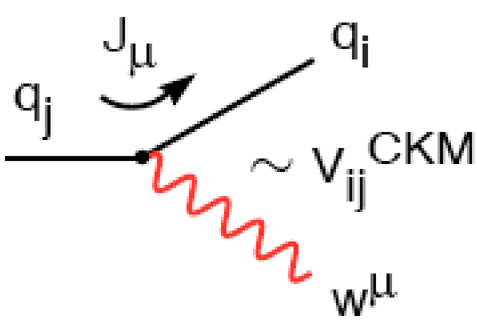
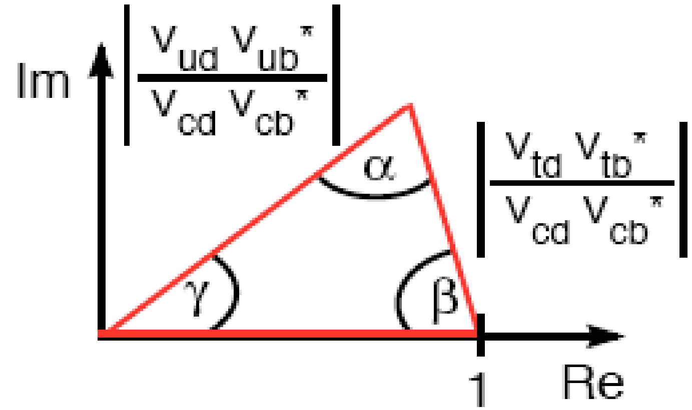
Role of flavour physics in the LHC era and new physics sensitivity of the decay $B \to K^* \ell^+ \ell^-$

Tobias Hurth (CERN, SLAC)

Flavour Physics within the SM

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





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

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 !!

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

Nobel Prize 2008

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

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

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

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

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

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

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

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

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

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

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

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

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

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

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

i) Case (A, C)

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

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

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

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

$$\varphi=e^{i\phi_i\tau_i}\begin{pmatrix}0\\ \lambda+\sigma\end{pmatrix}, \tag{2}$$

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

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

$$m=\begin{pmatrix}m_1 & 0 & 0 & 0\\ 0 & m_2 & 0 & 0\\ 0 & 0 & m_3 & 0\\ 0 & 0 & 0 & m_4\end{pmatrix},\qquad q=\begin{pmatrix}p\\ n\\ \zeta\\ \lambda\end{pmatrix}. \tag{3}$$

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

$$\sum_{j=1}^{3}A_{\mu}{}^{j}\bar{q}iA_j\gamma_{\mu}\frac{1+\gamma_5}{2}q. \tag{4}$$

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

$$A_{+}=\frac{A_1+iA_2}{2}=K\begin{pmatrix}0 & U\\ 0 & 0\end{pmatrix}K^{-1},\quad A_3=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & -1 & 0\\ 0 & 0 & 0 & -1\end{pmatrix},\quad K=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}, \tag{5}$$

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

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

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

ii) Case (A, B)

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

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

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

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

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

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

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

$$e^{i\alpha}m_1\sin\theta\cos\xi=m_3\cos\theta\sin\xi-e^{i\gamma}m_2\sin\eta,$$

$$e^{i\beta}m_1\cos\theta\cos\xi=-m_3\sin\theta\cos\xi+e^{i\gamma}m_4\cos\eta. \tag{8}$$

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

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

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

$$m_3/m_1\sim\cot\theta\cdot\tan\xi,$$

$$m_2/m_1\sim\sin\xi/\sin\theta. \tag{10}$$

We have no low-lying particle with a quantum number corresponding to ζ, so that m_2, which is a measure of chiral $SU(4)\times SU(4)$ breaking, should be sufficiently large compared to the masses of the other members. However, the present experimental results on the g_A/g_V ratios of the octet baryon β-decay would not permit $\sin\xi > \sin\theta$. Thus, it seems difficult to reconcile the hierarchy of chiral symmetry breaking with the experimental knowledge of the semileptonic processes.

iii) Case (B, B)

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

iv) Case (A, A)

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

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

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

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

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

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

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

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

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

with

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

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

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

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

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 model[4] is one of them. We can easily see that CP-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

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

Erratum

Equation (13) should read as

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

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:

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

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 model[4] is one of them. We can easily see that *CP*-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

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

Errata:

Equation (13) should read as

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

However,...

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

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

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

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

- Gauge principle governs the gauge sector of the SM.

- No guiding principle in the flavour sector:

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

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

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

Flavour problem of New Physics

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

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

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

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

(tree-level, generic new physics)

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

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

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

  (tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)

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

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

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

Example: Supersymmetry

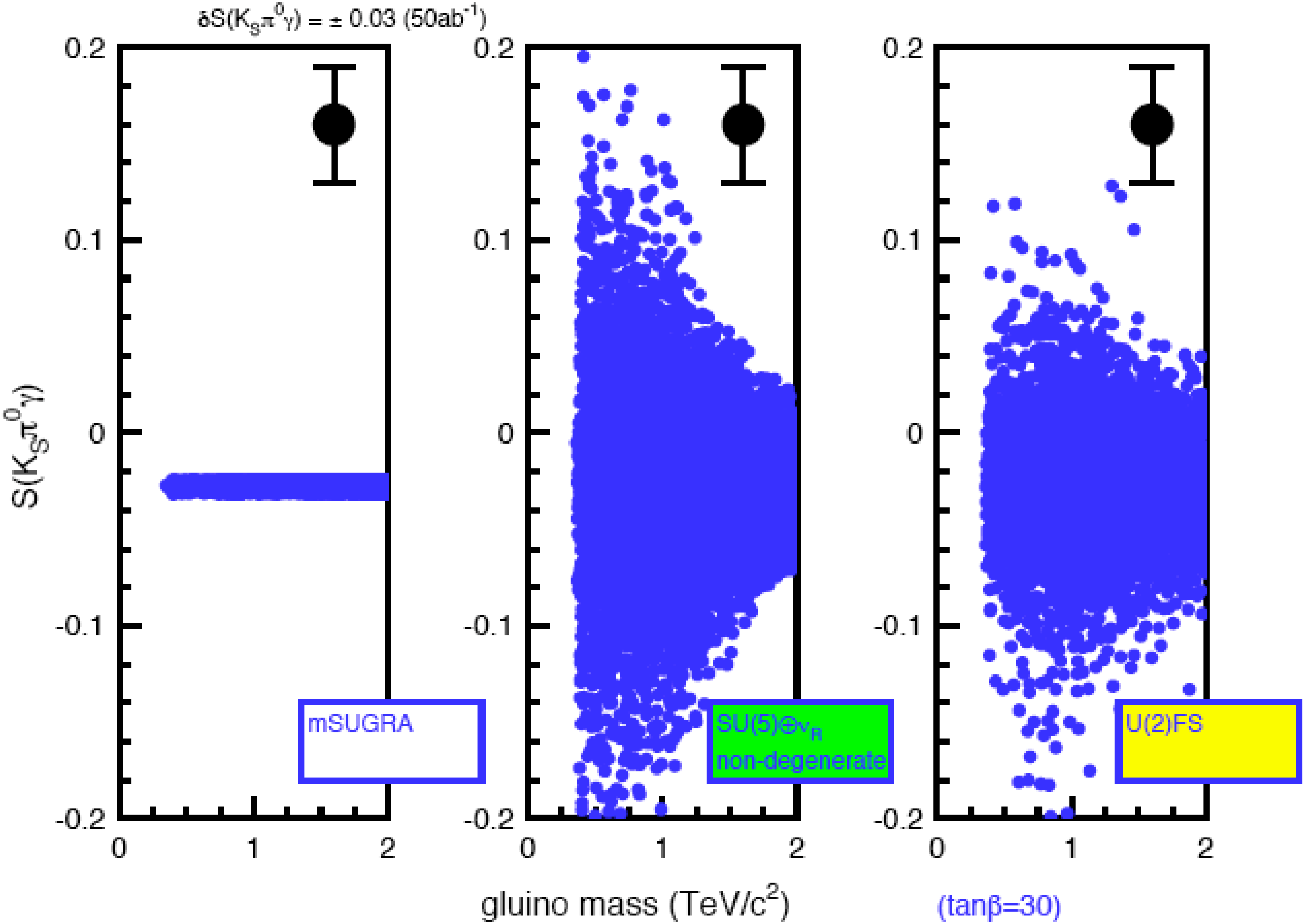
- In the general MSSM too many contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix

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

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

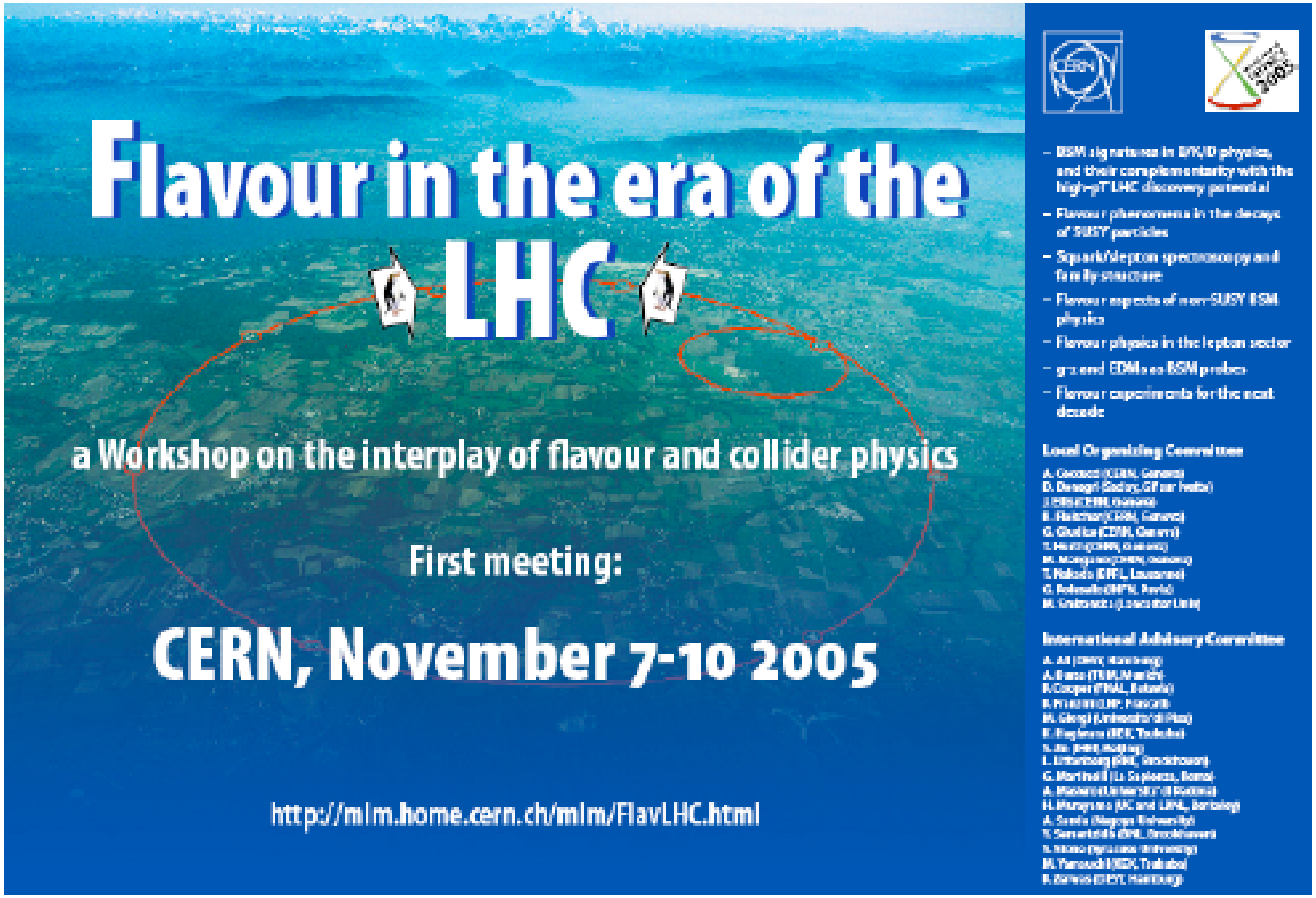
⇒ Discrimination between various SUSY-breaking mechanism

Goto,Okada,Shindou,Tanaka,arXiv:0711.2935



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

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



5 meetings between 11/2005 and 3/2007

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

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

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

published in EPJC 57 (2008) 1-492

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

Follow-up workshop:

Working Group on the Interplay Between Collider and Flavour Physics

The working group addresses the complementarity and synergy between the LHC and the flavour factories within the new physics search. New collaborations on this topic were triggered by the two recent CERN workshop series Flavour in the Era of the LHC and CP Studies and Non–Standard Higgs Physics at the border line of collider and flavour physics and experiment and theory. This follow–up working group wants to provide a continuous framework for such collaborations and trigger new research work in this direction. Regular meetings at CERN (well–connected by VRVS) are planned in the near future.

https://twiki.cern.ch/twiki/bin/view/Main/ColliderAndFlavour

Recent meeting 16.-18. of March 2009 at CERN

Next meeting 14.-16. of December 2009 at CERN

Please feel cordially invited !

Flavour@high-p_T interplay

Can ATLAS/CMS exclude MFV ?

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

Quark flavour at ATLAS/CMS

- Probing MFV at the LHC   Grossman,Nir,Thaler,Volansky,Zupan,arXiv:0706.1845

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

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

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

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

MFV prediction for events with B' pair production:

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

Flavour tagging efficiencies are crucial.

- Flavour-violating squark and gluino decays

Hurth,Porod,hep-ph/0311075
arXiv:0904.4574 [hep-ph], to appear in JHEP

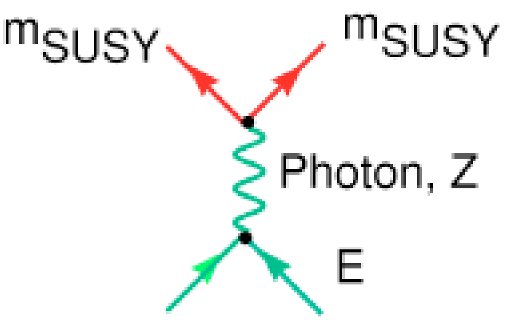
Squark decays: $\tilde{u}_i \to u_j \tilde{\chi}_k^0\,,\, d_j \tilde{\chi}_l^+ \qquad \tilde{d}_i \to d_j \tilde{\chi}_k^0\,,\, u_j \tilde{\chi}_l^-$

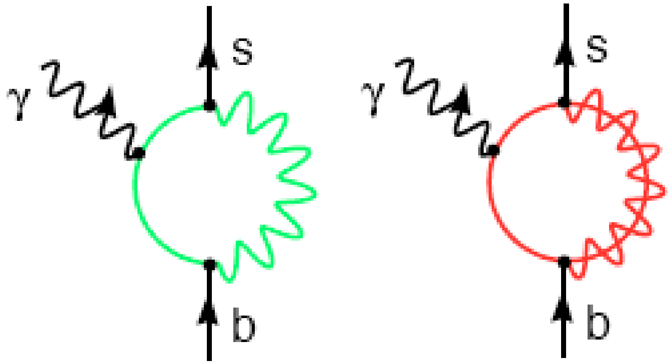
These tree decays are governed by the same mixing matrices as the contributions to flavour violating low-energy observables.

Squarks can have large flavour-violating decay modes (10% – 20%), which are compatible with present constraints from flavour physics.

Again: flavour-tagging at LHC important, but difficult

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





The indirect information will be most valuable when the general nature of new physics will be identified in the direct search.

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

Flavour@high-p_T

Concrete example of new physics search:

Separation of new physics effects and hadronic uncertainties

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

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

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

Key issue: separation of new physics and hadronic effects

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

for $B \to K^*$ formfactors

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

for the decay amplitudes

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

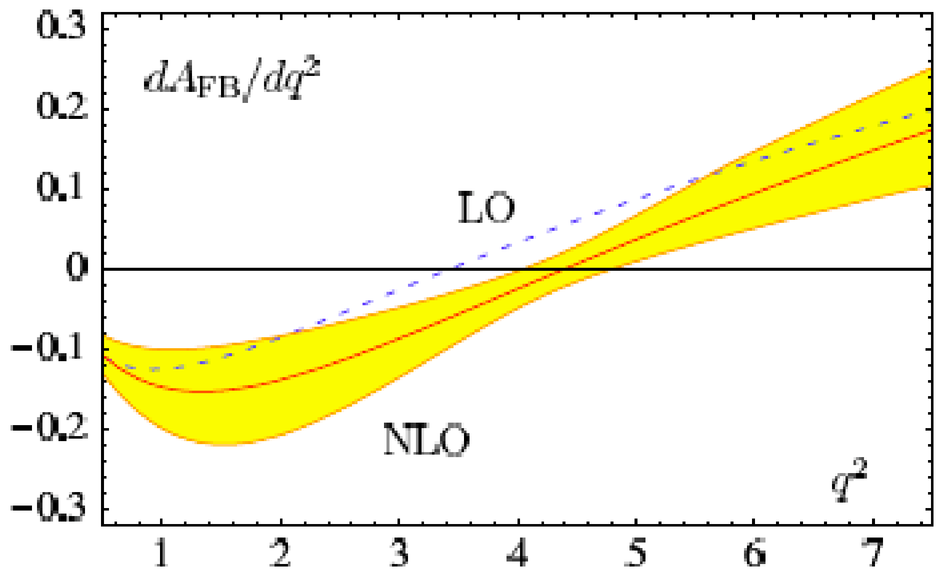
- Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors
- Relations between formfactors in large-energy limit
- Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

Phenomenologically highly relevant issue

general strategy of LHCb to look at ratios of exclusive modes

LHCb Strategy: Focus on ratios of exclusive modes

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



- 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:

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

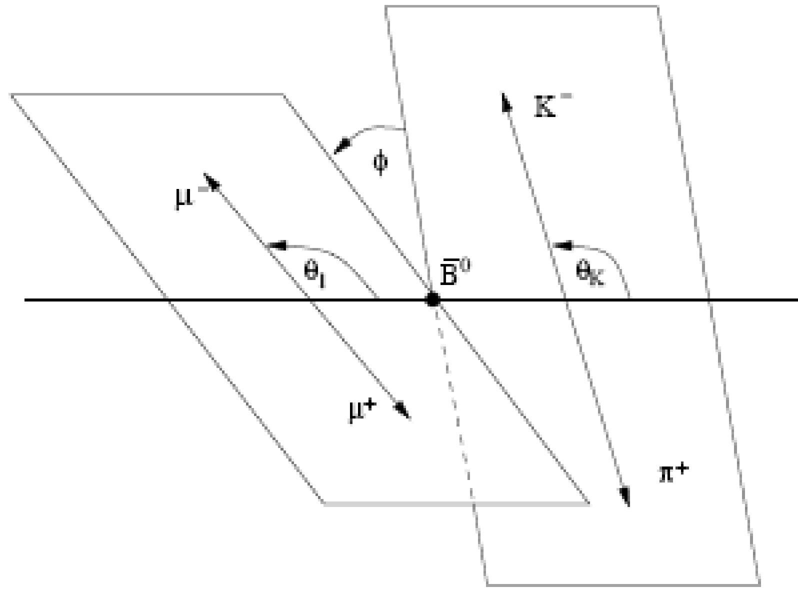
- NLO contribution calculated within QCD factorization approach leads to a large 30%-shift: (Beneke,Feldmann,Seidel 2001)

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

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

More opportunities in $B \to K^*(K\pi)\ell^+\ell^-$: angular distributions

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



After summing over the spins of the final particles:

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

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

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

- Angular distribution functions: depend on the 6 complex K^* spin amplitudes

$I_i = I_i(A_{\perp L/R}, A_{\| L/R}, A_{0L/R})$ (limit $m_{\text{lepton}} = 0$)

12 theoretical independent amplitudes $A_j \overset{?}{\Leftrightarrow}$ 9 independent coefficient functions in I

Only 9 amplitudes A_j are independent in respect to the angular distribution

Theoretical framework

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

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

  We focus on magnetic and semi-leptonic operators and their chiral partners

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

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

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

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

  Form factor relations broken by α_s and Λ/m_b corrections

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

  (IR structure of QCD)

- Above results are valid in the kinematic region in which

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

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

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

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

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

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

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

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

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

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

Careful construction of observables

- Good sensitivity to NP contribitions, i.e. to $C_7^{eff'}$
- Small theoretical uncertainties
  - Dependence of soft form factors, $\xi_\perp$ and $\xi_\|$, to be minimized !
    form factors should cancel out exactly at LO, best for all s
  - unknown Λ/m_b power corrections

    $A_{\perp,\|,0} = A^0_{\perp,\|,0}\left(1 + c_{\perp,\|,0}\right)$ vary c_i in a range of $\pm 10\%$ and also of $\pm 5\%$
  - Scale dependence of NLO result
  - Input parameters
- Good experimental resolution

Interesting observables

- Forward-backward asymmetry

$$A_{\rm FB} \equiv \frac{1}{d\Gamma/dq^2}\left(\int_0^1 d(\cos\theta)\,\frac{d^2\Gamma[\bar{B}\to\bar{K}^*\ell^+\ell^-]}{dq^2 d\cos\theta} - \int_{-1}^0 d(\cos\theta)\,\frac{d^2\Gamma[\bar{B}\to\bar{K}^*\ell^+\ell^-]}{dq^2 d\cos\theta}\right)$$

$$A_{\rm FB} = \frac{3}{2}\,\frac{{\rm Re}(A_{\parallel L}A^*_{\perp L}) - {\rm Re}(A_{\parallel R}A^*_{\perp R})}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

Form factors cancel out at LO only for Zero.

- Longitudinal polarisation of K^*

$$F_L(s) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

Form factors do not cancel at LO ($\rightarrow$ larger hadronic uncertainties)

- Transversity amplitude A_T^2 (Krüger,Matias 2005)

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

Sensitive to right-handed currents (in LO directly $\sim C_7^{eff'}$)

Formfactor cancel out at LO for all s

Zero of $A_T^{(2)}$ (for $C_7^{eff'} \neq 0$) coincides with the Zero of A_{FB} at LO and is also independent from $C_7^{eff'}$ as in A_{FB}.

Projection fit possible for $A_T^{(2)}$, F_L, A_{FB}

$$\frac{d\Gamma'}{d\phi} = \frac{\Gamma'}{2\pi}\left(1 + \frac{1}{2}(1 - F_\mathrm{L})A_T^{(2)}\cos 2\phi + A_\mathrm{Im}\sin 2\phi\right), \qquad \Gamma' = \frac{d\Gamma}{dq^2}$$

$$\frac{d\Gamma'}{d\theta_l} = \Gamma'\left(\frac{3}{4}F_\mathrm{L}\sin^2\theta_l + \frac{3}{8}(1 - F_\mathrm{L})(1 + \cos^2\theta_l) + A_\mathrm{FB}\cos\theta_l\right)\sin\theta_l,$$

$$\frac{d\Gamma'}{d\theta_K} = \frac{3\Gamma'}{4}\sin\theta_K\left(2F_\mathrm{L}\cos^2\theta_K + (1 - F_\mathrm{L})\sin^2\theta_K\right),$$

Observables appear linearly, fits performed on data binned in q^2

First experimental measurements with limited accuracy is possible

But: $A_T^{(2)}$ suppressed by $1 - F_L$

Full angular fit is superior, once the data set is large enough $(\succ 2fb^{-1})$

much better resolution (factor 3 even in $A_T^{(2)}$)

New observables are available

Unbinned analysis, q^2 dependence parametrised by polynomial

New observables

By inspection of the K^* spin amplitudes in terms of Wilson coefficients and SCET form factors one identifies further observables

- sensitive to $C_7^{eff'}$
- theoretical clean
- invariant under 3 $R-L$ symmetries
- with high experimental resolution

$$A_T^{(3)} = \frac{|A_{0L} A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2 |A_\perp|^2}} \qquad A_T^{(4)} = \frac{|A_{0L} A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}^* A_{\parallel L} + A_{0R} A_{\parallel R}^*|}$$

New observables allow crossschecks

Different sensibility to $C_7^{eff'}$ via A_0 in $A_T^{(3)}$, $A_T^{(4)}$

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

(see also Buras et al. 2008)

Phenomenological analysis

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

Specific model:

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

4 benchmark points

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

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

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

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

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

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

  mass insertion as in Scenario A.

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

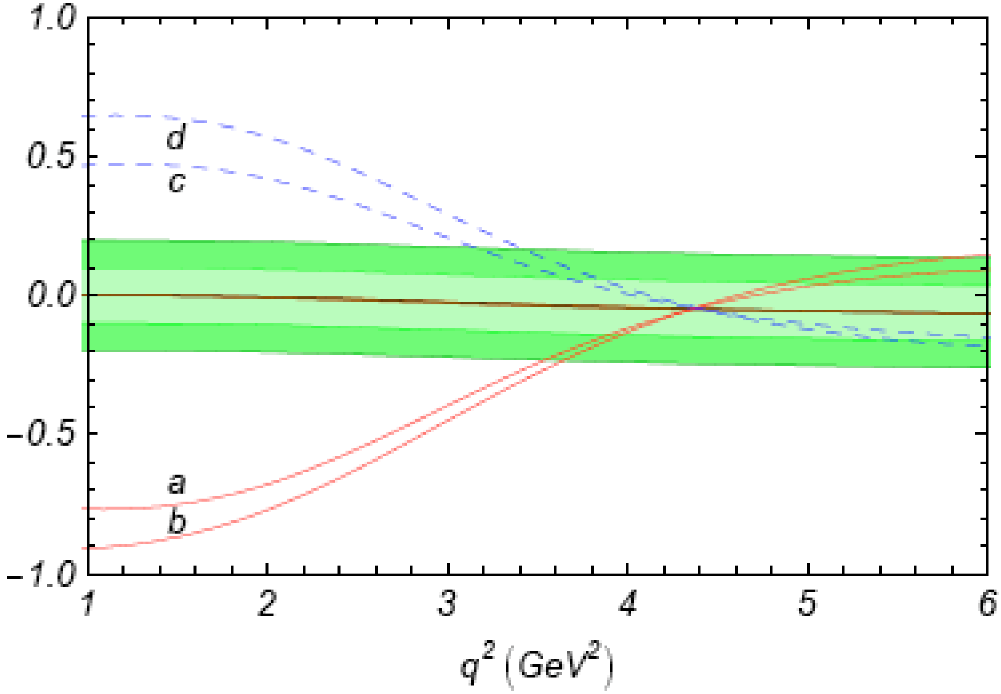
  d) $m_{\tilde{g}}/m_{\tilde{d}} = 0.6$, $(\delta^d_{LR})_{32} = -0.006$.

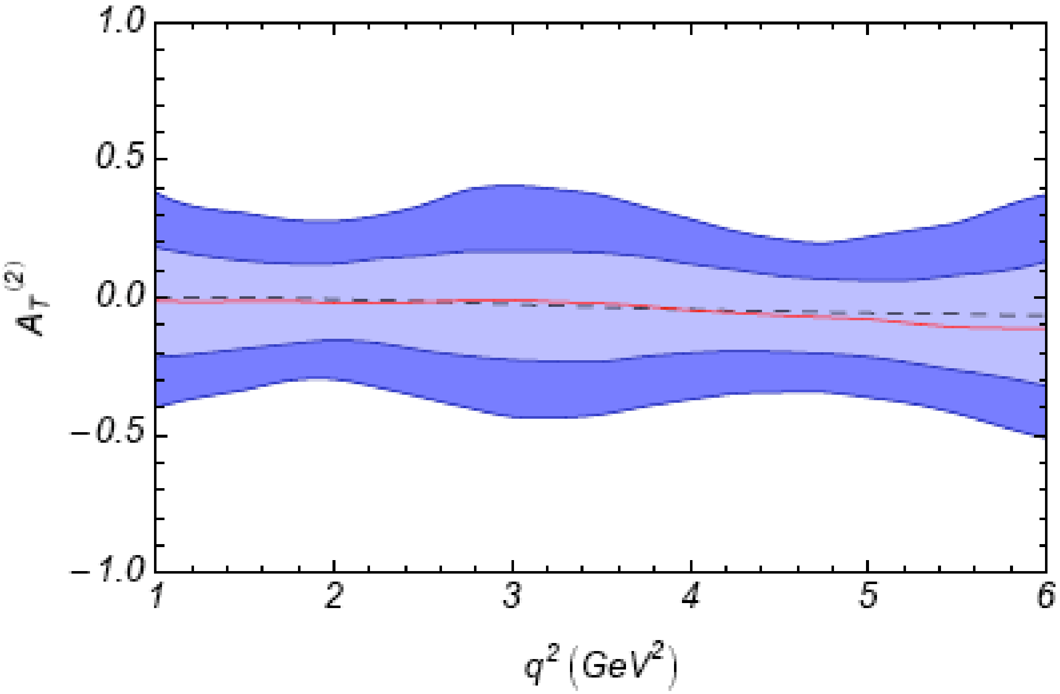
Check of compatibility with other constraints (B physics,ρ parameter,

Higgs mass, particle searches, vacuum stability constraints

Results

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





Theoretical sensitivity

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

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

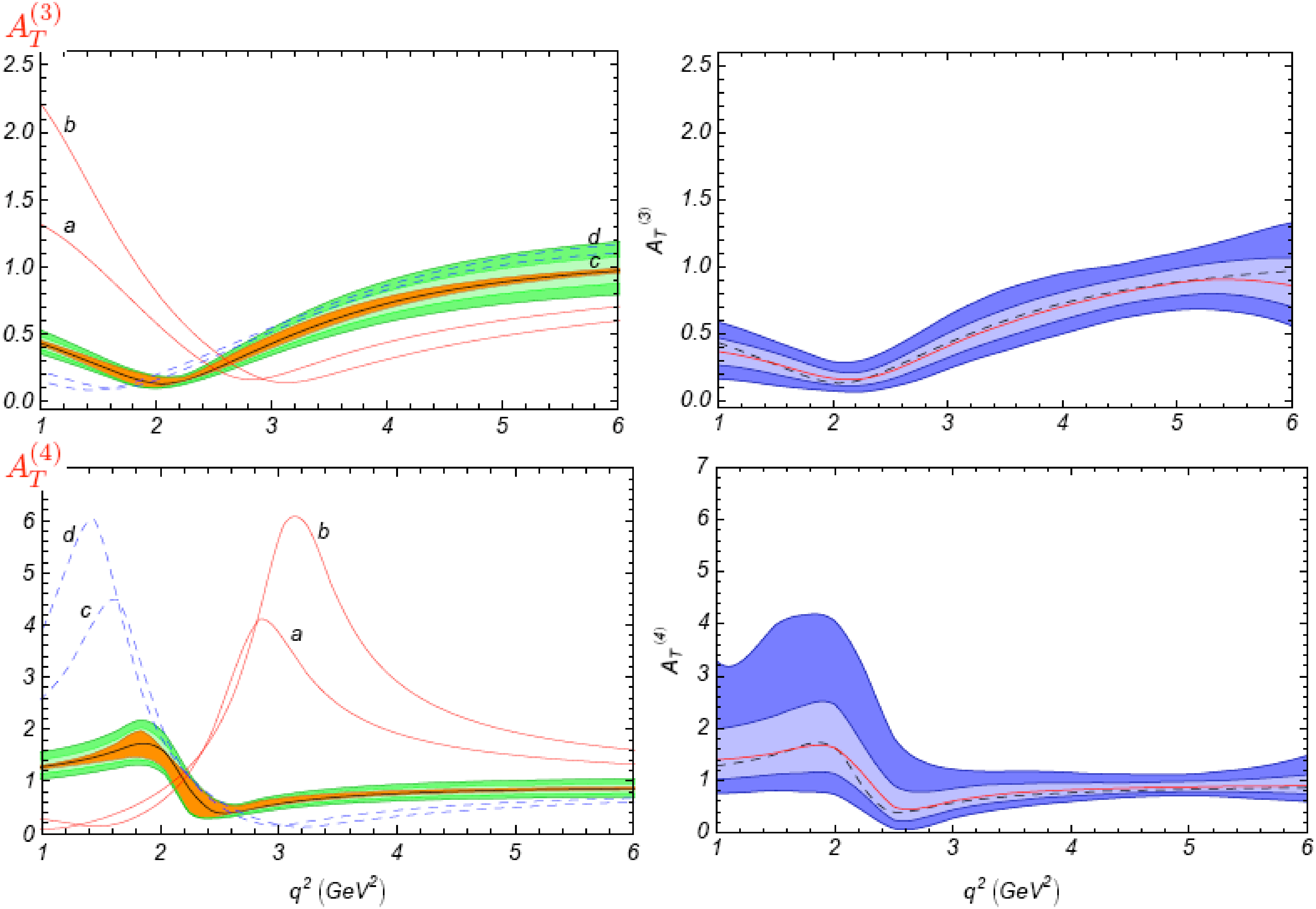
Experimental sensitivity $(10 fb^{-1})$

light green 1 σ

dark green 2 σ

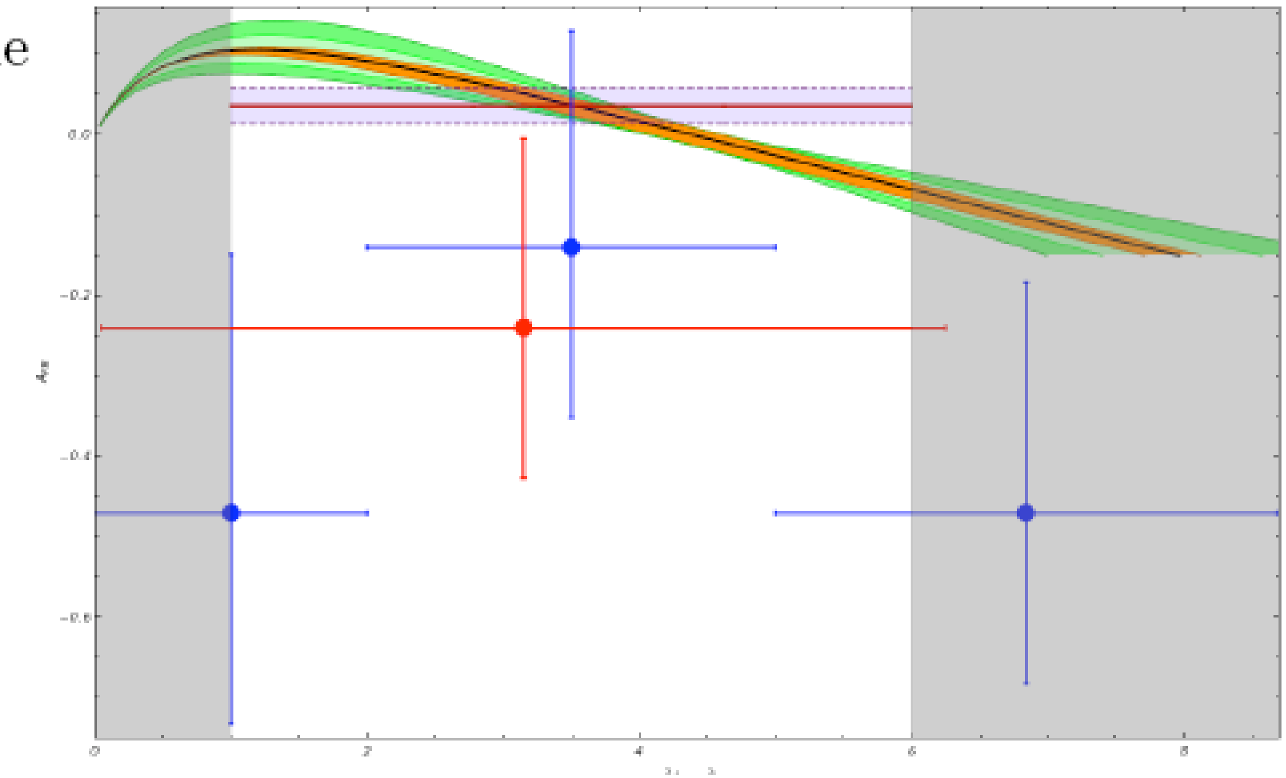
Remark: SuperLHCB/SuperB can offer more precision

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



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

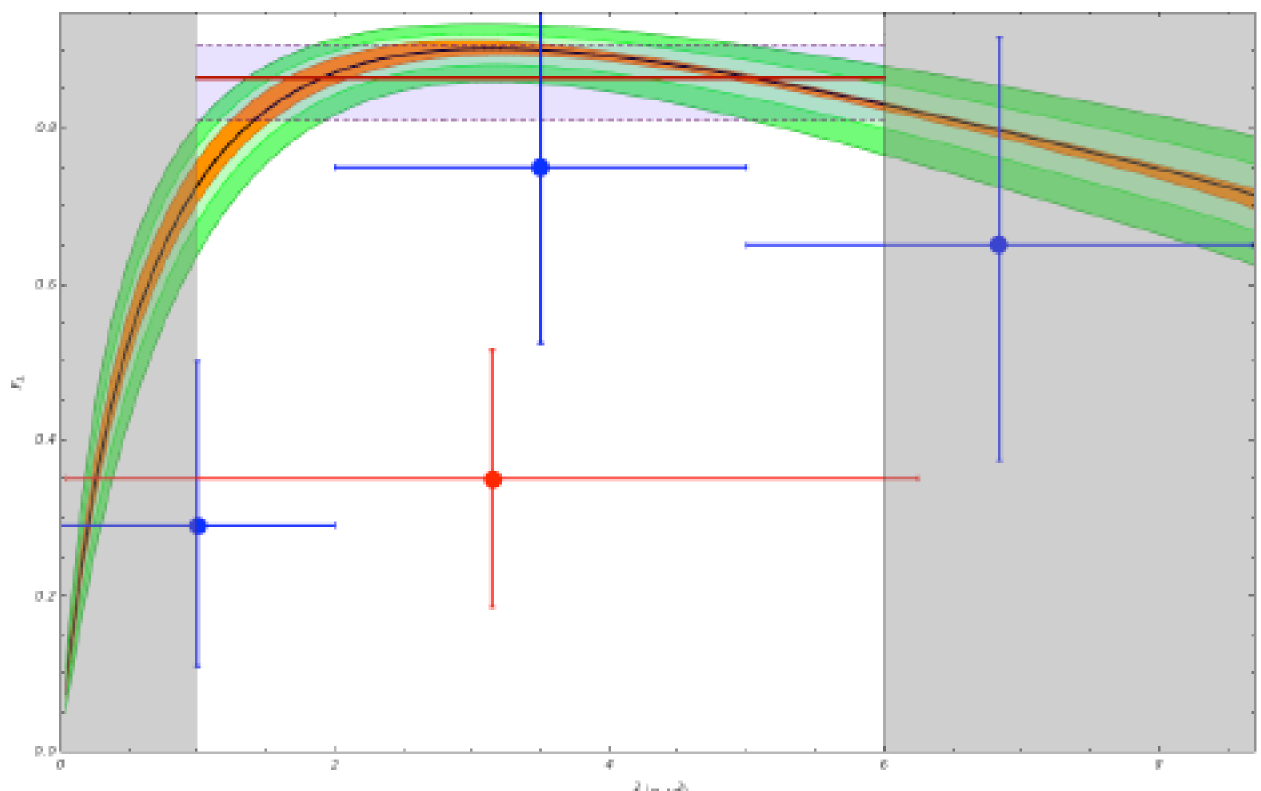
old observables : data available



Babar FPCP 2008

Belle ICHEP 2008

$$A_{\rm FB} = \frac{3}{2}\frac{{\rm Re}(A_{\parallel L}A^*_{\perp L}) - {\rm Re}(A_{\parallel R}A^*_{\perp R})}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

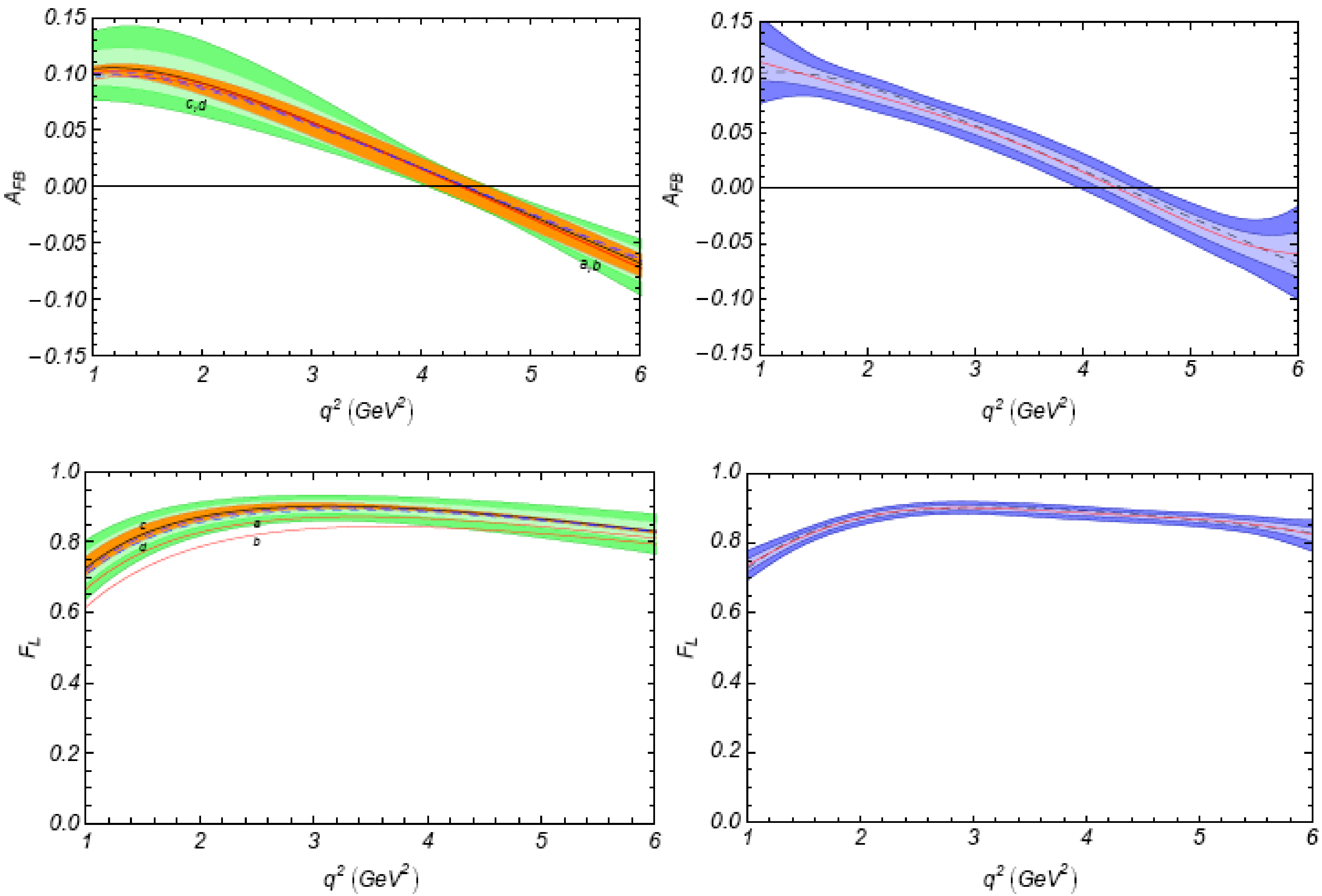


Babar FPCP 2008

Belle ICHEP 2008

$$F_L(s) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

LHCb ($10 fb^{-1}$) will clarify the situation

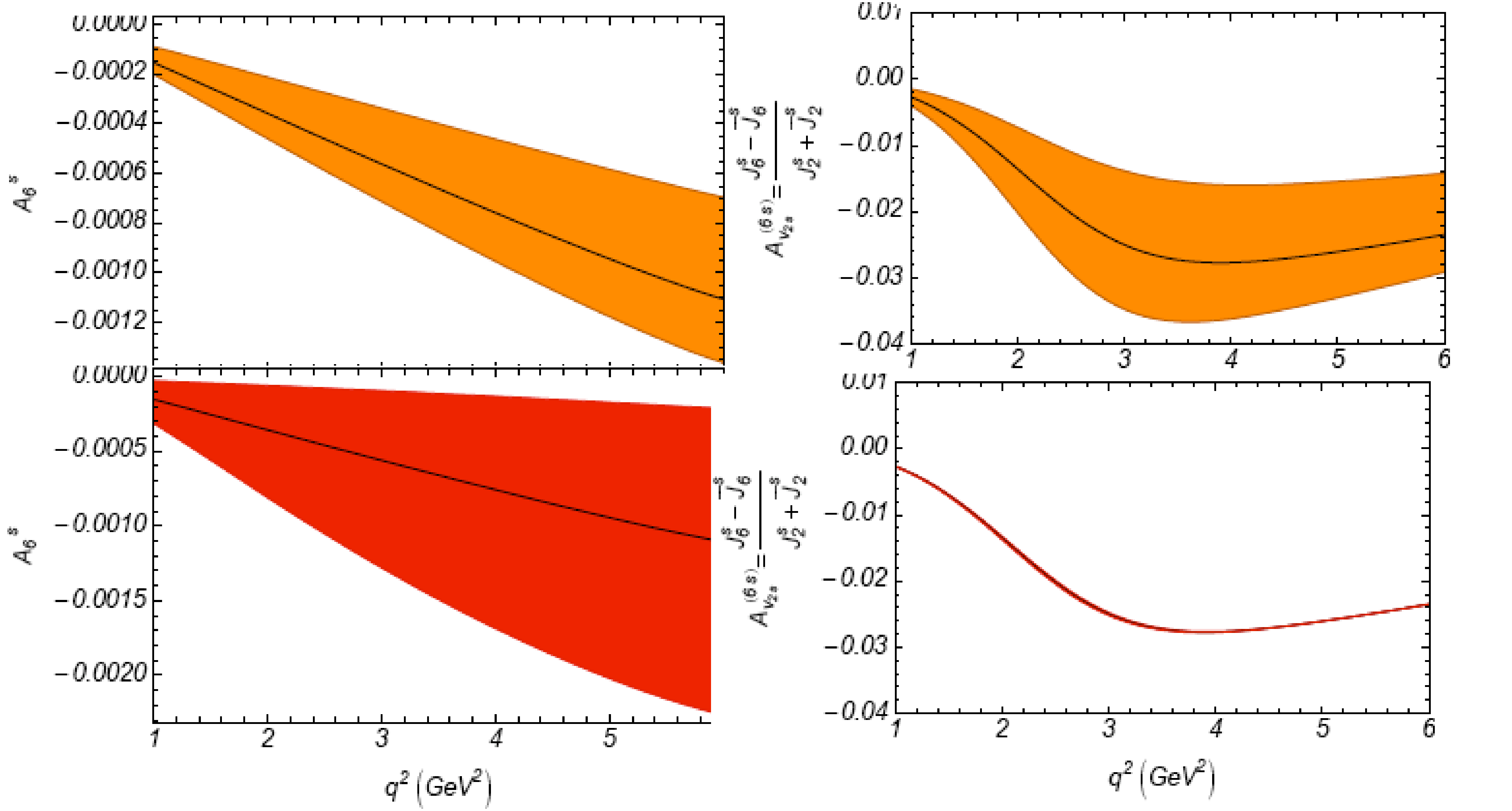


CP violating observables

- Angular distributions allow for the measurement of 7 CP asymmetries
  (Krüger,Seghal,Sinha^2 2000,2005)
- NLO (α_s) corrections included: scale uncertainties reduced
  (however, some CP asymmetries start at NLO only)
  (Bobeth,Hiller,Piranishvili 2008)
- New CP-violating phases in C_{10},C'_{10}, C_9, and C'_9 are by now NOT very much constrained and enhance the CP-violating observables drastically
  (Bobeth,Hiller,Piranishvili 2008; Buras et al. 2008)
- New physics reach of CP-violating observables of the angular distributions depends on the theoretical and experimental uncertainties:
  - soft/QCD formfactors
  - other input parameters
  - scale dependences
  - Λ/m_b corrections
  - experimental sensitivity in the full angular fit

Appropriate normalization eliminates the uncertainty due to form factors II

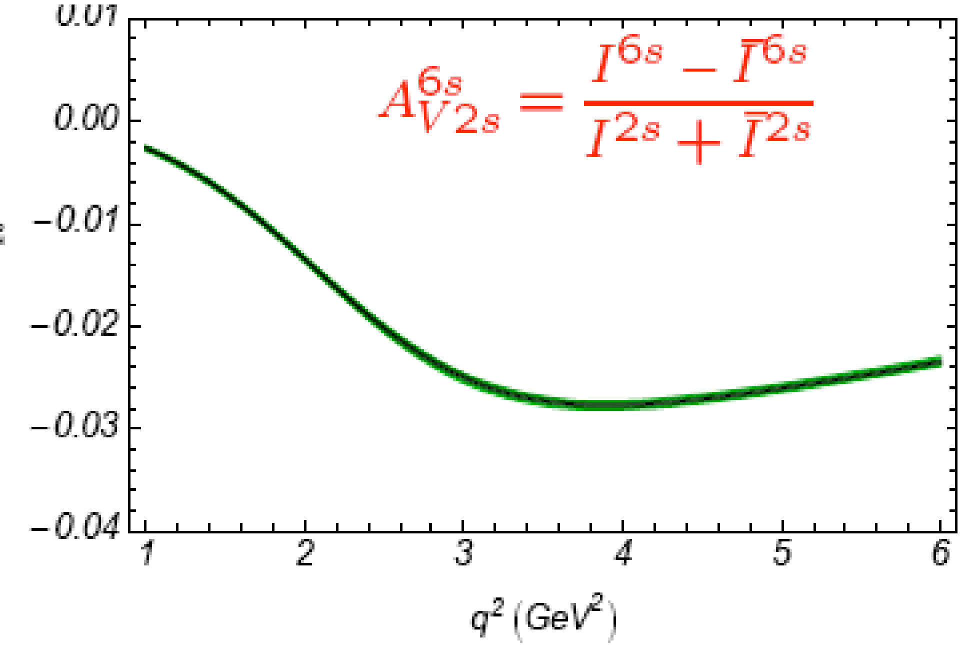
$$A^{6s} = \frac{I^{6s} - \bar{I}^{6s}}{d(\Gamma + \bar{\Gamma})/dq^2} \qquad A^{6s}_{V2s} = \frac{I^{6s} - \bar{I}^{6s}}{I^{2s} + \bar{I}^{2s}}$$

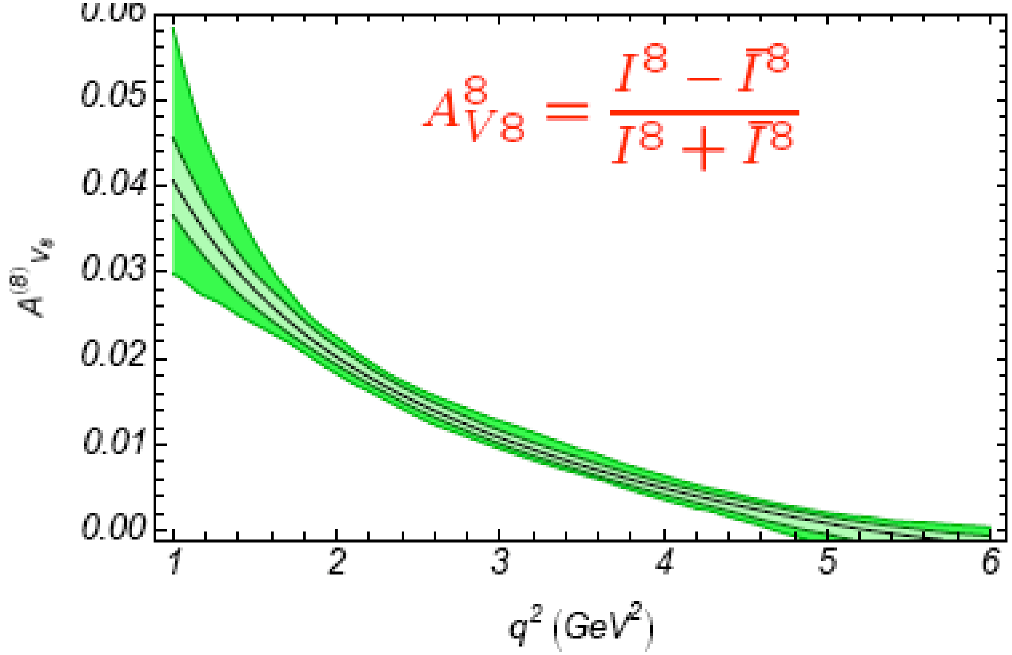


Orange bands: scale/input uncertainty including formfactors

Red bands: conservative estimate of uncertainty due to formfactors only

Λ/m_b corrections very small due to small weak SM phase





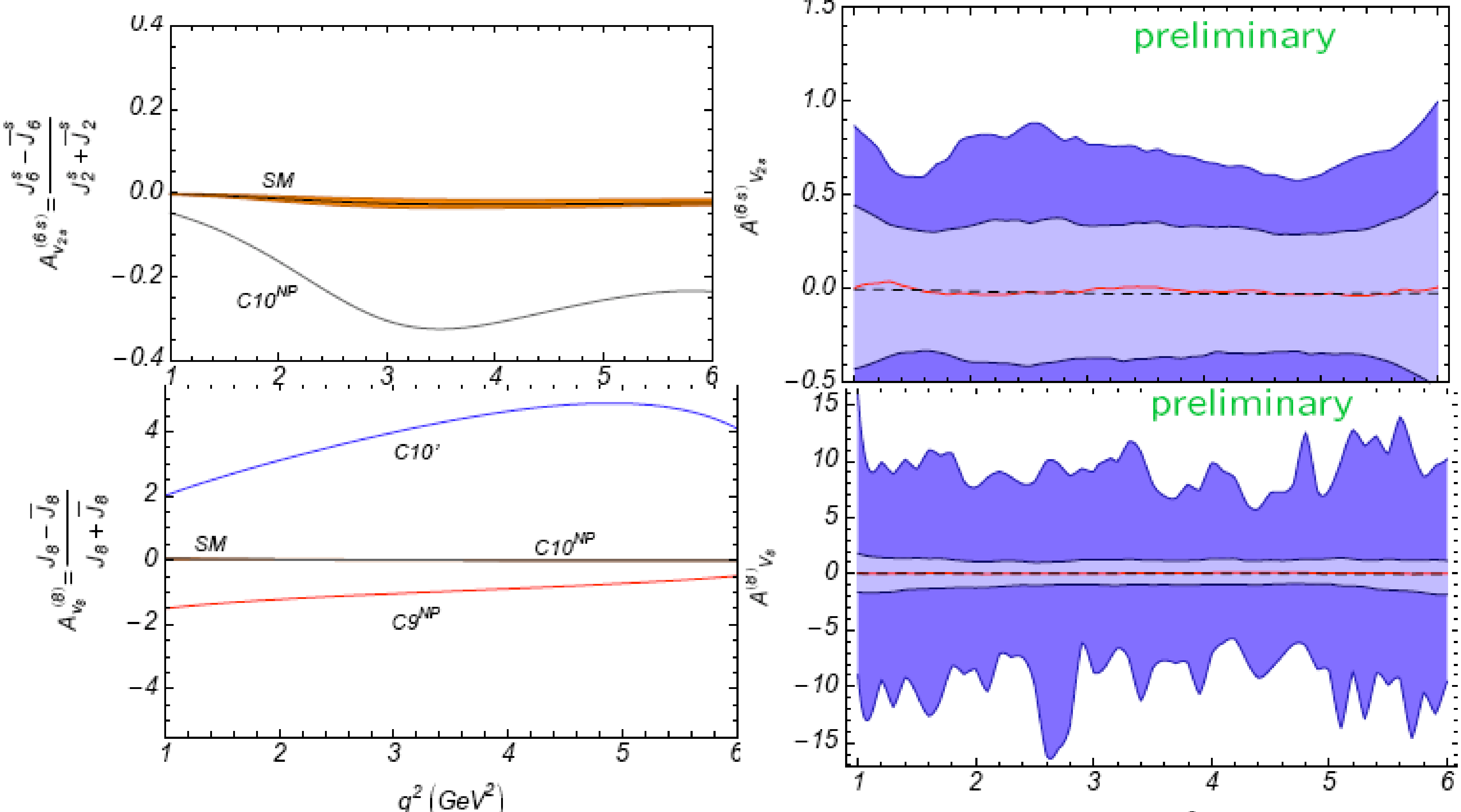
Uncertainty due Λ/m_b corrections significantly smaller than error due to input parameters

Ansatz with random strong phases $\Phi_{1/2}$ and $C_{1/2}$ with 5% and 10%

$$A = A_1(1 + C_1 e^{i\phi_1}) + e^{i\theta} A_2(1 + C_2 e^{i\phi_2})$$

Will significantly larger in scenarios with large new physics phases

Possible new physics effects versus experimental uncertainties



$|C_{9,NP}| = 2, \Phi_9 = \pi/8; |C_{10}, NP| = 1.5, \Phi_{10} = \pi/8; |C'_{10}| = 2, \Phi_{10'} = \pi/8$

New physics not outside the experimental 2σ range.

However, all phases ($0 \to 2\pi$) are compatible with the present data

In contrast to observables like A_T^i, CP observables call for Super-LHCb

Future opportunities

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

  highlights: B_s mixing phase, angle γ, $B \to K^* \mu\mu$, $B_s \to \mu\mu$,$B_s \to \phi\phi$
  then possibility for upgrade to $100 fb^{-1}$

- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:
  rare kaon decays $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- Two proposals for a Super-B factory:

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

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

Further issues

- NLO corrections included
- Λ/m_b corrections estimated for each amplitude as ±10% and ±5%

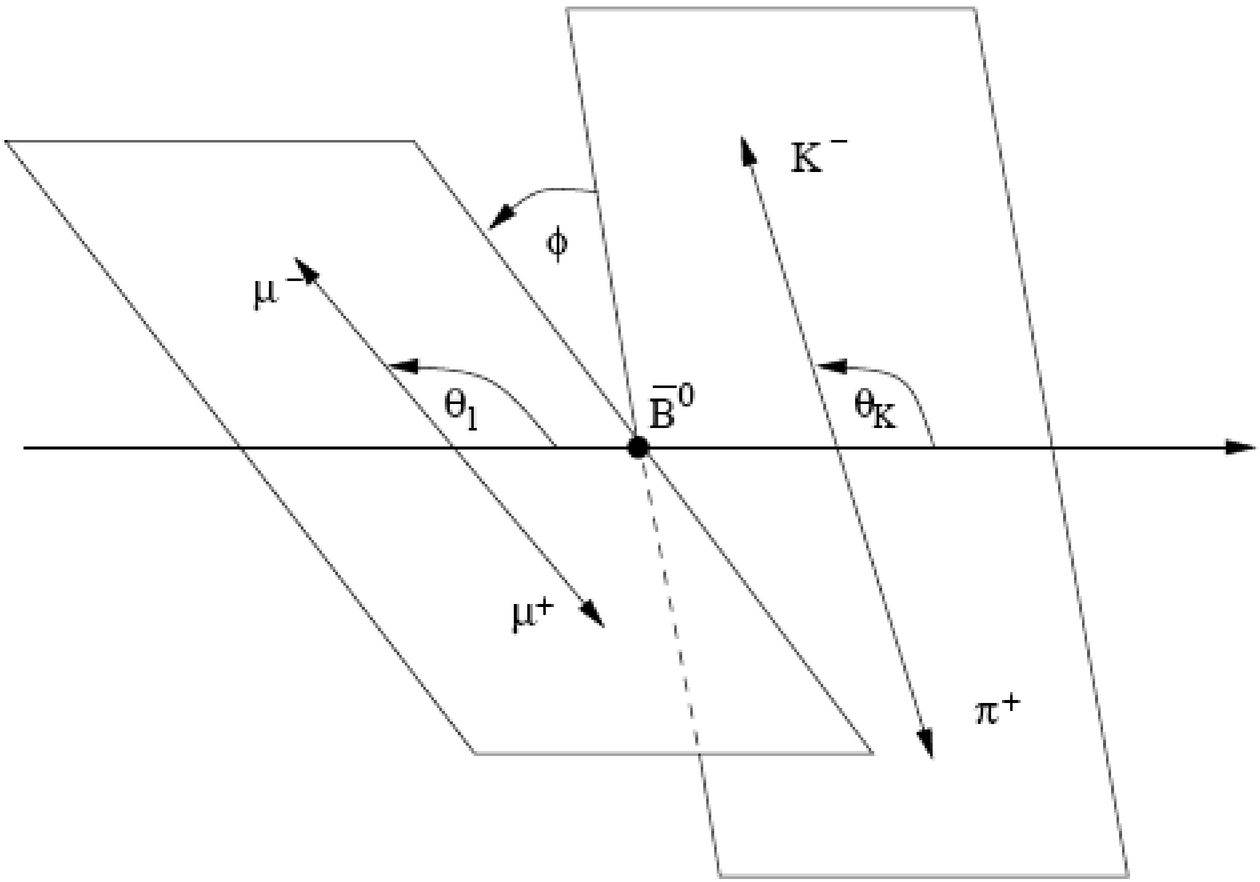
  this uncertainty fully dominant

- Input parameters:

m_B	$5.27950 \pm 0.00033\,\text{GeV}$	λ	0.2262 ± 0.0014
m_K	$0.896 \pm 0.040\,\text{GeV}$	A	0.815 ± 0.013
M_W	$80.403 \pm 0.029\,\text{GeV}$	$\bar{\rho}$	0.235 ± 0.031
M_Z	$91.1876 \pm 0.0021\,\text{GeV}$	$\bar{\eta}$	0.349 ± 0.020
$\hat{m}_t(\hat{m}_t)$	172.5 ± 2.7 GeV	$\Lambda_{\text{QCD}}^{(n_f=5)}$	$220 \pm 40\,\text{MeV}$
$m_{b,\text{PS}}(2\,\text{GeV})$	4.6 ± 0.1 GeV	$\alpha_s(M_Z)$	0.1176 ± 0.0002
m_c	1.4 ± 0.2 GeV	α_{em}	$1/137.035999679$
f_B	200 ± 30 MeV	$a_1(K^*)_{\perp,\parallel}$	0.20 ± 0.05
$f_{K^*,\perp}(1\,\text{GeV})$	185 ± 10 MeV	$a_2(K^*)_{\perp}$	0.06 ± 0.06
$f_{K^*,\parallel}$	218 ± 4 MeV	$a_2(K^*)_{\parallel}$	0.04 ± 0.04
$\xi_{K^*,\parallel}(0)$	0.16 ± 0.03	$\lambda_{B,+}(1.5\text{GeV})$	$0.485 \pm 0.115\,\text{GeV}$
$\xi_{K^*,\perp}(0)$¶	0.26 ± 0.02		

¶ $\xi_{K^*,\perp}(0)$ has been determined from experimental data.

More on kinematics:



z axis: Direction of anti-K^{*0} in rest frame of anti-B_d

θ_l : Angle between μ^- and **z** axis in $\mu\mu$ rest frame

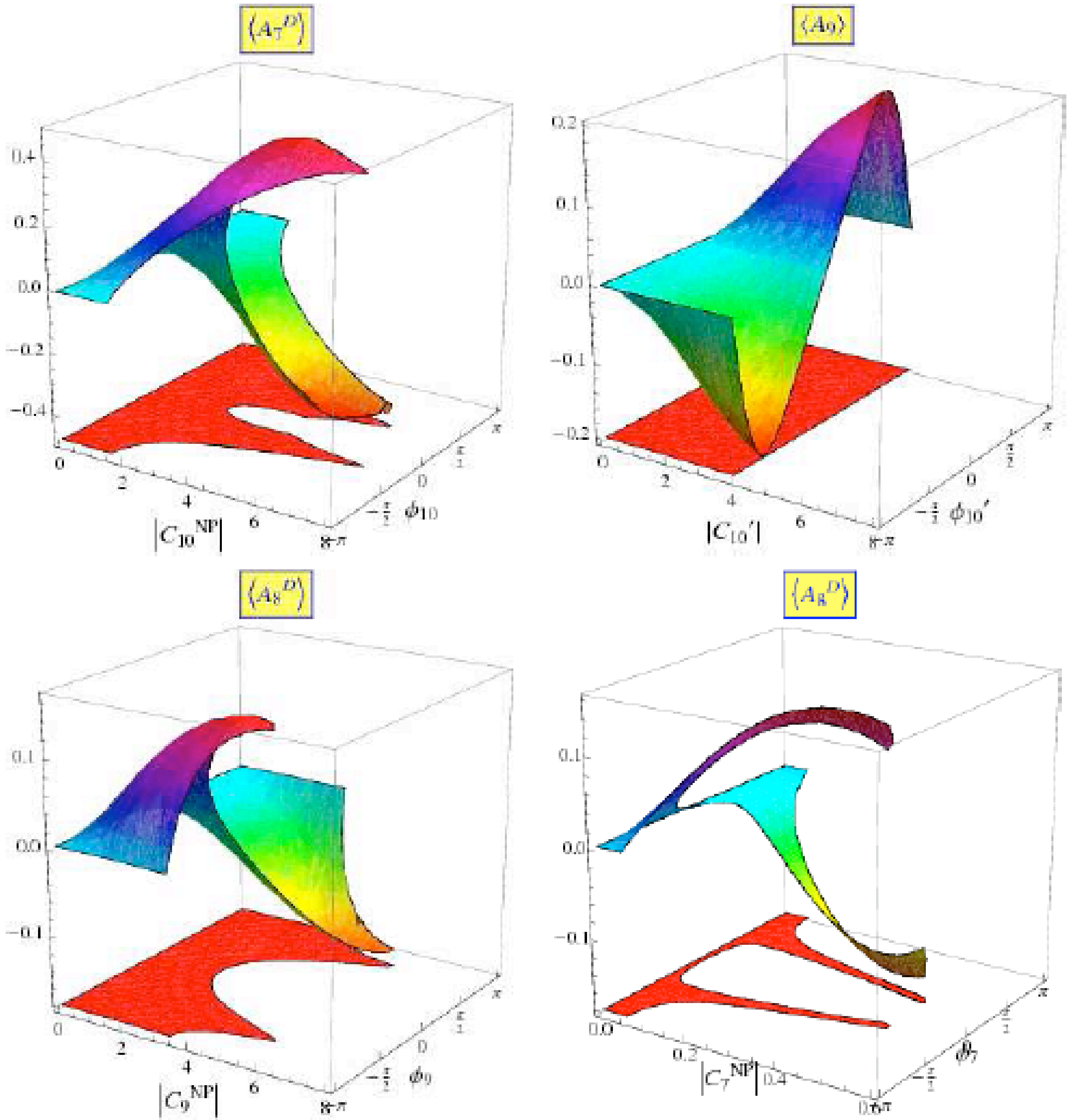
θ_K : Angle between K^- and **z** axis in anti-K^* rest frame

ϕ : Angle between the anti-K^* and $\mu\mu$ decay planes

$$\mathbf{e}_z = \frac{\mathbf{p}_{K^-} + \mathbf{p}_{\pi^+}}{|\mathbf{p}_{K^-} + \mathbf{p}_{\pi^+}|}\,, \quad \mathbf{e}_l = \frac{\mathbf{p}_{\mu^-} \times \mathbf{p}_{\mu^+}}{|\mathbf{p}_{\mu^-} \times \mathbf{p}_{\mu^+}|}\,, \quad \mathbf{e}_K = \frac{\mathbf{p}_{K^-} \times \mathbf{p}_{\pi^+}}{|\mathbf{p}_{K^-} \times \mathbf{p}_{\pi^+}|}$$

$$\cos\theta_l = \frac{\mathbf{q}_{\mu^-} \cdot \mathbf{e}_z}{|\mathbf{q}_{\mu^-}|}\,, \quad \cos\theta_K = \frac{\mathbf{r}_{K^-} \cdot \mathbf{e}_z}{|\mathbf{r}_{K^-}|}\,, \quad \sin\phi = (\mathbf{e}_l \times \mathbf{e}_K) \cdot \mathbf{e}_z\,, \quad \cos\phi = \mathbf{e}_K \cdot \mathbf{e}_l$$

New physics phases not very much constrained (Bobeth,Hiller,Piranishvili 2008)



Angular distributions functions depend on the 6 complex K^* spin amplitudes

$I_i = I_i(\,A_{\perp L/R}, A_{\parallel L/R}, A_{0L/R}\,)$ (limit $m_{\text{lepton}} = 0$)

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

$$
\begin{aligned}
I_1 &= \frac{3}{4}\left(|A_{\perp L}|^2 + |A_{\parallel L}|^2 + (L \to R)\right)\sin^2\theta_K + \left(|A_{0L}|^2 + |A_{0R}|^2\right)\cos^2\theta_K \\
&\equiv a\sin^2\theta_K + b\cos^2\theta_K, \\
I_2 &= \frac{1}{4}(|A_{\perp L}|^2 + |A_{\parallel L}|^2)\sin^2\theta_K - |A_{0L}|^2\cos^2\theta_K + (L \to R) \\
&\equiv c\sin^2\theta_K + d\cos^2\theta_K, \\
I_3 &= \frac{1}{2}\Big[(|A_{\perp L}|^2 - |A_{\parallel L}|^2)\sin^2\theta_K + (L \to R)\Big] \equiv e\sin^2\theta_K, \\
I_4 &= \frac{1}{\sqrt{2}}\Big[\mathrm{Re}(A_{0L}A^*_{\parallel L})\sin 2\theta_K + (L \to R)\Big] \equiv f\sin 2\theta_K, \\
I_5 &= \sqrt{2}\Big[\mathrm{Re}(A_{0L}A^*_{\perp L})\sin 2\theta_K - (L \to R)\Big] \equiv g\sin 2\theta_K, \\
I_6 &= 2\Big[\mathrm{Re}(A_{\parallel L}A^*_{\perp L})\sin^2\theta_K - (L \to R)\Big] \equiv h\sin^2\theta_K, \\
I_7 &= \sqrt{2}\Big[\mathrm{Im}(A_{0L}A^*_{\parallel L})\sin 2\theta_K - (L \to R)\Big] \equiv j\sin 2\theta_K, \\
I_8 &= \frac{1}{\sqrt{2}}\Big[\mathrm{Im}(A_{0L}A^*_{\perp L})\sin 2\theta_K + (L \to R)\Big] \equiv k\sin 2\theta_K, \\
I_9 &= \Big[\mathrm{Im}(A^*_{\parallel L}A_{\perp L})\sin^2\theta_K + (L \to R)\Big] \equiv m\sin^2\theta_K.
\end{aligned}
$$

11 coefficients to be fixed in the full angular fit, but $a = 3c$ and $b = -d$

12 theoretical independent amplitudes $A_j \overset{?}{\Leftrightarrow}$ 9 independent coefficient functions in I

Symmetries of the angular distribution functions $I_i = I_i(\, A_{\perp L/R}, A_{\| L/R}, A_{0L/R})$

(angular distribution spin averaged)

- Global phase transformation of the L amplitudes

$$A'_{\perp L} = e^{i\phi_L} A_{\perp L},\ A'_{\| L} = e^{i\phi_L} A_{\| L},\ A'_{0L} = e^{i\phi_L} A_{0L}$$

- Global phase transformations of the R amplitudes

$$A'_{\perp R} = e^{i\phi_R} A_{\perp R},\ A'_{\| R} = e^{i\phi_R} A_{\| R},\ A'_{0R} = e^{i\phi_R} A_{0R}$$

- Continuous L-R rotation

$$\begin{aligned}
A'_{\perp L} &= +\cos\theta A_{\perp L} + \sin\theta A^*_{\perp R} \\
A'_{\perp R} &= -\sin\theta A^*_{\perp L} + \cos\theta A_{\perp R} \\
A'_{0L} &= +\cos\theta A_{0L} - \sin\theta A^*_{0R} \\
A'_{0R} &= +\sin\theta A^*_{0L} + \cos\theta A_{0R} \\
A'_{\| L} &= +\cos\theta A_{\| L} - \sin\theta A^*_{\| R} \\
A'_{\| R} &= +\sin\theta A^*_{\| L} + \cos\theta A_{\| R}.
\end{aligned}$$

Only 9 amplitudes A_j are independent in respect to the angular distribution

Observables as $F(I_i)$ are also invariant under the 3 symmetries !

- Transversity amplitude A_T^1

  Defining the helicity distributions $\Gamma_\pm$ as $\Gamma_\pm = |H^L_{\pm 1}|^2 + |H^R_{\pm 1}|^2$

  one can define (Melikhov,Nikitin,Simula 1998)

$$A_T^{(1)} = \frac{\Gamma_- - \Gamma_+}{\Gamma_- + \Gamma_+} \qquad A_T^{(1)} = \frac{-2\mathrm{Re}(A_\parallel A_\perp^*)}{|A_\perp|^2 + |A_\parallel|^2}$$

  Very sensitive to right-handed currents (Lunghi,Matias 2006)

  Very insensitive to Λ/m_b corrections

  Formfactor cancel out at LO for all s

  Big surprise:

  $A_T^{(1)}$ is not invariant under the symmetries of the angular distribution

  - $A_T^{(1)}$ cannot be extracted from the full angular distribution
  - LHCb: practically not possible to measure the helicity of the final states on a event-by-event basis (neither as statistical distribution)
  - Not a principal problem, but $A_T^{(1)}$ not an observable at LHCb or at Super B (measure three-momentum and charge)

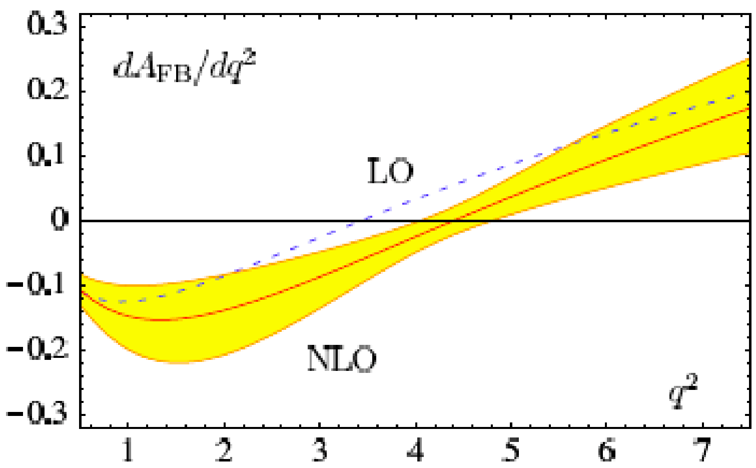
- Region $s \leq 1GeV^2$
  - corresponds to information which is tested out by the $b \to s\gamma$ mode
  - lower resonances complicate the theoretical description
  - longitudinal amplitude generates a logarithmic divergence in the limit $s \to 0$ indicating problems in the theoretical description

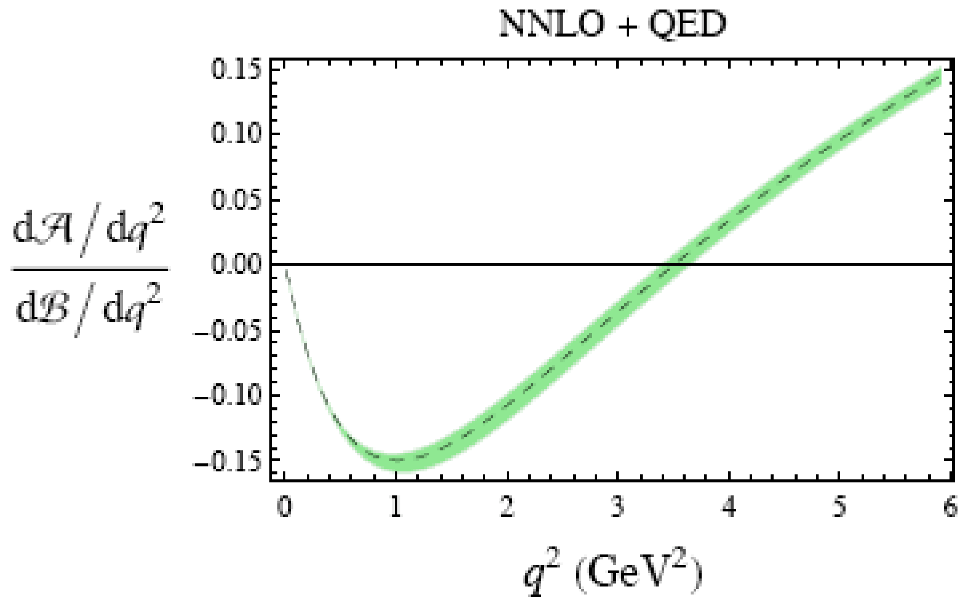
    transversal amplitude however is fine, so observables based on it free from this theoretical problem
  - electron modes preferable (lower cut)

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 $b \to s\ell^+\ell^-$





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

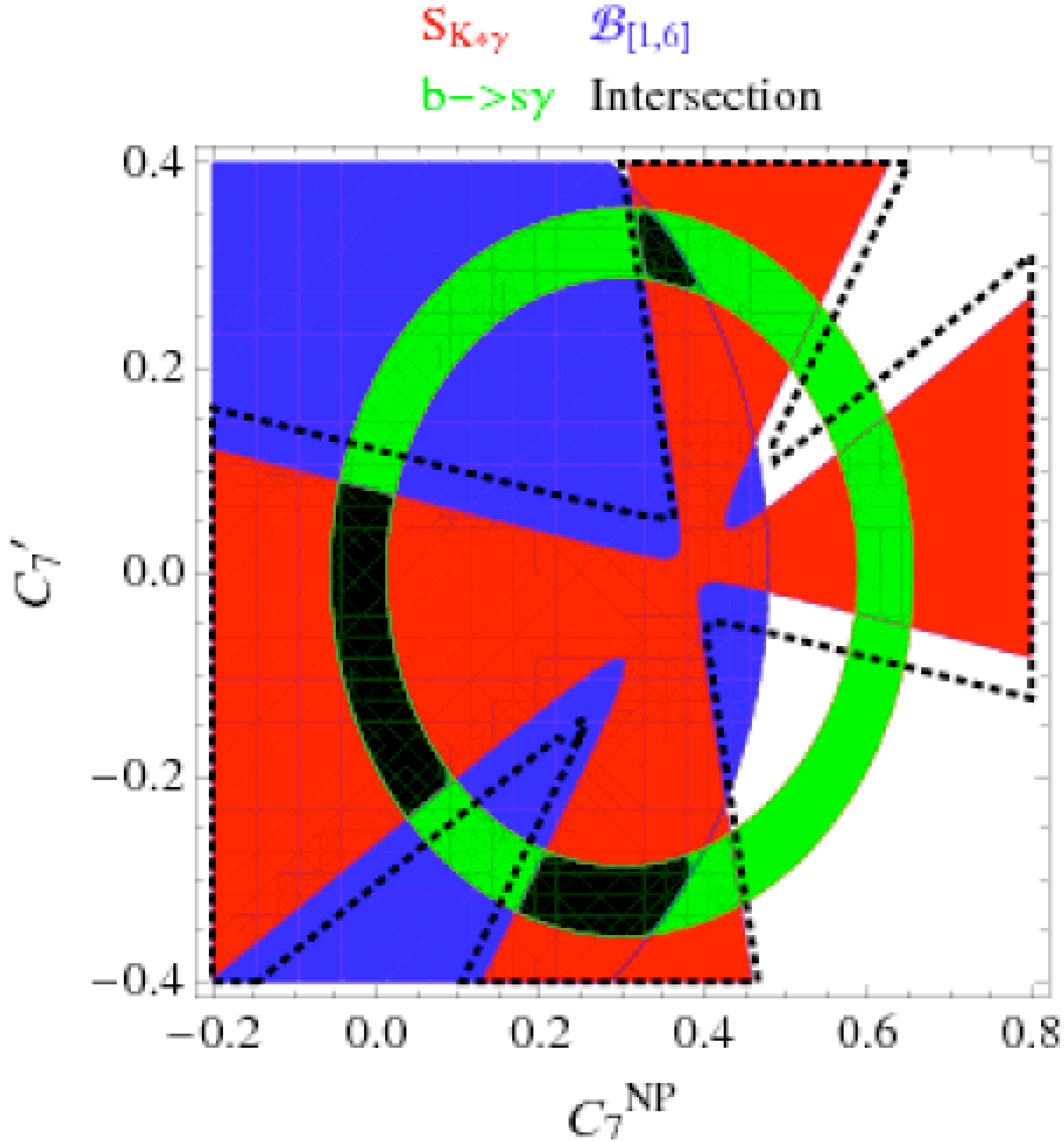
Inclusive Zero:

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

Experimental error at SFF: $4 - 6\%$ Browder,Ciuchini,Gershon,Hazumi,Hurth,Okada,Stocchi arXiv:0710.3799

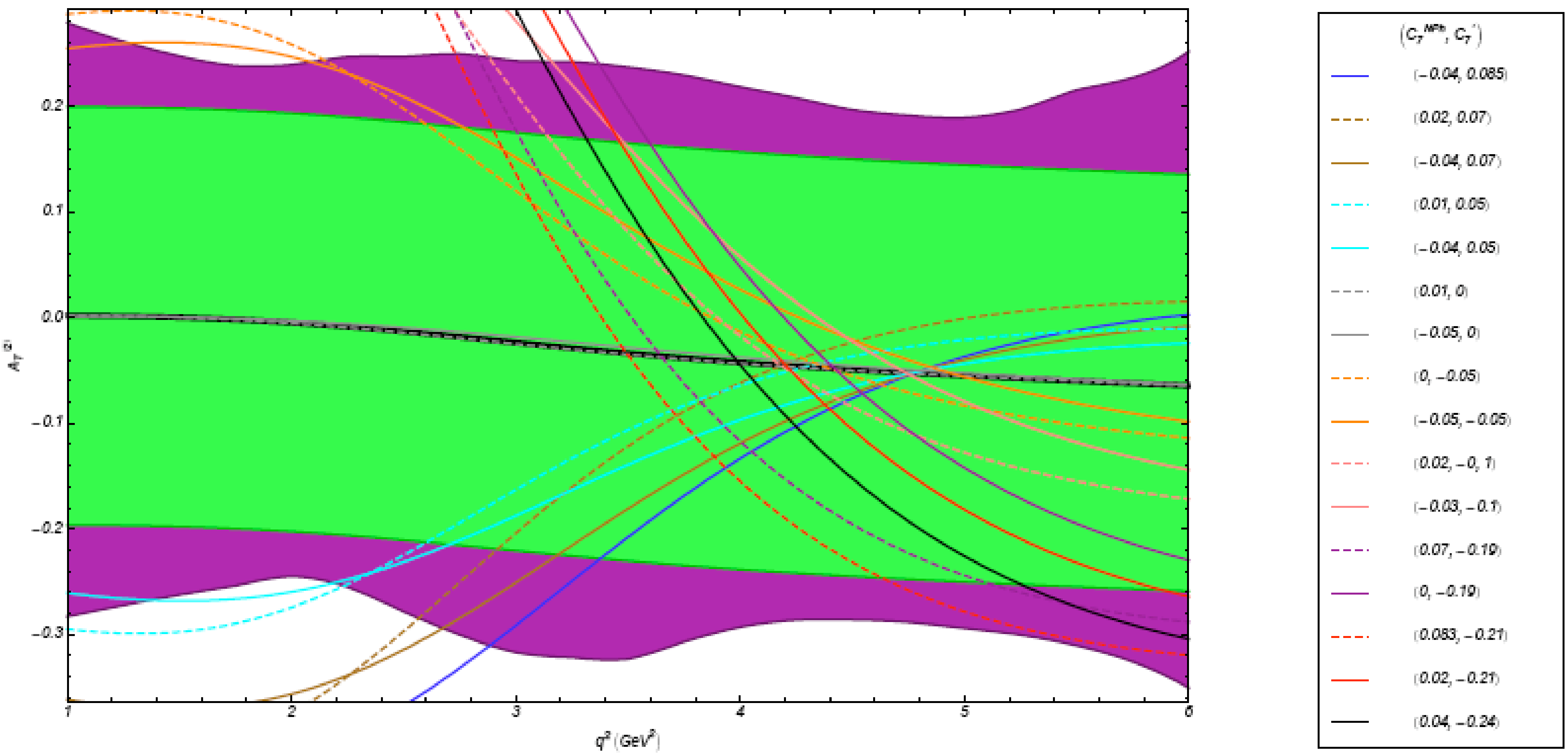
Present bounds on C_7 and C_7':

Bobeth et al, arXiv:0805.2525



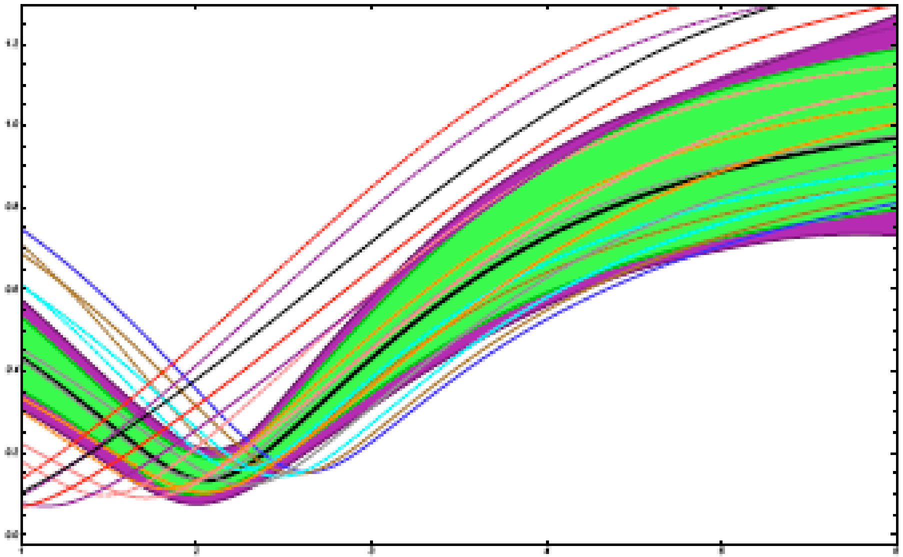
Test of allowed region around $C_7' = 0$ in the C_7 and C_7' plane

$A_T^{(2)}$

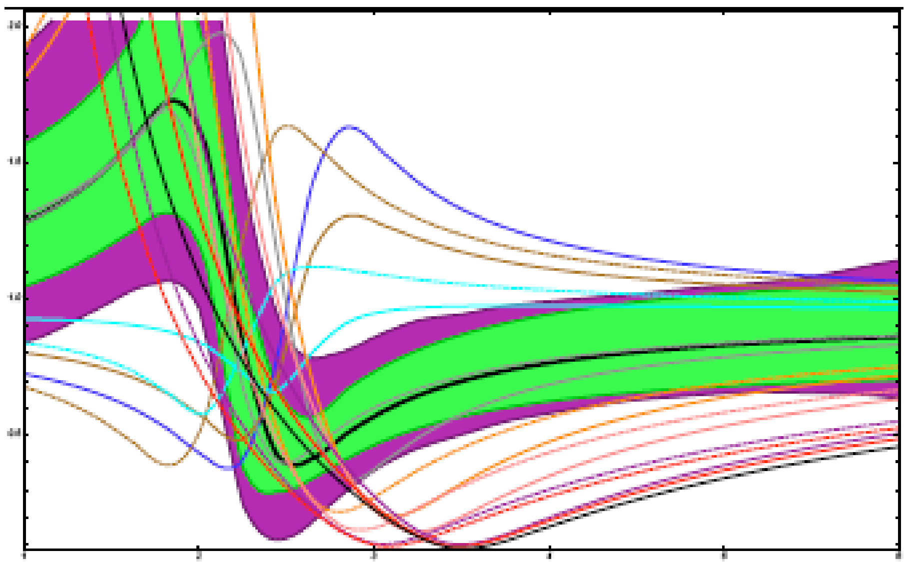


new observables

$A_T^{(3)}$

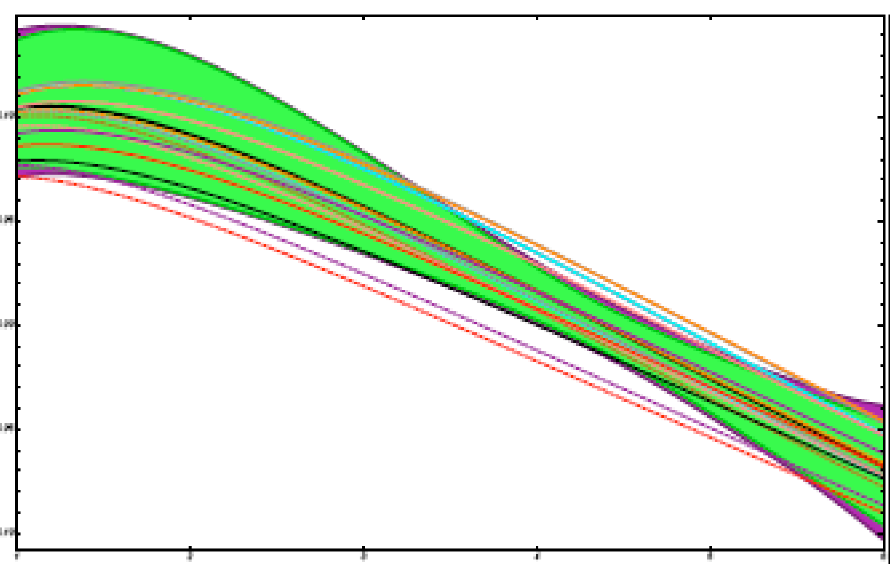


$A_T^{(4)}$

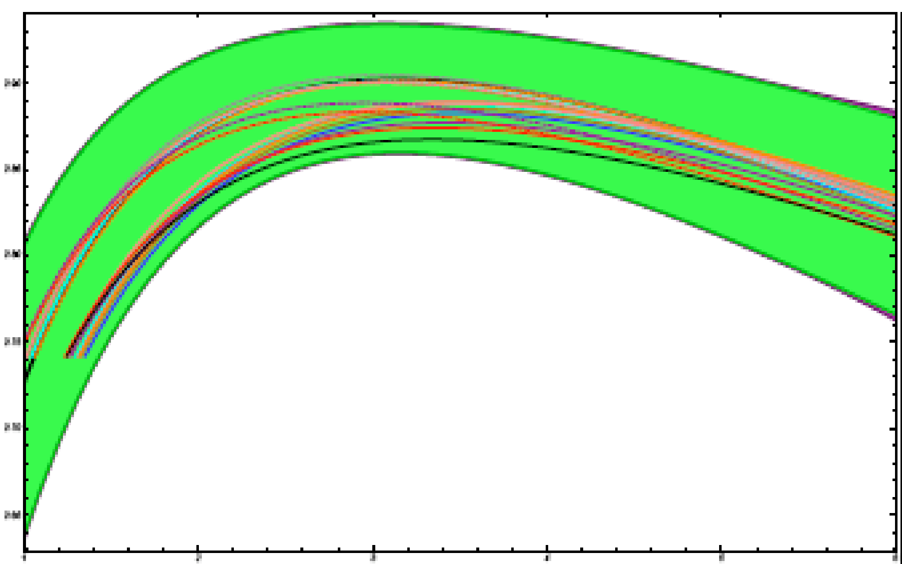


old observables

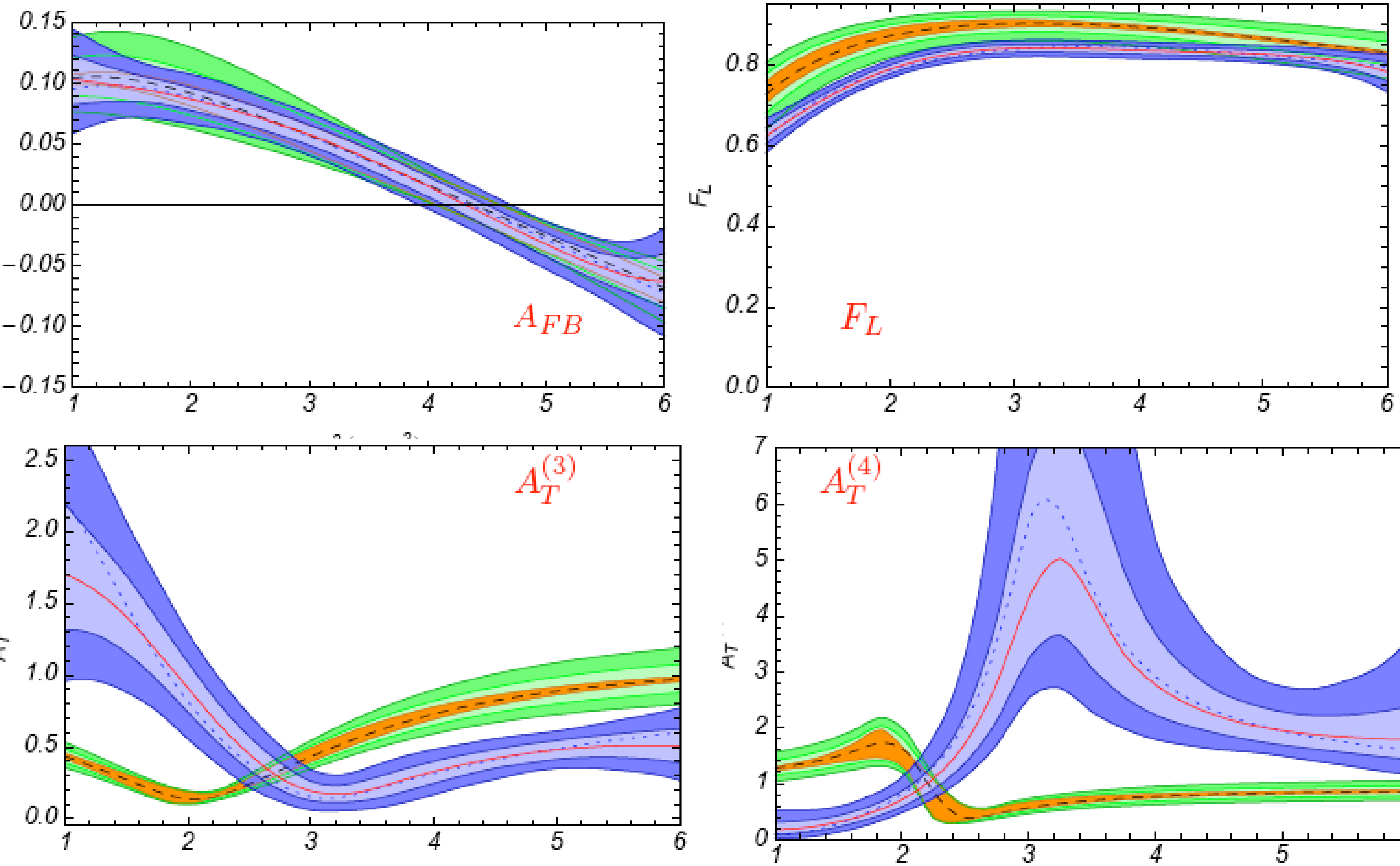
A_{FB}



F_L



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.

Present role of time-dependent CP asymmetry $B \to K^*\gamma$

Theoretical status of CP asymmetry

– General folklore: within the SM are small, $O(m_s/m_b)$

$$\mathcal{O}_{7L} \equiv \frac{e}{16\pi^2} m_b\, \bar{s}\sigma_{\mu\nu} P_R\, b F^{\mu\nu} \quad \mathcal{O}_{7R} \equiv \frac{e}{16\pi^2} m_{s/d}\, \bar{s}\sigma_{\mu\nu} P_L\, b F^{\mu\nu}\ .$$

Mainly: $\bar{B} \to X_s\gamma_L$ and $B \to X_s\gamma_R$ $\Rightarrow$ almost no interference in the SM

– But: within the inclusive case the assumption of a two-body decay is made, the argument does not apply to $b \to s\gamma gluon$

Corrections of order $O(\alpha_s)$, mainly due operator $\mathcal{O}_2$ $\Rightarrow \Gamma_{22}^{\text{brems}}/\Gamma_0 \sim 0.025$
$\Rightarrow$ 11% right-handed contamination
Grinstein,Grossman,Ligeti,Pirjol, hep-ph/0412019

– QCD sum rule estimate of the time-dependent CP asymmetry in $B^0 \to K^{*0}\gamma$ including long-distance contributions due to soft-gluon emission from quark loops versus dimensional estimate of the nonlocal SCET operator series:
Ball,Zwicky,hep-ph/0609037 $\leftrightarrow$ Grinstein,Pirjol,hep-ph/0510104

$$S = -0.022 \pm 0.015^{+0}_{-0.01},\ S^{sgluon} = -0.005 \pm 0.01 \leftrightarrow |S^{sgluon}| \approx 0.06$$

Note: Expansion parameter is Λ_{QCD}/Q where Q is the kinetic energy of the hadronic part. There is no contribution at leading order. Therefore, the effect is expected to be larger for larger invariant hadronic mass, thus, the K^* mode has to have the smallest effect, below the 'average' 10%

Experiment: $S = 0.19 \pm 0.23$ (HFAG)

Future role of time-dependent CP asymmetry $B \to K^* \gamma$

$$S_{K^*\gamma} = -\frac{2|r|}{1+|r|^2} \sin\left(2\beta - \arg(C_7^{(0)} C_7')\right), \qquad r = C_7'/C_7^{(0)}$$

SuperB: $\Delta S = \pm 0.04$ arXiv:hep-ex/0406071

LHCb: $B_s \to \Phi\gamma$

$S_{\Phi\gamma} = 0 \pm 0.002$ $\sin(\phi_s)$! Muheim,Xie,Zwicky,arXiv:0802.0876

$A_{\Phi\gamma}^{\Delta\Gamma} = 0.047 \pm 0.025 + 0.015$ $\cos(\phi_s)$!

LHCb ($2fb^{-1}$): $\Delta A = 0.22$ Golutvin et al., LHCb-PHYS-2007-147