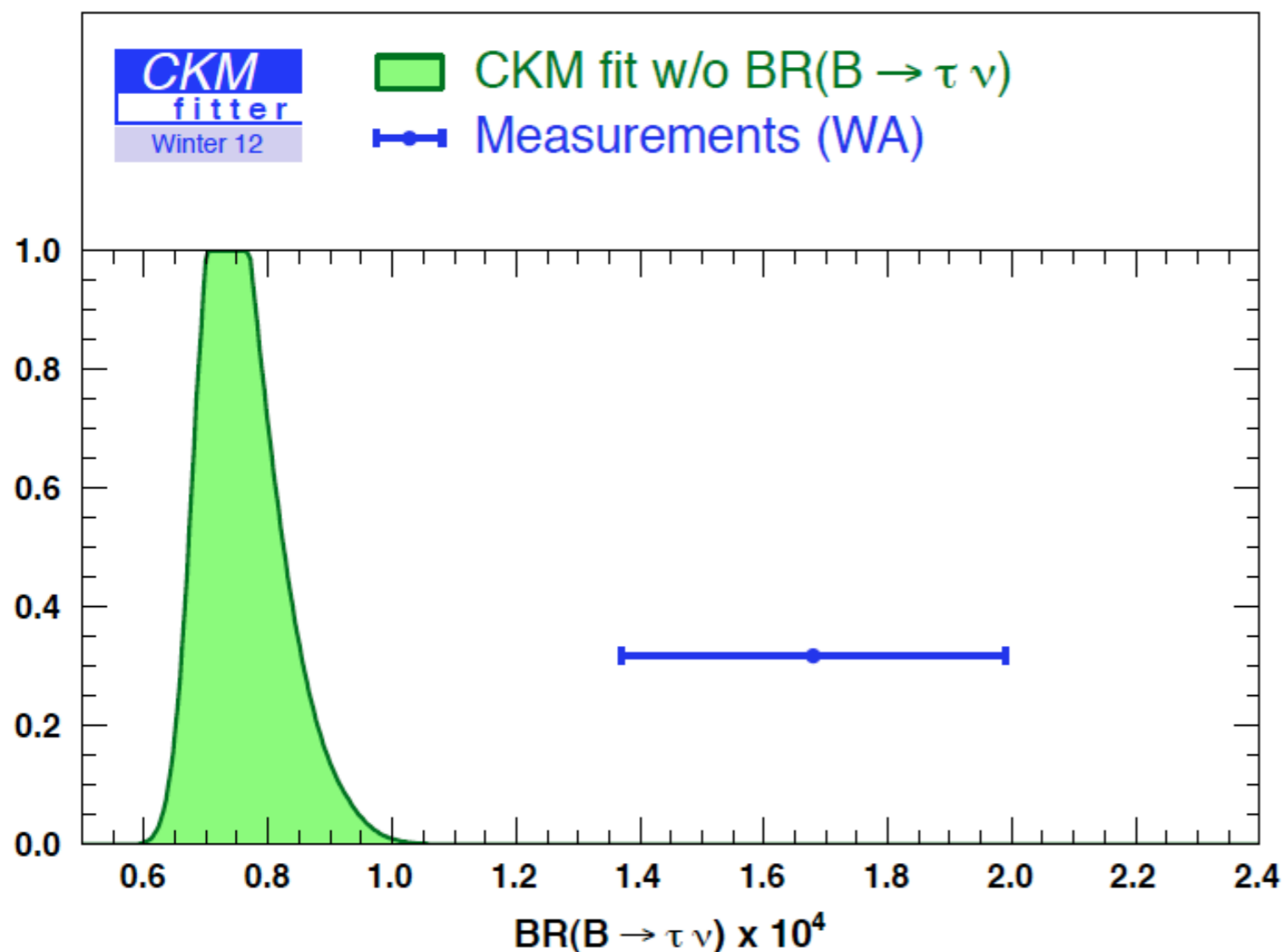
It is a bit at odds with the direct experimental determination: $\mathcal{B}(B \rightarrow \tau\nu)$ too high, $\sin\beta$ too low! ($\approx 3\sigma$)



$$\frac{\text{BR}(B \rightarrow \tau\nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+} \frac{1}{B_{\text{SM}}} \frac{1}{|V_{ud}|^2} \left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

May be solved by NP mixing phase $\Phi_d^\Delta < 0$

$\mathcal{B}(B \rightarrow \tau \nu)$: Tension between direct measurement and indirect fit

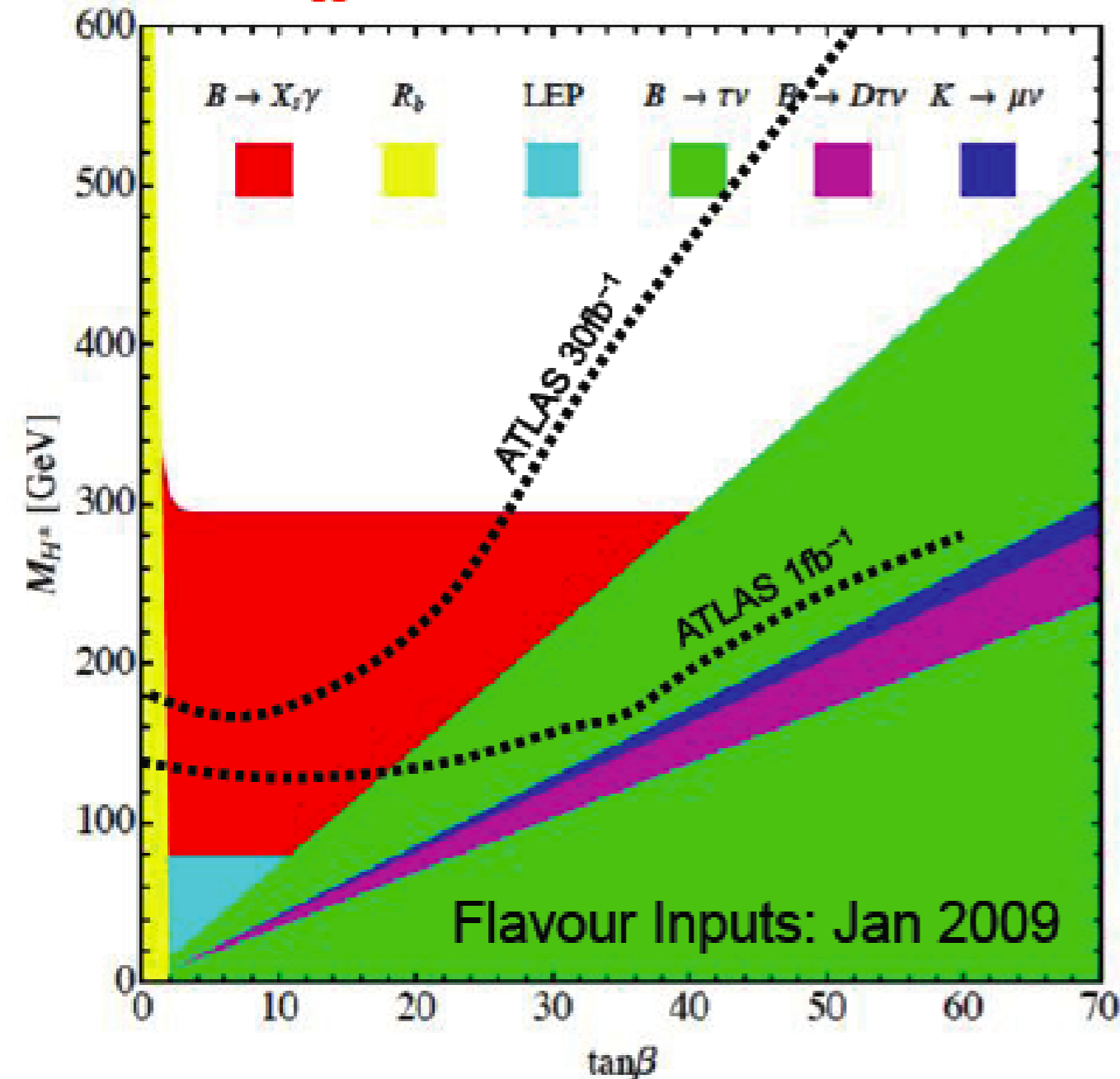


$$B_{\text{SM}}(B^+ \rightarrow \tau^+ \nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

$$\text{2HDM (type II): } B(B^+ \rightarrow \tau^+ \nu) = B_{\text{SM}} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)^2$$

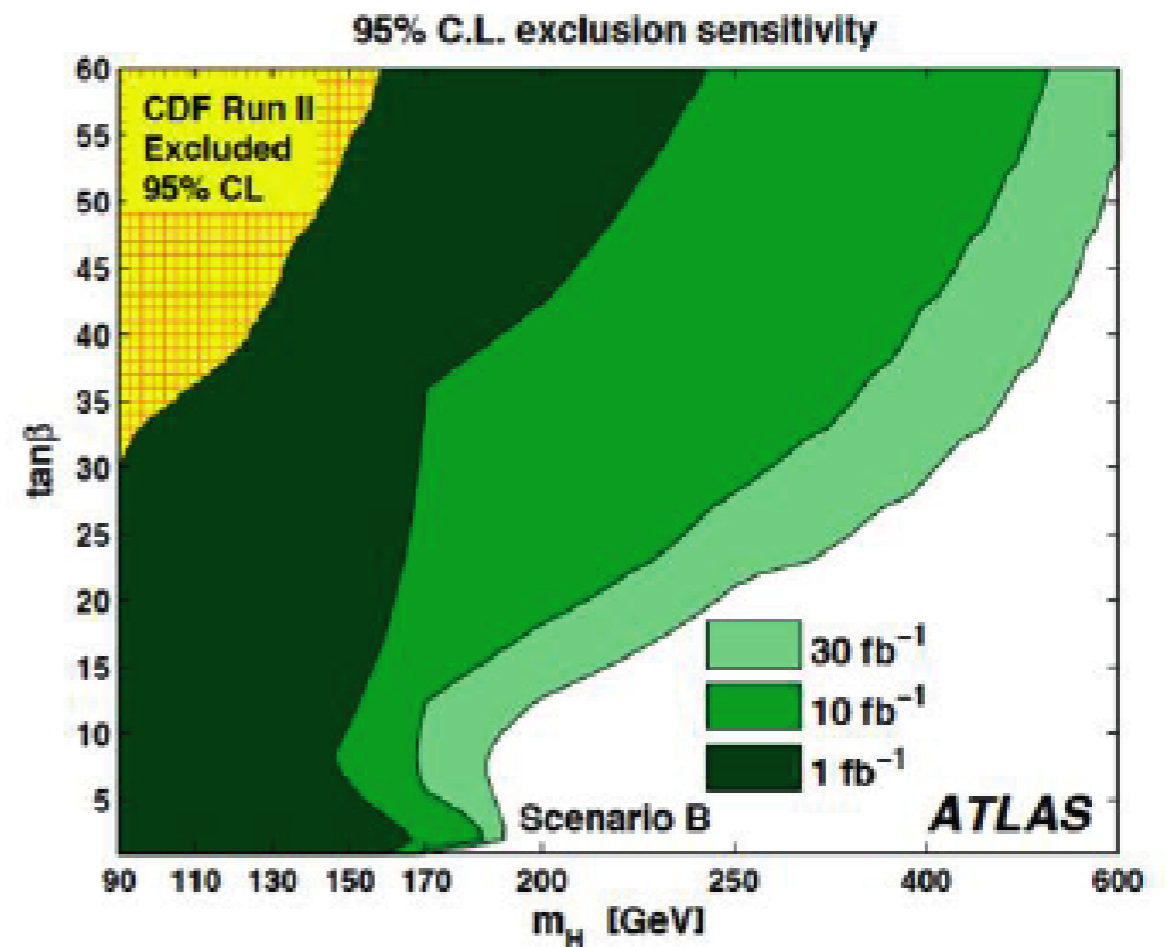
LHC versus Flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



U. Haisch 0805.2141
2HDM

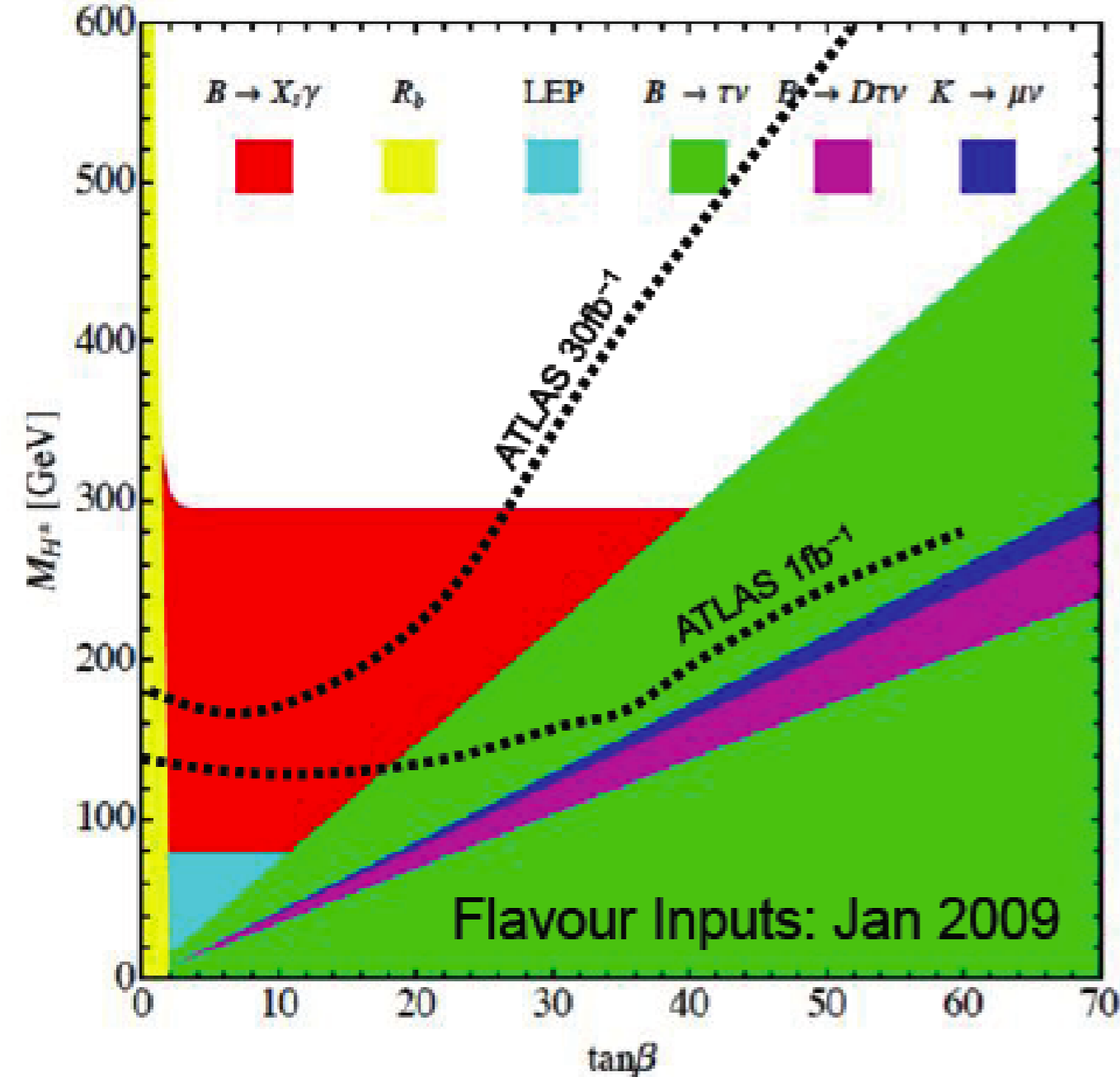
Converted constraints expected from ATLAS onto the plot by hand.



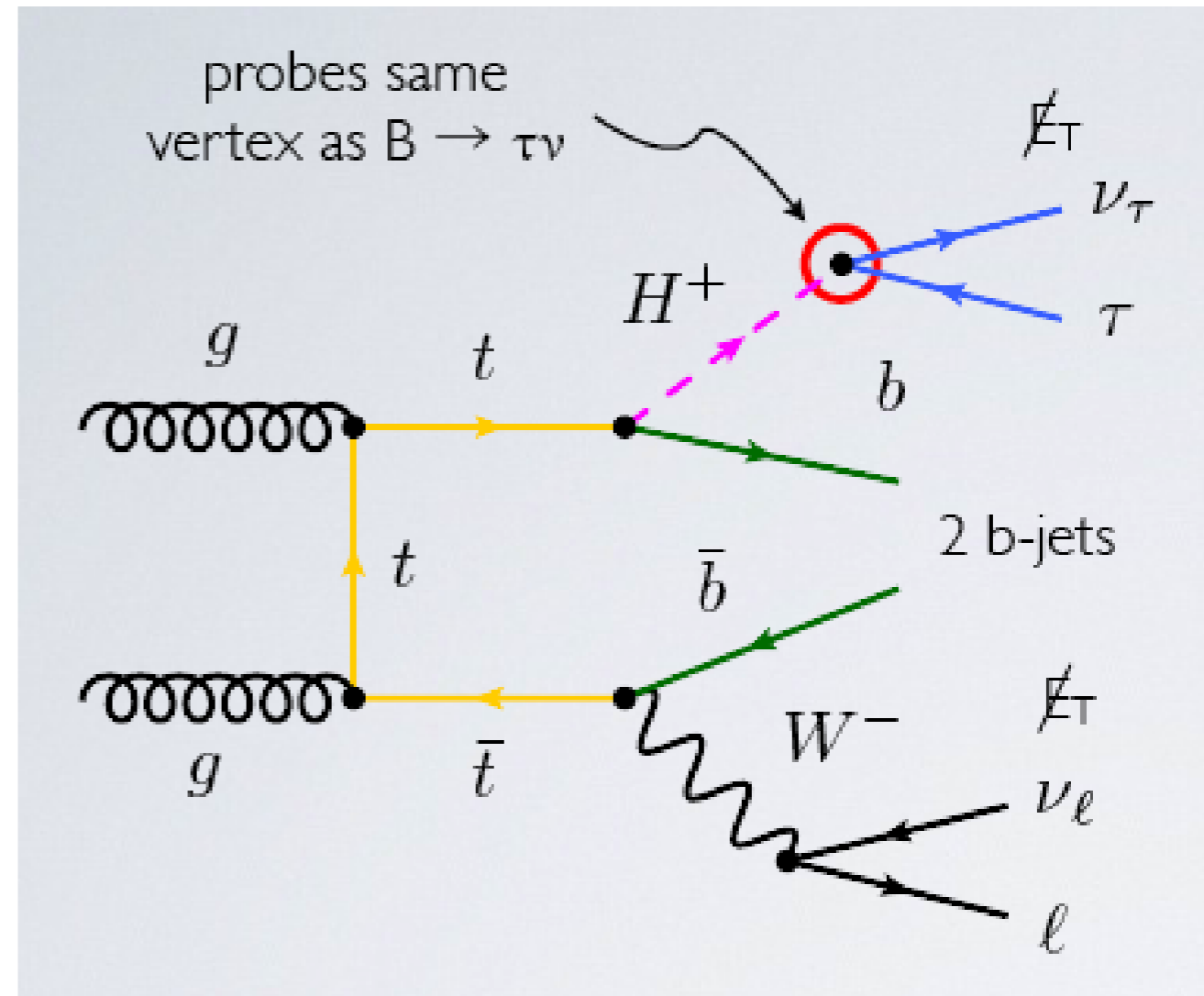
Courtesy of Adrian Bevan

LHC versus Flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



U. Haisch 0805.2141
2HDM



Courtesy of Uli Haisch

$B_q - \bar{B}_q$ mixing in the LHCb era

Is there new physics in the mixing phase ?

Some theory on B_q mixing

- $B_q - \bar{B}_q$ oscillations are governed by the Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2} \hat{\Gamma} \right) \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

- Off-diagonal elements M_{12} and Γ_{12} with $\phi^{\text{mix}} = \arg(-M_{12}/\Gamma_{12})$

Mass difference of physical eigen states B_H and B_L

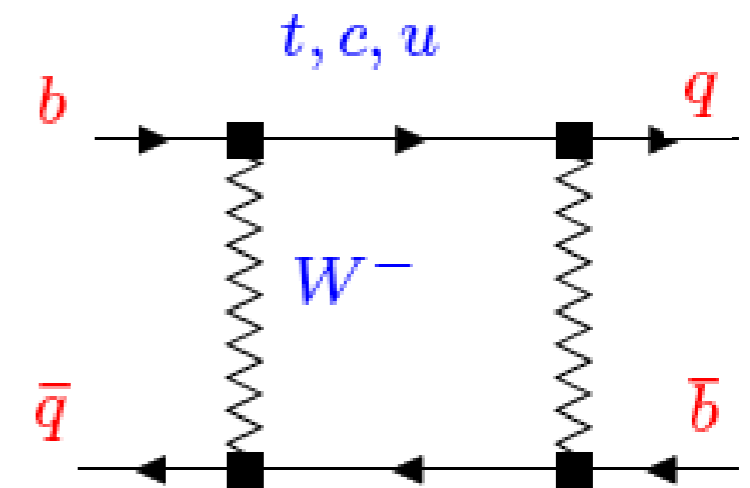
$$\Delta M := M_H - M_L = 2|M_{12}|$$

M_{12} dispersive part (sensitive to heavy particles)

Decay rate difference

$$\Delta\Gamma := \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos\phi$$

Γ_{12} absorptive part (light internal particles, not new physics)



- Large uncertainties: M_{12} (Bag parameter, f_B), Γ_{12} (OPE: $m_b \gg \Lambda_{QCD}$)

Γ_{12}/M_{12} best (improved by new operator basis)

Nierste, Lenz, hep-ph/0612167, 0802.0977

Model-independent approach to $\Delta F = 2$ amplitudes

- $\langle B_q | \mathcal{H}_{\Delta F=2}^{SM+NP} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}_{\Delta F=2}^{SM} | \bar{B}_q \rangle \times \text{Re}(\Delta_q) + i\text{Im}(\Delta_q)$

$$2\theta_q \equiv \text{arg}(\Delta_q)$$

- If we assume $\Gamma_{12,q} = \Gamma_{12,q}^{SM}$: $M_{12,q} \equiv M_{12,q}^{SM} \times \Delta_q$

- Some observables sensitive to $\Delta F = 2$ new physics:

- $\Delta M_q = 2|M_{12,q}^{SM}| \times |\Delta_q|$

- $\Delta|\Gamma_q| = 2|\Gamma_{12,q}| \times \cos(\phi_q^{SM} + 2\theta_q)$

- $a_{\text{SI}}^q = \text{Im}(\Gamma_{12,q}/M_{12,q}) = (|\Gamma_{12,q}|/|M_{12,q}|) \times \sin(\phi_q^{SM} + 2\theta_q) / |\Delta_q|$

- $B_d \rightarrow J/\psi K : 2\beta_d^{SM} + 2\theta_d$

- $B_s \rightarrow J/\psi \phi : 2\beta_s^{SM} - 2\theta_s$

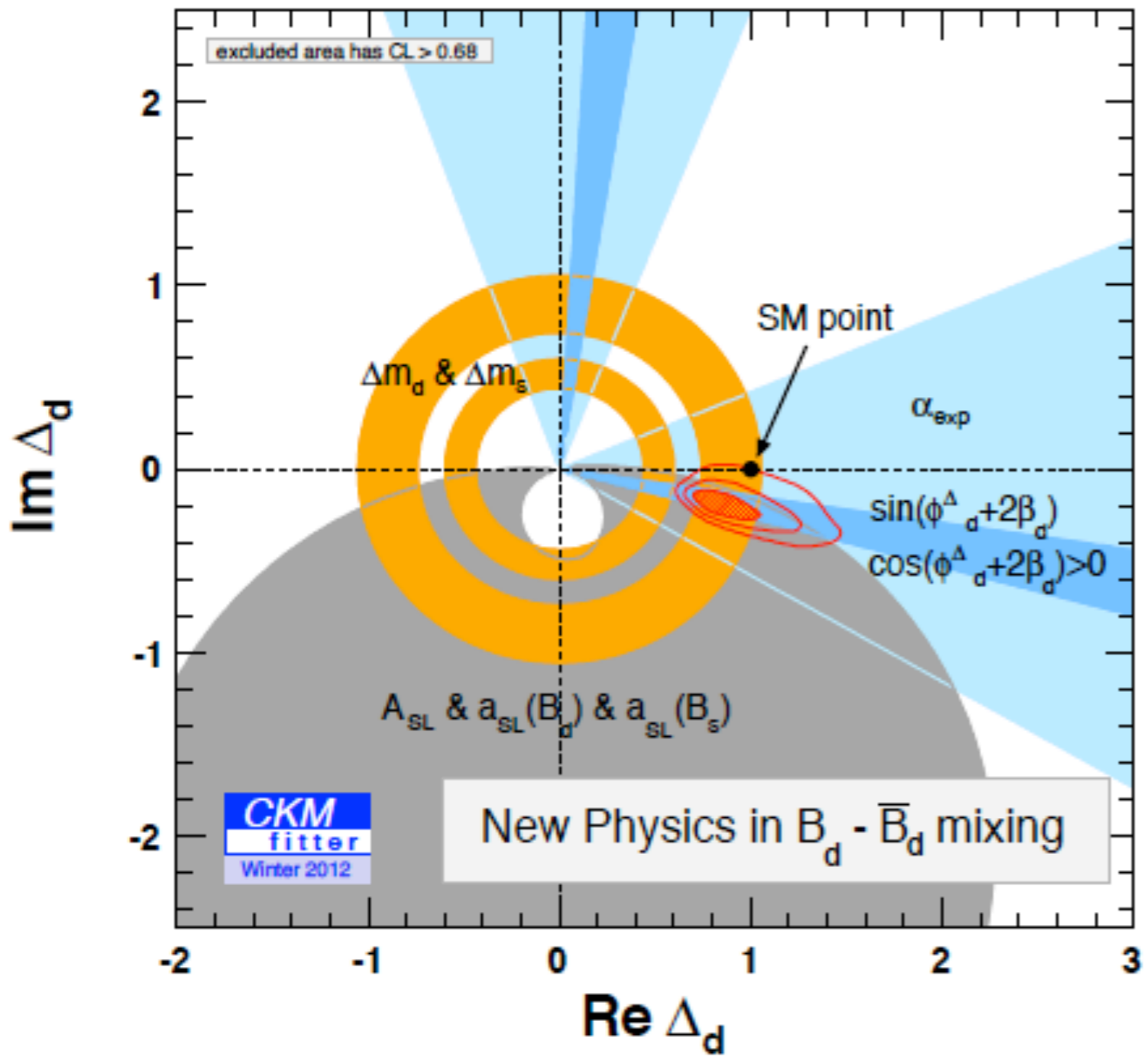
New physics in $B_d - \bar{B}_d$ mixing ?

- $\langle B_q | \mathcal{H}_{\Delta F=2}^{SM+NP} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}_{\Delta F=2}^{SM} | \bar{B}_q \rangle \times \text{Re}(\Delta_q) + i \text{Im}(\Delta_q)$

$\text{arg}(\Delta_q) = 2\theta_q = \Phi_q^\Delta, q = d$

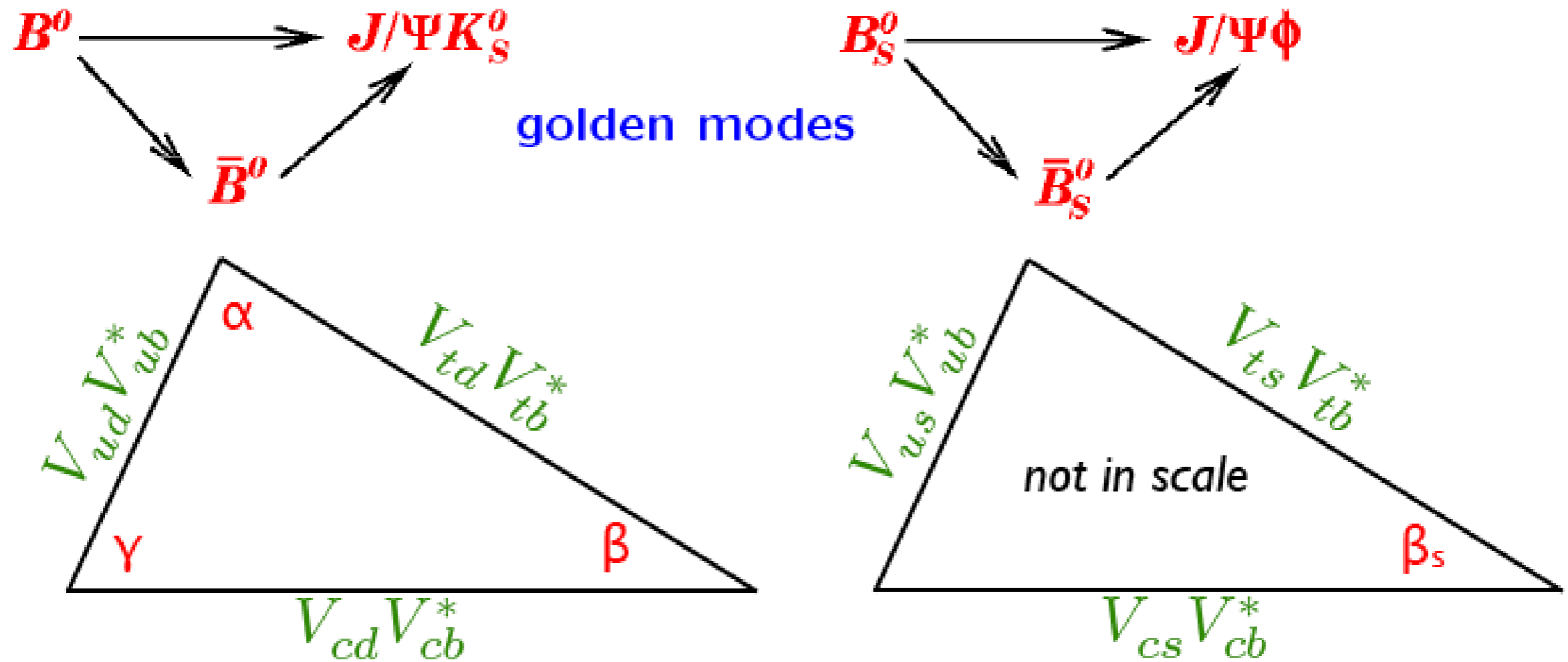
- SM hypothesis $\Delta_d = 1$ (2D) disfavored by 3σ (2.7σ 2010)

- NP phase $\Phi_d^\Delta < 0$ would resolve $\mathcal{B}(B \rightarrow \tau\nu)$ - $\sin\beta$ tension



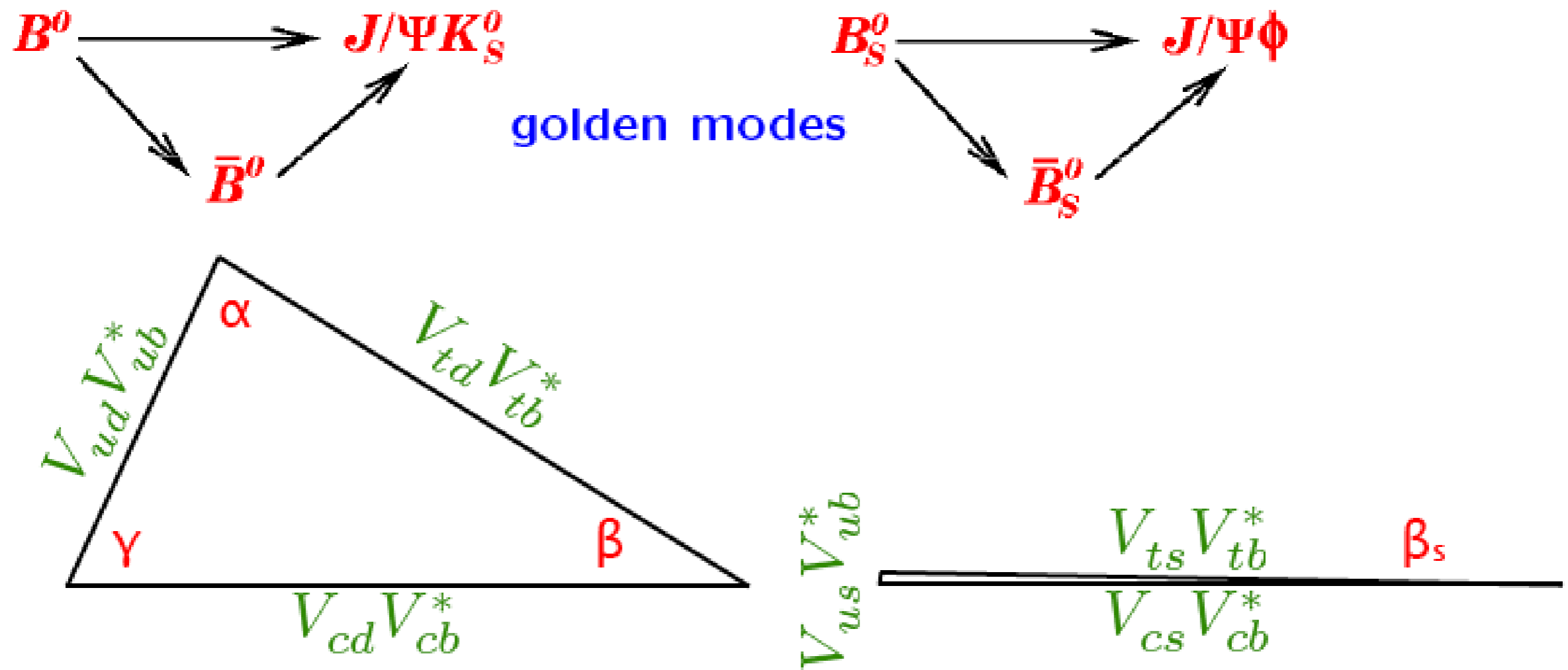
CP violation in $B_s \rightarrow J/\psi\Phi$ decays

- CP violation through interference of decay with and without mixing



CP violation in $B_s \rightarrow J/\psi\Phi$ decays

- CP violation through interference of decay with and without mixing



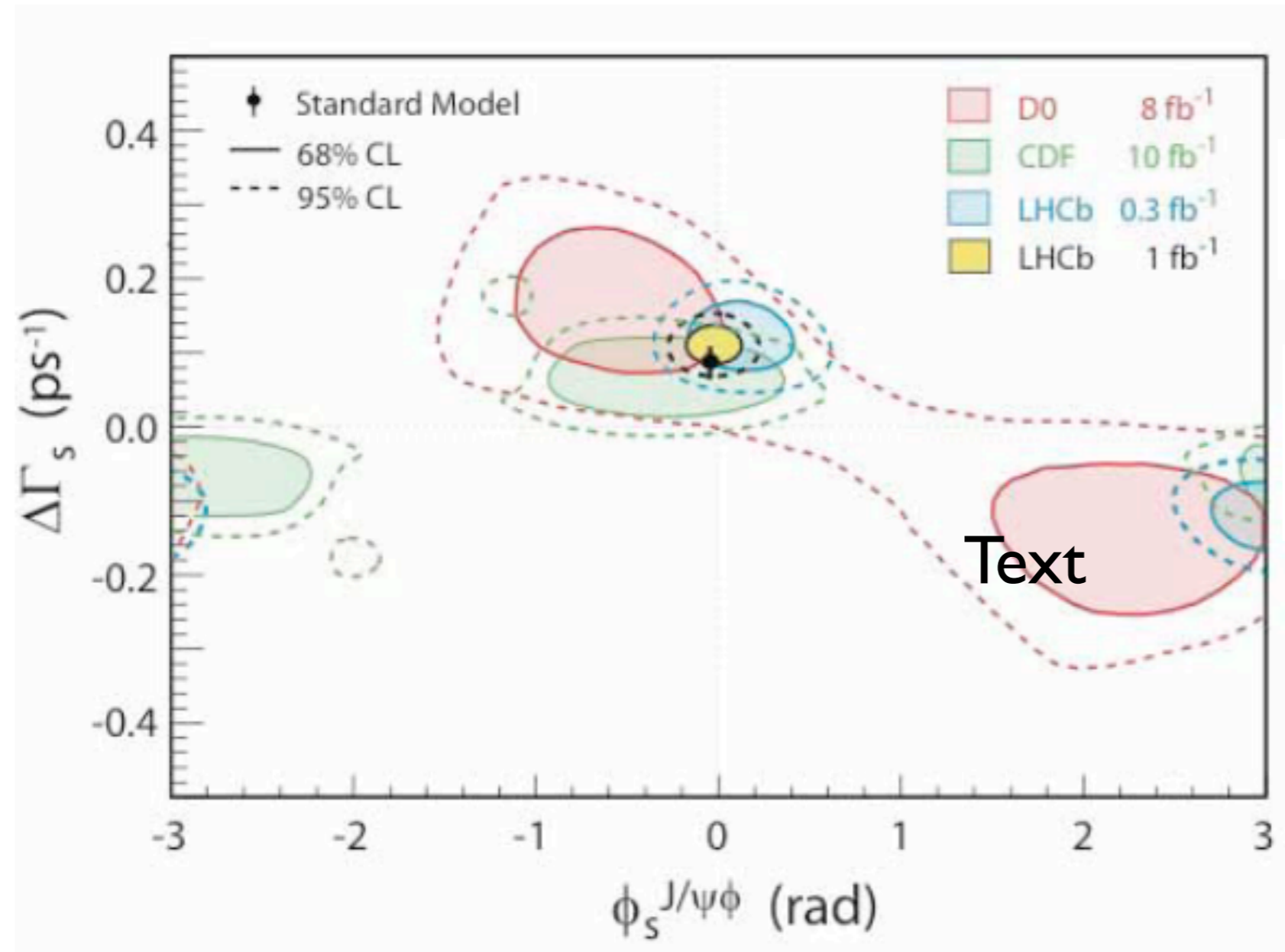
- Phase small: $2\beta_s^{\text{SM}} = -\arg\left(\frac{(V_{ts}V_{tb}^*)^2}{(V_{cs}V_{cb}^*)^2}\right) = (2.1 \pm 0.1)^\circ$

CKM-fitter, arXiv:1008.1593

- New physics affects the CP violation phase as: $2\beta_s^{\text{SM}} - 2\theta_s^{\text{NP}}$

New LHCb measurement (1fb^{-1})

LHCb-CONF-2012-002



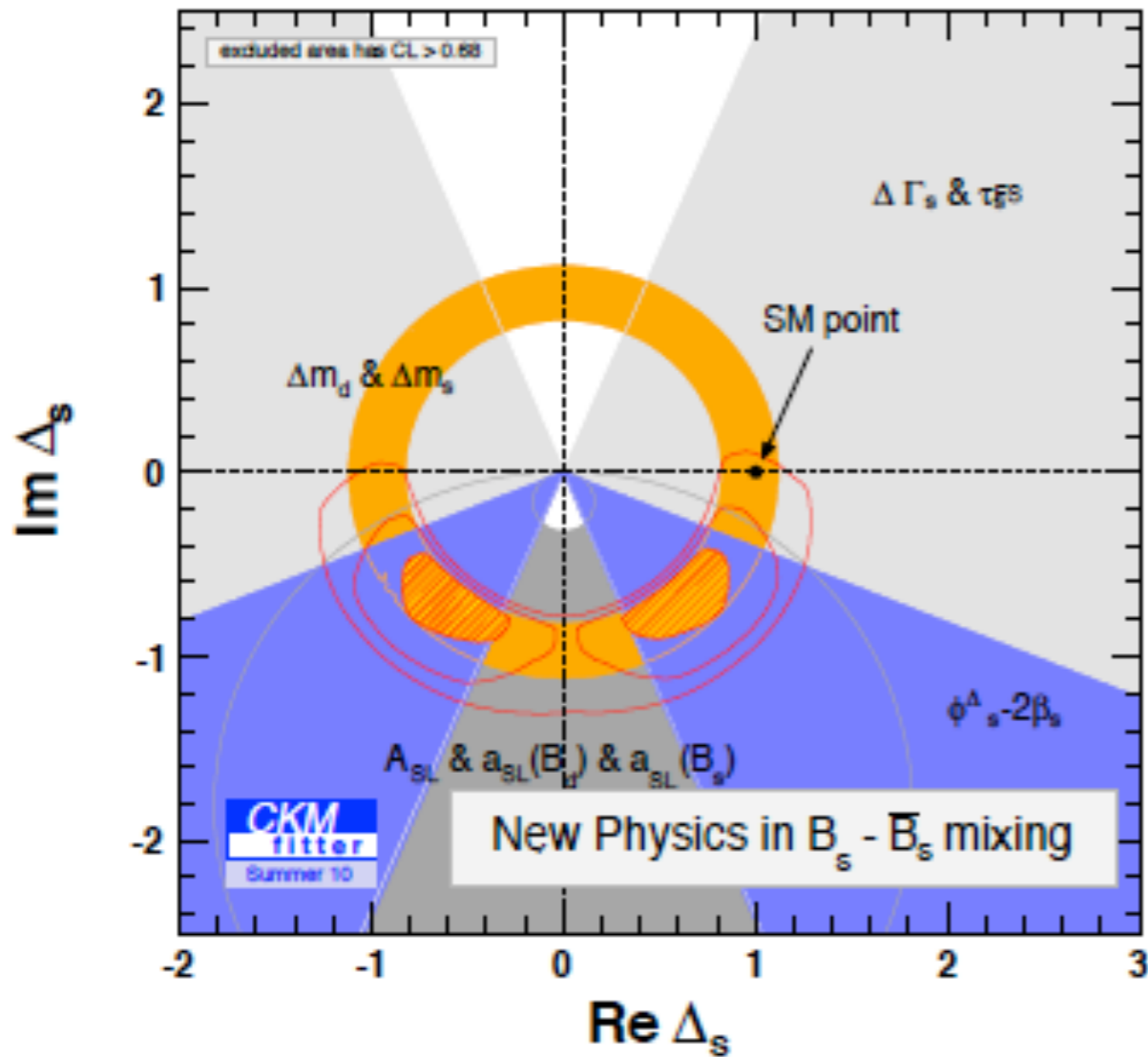
- Measurement right on the SM prediction!
- Fully consistent with previous CDF and D0 measurements of $B_s \rightarrow J/\psi\Phi$.
- Two-fold ambiguity resolved.

LHCb-PAPER-2012-28

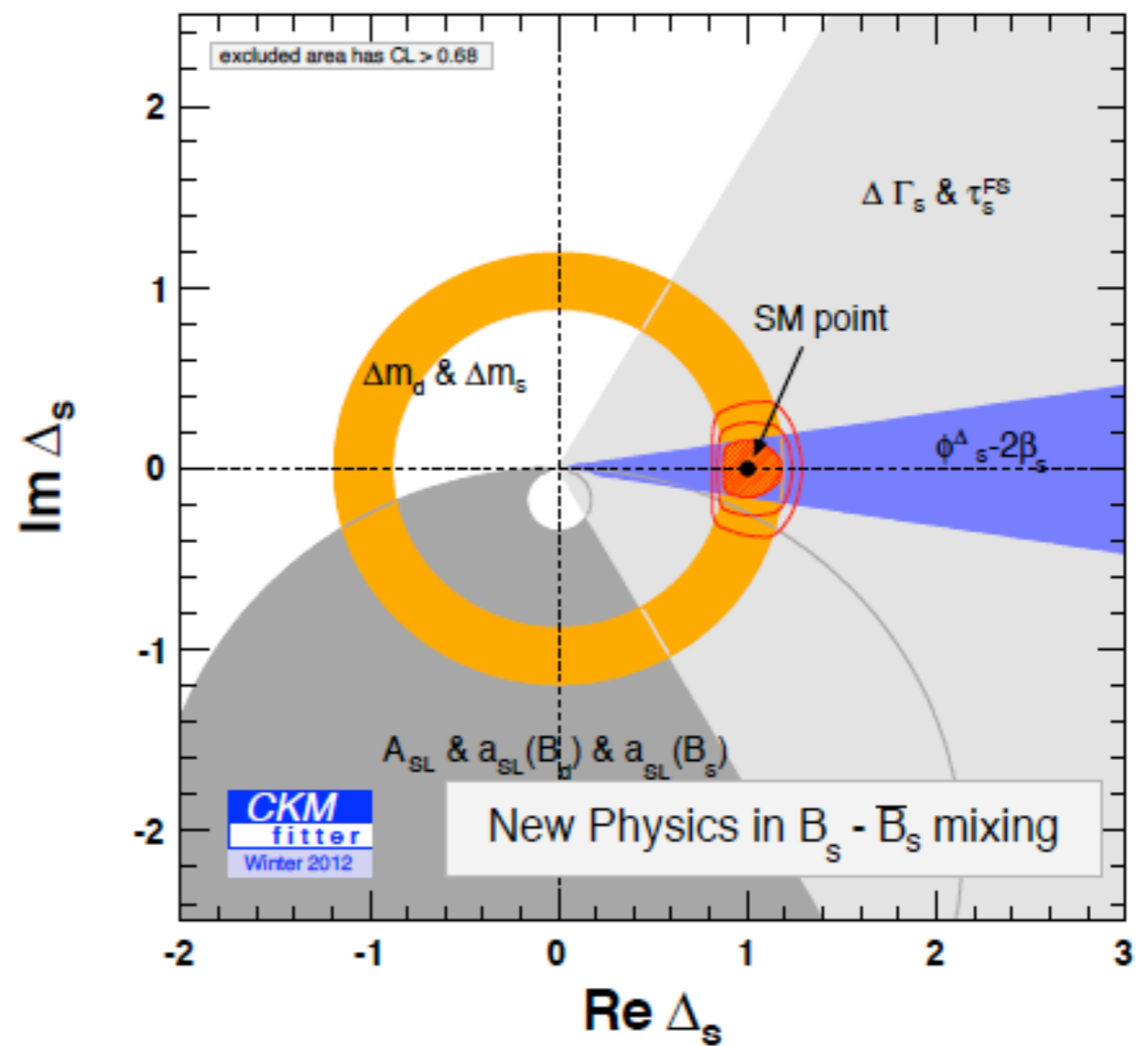
In $B_s \rightarrow J/\psi\Phi$ angular analysis for disentangling CP eigenstates necessary

Other decays like $B_s \rightarrow J/\psi f_0$ provide pure eigenstates, but lower BR

Pre-LHCb (2010)



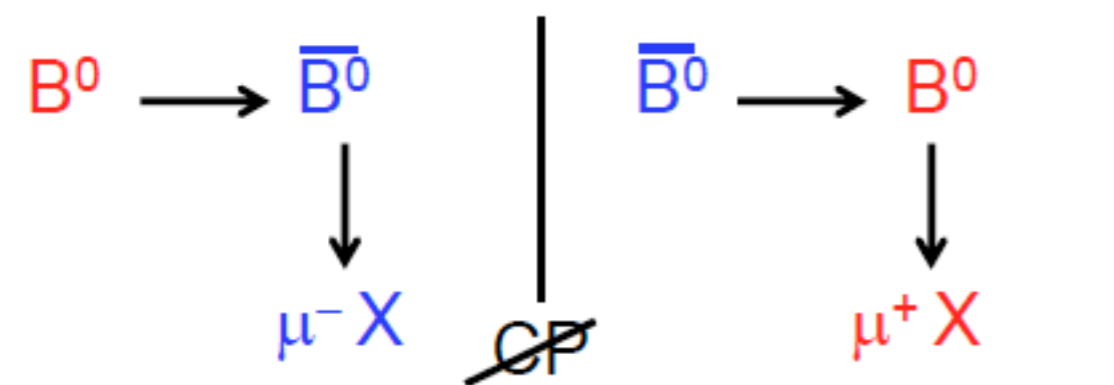
LHCb (2012)



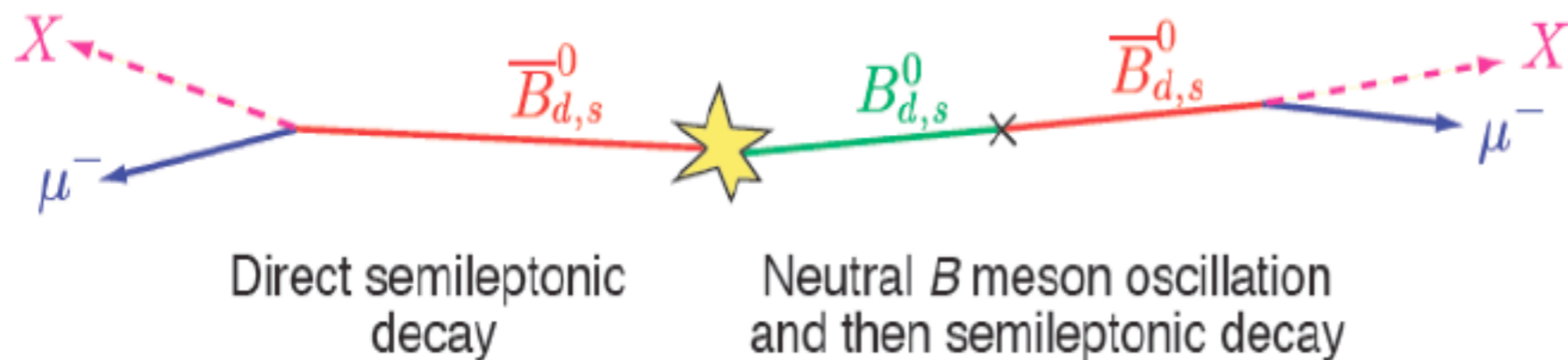
SM hypothesis of $\Delta = 1$ (2D) disfavored
 by 3σ by 0σ

CKM-fitter, arXiv:1008.1593 1203.0238

However: Like-sign dimuon charge asymmetry



$$a_{Sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \rightarrow \mu^+ X) - \Gamma(B_q^0 \rightarrow \mu^- X)}{\Gamma(\bar{B}_q^0 \rightarrow \mu^+ X) + \Gamma(B_q^0 \rightarrow \mu^- X)}$$



$$A_{Sl}^b = \frac{N_{b\bar{b}}^{++} - N_{b\bar{b}}^{--}}{N_{b\bar{b}}^{++} + N_{b\bar{b}}^{--}}$$

$$= C_d a_{Sl}^d + C_s a_{Sl}^s$$

SM prediction

Lenz, Nierste arXiv:1102.4274 [hep-ph]

$$A_{Sl}^b(SM) = (-0.028_{-0.006}^{+0.005})\%$$

DO measurement, update 2011

arXiv:1106.6308 [hep-ex]

$$A_{Sl}^b = (-0.787 \pm 0.172(stat) \pm 0.093(syst))\%$$

3.9 σ from the SM value

LHCb versus D0

Possible solutions:

Neglected Penguins in $B_s \rightarrow J/\psi\Phi$?

$$S_{\psi\phi}^{\text{SM}} = 0.0036 \pm 0.002 \rightarrow \sin(2\beta_s - \phi_s^\Delta - \delta_s^{\text{Peng,SM}} - \delta_s^{\text{Peng,NP}}) = 0.002 \pm 0.087$$

Lenz arXiv:1106.3200

Large new physics in Γ_{12} ?

New operator $bs \rightarrow X$ with $M_x < M_B$ contributes not only to Γ_{12} but to many other observables

But $X = \tau\tau$ Bobeth,Haisch arXiv:1109.1826, Moriond talk 2012 by Haisch

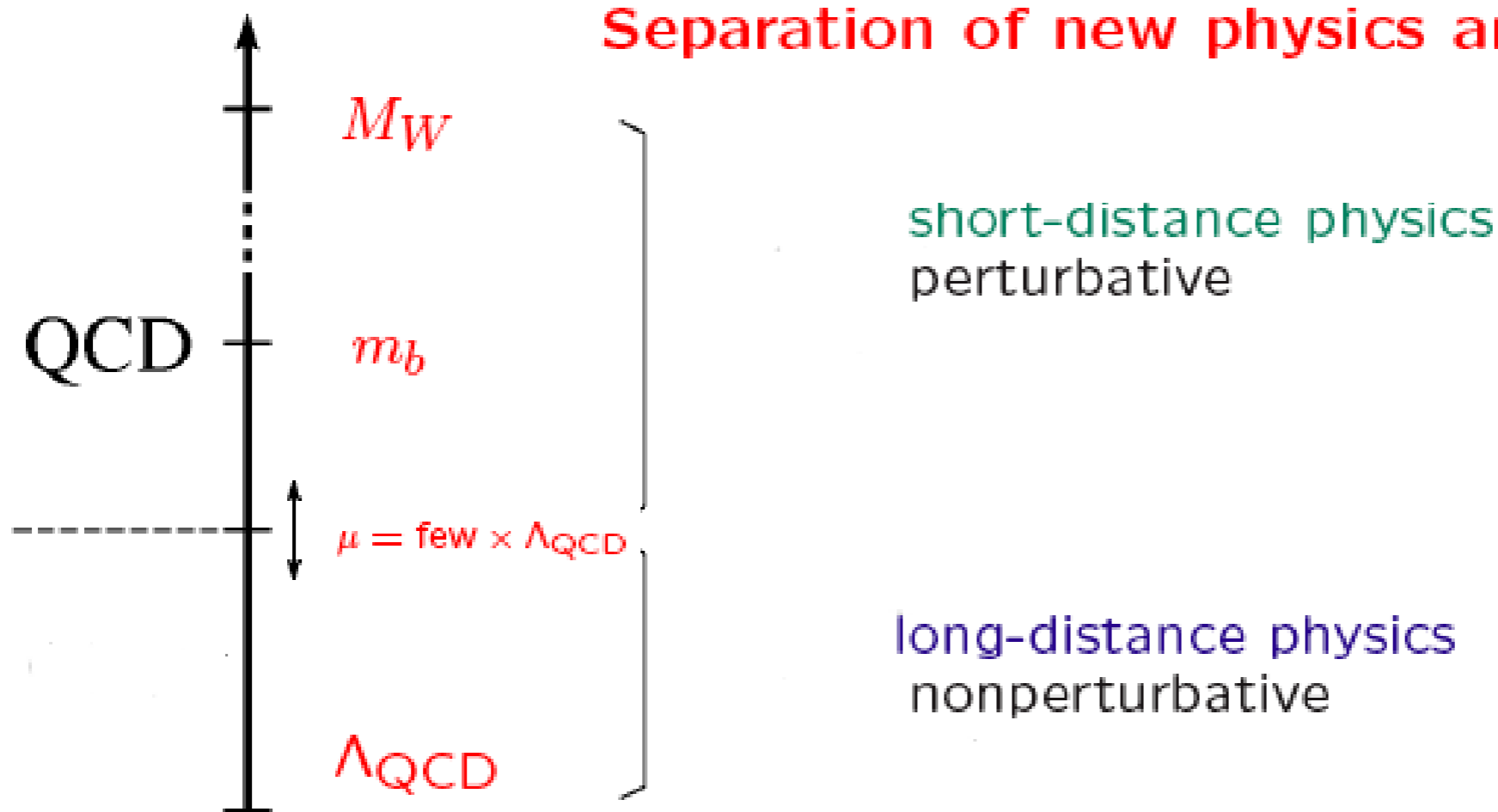
Obviously independent measurements of semileptonic asymmetries needed!

Radiative and semileptonic penguin decays

Separation of new physics and hadronic effects

Challenge for our understanding of QCD

Separation of new physics and hadronic effects



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 $\mathcal{O}_i(\mu = m_b)$?

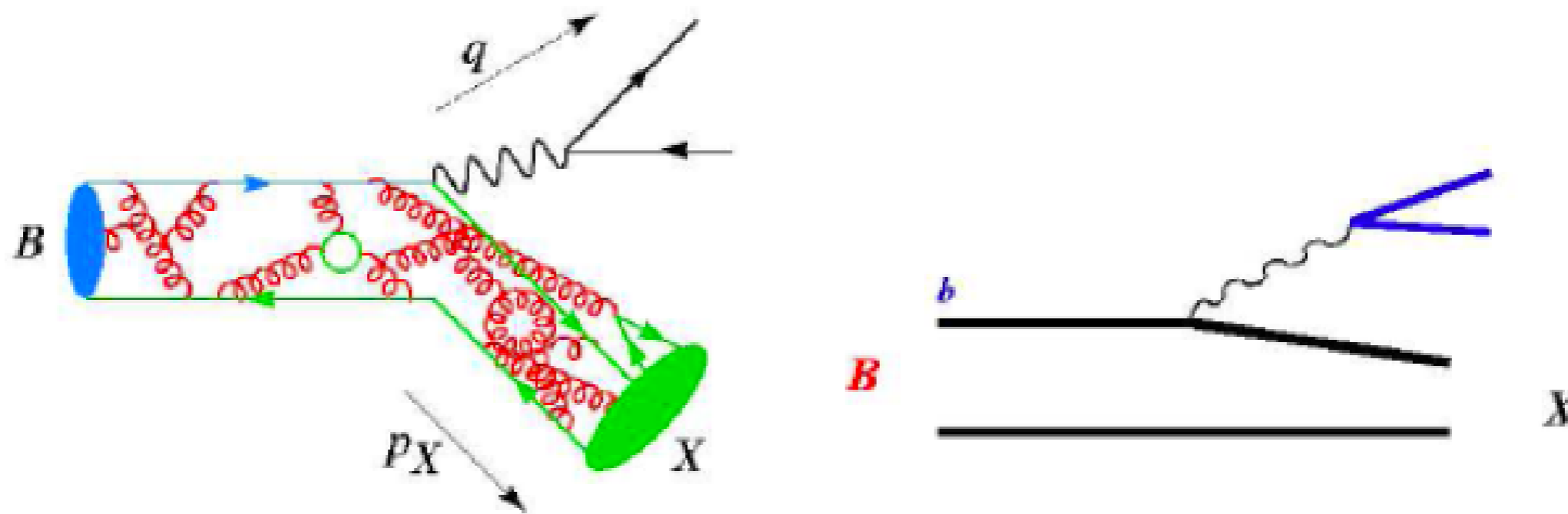
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

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

- 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)



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

- Heavy mass expansion for inclusive modes:

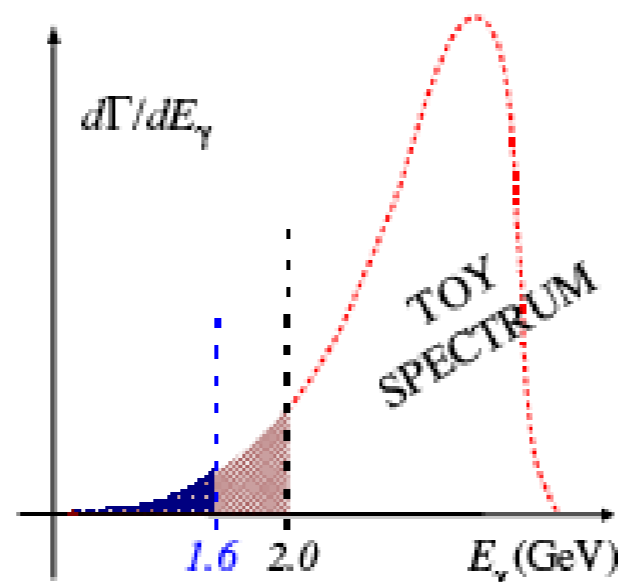
$$\Gamma(\bar{B} \rightarrow X_s \gamma) \xrightarrow{m_b \rightarrow \infty} \Gamma(b \rightarrow X_s^{\text{parton}} \gamma), \quad \Delta^{\text{nonpert.}} \sim \Lambda_{QCD}^2 / m_b^2$$

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

An old story:

- 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)

Another old story:

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

A new dedicated analysis:

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

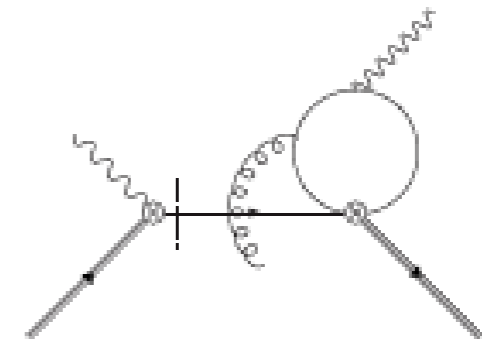
[Benzke, Lee, Neubert, Paz, arXiv:1003.5012](#)



Another consequence of this: a positive one

$$B \rightarrow X_d \gamma$$

- In $B \rightarrow X_d \gamma$, there is no CKM suppression of the up-quark loop contributions like in $B \rightarrow X_s \gamma$
- General belief: There are large uncertainties due to the corresponding nonperturbative contributions



- However:

It was shown that the dominating nonperturbative contribution due to the operator \mathcal{O}_1^u (the \mathcal{O}_1^u - \mathcal{O}_7 interference term) vanishes in the CP-averaged rate at order Λ/m_b . [Benzke, Lee, Neubert, Paz, arXiv:1003.5012](#)

- The CP-averaged decay rate of $B \rightarrow X_d \gamma$ is theoretically as clean as the decay rate of $B \rightarrow X_s \gamma$

NLL prediction Hurth,Lunghi,Porod, Nucl.Phys.B704(2004)56

$$\mathcal{B}(\bar{B} \rightarrow X_d \gamma) \times 10^5 |_{E_\gamma > 1.6 \text{ GeV}} = (1.38 \begin{matrix} +0.14 \\ -0.21 \end{matrix} |_{m_c/m_b} \pm 0.15_{\text{CKM}} \pm 0.09_{\text{param}} \pm 0.05_{\text{scale}})$$

NNLL update to be done

To be compared with NLL of $b \rightarrow s \gamma$, large CKM error due to V_{td}

$$\mathcal{B}(\bar{B} \rightarrow X_s \gamma) \times 10^4 |_{E_\gamma > 1.6 \text{ GeV}} = (3.61 \begin{matrix} +0.24 \\ -0.40 \end{matrix} |_{m_c/m_b} \pm 0.02_{\text{CKM}} \pm 0.25_{\text{param}} \pm 0.15_{\text{scale}})$$

Babar measurement 2010

$$\mathcal{B}(\bar{B} \rightarrow X_d \gamma) \times 10^5 |_{E_\gamma > 1.6 \text{ GeV}} = (1.41 \pm 0.57)$$

But also a negative consequence: **direct CP asymmetries in $b \rightarrow s/d\gamma$**

$$A_{CP}^{b \rightarrow q\gamma} \equiv \frac{\Gamma[\bar{B} \rightarrow X_q \gamma] - \Gamma[B \rightarrow X_{\bar{q}} \gamma]}{\Gamma[\bar{B} \rightarrow X_q \gamma] + \Gamma[B \rightarrow X_{\bar{q}} \gamma]}$$

- NLL prediction [Hurth,Lunghi,Porod, hep-ph/0312260](#)

$$A_{CP}(b \rightarrow s\gamma) = \left(0.44 \left. \begin{array}{l} +0.15 \\ -0.10 \end{array} \right|_{m_c/m_b} \pm 0.03_{\text{CKM}} \left. \begin{array}{l} +0.19 \\ -0.09 \end{array} \right|_{\text{scale}} \right) \times 10^{-2}$$

Smallness of $A_{CP}(b \rightarrow s\gamma)$ results from three factors:

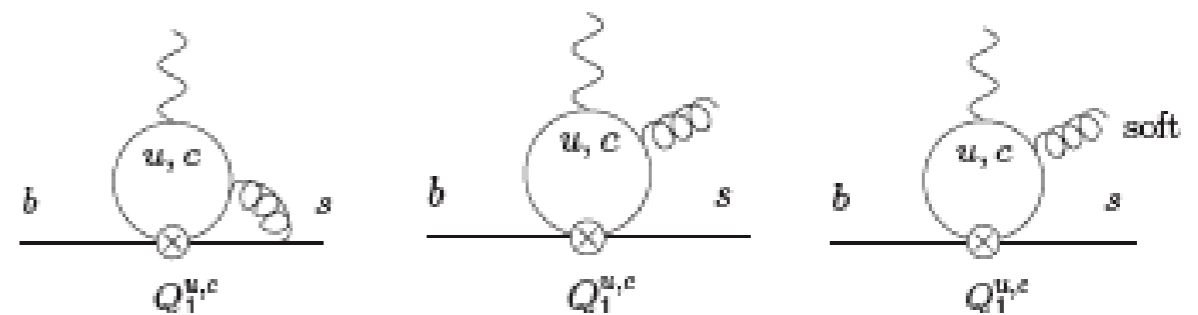
α_s (strong phase), λ^2 (CKM), m_c^2/m_b^2 (GIM)

- However: Long-distance dominance [Benzke, Lee, Neubert, Paz arXiv:1012.31.67 \[hep-ph\]](#)

$$-0.6 \times 10^{-2} < A_{CP}(b \rightarrow s\gamma) < +2.8 \times 10^{-2}$$

Resolved photon contribution:

no α_s -suppression



But untagged direct CP asymmetries in $b \rightarrow s/d$ transitions survives:

Resolved contributions cancel at order Λ/m_b

KM mechanism CKM unitarity + U spin symmetry of matrix elements $d \leftrightarrow s$:

$$|\Delta BR_{CP}(B \rightarrow X_s \gamma) + \Delta BR_{CP}(B \rightarrow X_d \gamma)| \sim 1 \cdot 10^{-9} \approx 0$$

Clean test, whether new CP phases are active or not

Hurth, Mannel, Phys.Lett.B511(2001)196; Hurth, Lunghi, Porod, Nucl.Phys.B704(2004)56

Three open issue in $\bar{B} \rightarrow X_s \gamma$

- The semileptonic phase factor:

$$\text{BR}_\gamma(E_0) \equiv \text{BR}[B \rightarrow X_s \gamma]_{E_\gamma > E_0} = \frac{\text{BR}_{clv}}{C} \left(\frac{\Gamma[B \rightarrow X_s \gamma]_{E_\gamma > E_0}}{|V_{cb}/V_{ub}|^2 \Gamma[B \rightarrow X_u e \bar{\nu}]} \right)$$

$$C = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma[\bar{B} \rightarrow X_c e \bar{\nu}]}{\Gamma[\bar{B} \rightarrow X_u e \bar{\nu}]} = \begin{cases} 0.582 \pm 0.016, & \text{1S scheme has to be updated!} \\ 0.546^{+0.023}_{-0.033}, & \text{kinetic scheme} \end{cases}$$

Trott et al., hep-ph/0408002
Gambino, Giordano, arXiv:0805.0271

Enhancement of BR_γ in kinematic scheme

$$+4.8\%!? \quad \frac{\delta}{\delta m_c} \text{Pert}(E_0) < 0, \quad \bar{m}_c(\bar{m}_c)_{1S} < \bar{m}_c(\bar{m}_c)_{kinetic}$$

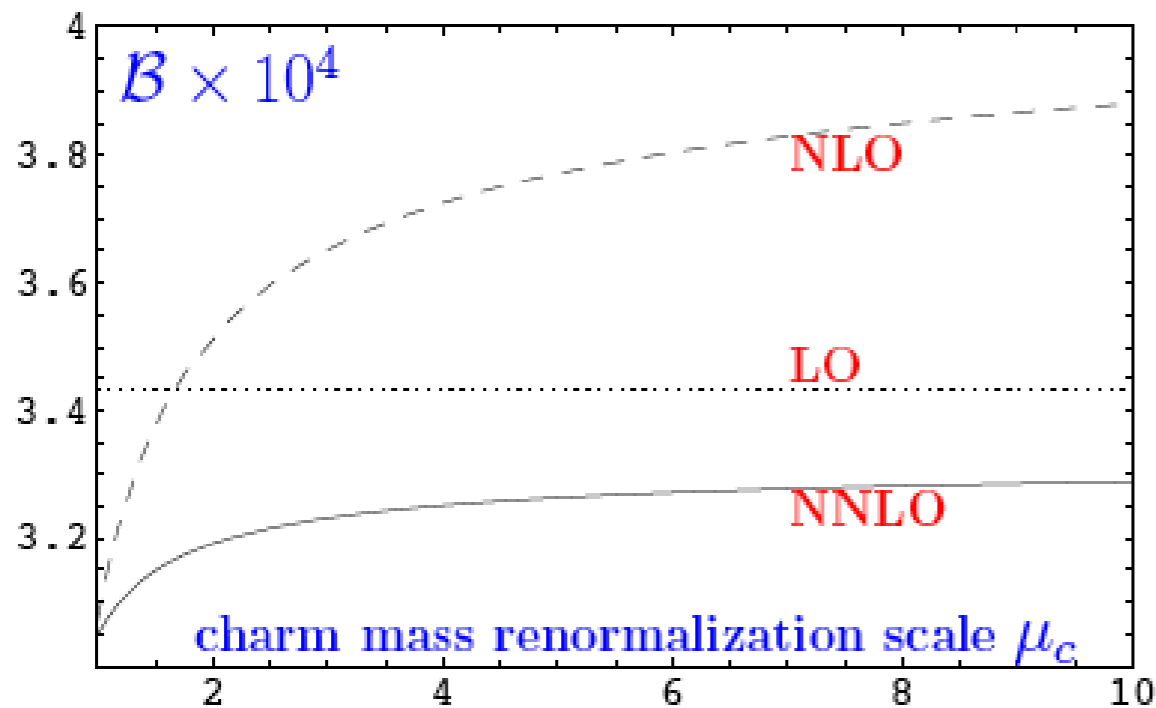
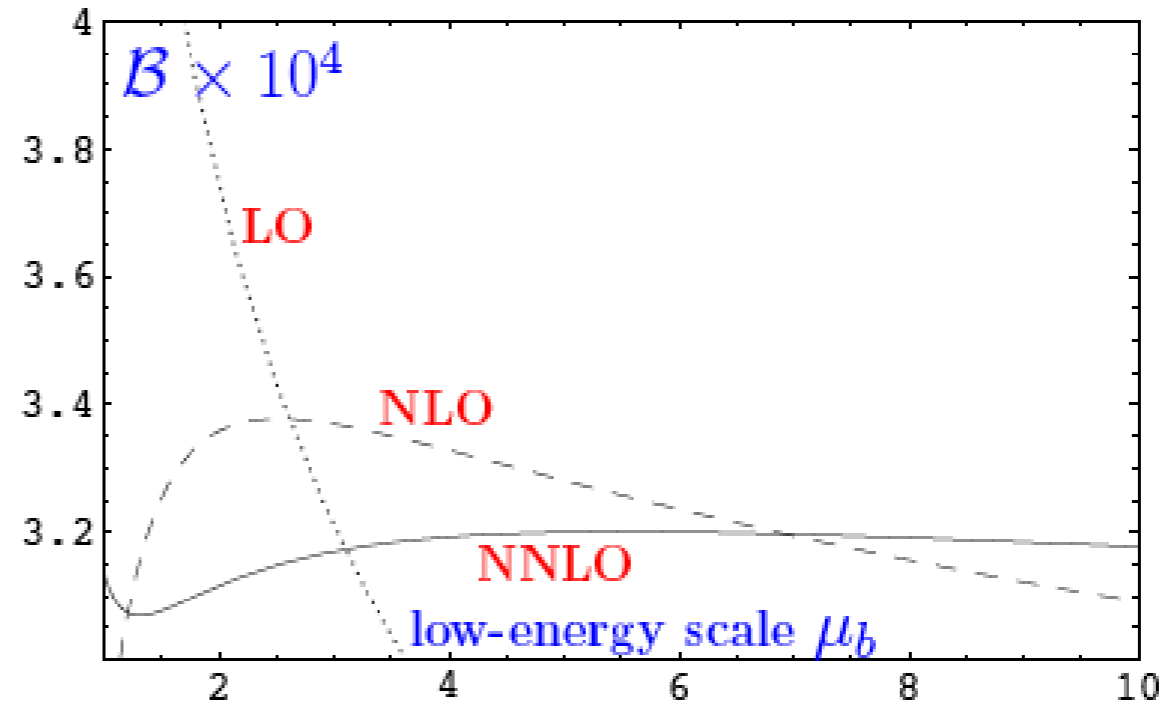
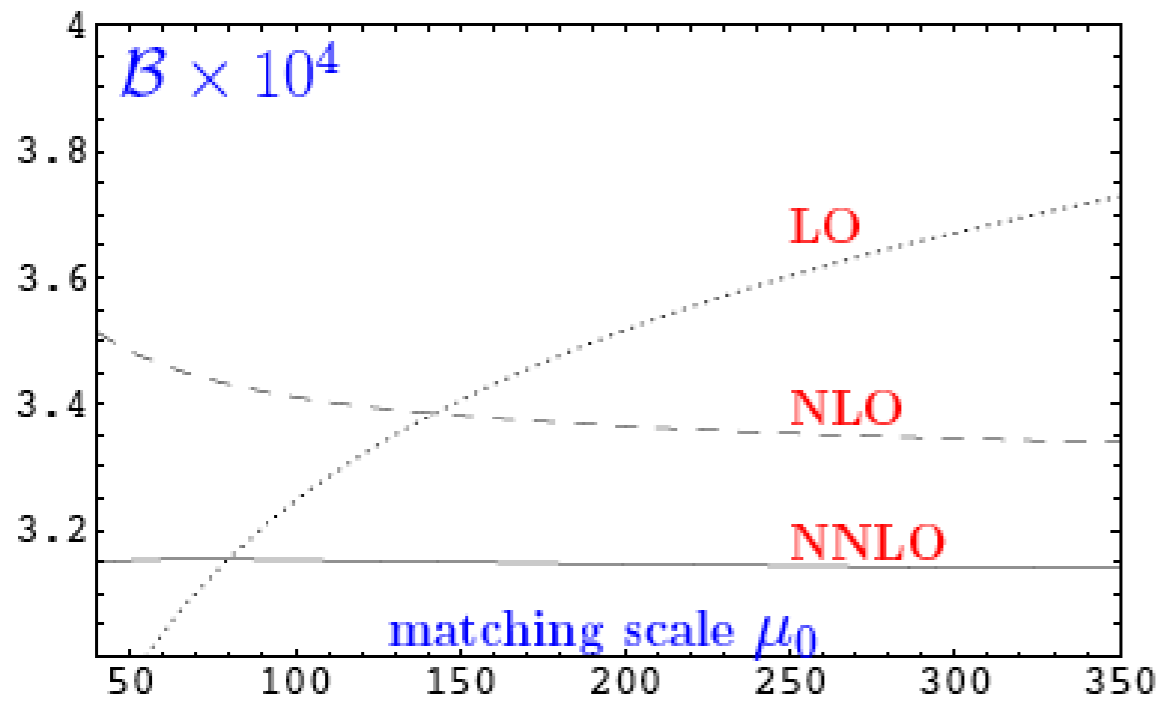
- Multiscale OPE: [Becher, Neubert, hep-ph/0610067](#)

Misiak et al.	$\text{BR}_\gamma(1\text{GeV})$	$\text{BR}_\gamma(1.6\text{GeV})$
hep-ph/0609232 'fixed order'	$3.27 \cdot 10^{-4}$	$(3.15 \pm 0.23) \cdot 10^{-4}$
hep-ph/0610067 multisc. OPE	$3.27 \cdot 10^{-4}$ (adapted from above)	$(2.98 \pm 0.26) \cdot 10^{-4}$

without
-1.5% of $\mathcal{O}(\alpha_s \Lambda/m_b)$
 $3.05 \cdot 10^{-4}$

Applicability of M-OPE questioned by Misiak [arXiv:0808.3134](#)

● Perturbative calculation at NNLL:



“Central” values:

$$\mu_0 = 160 \text{ GeV}$$

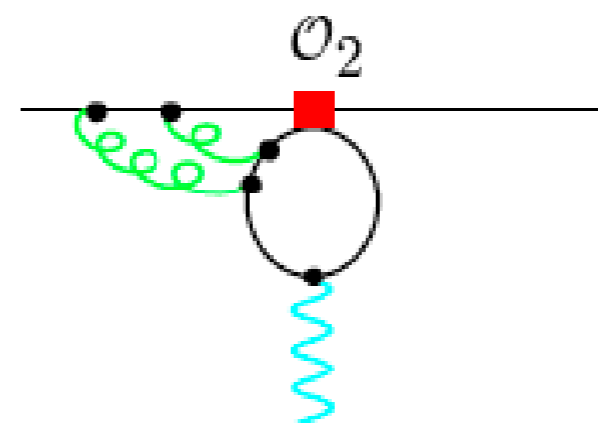
$$\mu_b = 2.5 \text{ GeV}$$

$$\mu_c = 1.5 \text{ GeV}$$

Only the large charm mass renormalization scheme dependence made NNLO calculation really necessary.

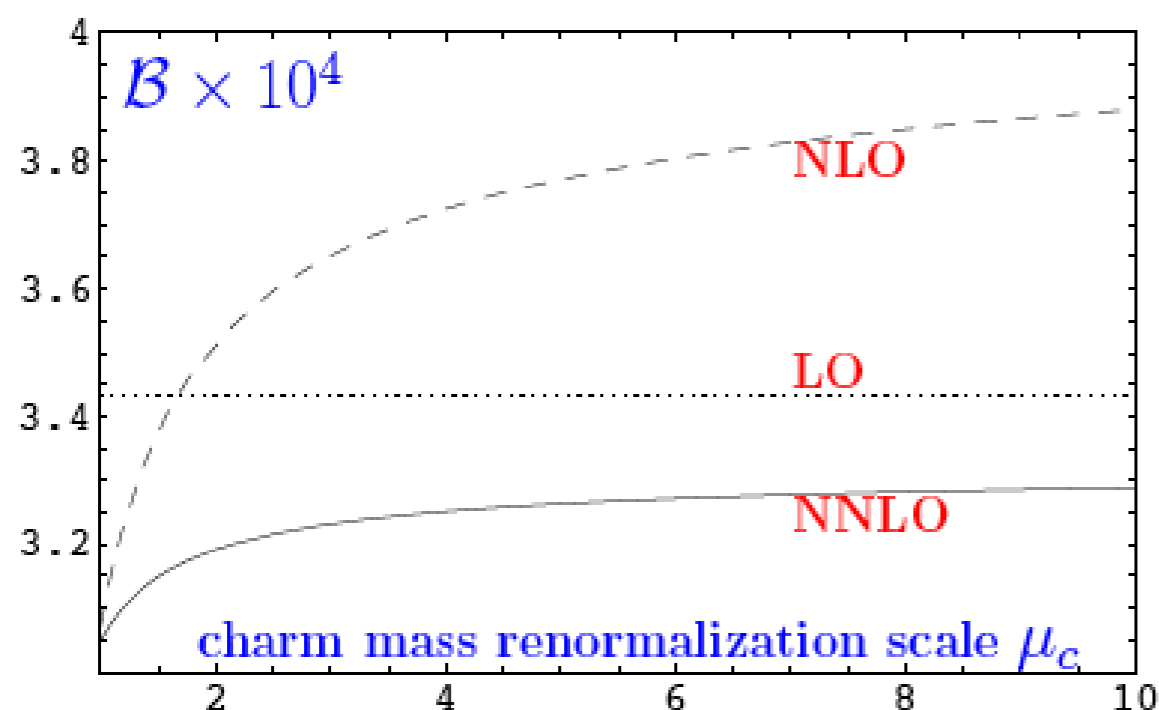
- Perturbative calculation at NNLL:

Matrix elements: $\langle O_2(\mu \simeq m_b) \rangle$



Interpolation between the formal $m_c \gg m_b/2$ limit and the $\alpha_s^2 n_f$ approximation, this part is the main origin of charm dependence \Rightarrow space for improvements

work in progress



“Central” values:

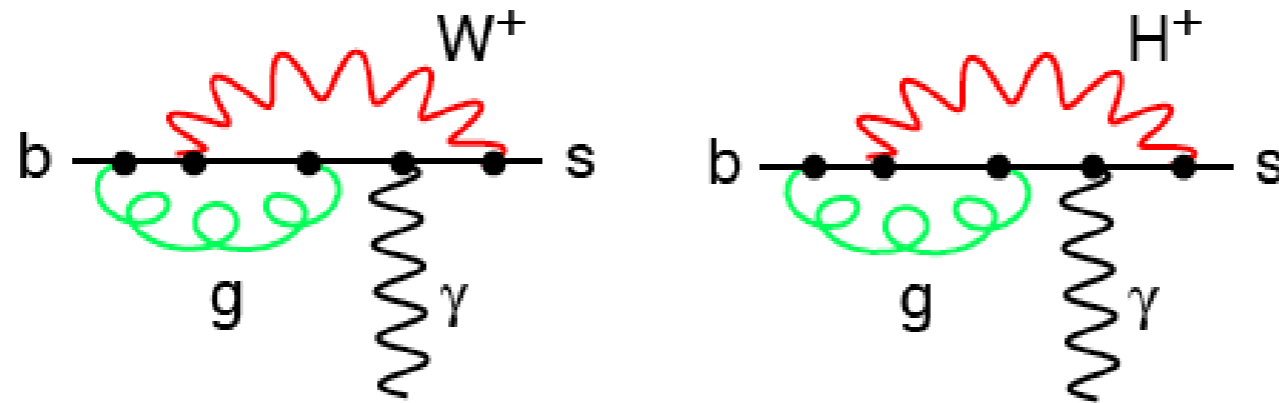
$$\mu_0 = 160 \text{ GeV}$$

$$\mu_b = 2.5 \text{ GeV}$$

$$\mu_c = 1.5 \text{ GeV}$$

Only the large charm mass renormalization scheme dependence made NNLO calculation really necessary.

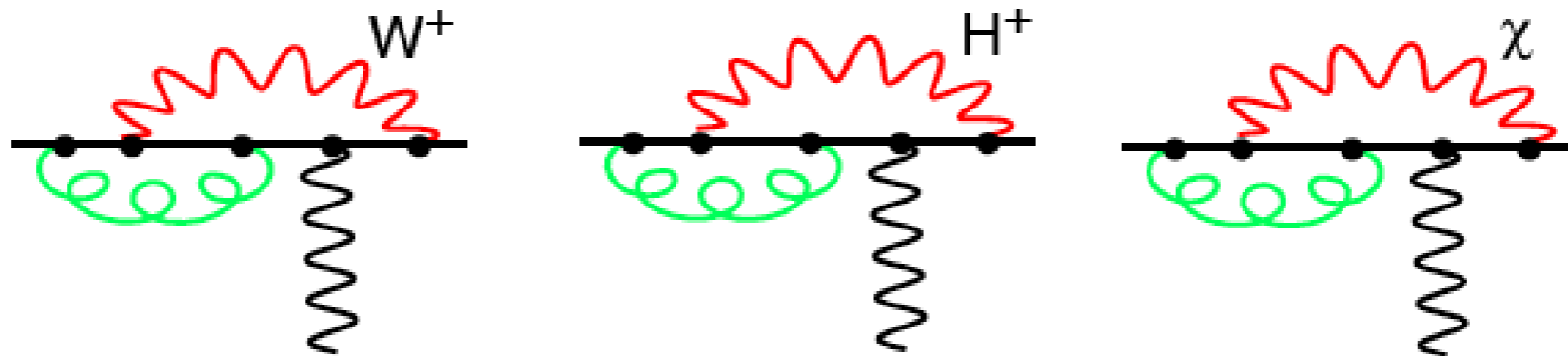
$\bar{B} \rightarrow X_s \gamma$ in the MSSM



$M_{H^+} > 295 \text{ GeV}$
at 95% CL

$$C_{NLL}(M_W) = C_{NLL}^{SM}(M_W) + C_{NLL}^{NEW}(M_W)$$

Charged Higgs contribution always adds to SM one



$$C_{NLL}(M_W) = C_{NLL}^{SM}(M_W) + C_{NLL}^{H^+}(M_W) + C_{NLL}^{\chi}(M_W)$$

Within supersymmetry possible cancellation with chargino contribution

Existing NLL calculations in the MSSM:

NLL analysis in MFV-Supersymmetry

Degrassi, Gambino, Slavich, hep-ph/0602198

NLL in general supersymmetry (uMSSM)

New sources of flavour violation via squark mixing

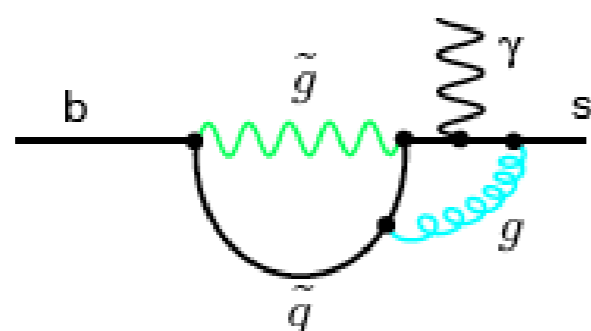
Complete NLL

$W g$ $H^+ g$ $\chi^+ g$ $\chi^0 g$ $\tilde{g} g$

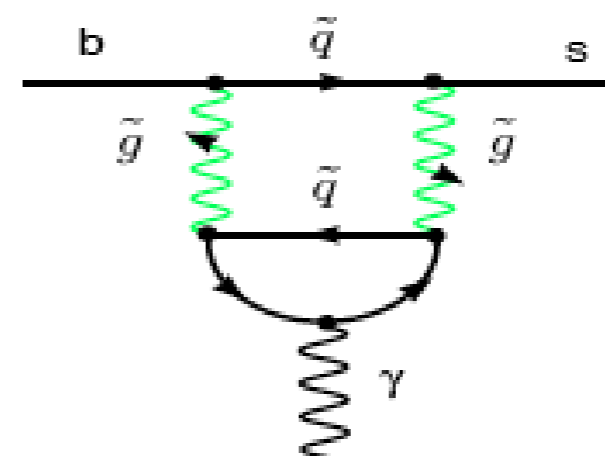
Bobeth, Misiak, Urban hep-ph/9904413

$W \tilde{g}$ $H^+ \tilde{g}$ $\chi^+ \tilde{g}$ $\chi^0 \tilde{g}$ $\tilde{g} \tilde{g}$

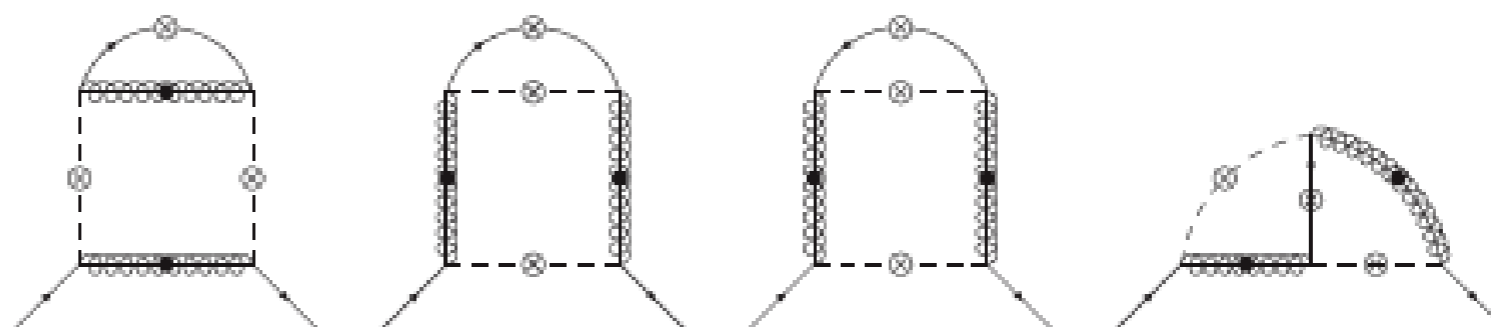
Gluonic Parts ($\tilde{g} g$)



Two-Gluino Parts ($\tilde{g} \tilde{g}$)



Greub, Hurth, Pilipp, Schupbach, Steinhauser arXiv:1105.1330 [hep-ph]



Gluino contribution dominant due to strong coupling

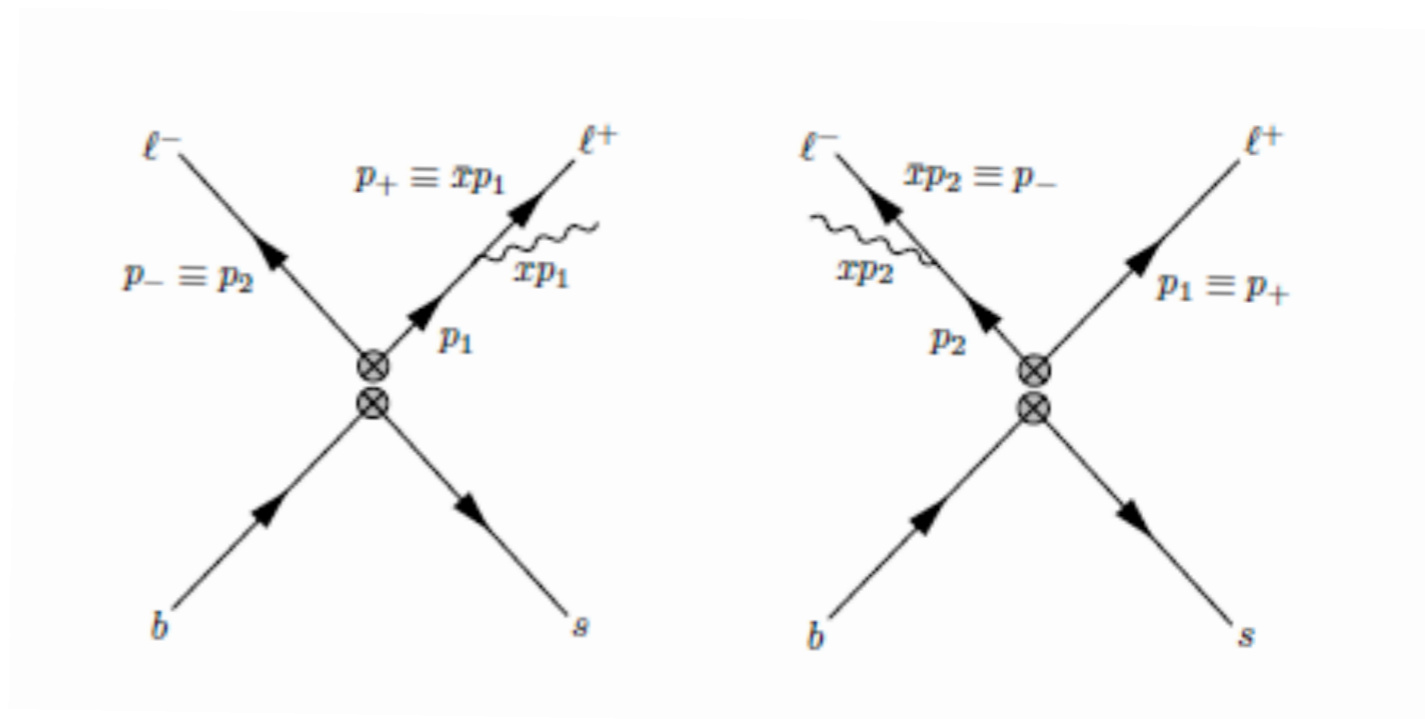
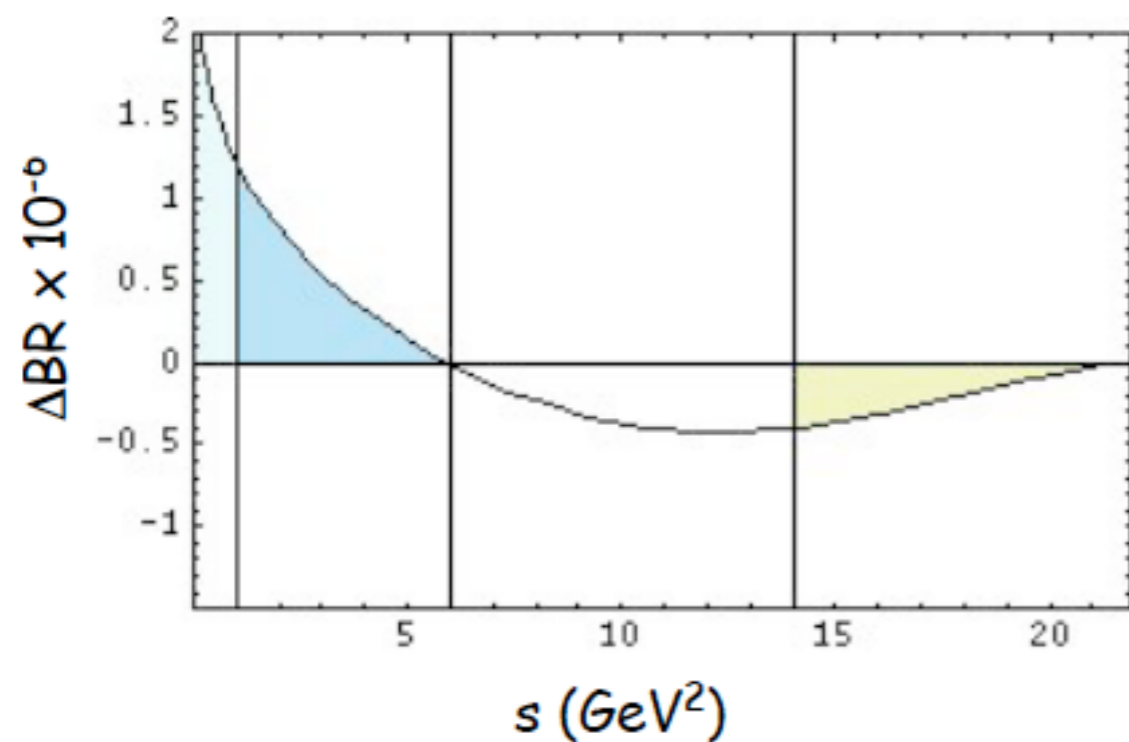
Latest improvements of inclusive $\bar{B} \rightarrow X_s \ell^+ \ell^-$

Beyond existing NNLL QCD precision electromagnetic corrections

were calculated: Huber, Hurth, Lunghi, Nucl. Phys. B802(2008)40 and work in progress

Corrections to matrix elements lead to large collinear $\text{Log}(m_b/m_\ell)$

$$\delta\text{BR}(B \rightarrow X_s \mu^+ \mu^-) = \begin{cases} (+2.0\%) & \text{low } q^2 \\ (-6.8\%) & \text{high } q^2 \end{cases} \quad \delta\text{BR}(B \rightarrow X_s e^+ e^-) = \begin{cases} (+5.2\%) & \text{low } q^2 \\ (-17.6\%) & \text{high } q^2 \end{cases}$$

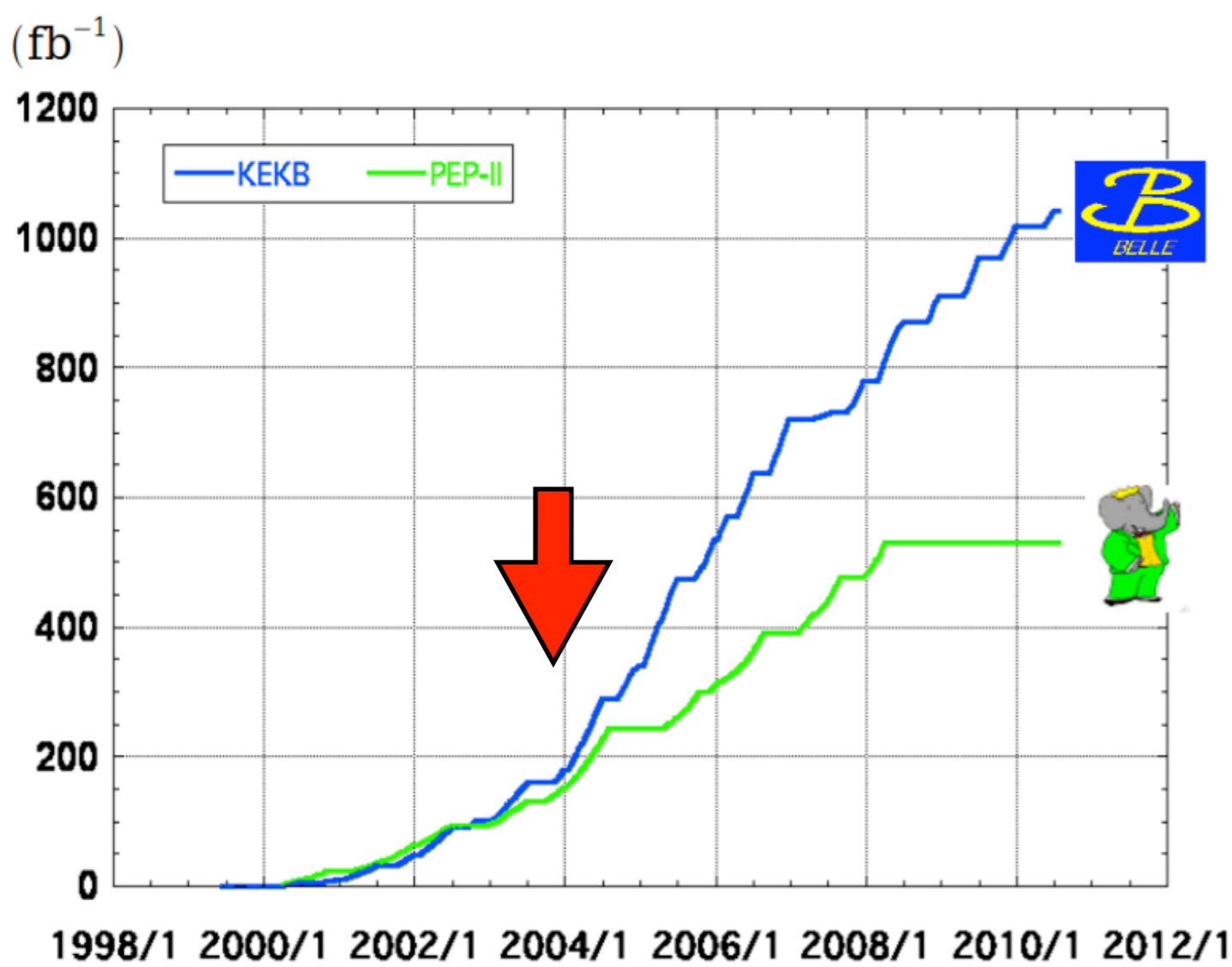


'Latest' Babar and Belle measurements of inclusive $\mathcal{B}(b \rightarrow sll)$

Belle hep-ex/0503044 (!!!) (based $152 \times 10^6 B\bar{B}$ events)

Babar hep-ex/0404006 (!!!) (based $89 \times 10^6 B\bar{B}$ events)

Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
 $Y(5S): 121 \text{ fb}^{-1}$
 $Y(4S): 711 \text{ fb}^{-1}$
 $Y(3S): 3 \text{ fb}^{-1}$
 $Y(2S): 25 \text{ fb}^{-1}$
 $Y(1S): 6 \text{ fb}^{-1}$
Off reson./scan:
 $\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$
On resonance:
 $Y(4S): 433 \text{ fb}^{-1}$
 $Y(3S): 30 \text{ fb}^{-1}$
 $Y(2S): 14 \text{ fb}^{-1}$
Off resonance:
 $\sim 54 \text{ fb}^{-1}$

Future measurements: Super-flavour factories in Italy and Japan

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

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

Naive approach:

Parametrize the hadronic matrix elements in terms of form factors

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

QCD-improved factorization: BBNS 1999

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

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

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

- 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

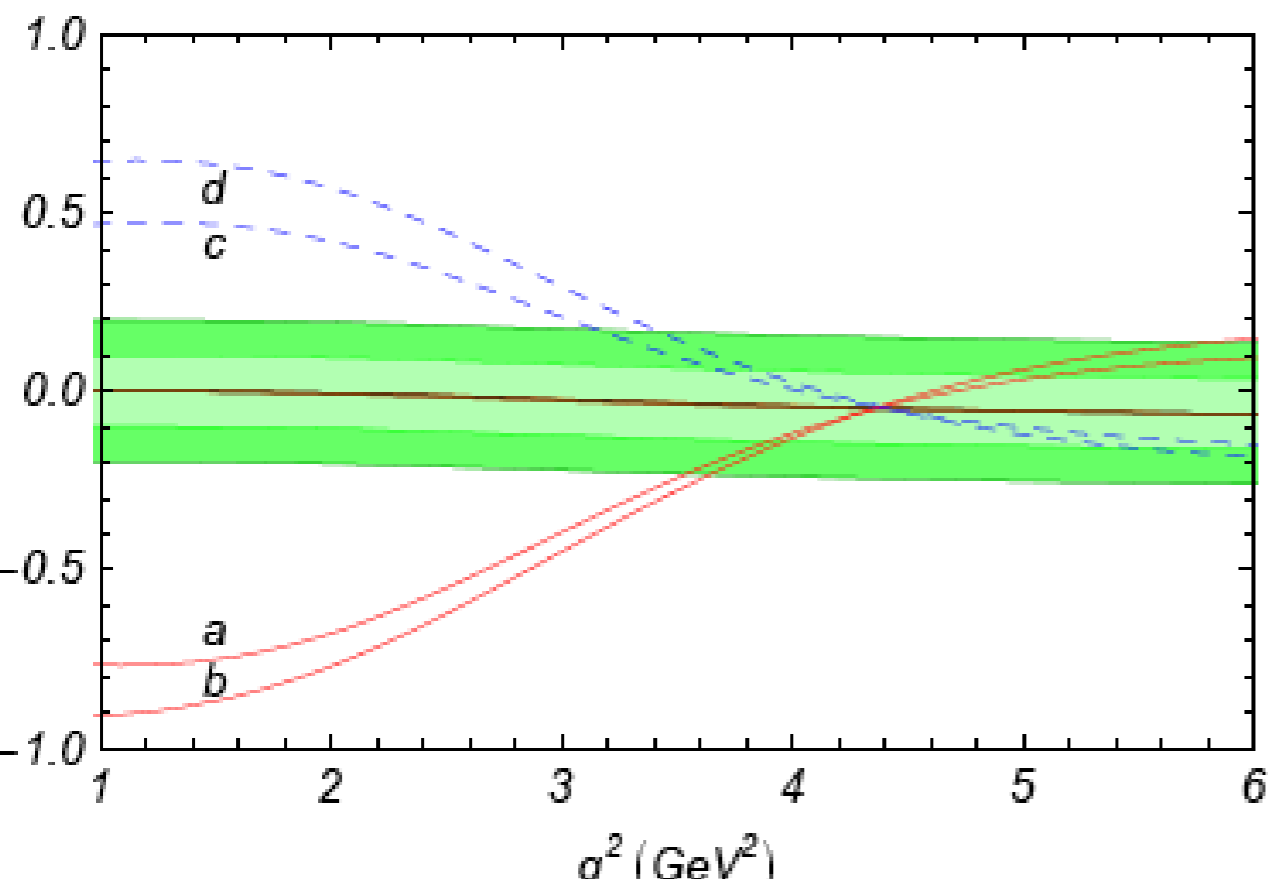
Egede, Hurth, Matias, Ramon, Reece, arXiv:0807.2589, arXiv:1005.0571

see also Altmannshofer et al., arXiv:0811.1214; Bobeth et al., arXiv:0805.2525

Careful design of theoretically clean angular observables in $B \rightarrow K^* \ell^+ \ell^-$

Egede, Hurth, Matias, Ramon, Reece, arXiv:0807.2589, arXiv:1005.0571

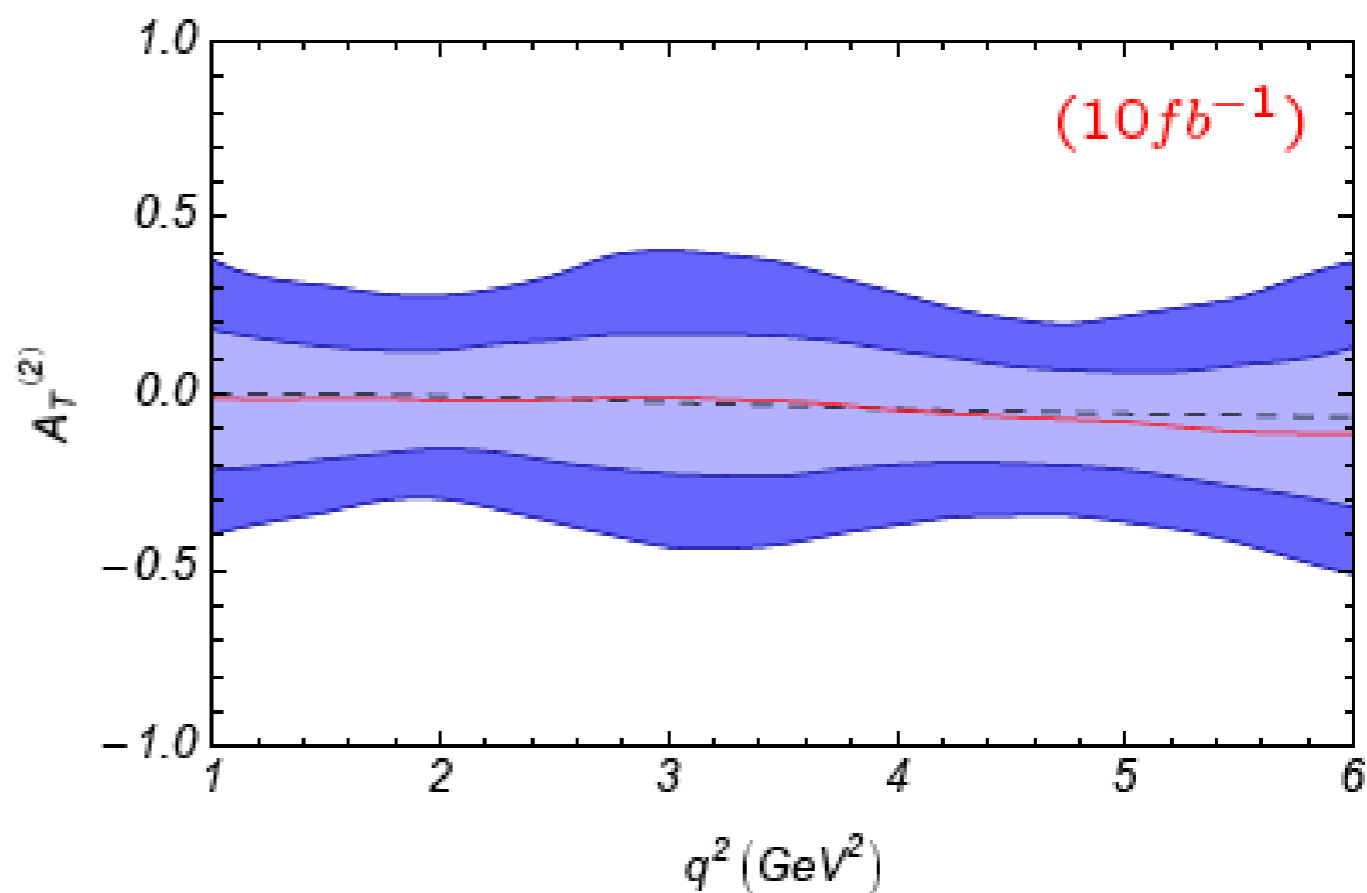
$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$



Theoretical sensitivity

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

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



Experimental sensitivity

light green 1 σ

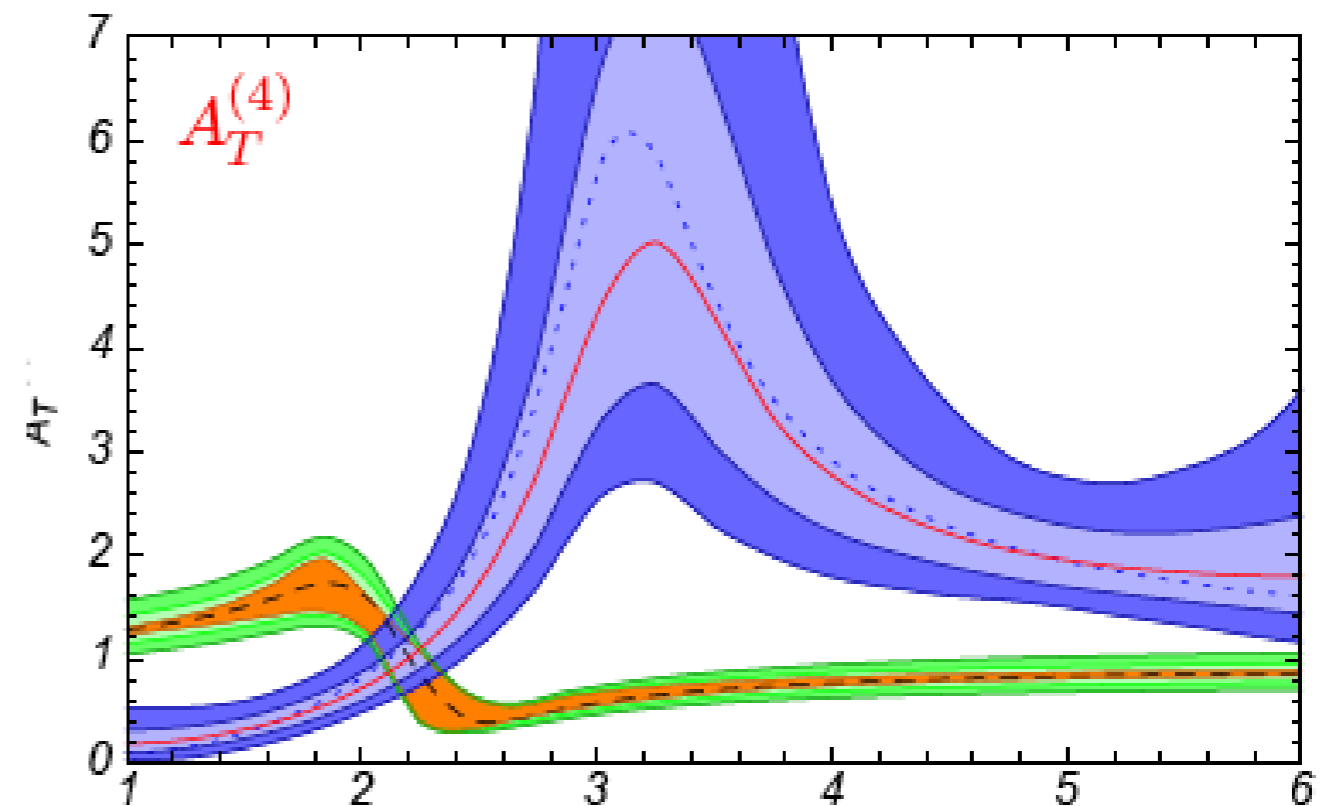
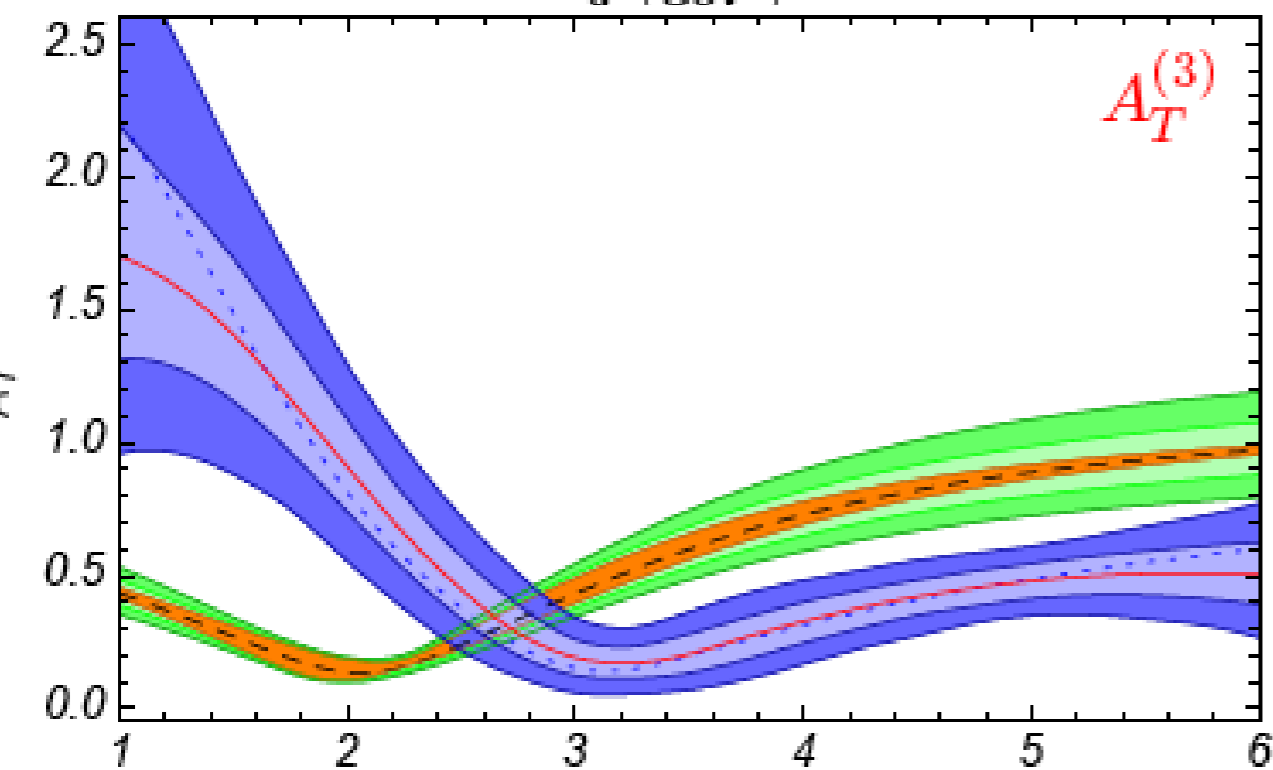
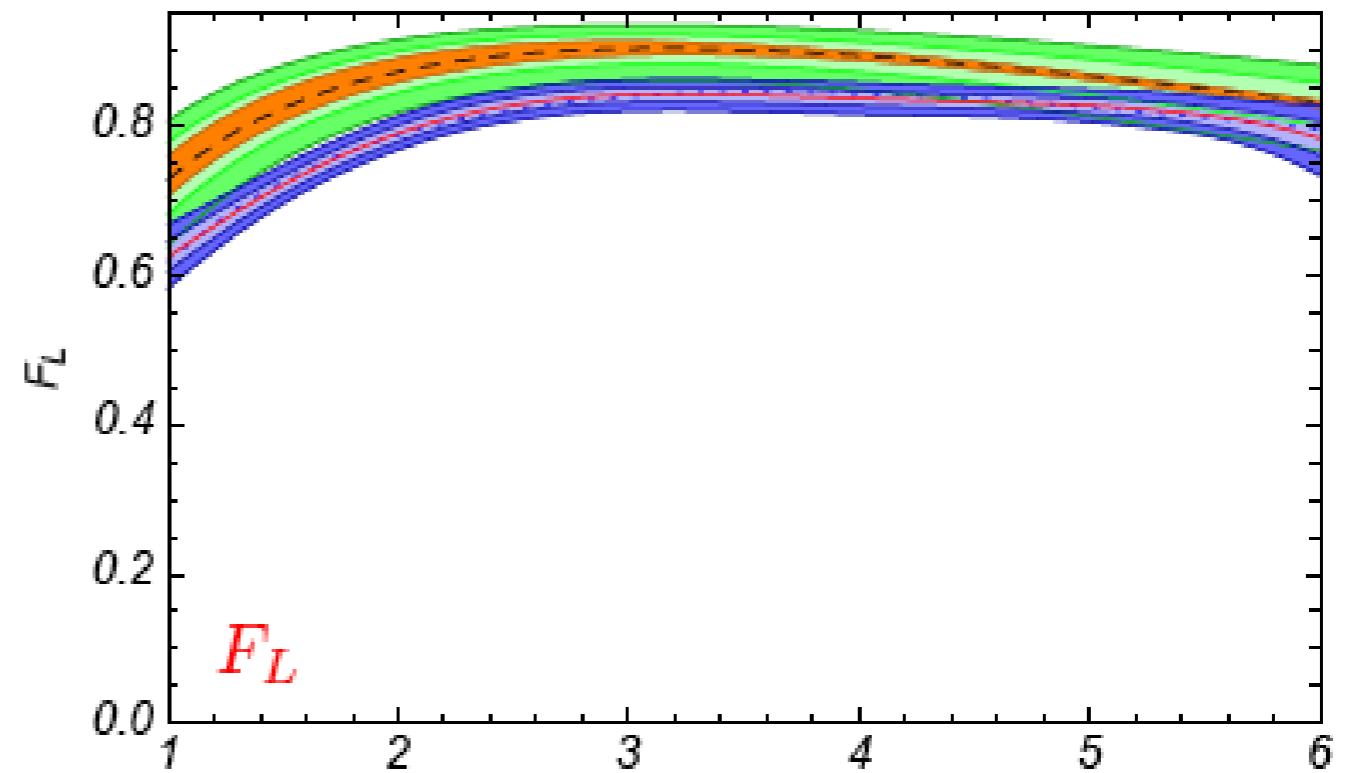
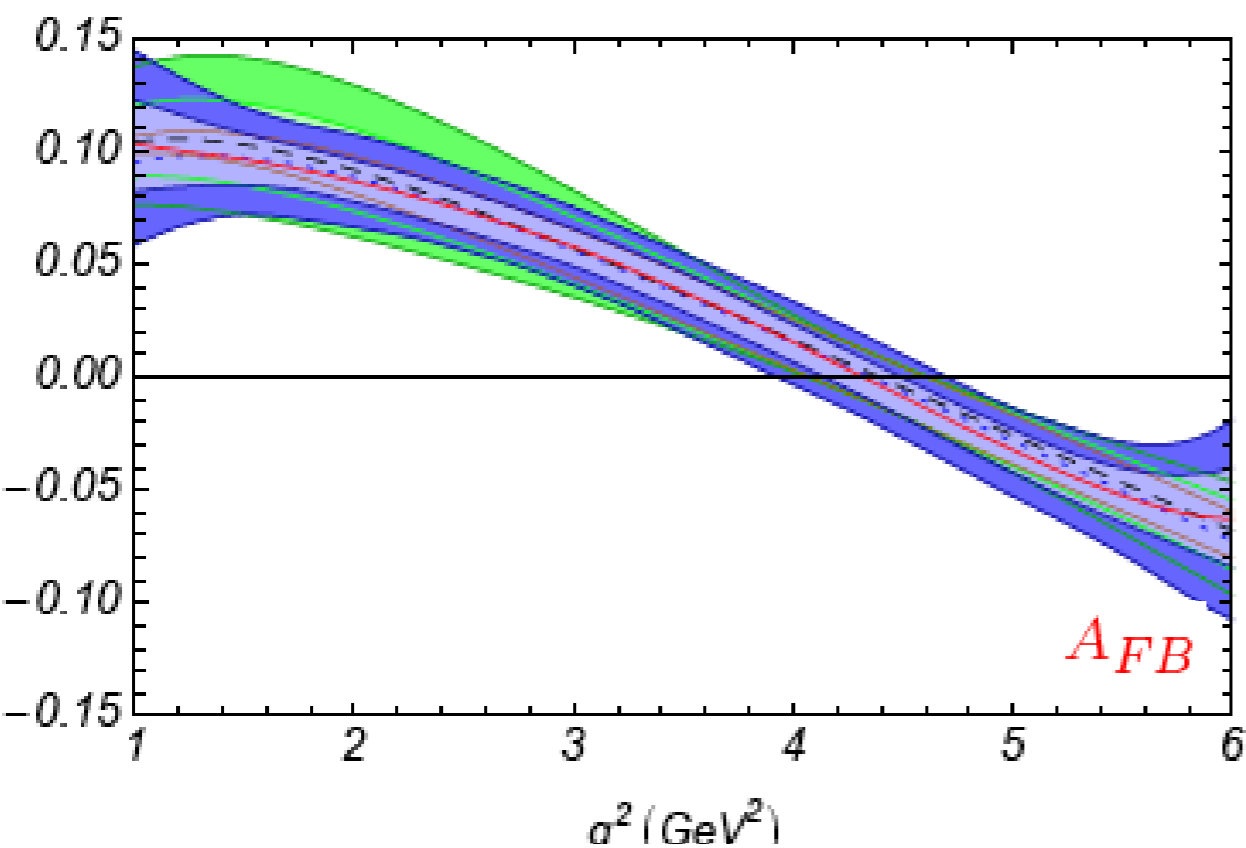
dark green 2 σ

SuperLHCb/SuperB can offer more precision

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

Comparison of new physics reach of old and new observables

Egede, Hurth, Matias, Ramon, Reece, arXiv:0807.2589, arXiv:1005.0571



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

New developments of angular $B \rightarrow K^* \ell^+ \ell^-$ observables defined in the high- q^2 region

Grinstein, Pirjol hep-ph/0404250, Beylich, Buchalla, Feldmann arXiv:1101.5118

Bobeth, Hiller, van Dyk arXiv:1006.5013, 1105.0376

local operator product expansion is applicable ($q^2 \sim m_b^2$)

the leading power corrections are shown to be suppressed by $(\Lambda/m_b)^2$ or $\alpha_s \Lambda/m_b$

Magnitude of Λ/m_b can be estimated due to existence of an OPE/HQET

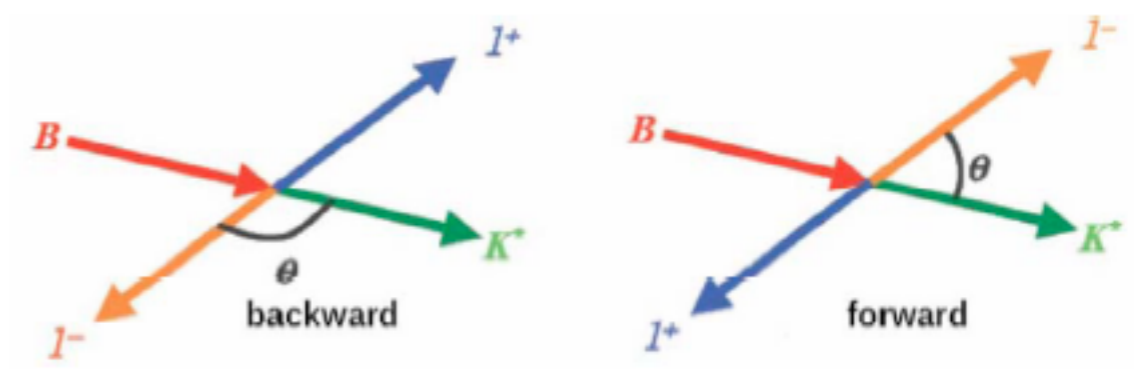
Formfactors at high- q^2 : extrapolation, future unquenched lattice results

The theoretical treatment in the low- and high- q^2 based on different theoretical concepts.

⇒ the consistency of the consequences out of the two sets of measurements will allow for an important crosscheck.

Measurements of forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

$$A_{FB} \left(s = m_{\mu^+ \mu^-}^2 \right) = \frac{N_F - N_B}{N_F + N_B}$$



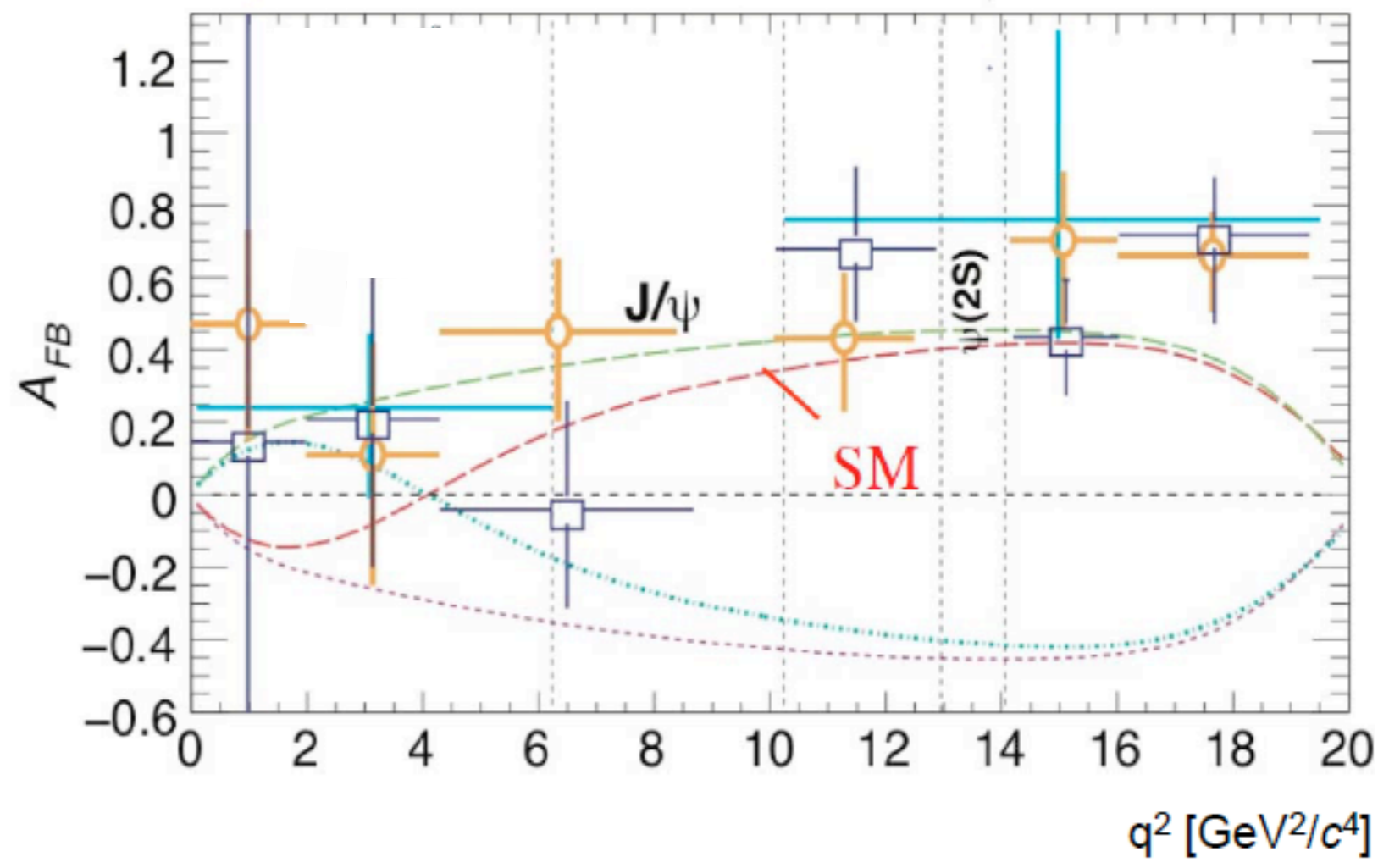
250 $K^* I^+ I^-$
80% of data



100 $K^* I^+ I^-$
75% of data

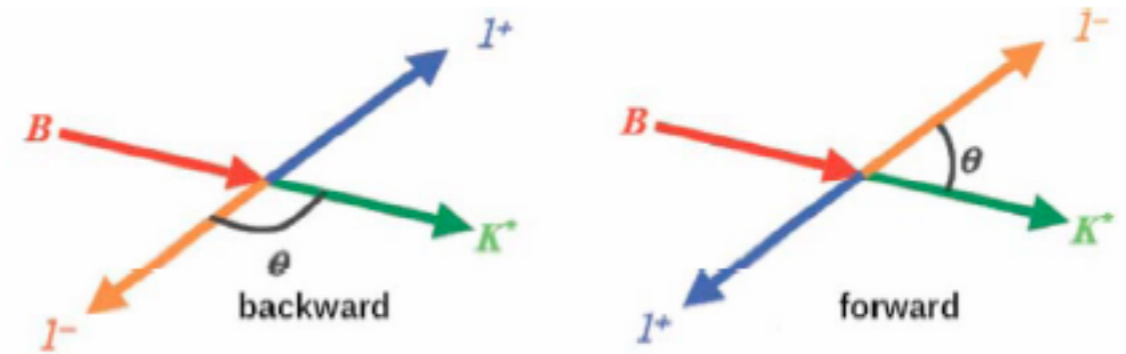


100 $K^* \mu^+ \mu^-$
4.4 fb^{-1}



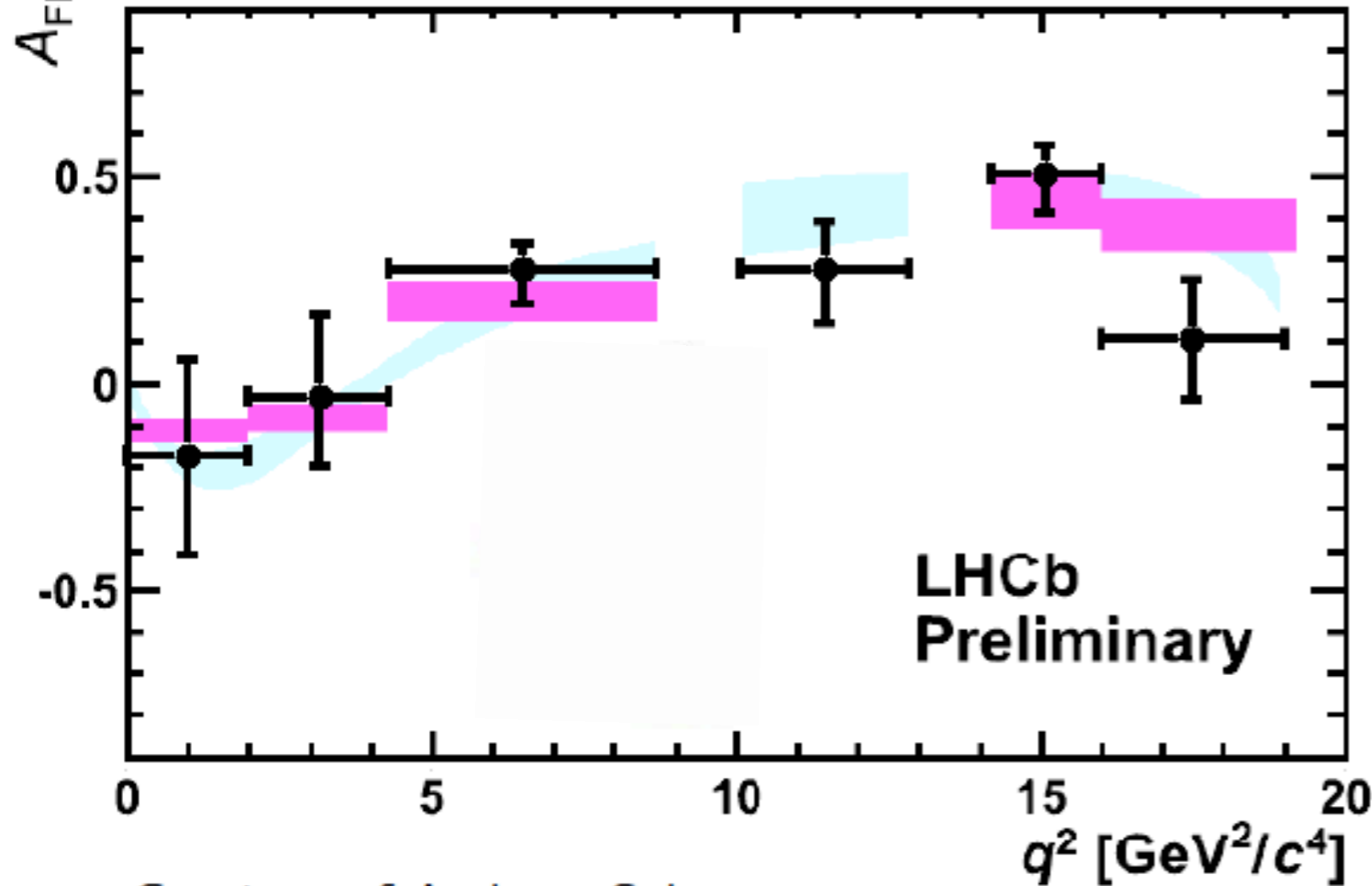
Measurements of forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

$$A_{FB}(s = m_{\mu^+ \mu^-}^2) = \frac{N_F - N_B}{N_F + N_B}$$



■ Theory
 ■ Binned theory [LHCb-CONF-2011-038]

● LHCb



Courtesy of Andreas Schopper

Excellent agreement with SM at current level of precision.

However:

Many more angular observables in $B \rightarrow K^* \mu \mu$ to be measured, more sensitive to NP than AFB. New flavour structures needed !

Minimal flavour violation hypothesis

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

Hall, Randall, Phys. Rev. Lett. 65(1990)2939

MFV at work

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

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

- If additional Higgs-doublets are added, then another spurion combination is numerically important:

$$(Y_D Y_D^\dagger)_{ij} \approx 2m_b^2 \tan^2 \beta / v^2 \Delta_{ij}, \quad \Delta = \text{diag}(0, 0, 1)$$

Thus, MFV allows for large- $\tan \beta$ effects in particular in helicity-suppressed observables $B \rightarrow \mu\mu$ and $B \rightarrow \tau\nu$.

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

More details:

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

is broken by the Yukawa couplings only as in the SM $Y_D (3, 1, \bar{3}); Y_U (3, \bar{3}, 1)$

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

$$\overline{Q}_L(\bar{3}, 1, 1), D_R(1, 1, 3), U_R(1, 3, 1) \Rightarrow \mathcal{L}(1, 1, 1)$$

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

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

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 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**

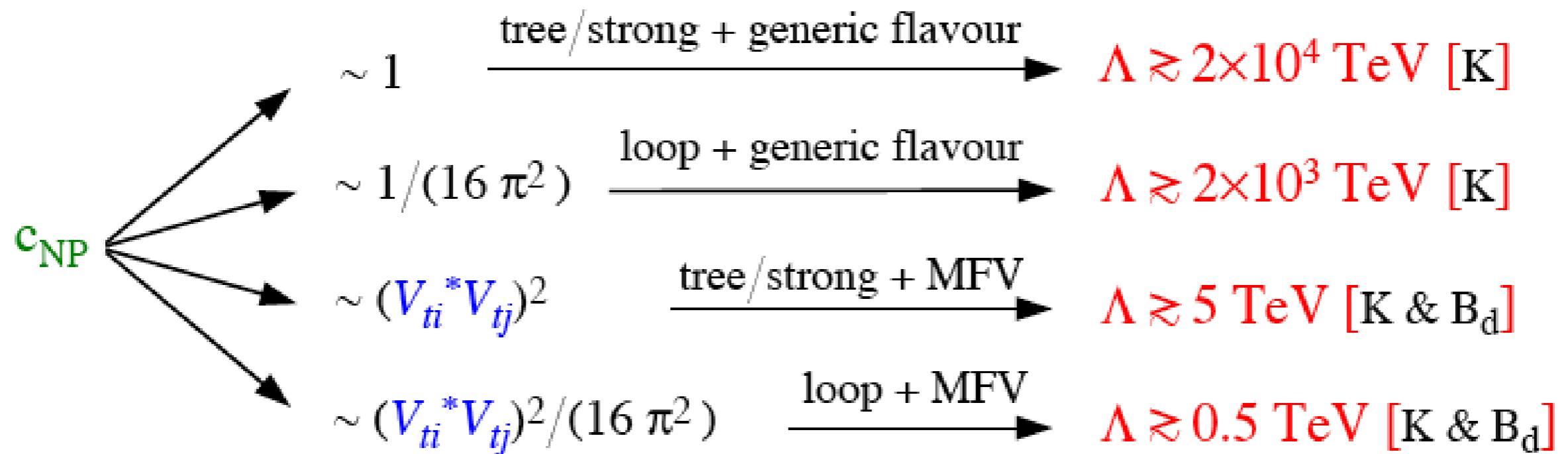
$\Delta F = 2$	UTfit, arXiv:0707.0636	$\Delta F = 1$	H., Isidori, Kamenik, Mescia, arXiv:0807.5039
Update	CKM-fitter, arXiv: 1203.0238		H., Mahmoudi, work in progress

- **The MFV hypothesis is far from being verified**
 New spurions allowed: Next-to-MFV

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

MFV is NOT a theory of flavour

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](#)
- Warped extra dimensions [Weiler et al., arXiv:0709.1714](#)

CP-problem of NP (44 NP phases in MSSM)

- Add flavourblind phases in MFV \rightarrow EDM constraints!
- CP violation in Susy with effective MFV

Barbieri et al. arXiv:1011.0730, 1102.0726

- MFV ansatz RG-invariant by construction

$$m_Q^2 = \alpha_1 \mathbb{1} + \beta_1 Y_u^\dagger Y_u + \beta_2 Y_d^\dagger Y_d + \beta_3 Y_d^\dagger Y_d Y_u^\dagger Y_u + \beta_3 Y_u^\dagger Y_u Y_d^\dagger Y_d ,$$

$$m_u^2 = \alpha_2 \mathbb{1} + \beta_5 Y_u Y_u^\dagger ,$$

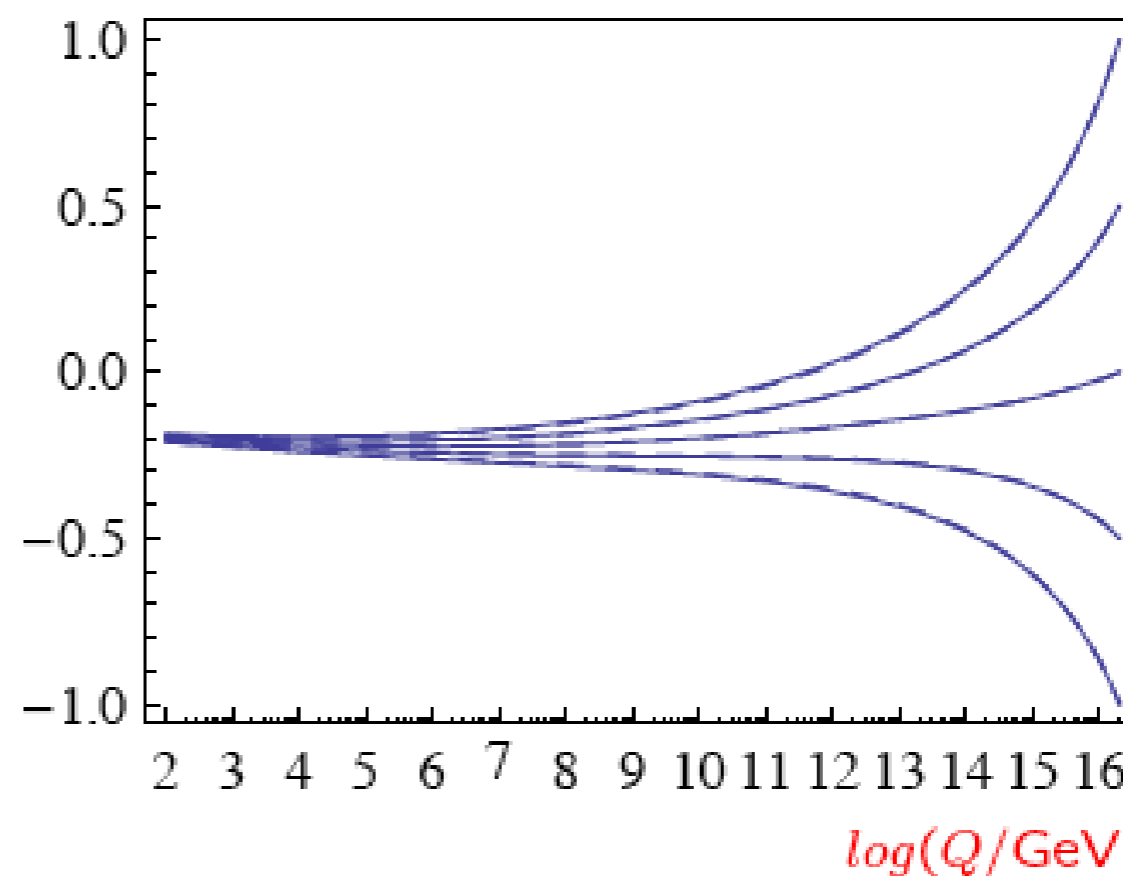
$$m_d^2 = \alpha_3 \mathbb{1} + \beta_6 Y_d Y_d^\dagger ,$$

$$A_u = \alpha_4 Y_u + \beta_7 Y_u Y_d^\dagger Y_d ,$$

$$A_d = \alpha_5 Y_d + \beta_8 Y_d Y_u^\dagger Y_u ,$$

$$A_e = \alpha_e Y_e .$$

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



'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

See also:

MFV SUSY, a natural theory for R-parity violation

Csaki,Grossman,Heidenreich arXiv:1111.1239

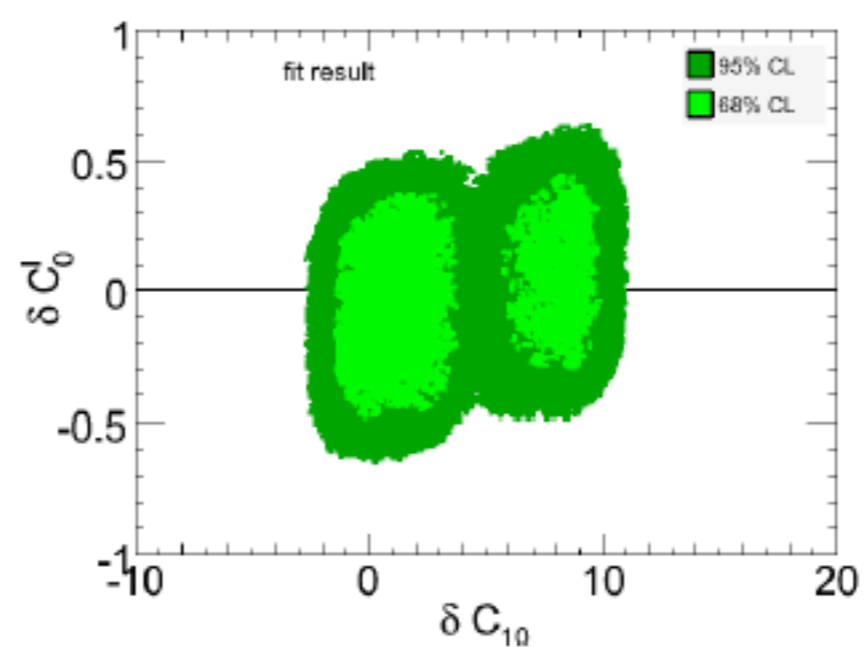
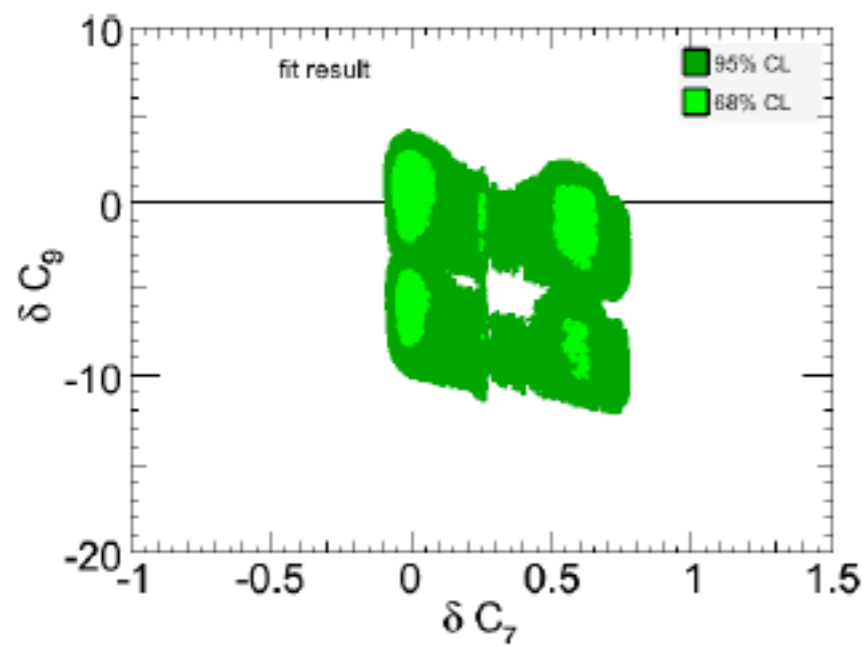
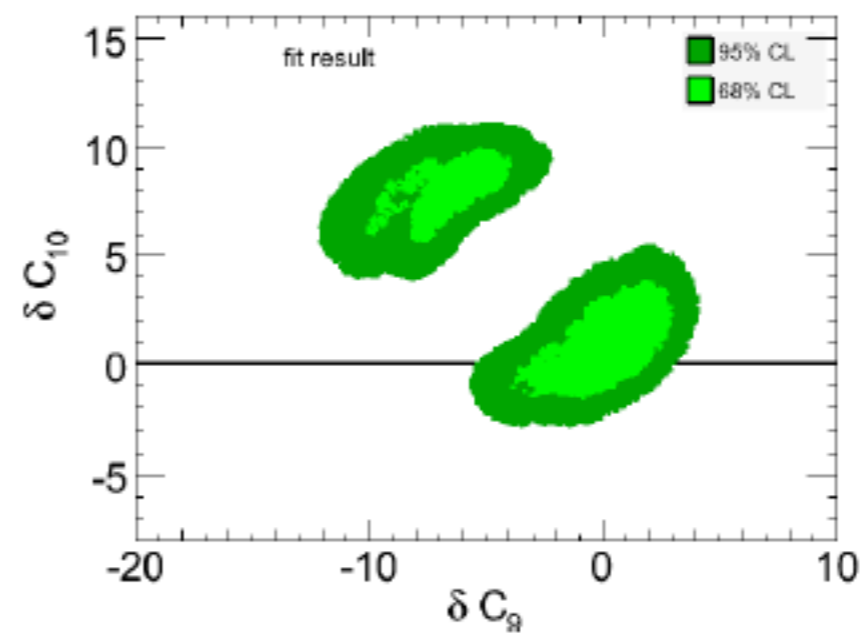
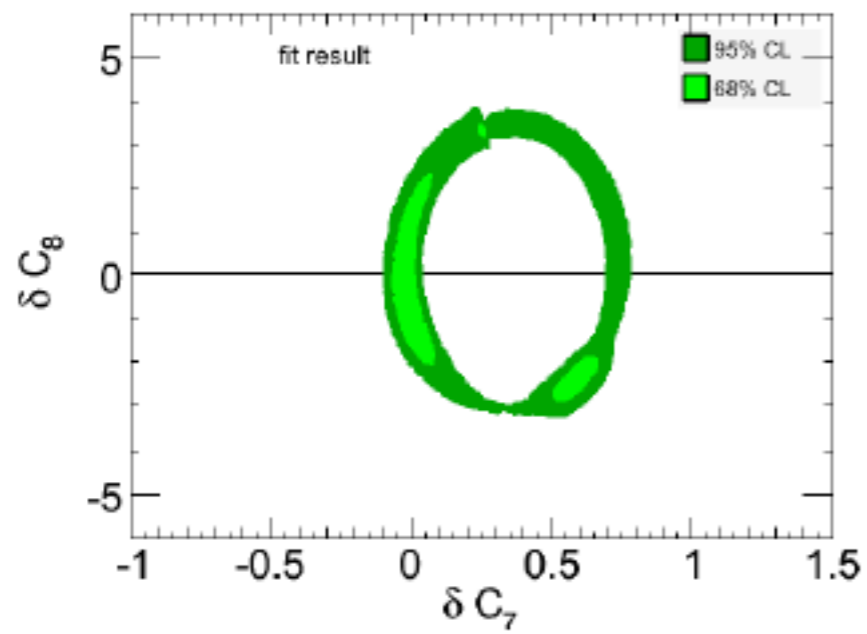
Relevant MFV Operators ($b \rightarrow s$): $\mathcal{O}_7, \mathcal{O}_8, \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_S = (\bar{s}P_R b)(\bar{\mu}P_L \mu)$

$$C_i(\mu) = C_i^{\text{SM}}(\mu) + \delta C_i$$

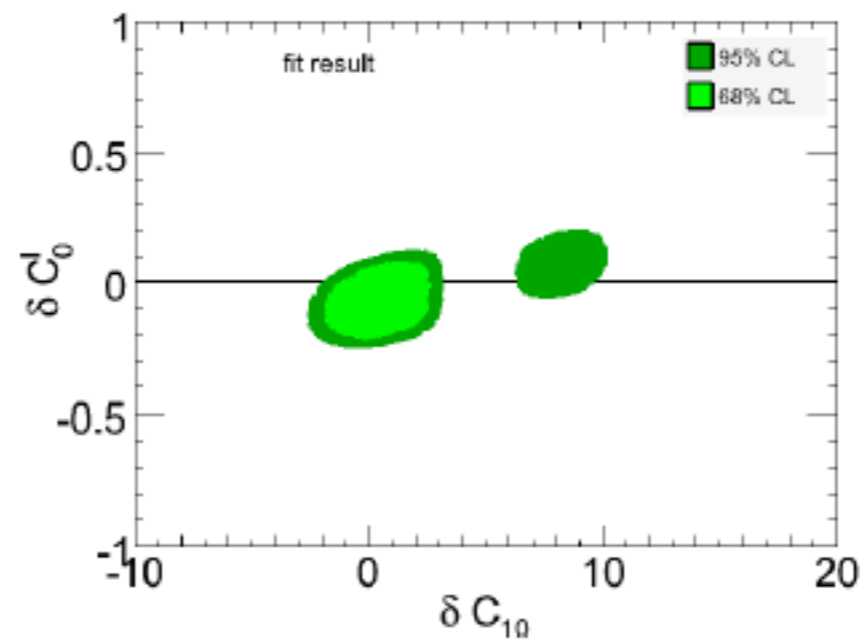
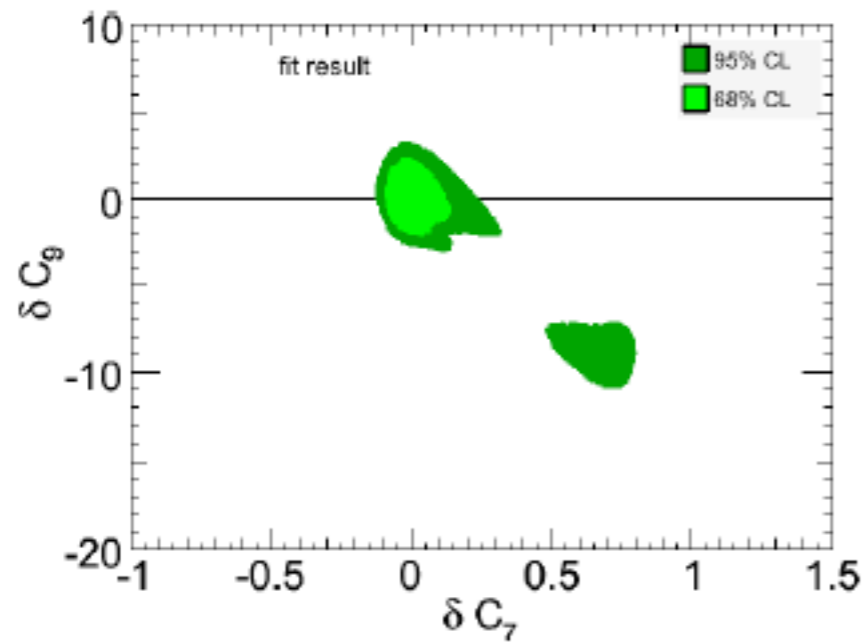
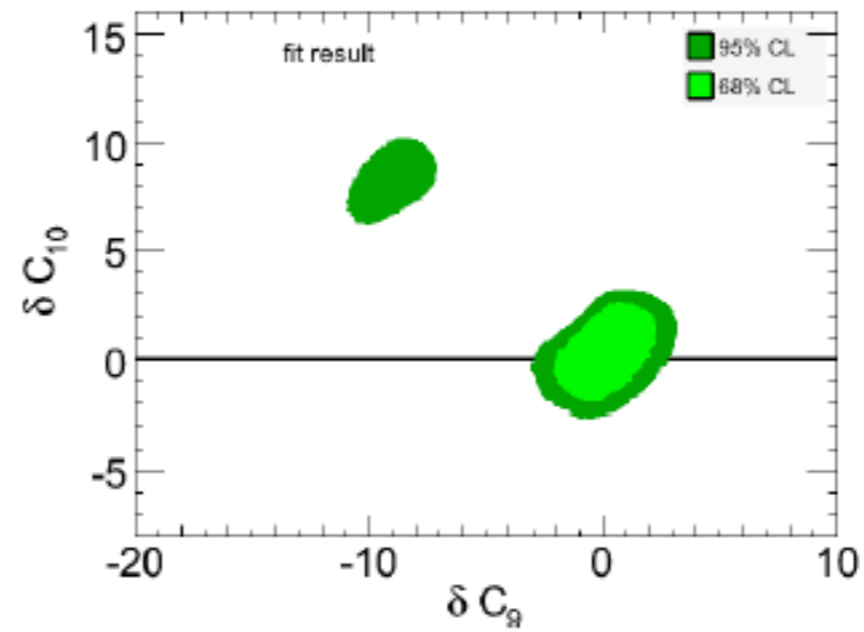
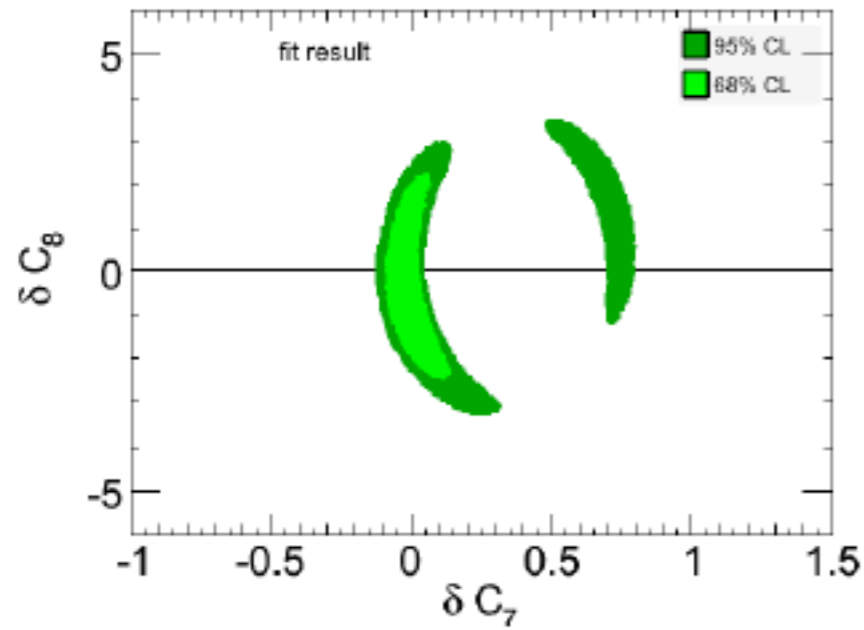
Observables

Observable	Experiment	SM prediction
$\text{BR}(B \rightarrow X_s \gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ [14]	$(3.08 \pm 0.24) \times 10^{-4}$
$\Delta_0(B \rightarrow X_s \gamma)$	$(5.2 \pm 2.6 \pm 0.09) \times 10^{-2}$ [14]	$(8.0 \pm 3.9) \times 10^{-2}$
$\text{BR}(B \rightarrow X_d \gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$ [15, 16]	$(1.49 \pm 0.30) \times 10^{-5}$
$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$	$< 4.5 \times 10^{-9}$ [17]	$(3.53 \pm 0.38) \times 10^{-9}$
$\langle d\text{BR}/dq^2(B \rightarrow K^* \mu^+ \mu^-) \rangle_{q^2 \in [1,6]\text{GeV}^2}$	$(0.42 \pm 0.04 \pm 0.04) \times 10^{-7}$ [18]	$(0.47 \pm 0.27) \times 10^{-7}$
$\langle d\text{BR}/dq^2(B \rightarrow K^* \mu^+ \mu^-) \rangle_{q^2 \in [14.18,16]\text{GeV}^2}$	$(0.59 \pm 0.07 \pm 0.04) \times 10^{-7}$ [18]	$(0.71 \pm 0.18) \times 10^{-7}$
$\langle A_{FB}(B \rightarrow K^* \mu^+ \mu^-) \rangle_{q^2 \in [1,6]\text{GeV}^2}$	$-0.18 \pm 0.06 \pm 0.02$ [18]	-0.06 ± 0.05
$\langle A_{FB}(B \rightarrow K^* \mu^+ \mu^-) \rangle_{q^2 \in [14.18,16]\text{GeV}^2}$	$0.49 \pm 0.06 \pm 0.05$ [18]	0.44 ± 0.10
$q_0^2(A_{FB}(B \rightarrow K^* \mu^+ \mu^-))$	$4.9_{-1.3}^{+1.1} \text{ GeV}^2$ [18]	$4.26 \pm 0.34 \text{ GeV}^2$
$\langle F_L(B \rightarrow K^* \mu^+ \mu^-) \rangle_{q^2 \in [1,6]\text{GeV}^2}$	$0.66 \pm 0.06 \pm 0.04$ [18]	0.71 ± 0.13
$\text{BR}(B \rightarrow X_s \mu^+ \mu^-)_{q^2 \in [1,6]\text{GeV}^2}$	$(1.60 \pm 0.68) \times 10^{-6}$ [19, 20]	$(1.78 \pm 0.16) \times 10^{-6}$
$\text{BR}(B \rightarrow X_s \mu^+ \mu^-)_{q^2 > 14.4\text{GeV}^2}$	$(4.18 \pm 1.35) \times 10^{-7}$ [19, 20]	$(2.18 \pm 0.65) \times 10^{-7}$

Global MFV fit before LHCb



Global MFV with LHCb data



Test of MFV hypothesis:

Some positive and negative predictions

$$\text{BR}(B_d \rightarrow \mu^+ \mu^-) < 0.32 \times 10^{-9}$$

$$\text{Current LHCb limit: } \text{BR}(B_d \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-9}$$

$B \rightarrow K^* \mu^+ \mu^-$ transverse asymmetries:

- $A_T^{(2)} \in [-0.068, -0.02]$
- $A_T^{(3)} \in [0.35, 1.00]$
- $A_T^{(4)} \in [0.18, 1.30]$
- $A_T^{(5)} \in [0.15, 0.49]$

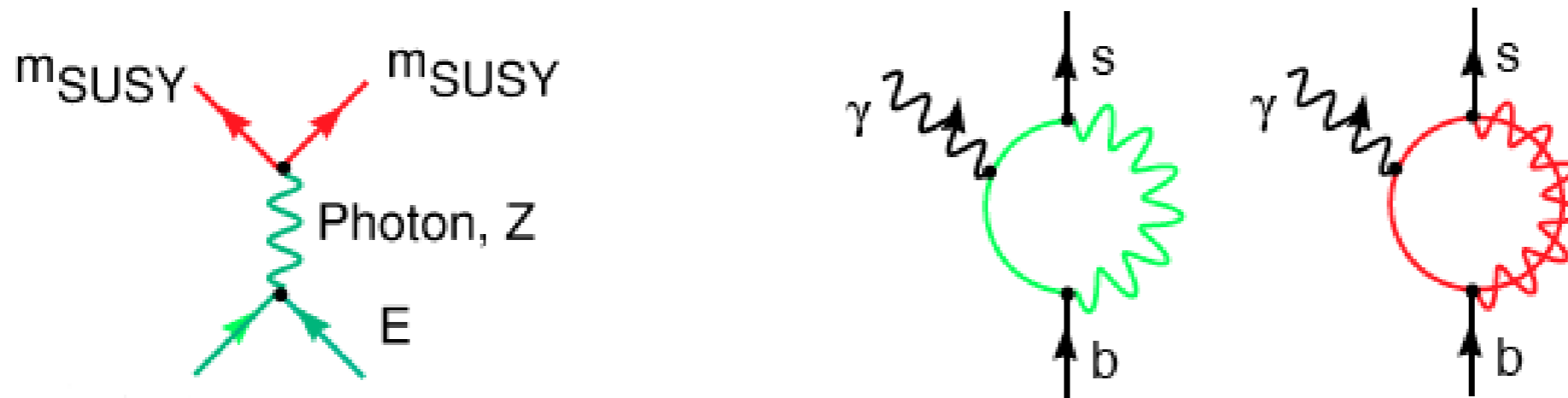
If there is MFV, LHCb will not measure any NP in A_i^T observables

$B \rightarrow X_d \gamma$ measurement already within the MFV region

Another MFV correlation: $B \rightarrow X_s \nu \bar{\nu}$ versus $K \rightarrow \pi \nu \bar{\nu}$

Flavour@high- p_T interplay

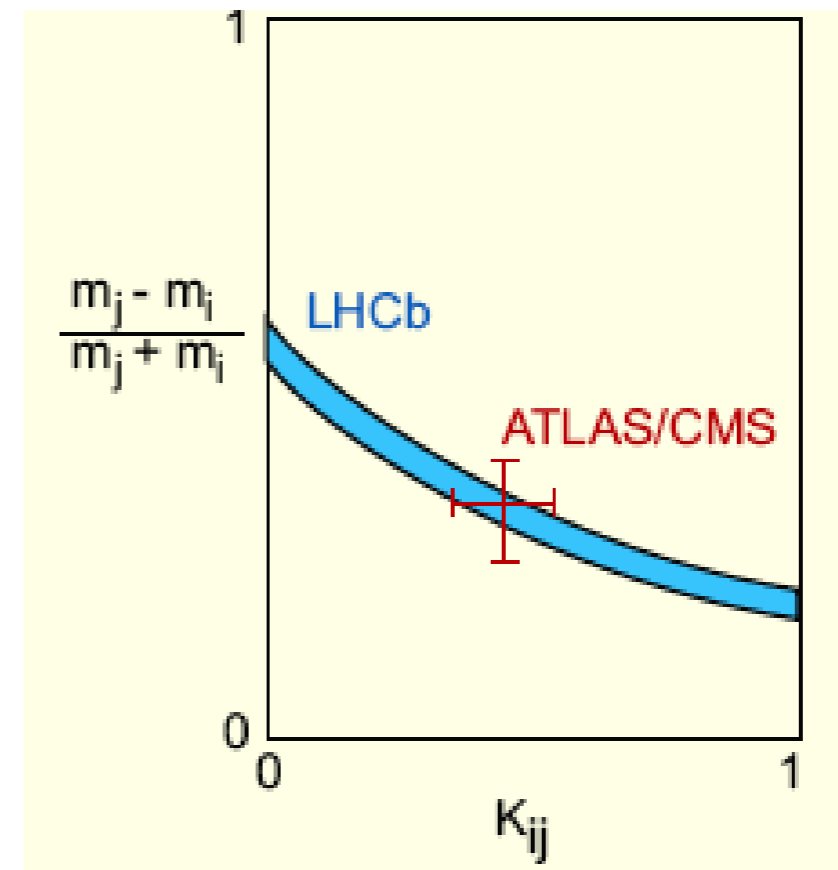
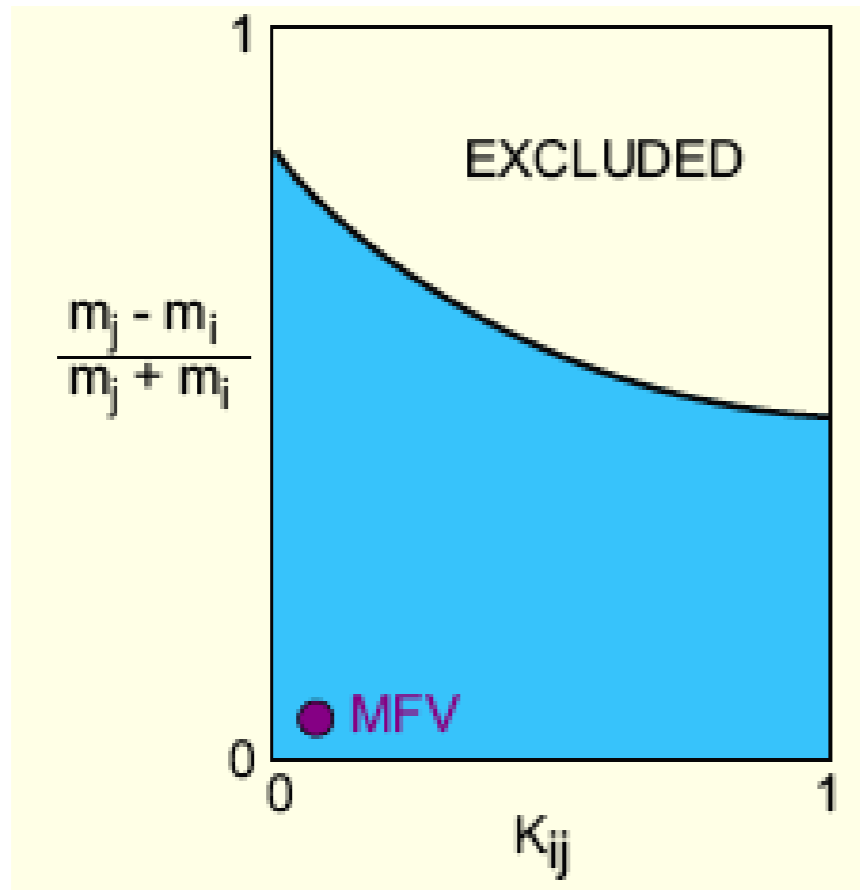
Immense potential for synergy and complementarity between high- p_T and flavour physics within the search for new physics



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.

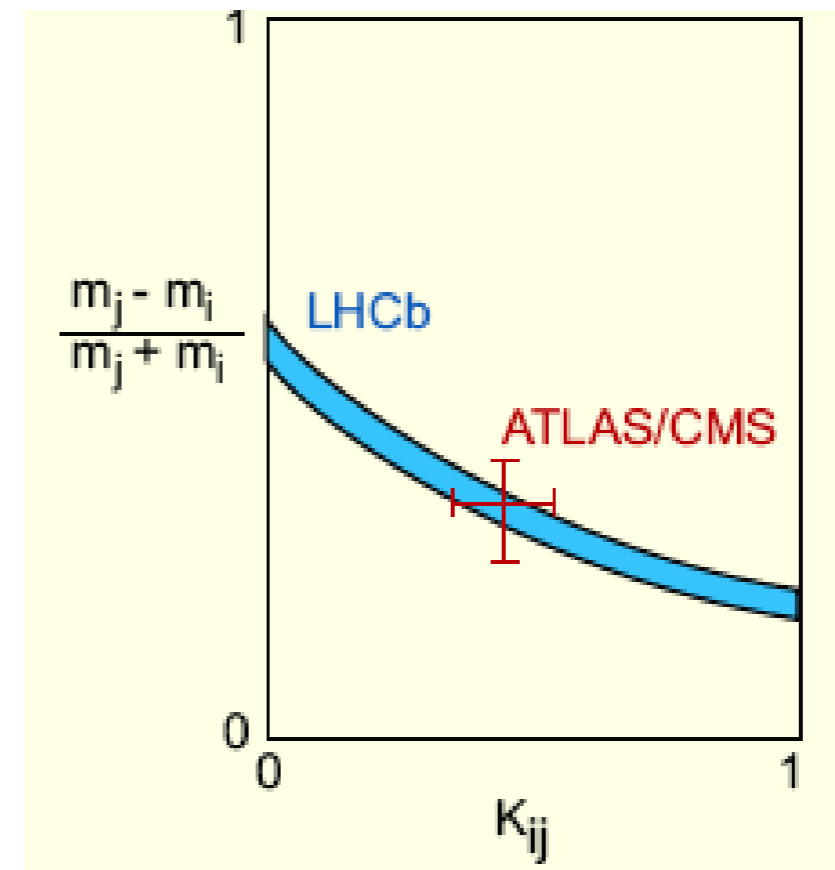
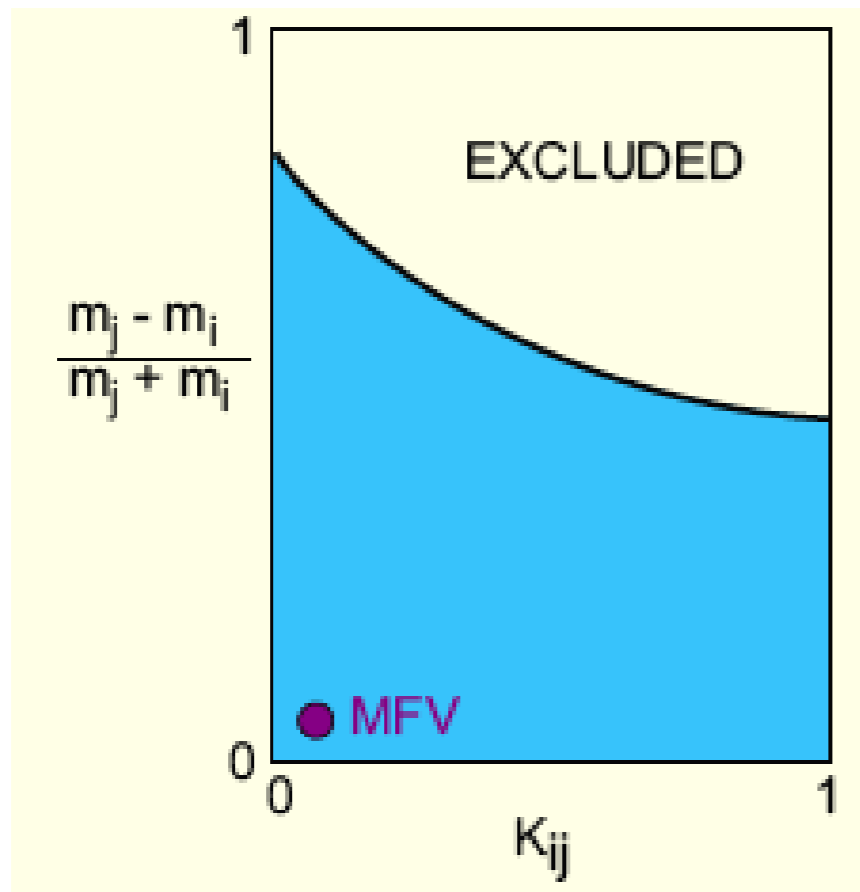
$$\left(C_{SM}^i / M_W + C_{NP}^i / \Lambda_{NP} \right) \times \mathcal{O}_i$$

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



Courtesy of Yossi Nir

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



Courtesy of Yossi Nir

DNA-Flavour-test of NP models:

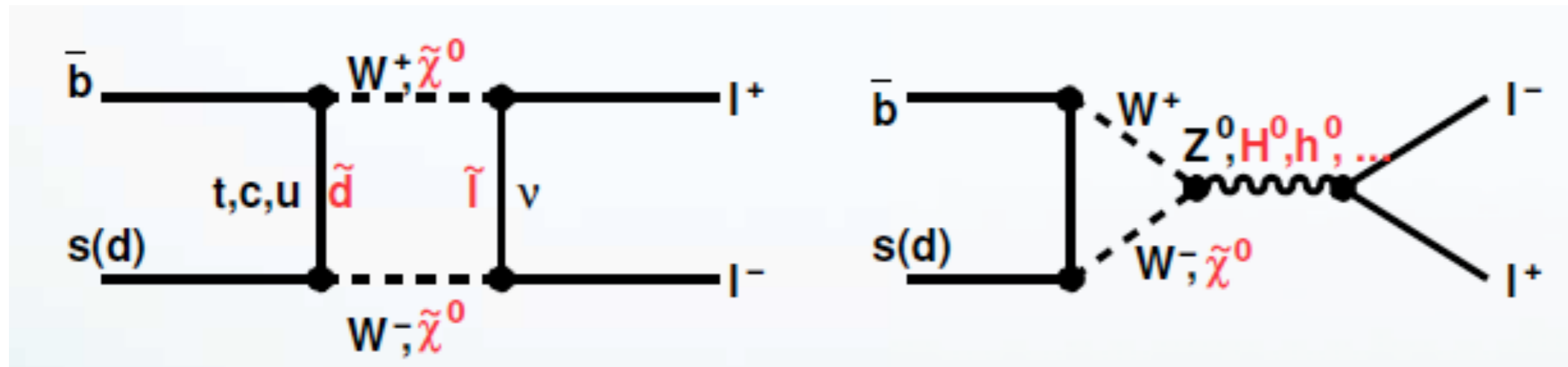
Correlations between flavour observables are significant pieces of information to identify a given extension of SM

Buras et al. [arXiv:1012.1447](https://arxiv.org/abs/1012.1447), [1204.5064](https://arxiv.org/abs/1204.5064)

Implications of the latest LHCb measurement of $B_s \rightarrow \mu\mu$

Implications of the latest LHCb measurement of $B_s \rightarrow \mu\mu$

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



ATLAS: $Br(B_s \rightarrow \mu^+\mu^-) < 2.2 \times 10^{-8}$ (2.4 fb^{-1})

CMS: $Br(B_s \rightarrow \mu^+\mu^-) < 7.7 \times 10^{-9}$ (4.9 fb^{-1})

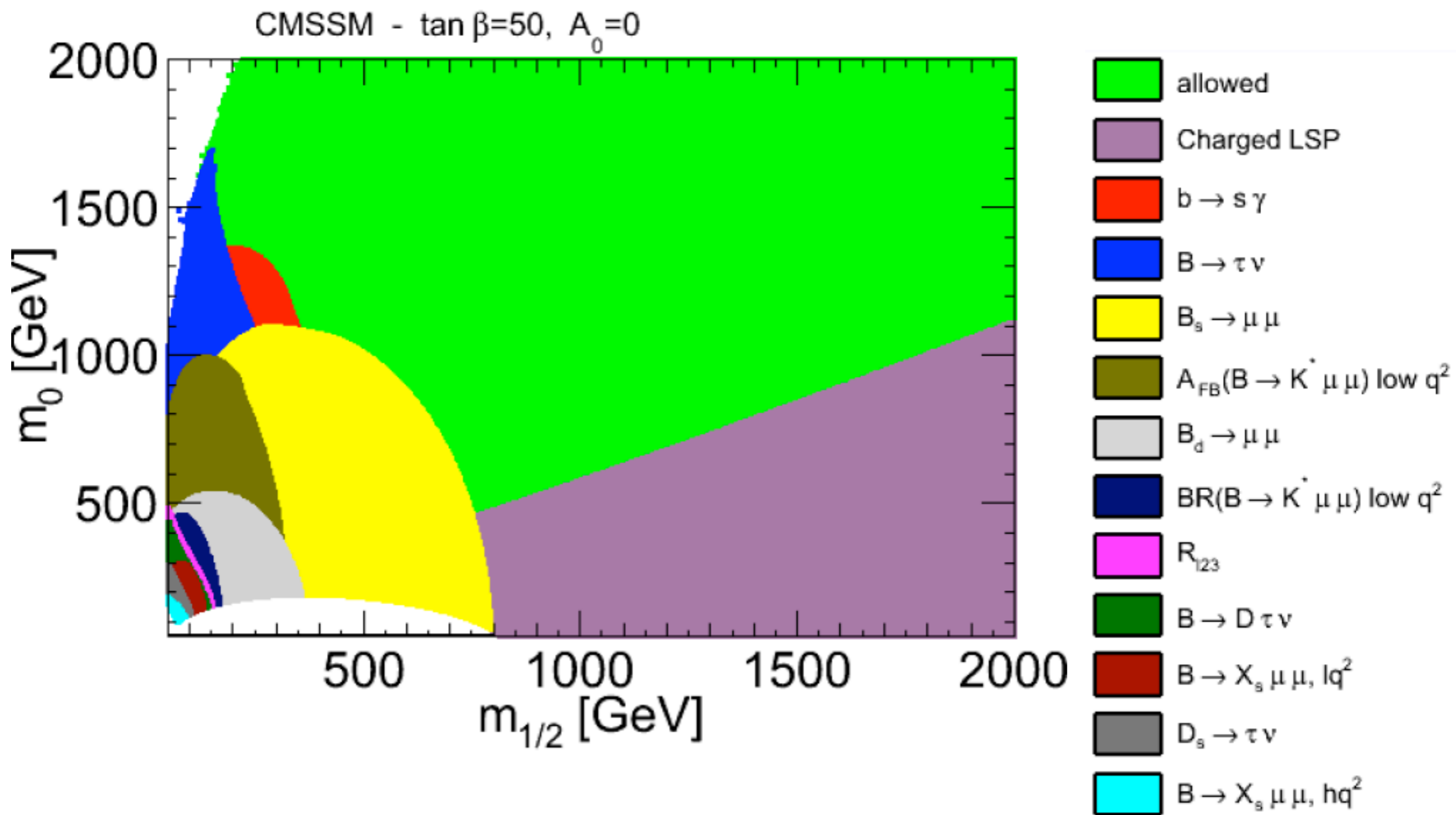
LHCb: $Br(B_s \rightarrow \mu^+\mu^-) < 4.5 \times 10^{-9}$ (1 fb^{-1})

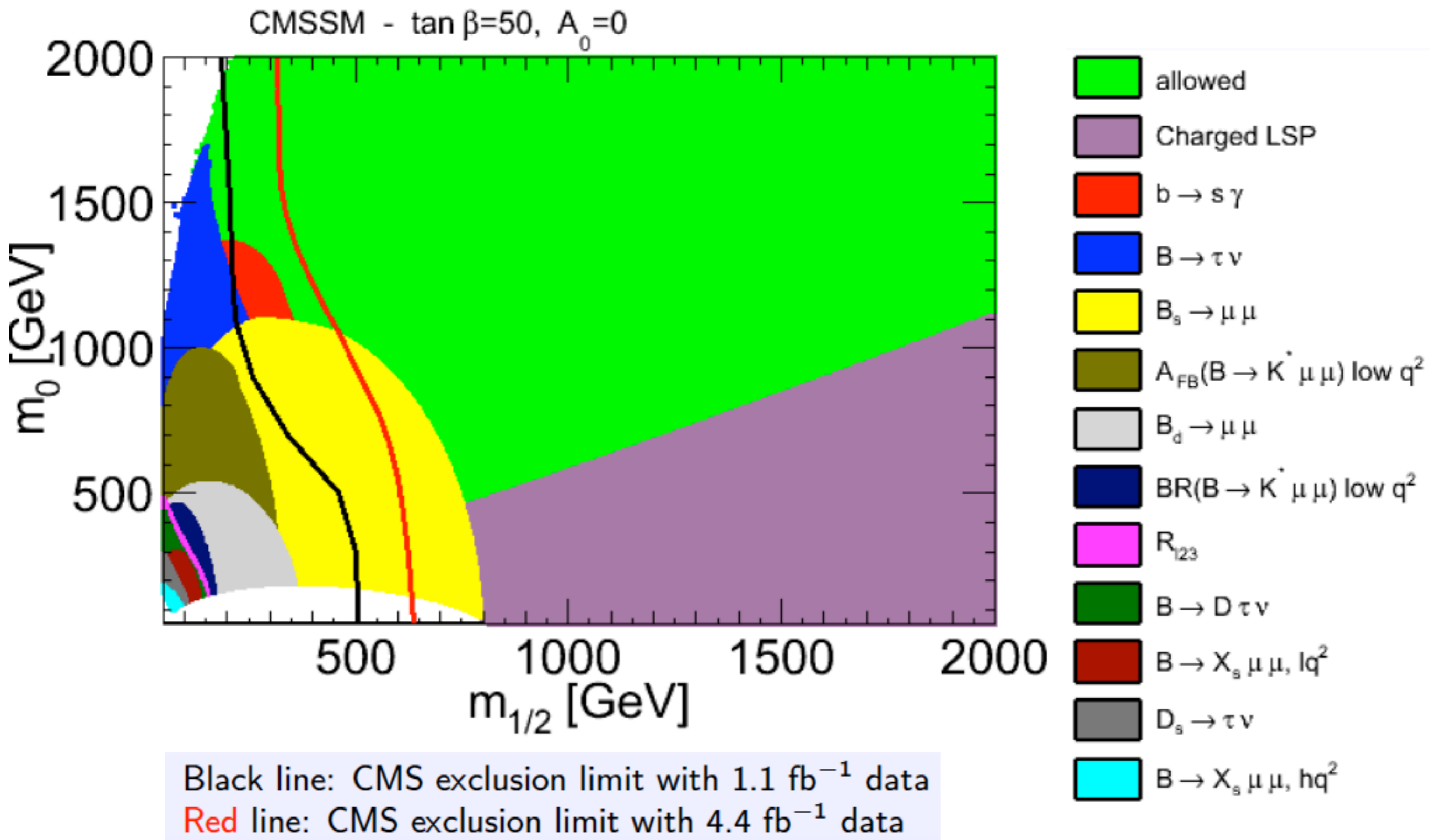
Already very close to the SM prediction

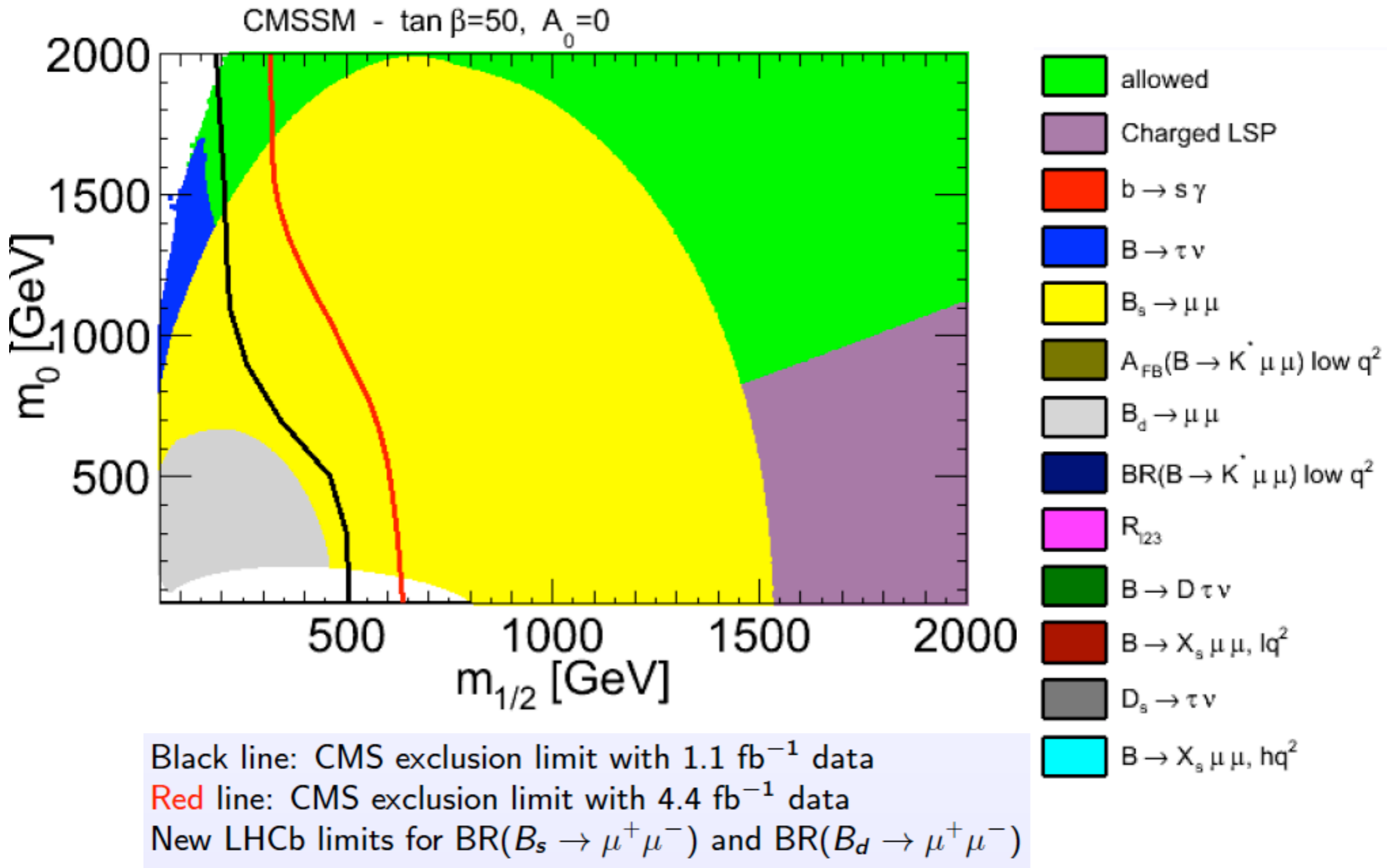
$$Br(B_s \rightarrow \mu\mu) = (3.53 \pm 0.38) \times 10^{-9} !$$

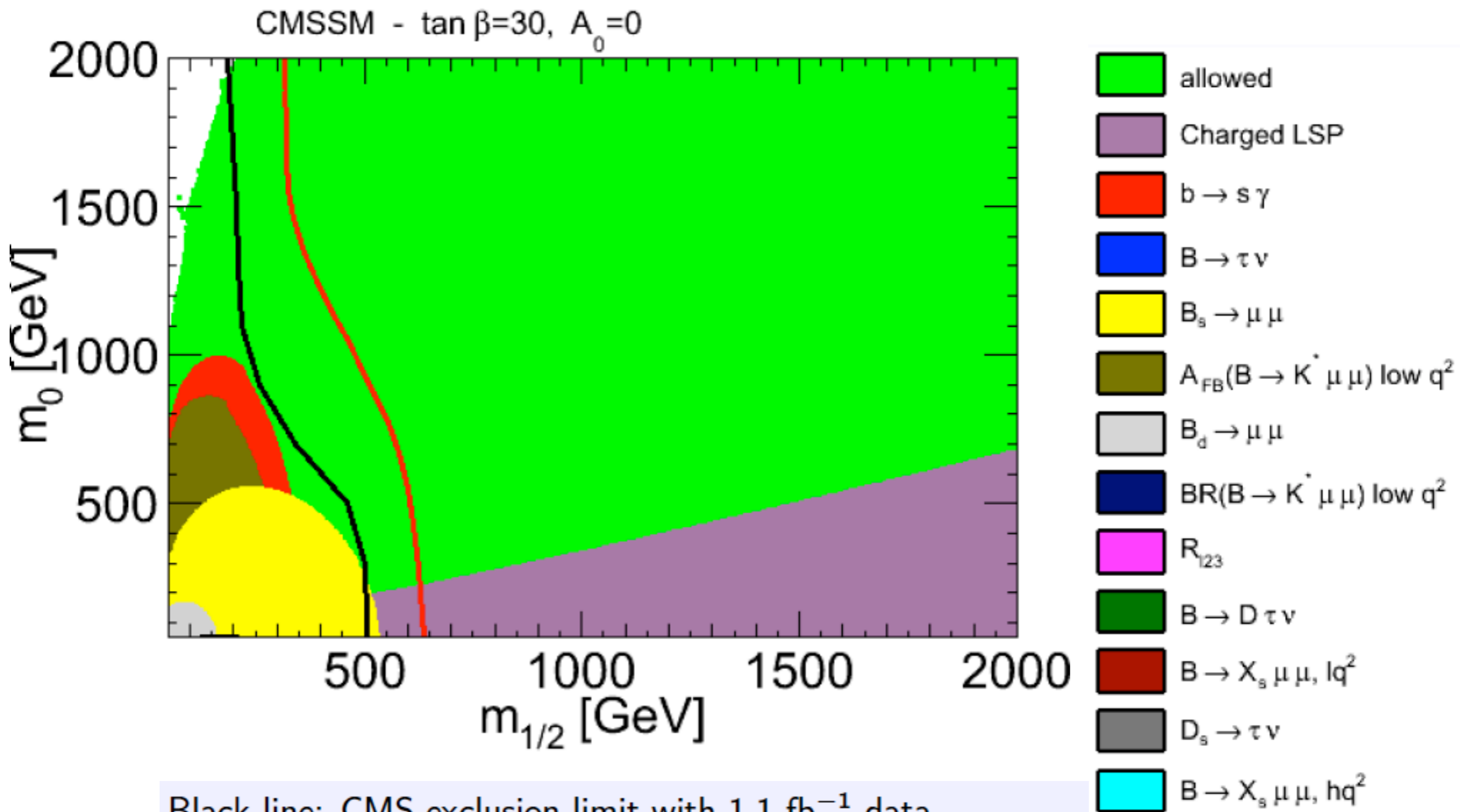
CDF presented first double sided limit (9.6 fb^{-1})

$$0.8 \times 10^{-9} < Br(B_s \rightarrow \mu\mu) < 3.4 \times 10^{-8} \text{ at } 95\% C.L.$$









Black line: CMS exclusion limit with 1.1 fb^{-1} data
 Red line: CMS exclusion limit with 4.4 fb^{-1} data
 New LHCb limits for $BR(B_s \rightarrow \mu^+ \mu^-)$ and $BR(B_d \rightarrow \mu^+ \mu^-)$

Future Opportunities

- **LHCb (5 years) $5fb^{-1}$** : 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 $50fb^{-1}$**
- **Dedicated kaon experiments J-PARC E14 and CERN Na62:**
rare kaon decays $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- **Two partially-funded Super-B factories:**
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 $\tau \rightarrow \mu \gamma, \dots$

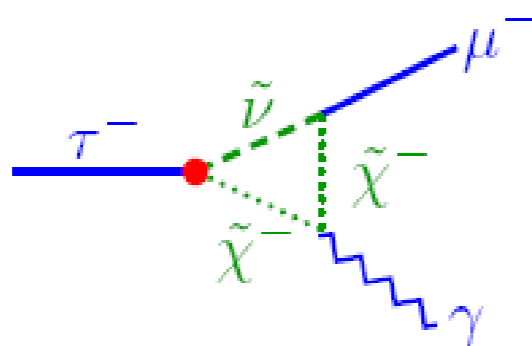
Opportunities at a Super Flavour Factory

see JHEP 0802 (2008) 110, arXiv:0710.3799

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 limited	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

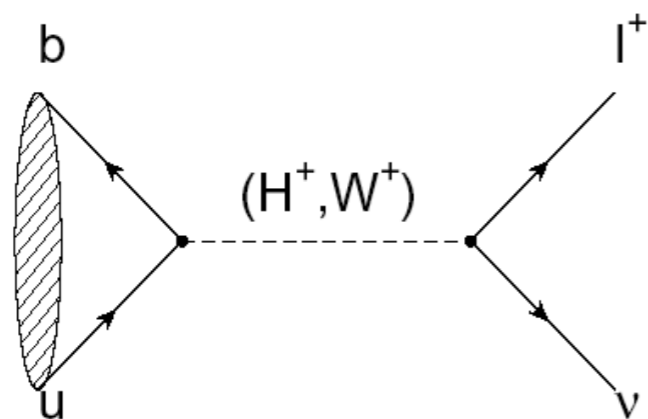
Blanke et al.

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

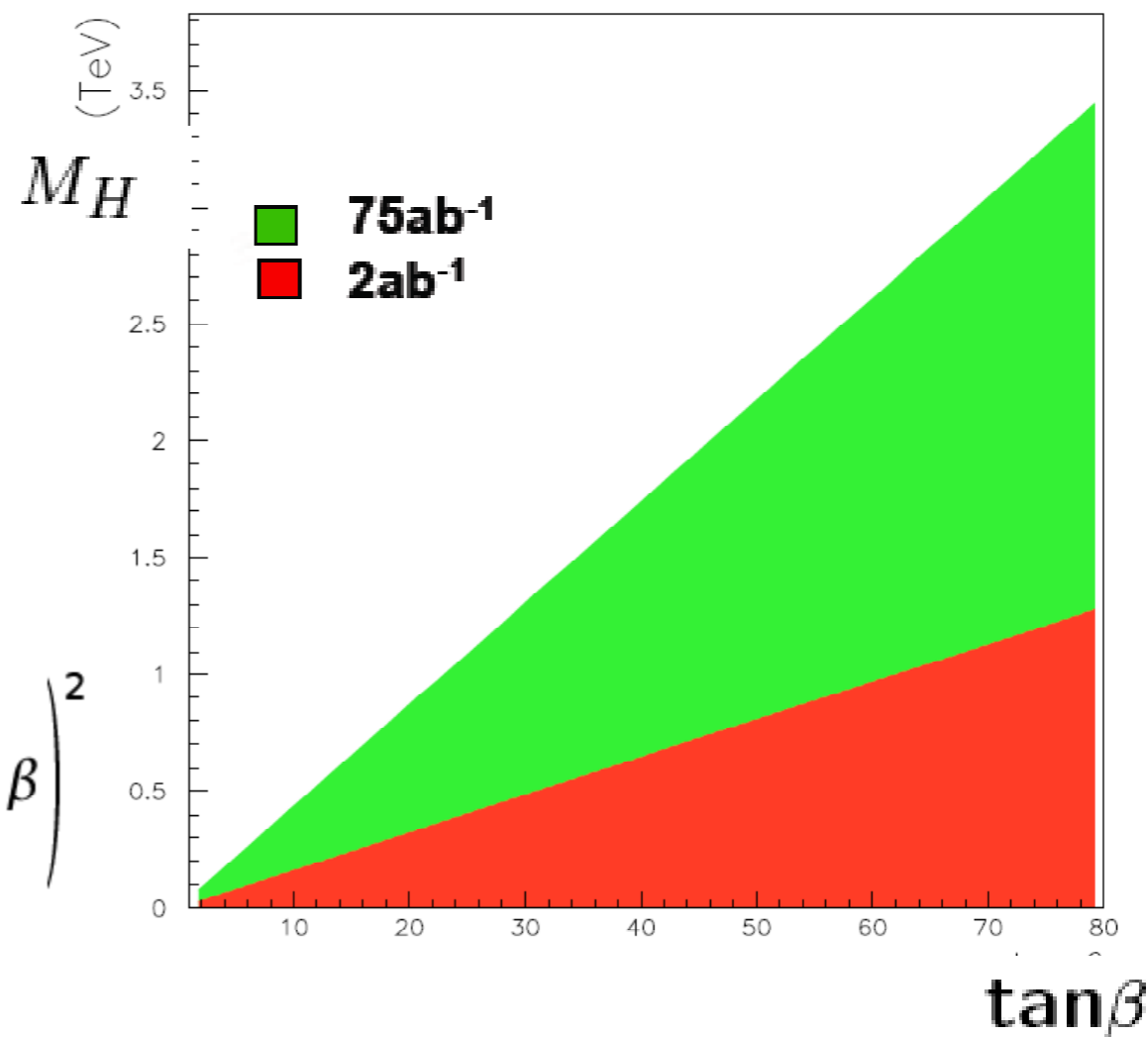
Superflavour factory: measurement of clean modes

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

2HDM-II



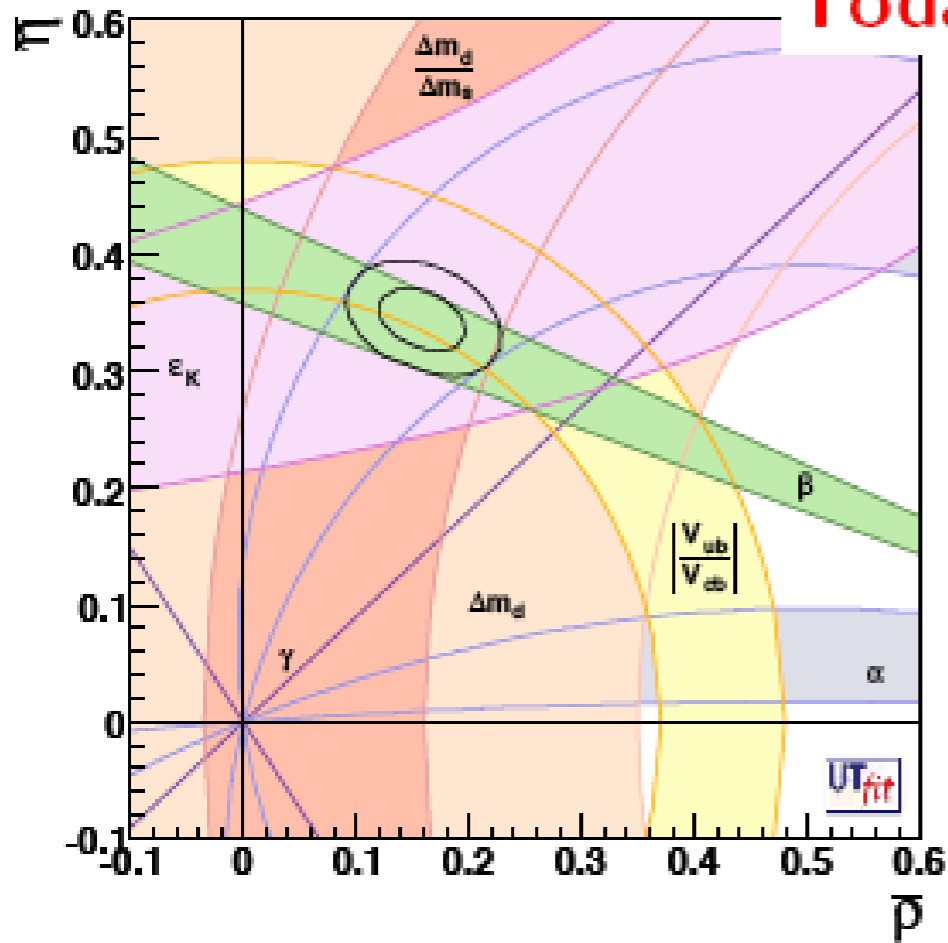
$$\text{BR}(B \rightarrow \tau \nu) = \text{BR}_{\text{SM}}(B \rightarrow \tau \nu) \left(1 - \frac{m_B^2}{M_H^2} \tan^2 \beta \right)^2$$



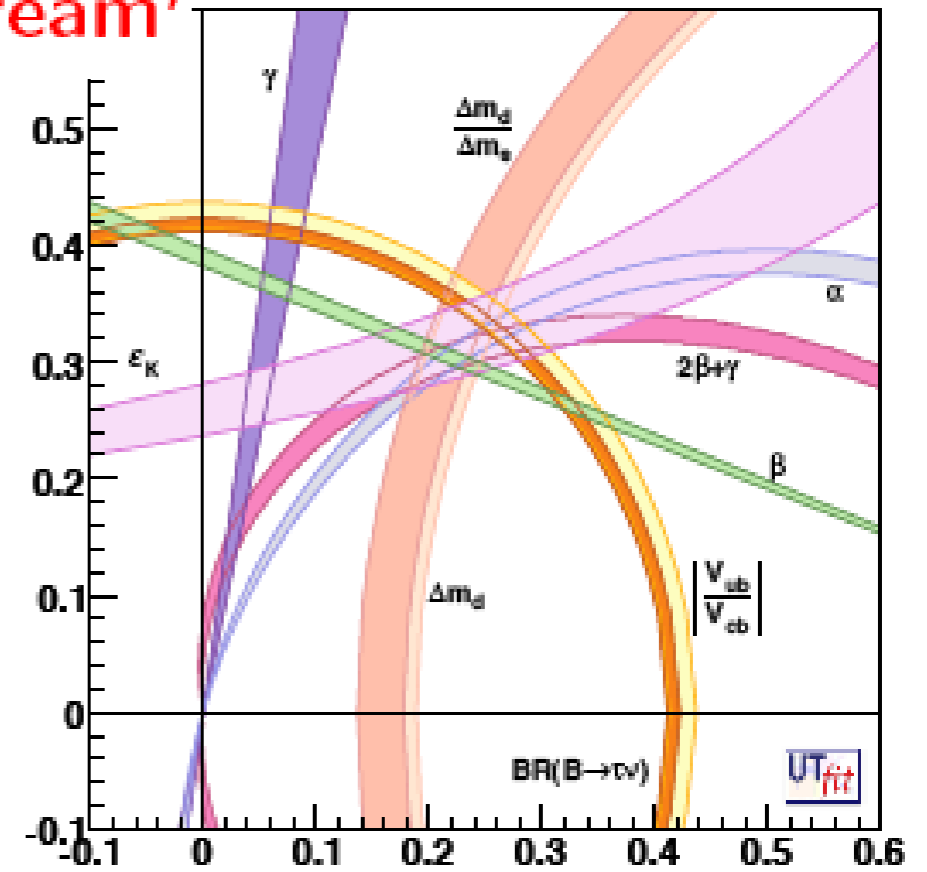
(Assuming SM branching fraction is measured)

Superflavour factory: CKM theory gets tested at 1%

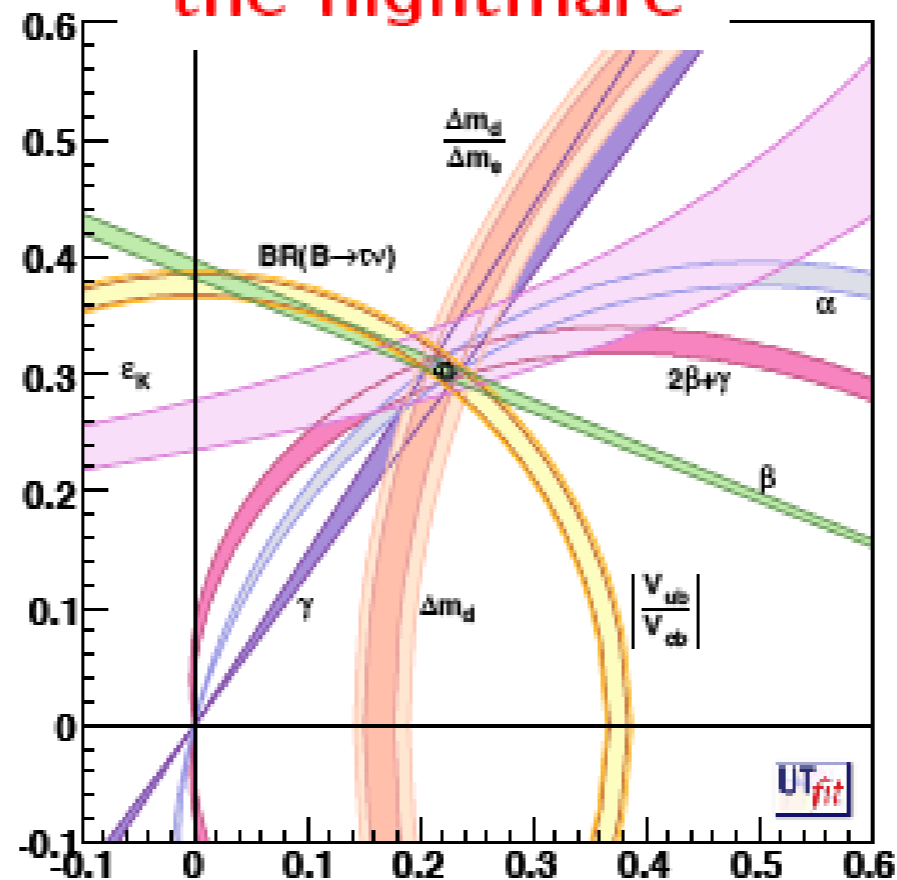
Today



'the dream'



'the nightmare'



Epilogue

Possible future scenarios:

(see T. Nakada LHCb spokesperson at EuroFlavour06, Barcelona, 11/2006)

A couple of years after the start of the LHC, may be

1. many new degrees of freedom discovered at ATLAS and CMS, and new FCNCs at LHCb
2. many new particles discovered at ATLAS and CMS, but no new FCNCs at LHCb \Rightarrow important input to understand the New Physics
3. No new particles discovered at ATLAS and CMS (except one Higgs), but new FCNCs at LHCb \Rightarrow tells us something about the mass scale to aim at (modulo flavour problem)
4.
5.

LHC discovers 'only' the Higgs,
then precision experiments like ILC and BelleII/SuperB/SuperLHCb
will show us the way to the NP energy scale

Charming surprises at LHCc

$$\Delta A_{CP} = A_{CP}^{dir}(K^+K^-) - A_{CP}^{dir}(\pi^+\pi^-) = -(0.82 \pm 0.21 \pm 0.11)\%$$

$\Rightarrow 3.5\sigma$ away from zero.. [LHCb Collaboration (2011)]

$$\Delta A_{CP} = (-0.645 \pm 0.180)\% \quad \text{HFAG}$$

Poorly known SM dynamics ??

BSM physics playing a role ??

Explanations of the LHCb result in SM, and in NP models:

- Isidori et.al. arxiv:1103.5785 \Rightarrow NP explanation in a model independent way Courtesy of Soumitra Nandi
 - Brod et.al. arxiv:1111.4987 \Rightarrow Large $1/m_c$ suppressed amplitude
 - Rozanov et.al. arxiv:1111.5000 \Rightarrow Large penguin in sequential 4th generation model
 - Pirtskhalava et.al. arxiv:1112.5451 \Rightarrow Badly broken $SU(3)_F$ symmetry
 - Cheng et.al. arxiv:1201.0785 \Rightarrow Large weak penguin annihilation contribution
 - Bhattacharya et.al. arxiv:1201.2351 \Rightarrow CP conserving NP in penguin
 - Giudice et.al. arxiv:1201.6204 \Rightarrow Left-right flavour mixing via chromomagnetic operator
 - Altmannshofer et.al. arxiv:1202.2866 \Rightarrow Chirally enhanced chromomagnetic penguins
 - Brod et.al. arxiv:1203.6659 \Rightarrow In SM via s- and d-quark penguin contraction
-many more

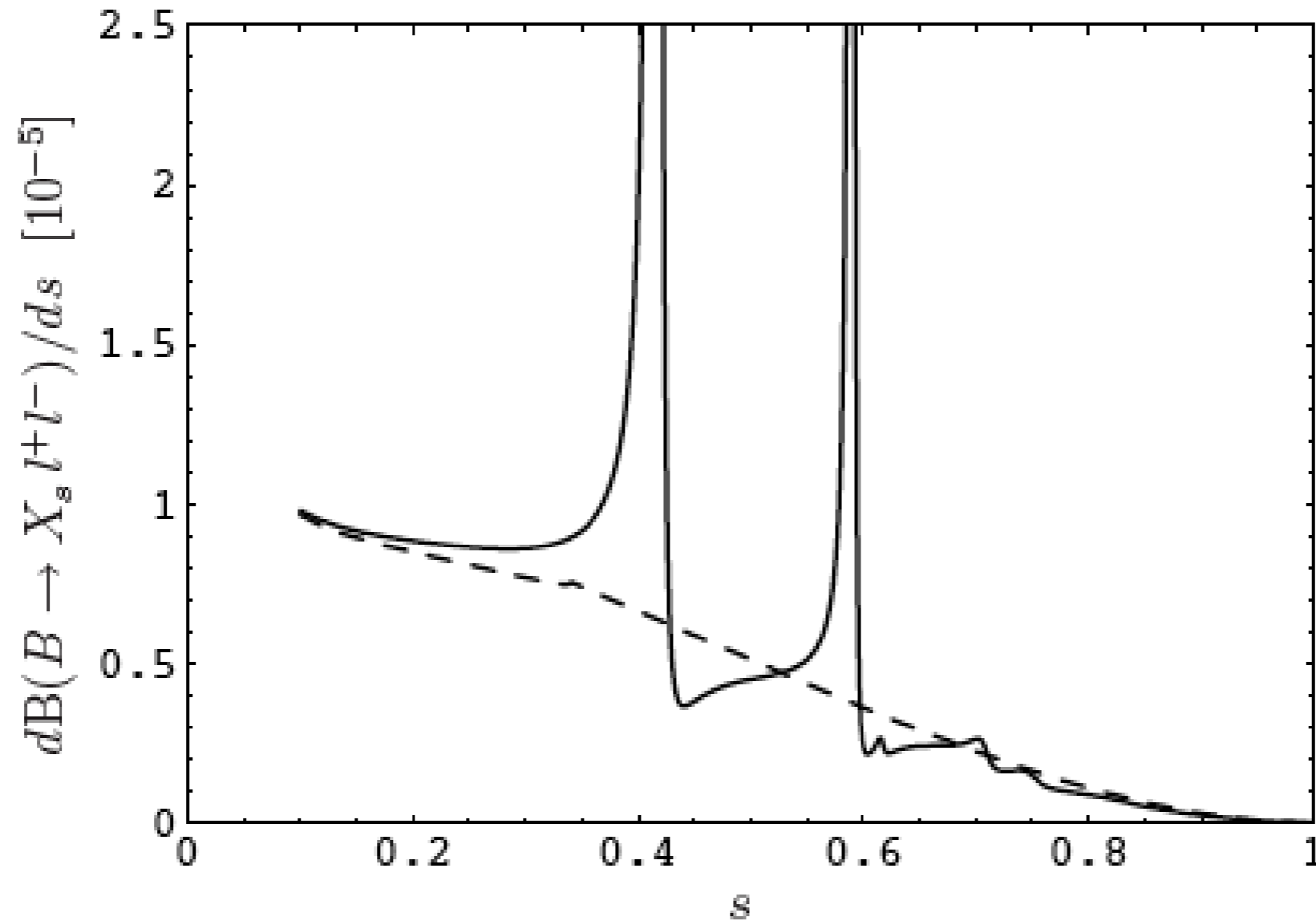
Read recommended SM papers first before move to NP explanations !

Extra

Quark-hadron duality violated in $\bar{B} \rightarrow X_s \ell^+ \ell^-$?

BBNS, arXiv:0902.4446

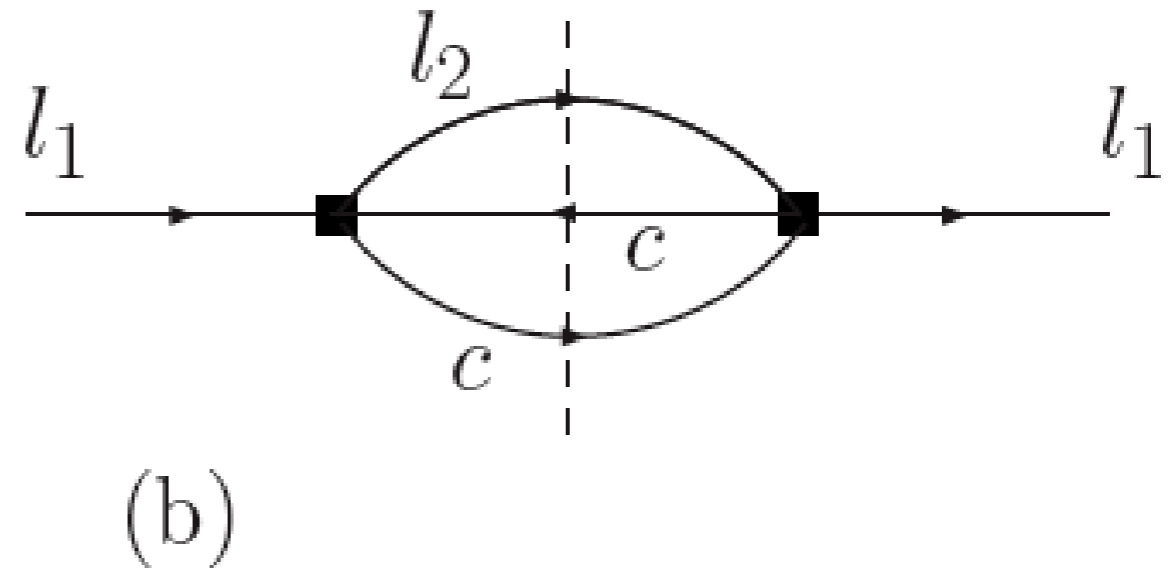
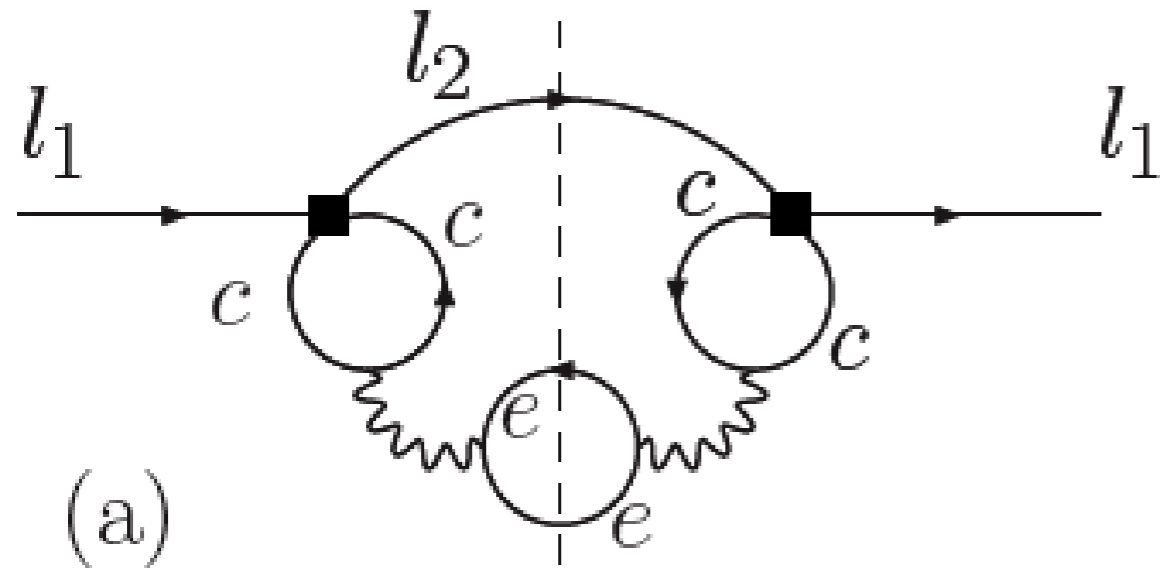
Within integrated branching ratio the resonances J/ψ and ψ' exceed the perturbative contributions **by two orders** of magnitude.



Quark-hadron duality violated in $\bar{B} \rightarrow X_s l^+ l^-$?

BBNS, arXiv:0902.4446

Within integrated branching ratio the resonances J/ψ and ψ' exceed the perturbative contributions **by two orders** of magnitude.

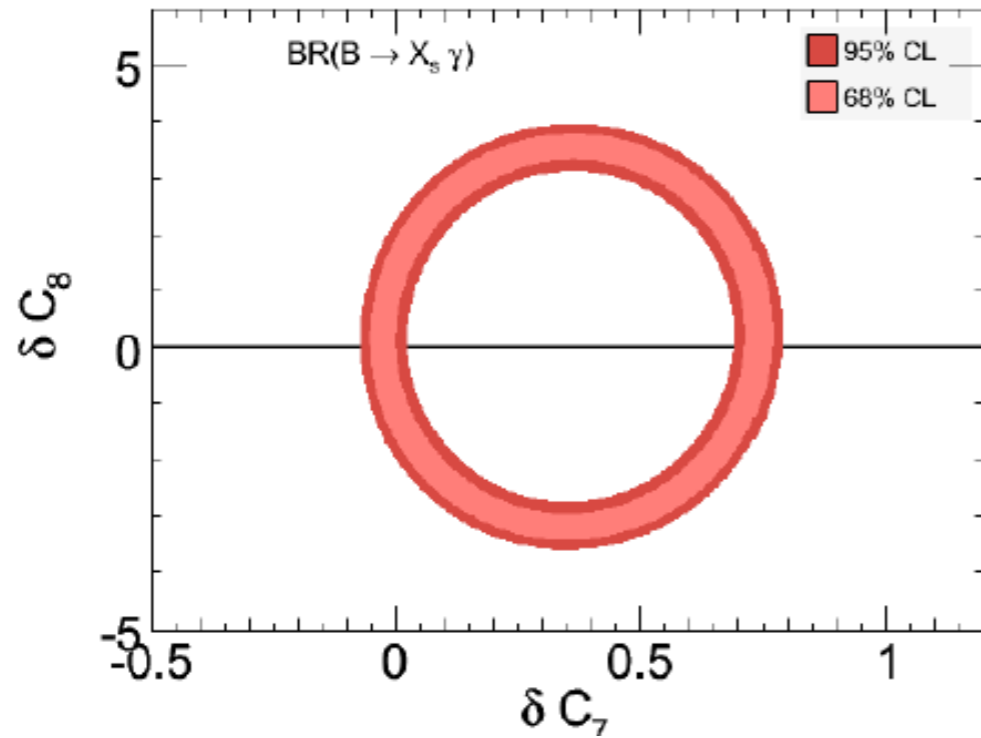


The rate $l_1 \rightarrow l_2 e^+ e^-$ (a) is connected to the integral over $|\Pi(q^2)|^2$ for which global duality is **NOT** expected to hold.

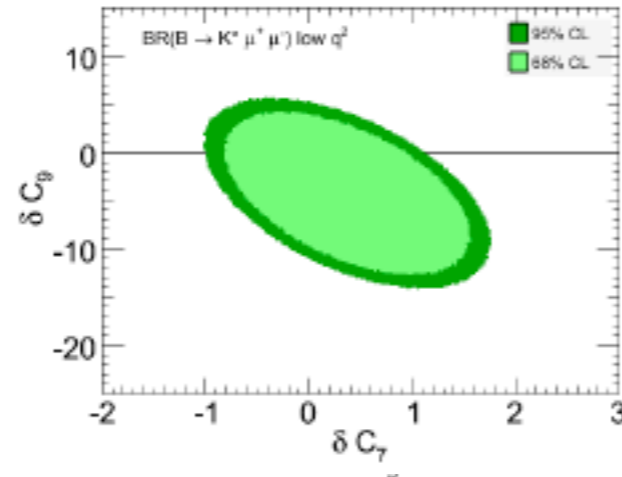
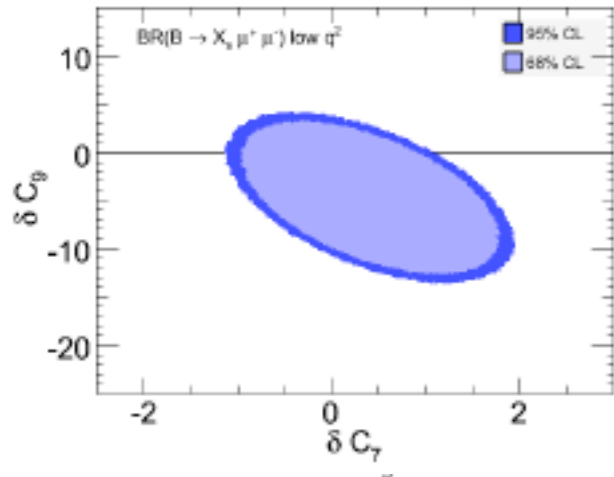
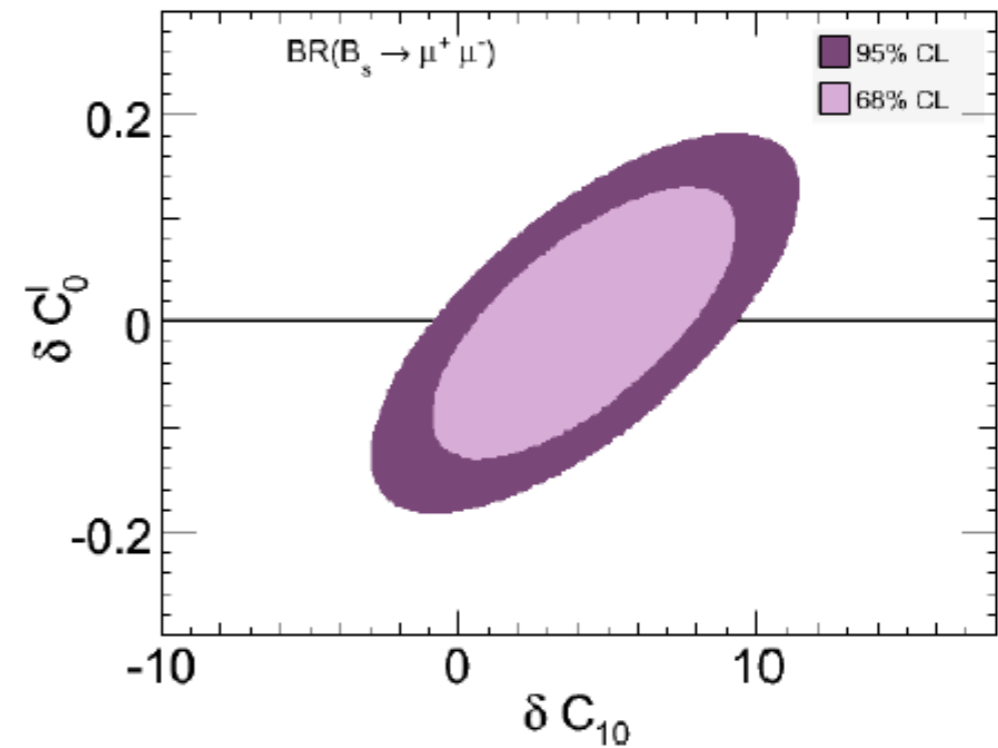
In contrast the inclusive hadronic rate $l_1 \rightarrow l_2 X$ (b) corresponds to the imaginary part of the correlator $\Pi(q^2)$.

Main players

$$B \rightarrow X_s \gamma$$



$$B_s \rightarrow \mu^+ \mu^-$$



$B \rightarrow X_s \mu^+ \mu^-$ (left)

$B \rightarrow K^* \mu^+ \mu^-$ (right)

