New physics sensitivity of the decay $B \to K^* \ell^+ \ell^-$

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in collaboration

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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

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

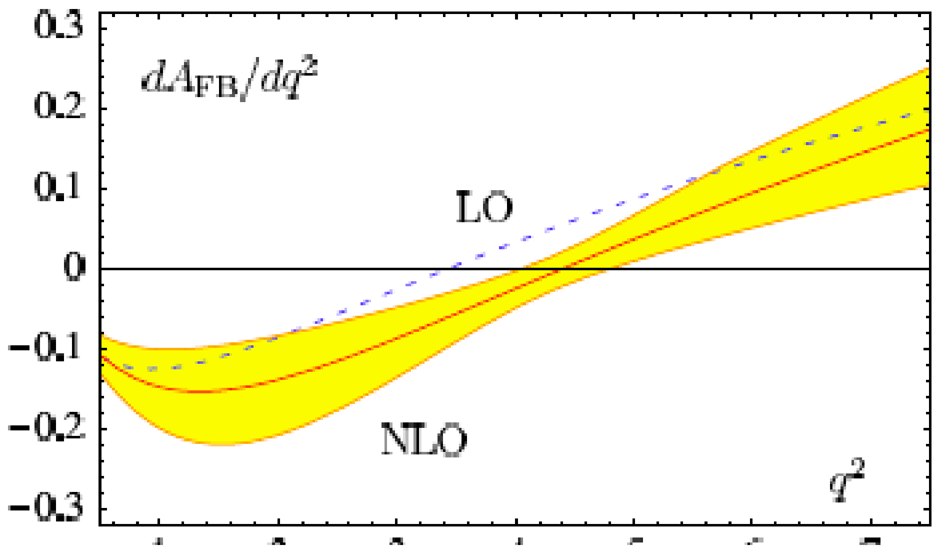
- Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors
- Relations between formfactors in large-energy limit
- Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

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)

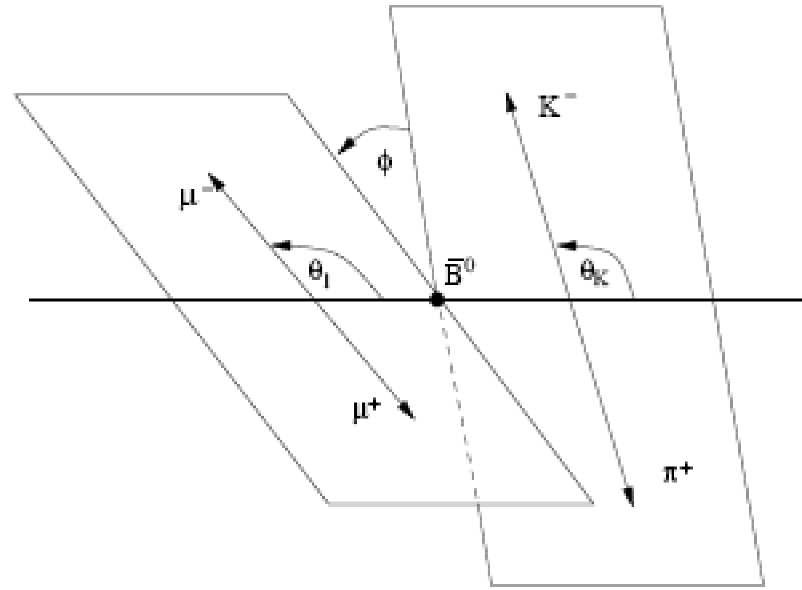
$$q_0^2 = (4.39 + 0.38 - 0.35) GeV^2 \quad (NLO)$$

- 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

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

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

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

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

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

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

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

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

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

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

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

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

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}

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

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

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

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

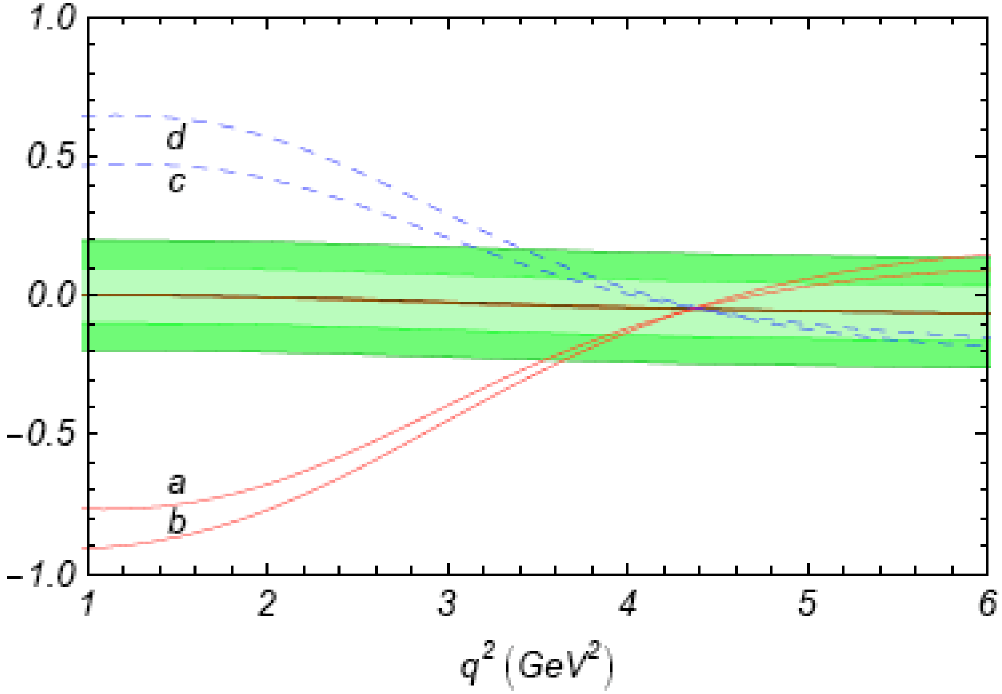
  d) $m_{\tilde{g}}/m_{\tilde{d}} = 0.6$, $(\delta^d_{LR})_{32} = -0.006$.

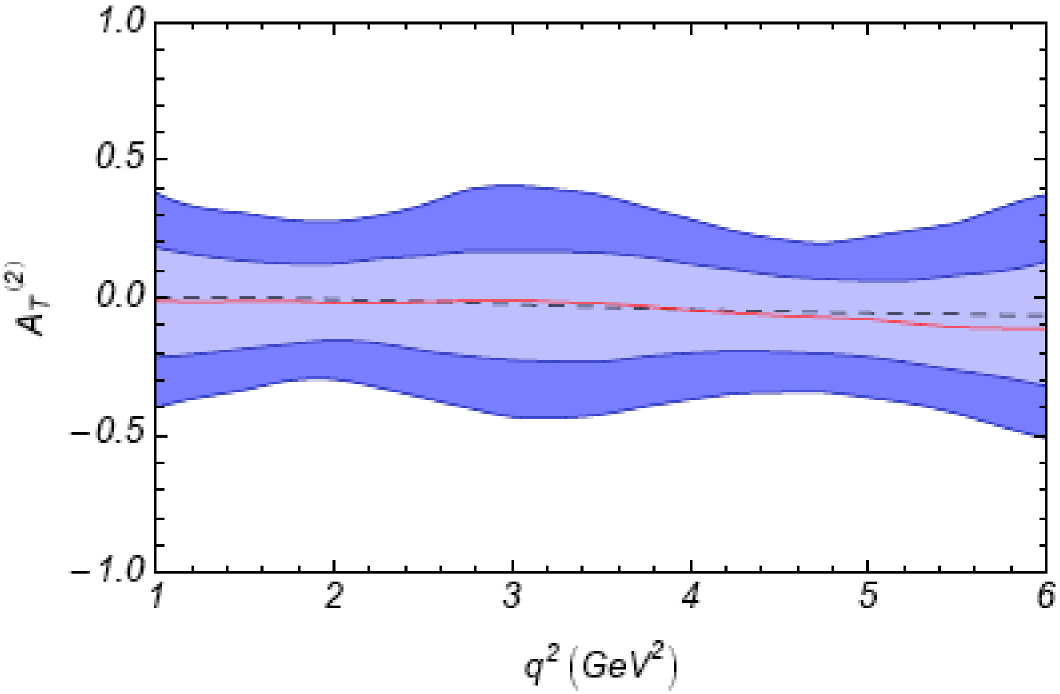
Check of compatibility with other constraints (B physics,ρ parameter,

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 $\pm 10\% \Lambda/m_b$

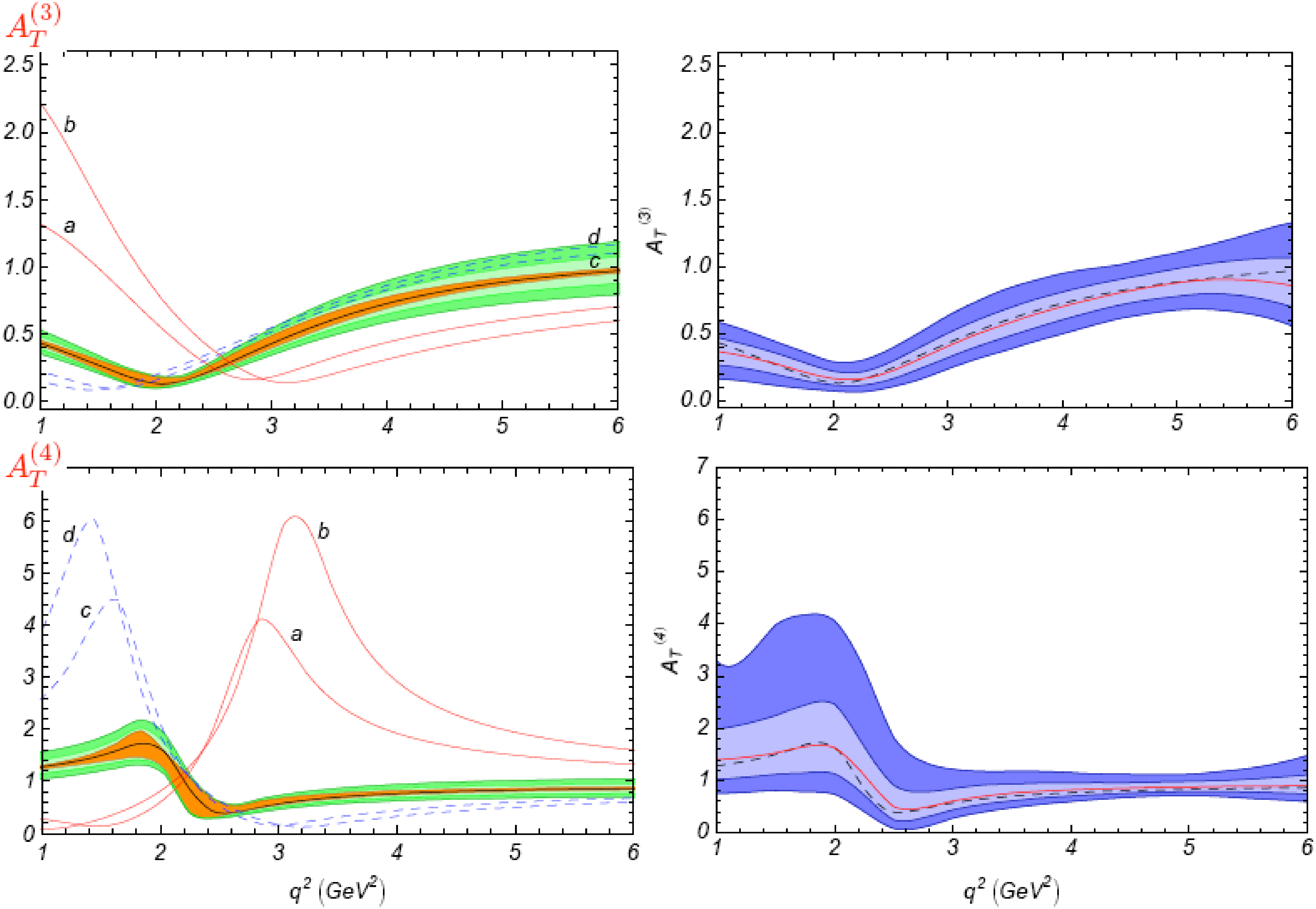
Experimental sensitivity $(10 fb^{-1})$

light green $1\ \sigma$

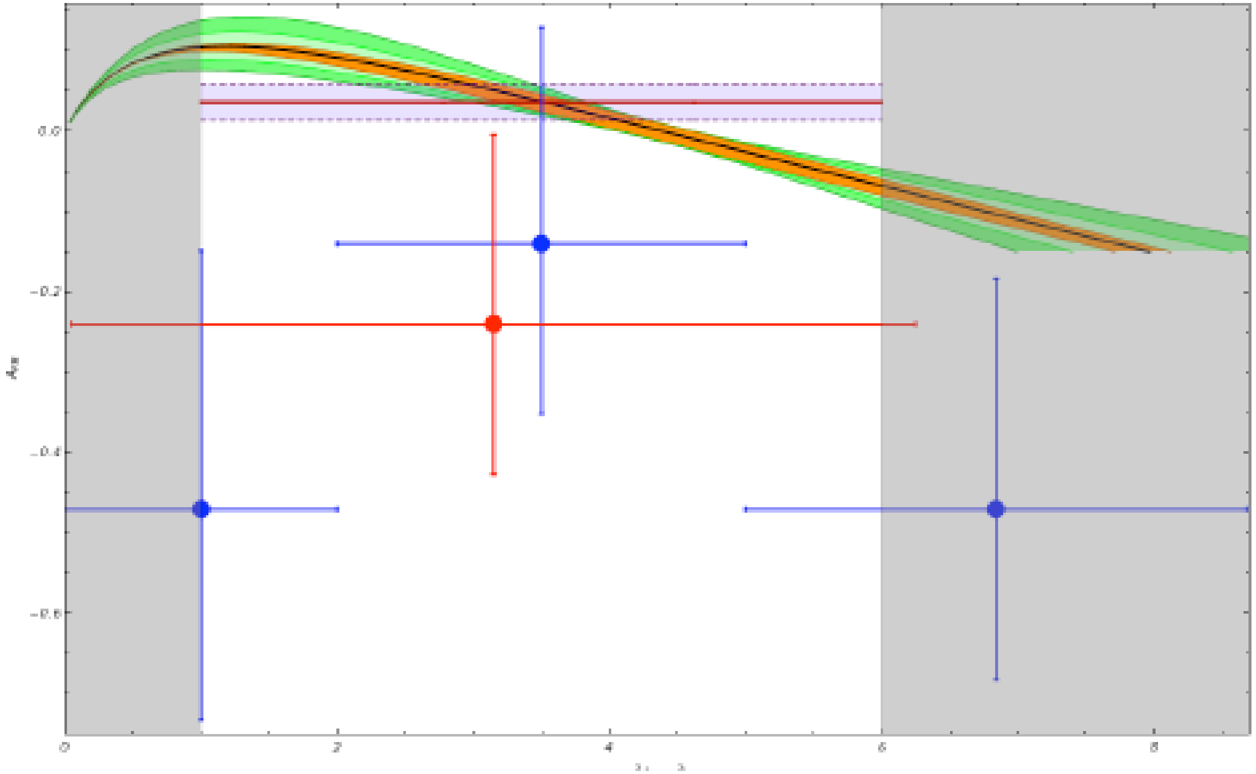
dark green $2\ \sigma$

Remark: SuperLHCB/SuperB can offer more precision

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


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

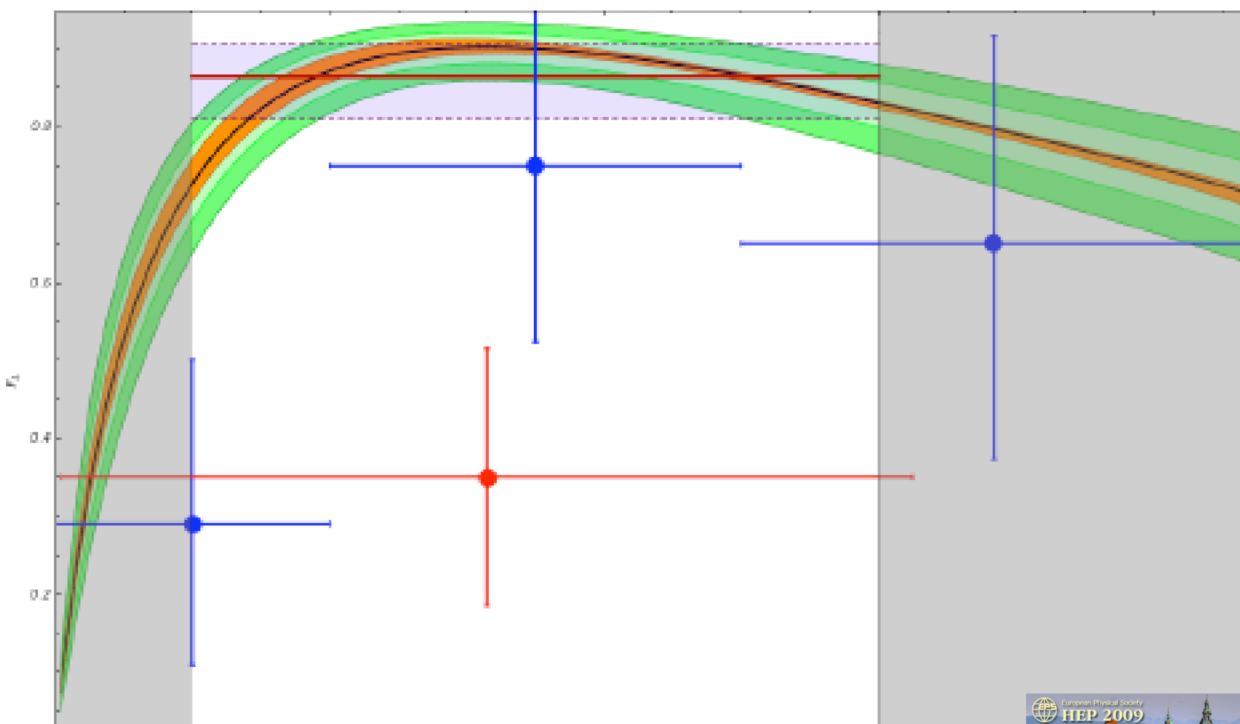
old observables : data available



Babar FPCP 2008

Belle ICHEP 2008

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



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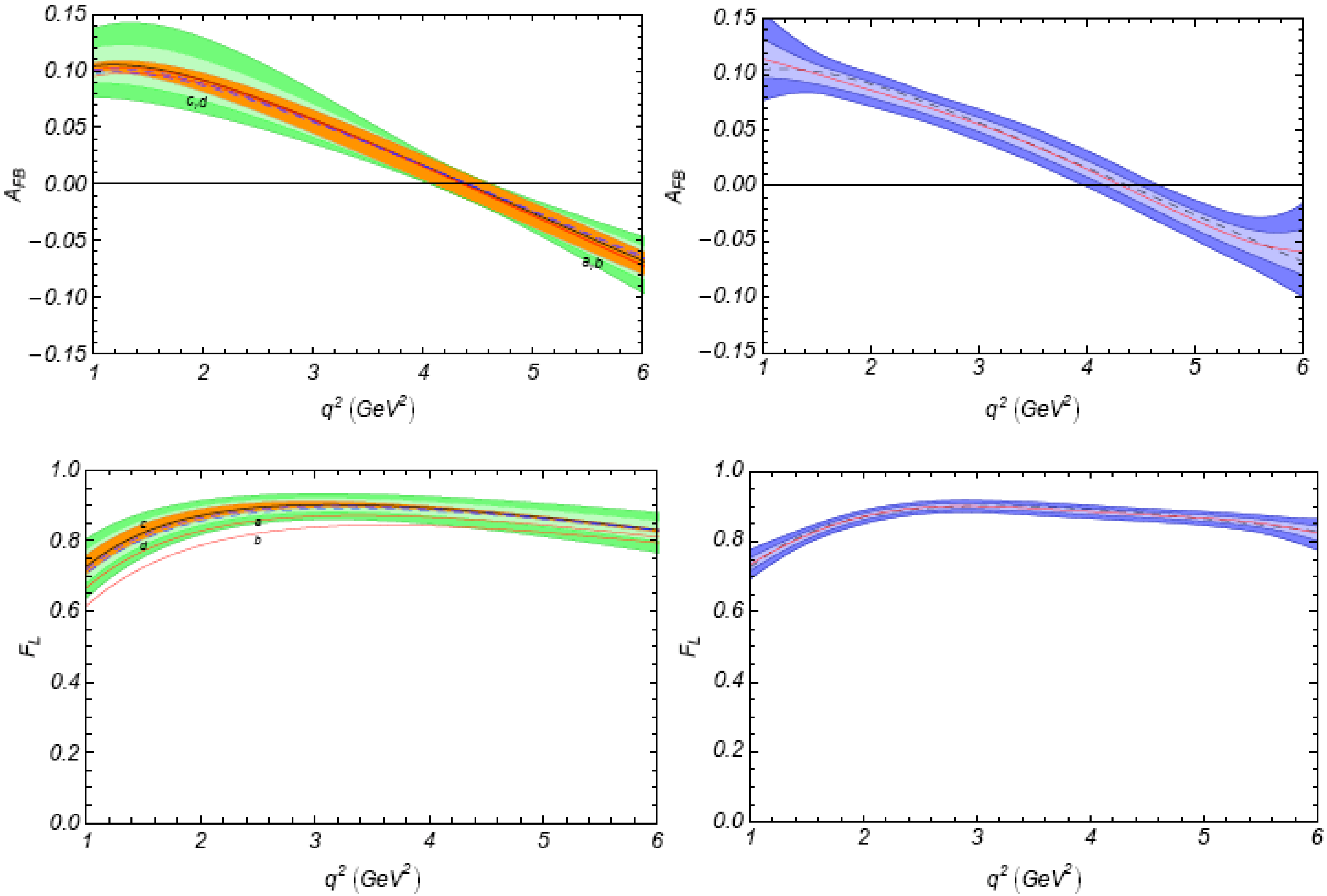
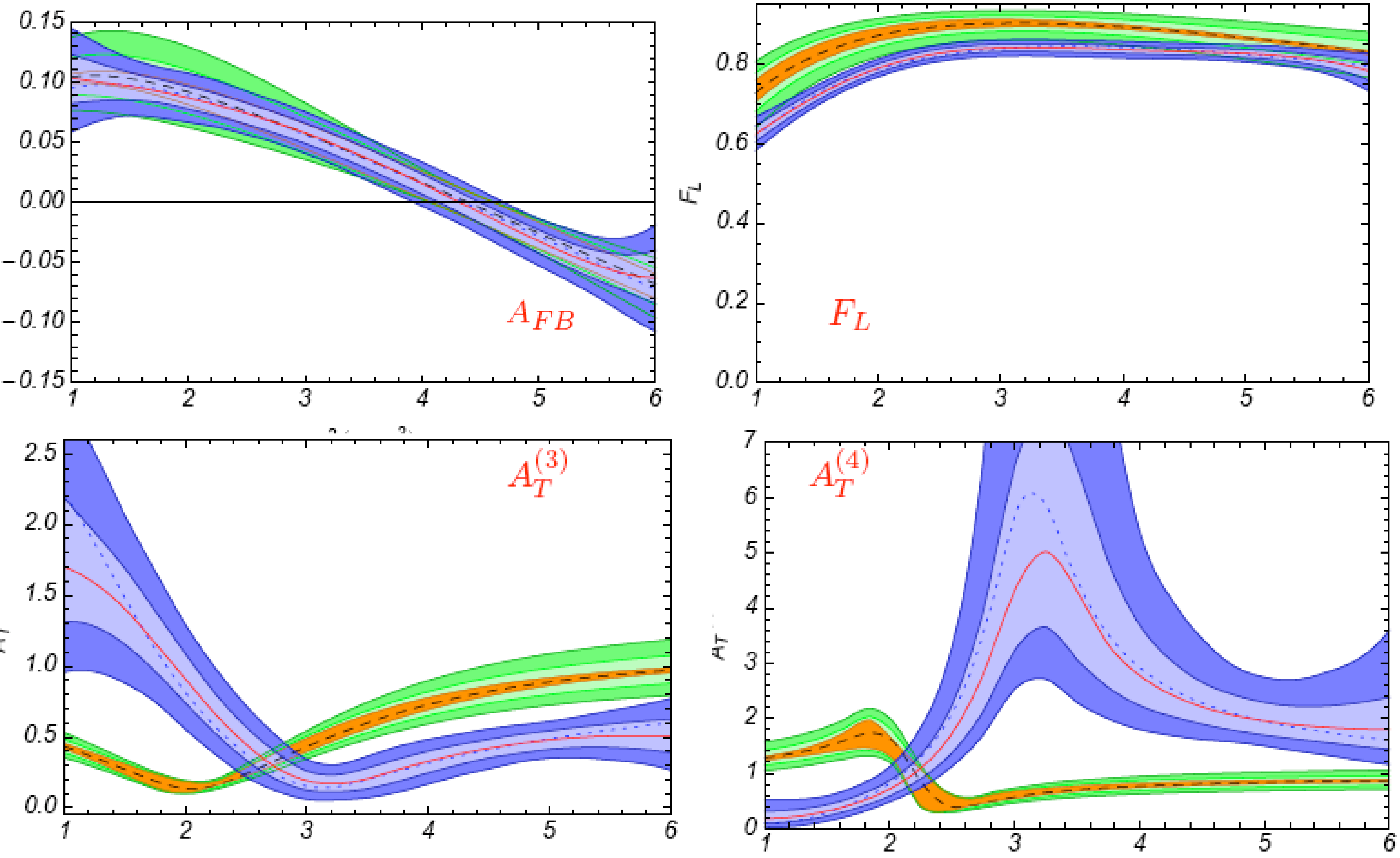
$$F_L(s) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

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



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.

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

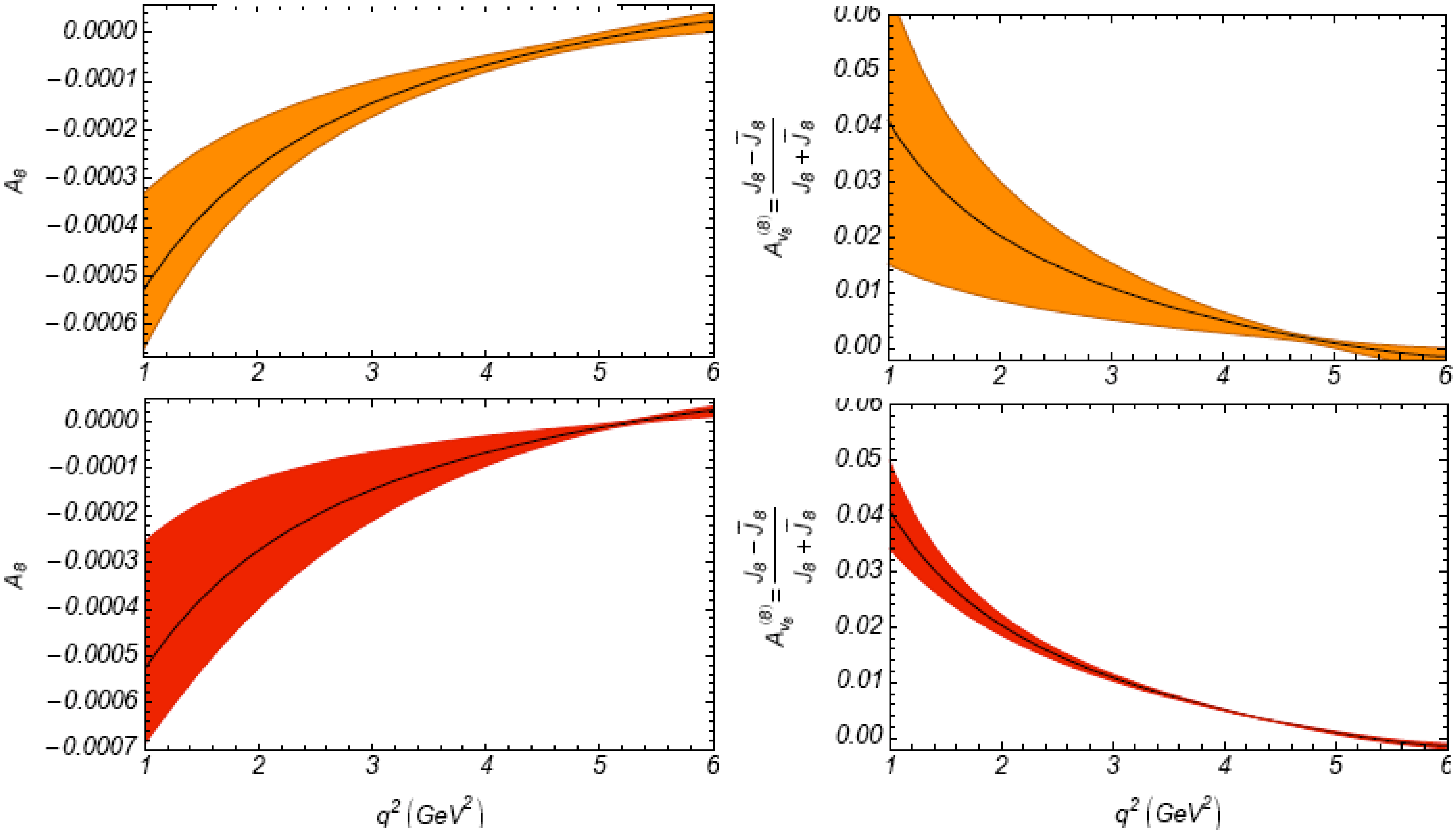
  – scale dependences

  – Λ/m_b corrections

  – experimental sensitivity in the full angular fit

Appropriate normalization eliminates the uncertainty due to form factors

$$A^8 = \frac{I^8 - \bar{I}^8}{d(\Gamma + \bar{\Gamma})/dq^2} \qquad A^8_{V8} = \frac{I^8 - \bar{I}^8}{I^8 + \bar{I}^8}$$

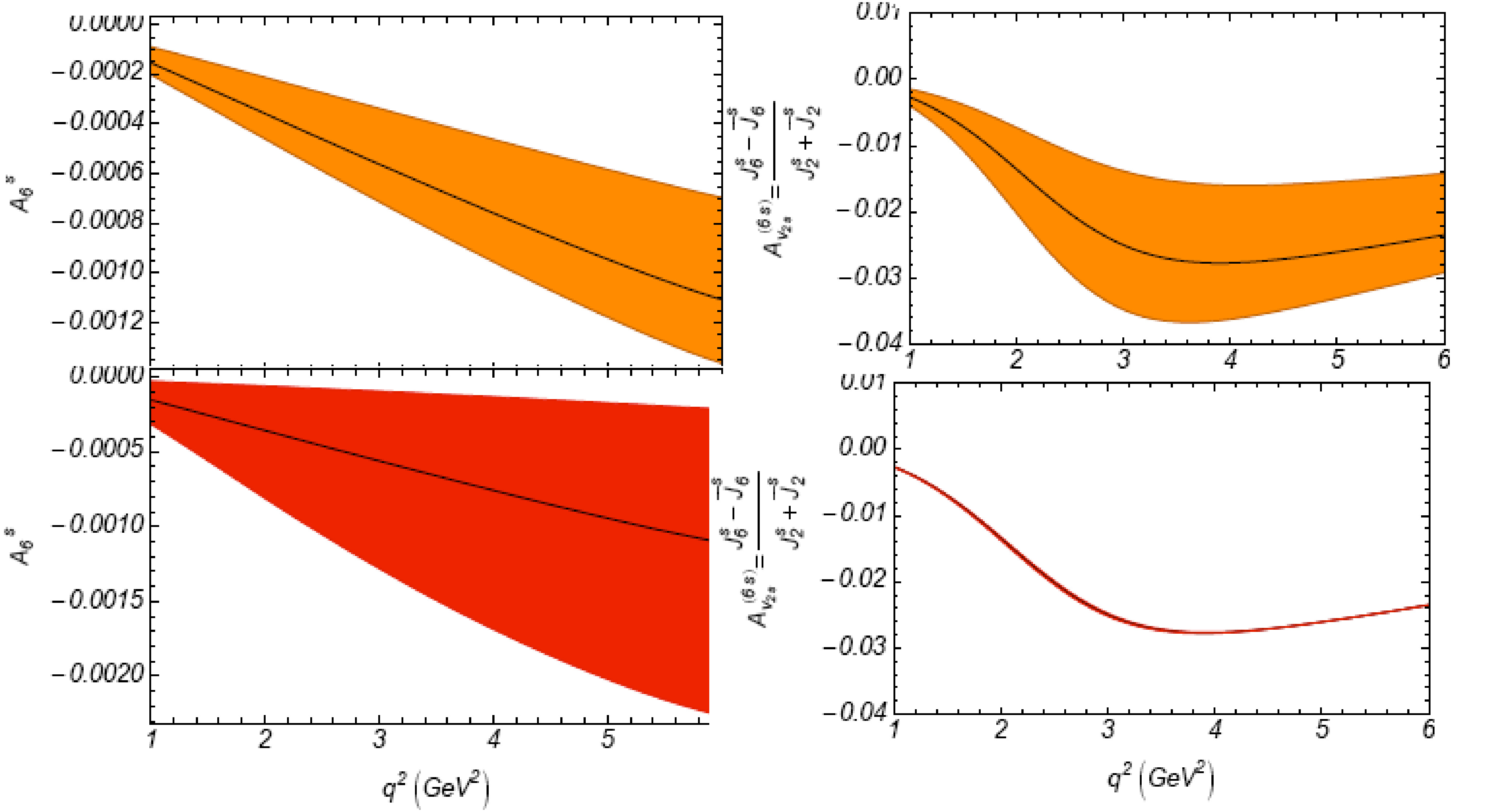


Orange bands: scale/input uncertainty including formfactors

Red bands: conservative estimate of uncertainty due to formfactors only

Appropriate normalization eliminates the uncertainty due to form factors II

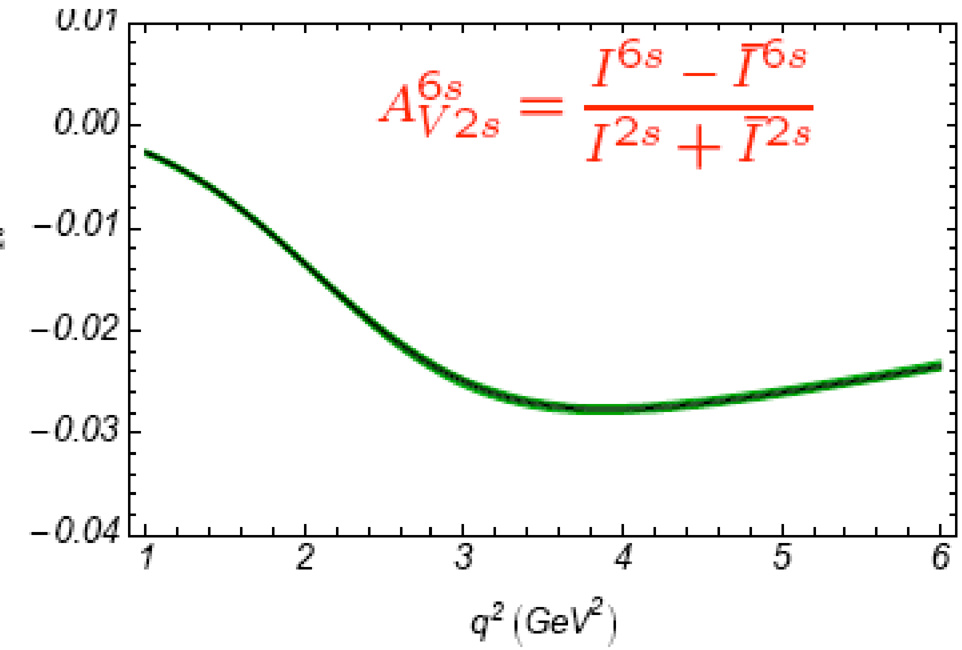
$$A^{6s} = \frac{I^{6s} - \bar{I}^{6s}}{d(\Gamma + \bar{\Gamma})/dq^2} \qquad A^{6s}_{V2s} = \frac{I^{6s} - \bar{I}^{6s}}{I^{2s} + \bar{I}^{2s}}$$

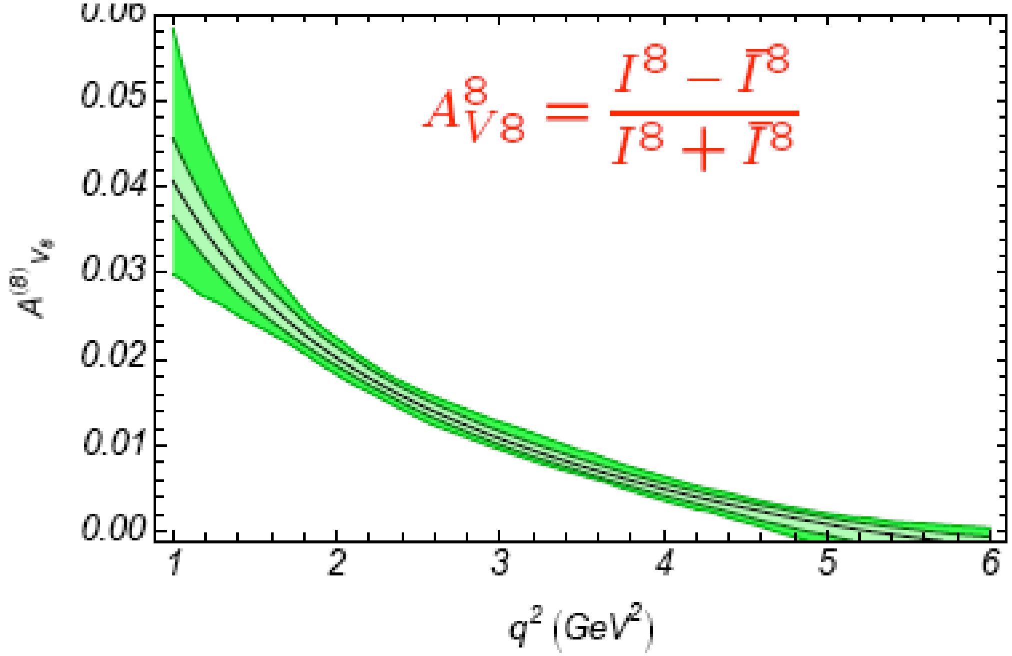


Orange bands: scale/input uncertainty including formfactors

Red bands: conservative estimate of uncertainty due to formfactors only

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





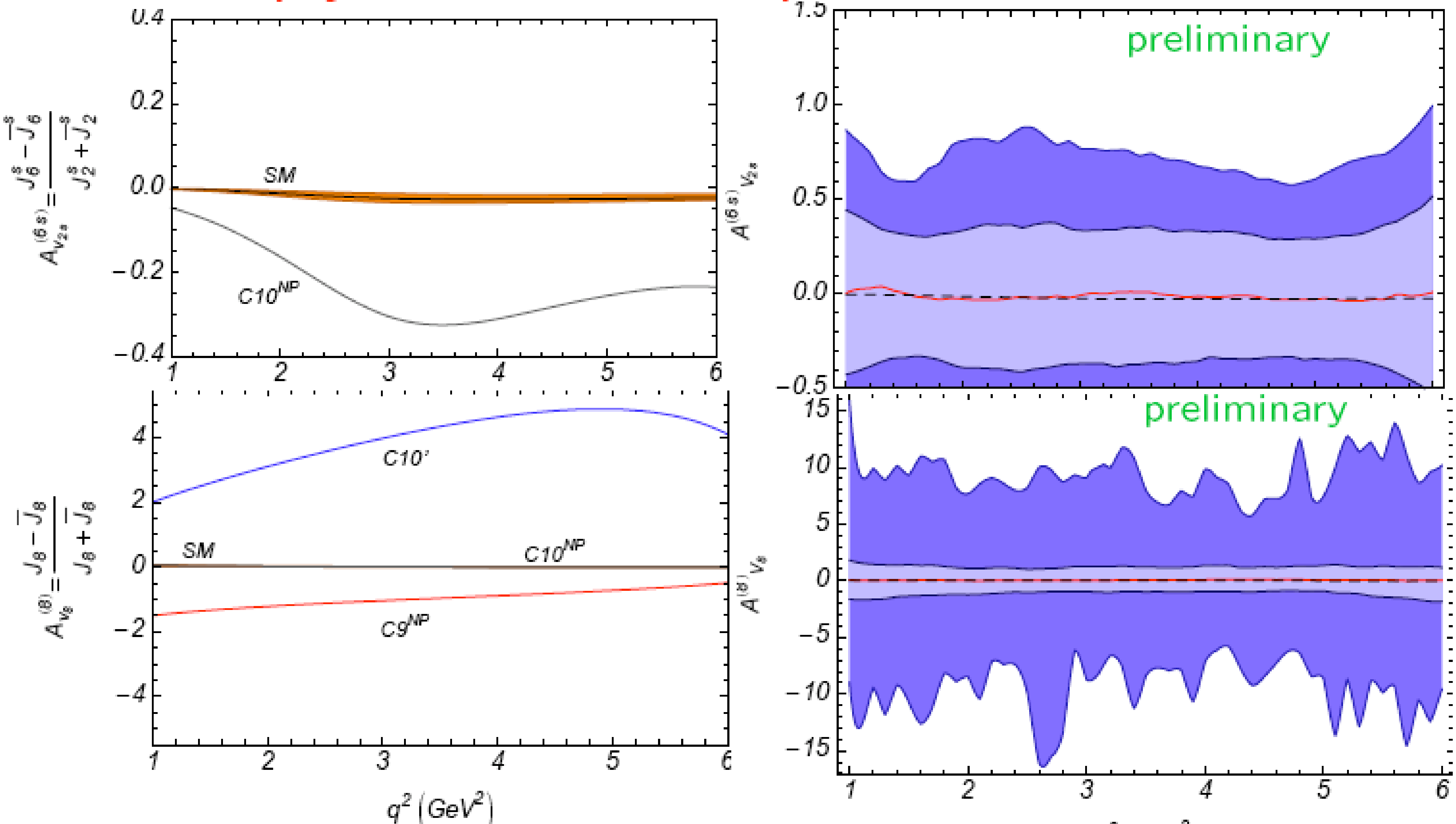
Uncertainty due Λ/m_b corrections significantly smaller than error due to input parameters

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

Further issues

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

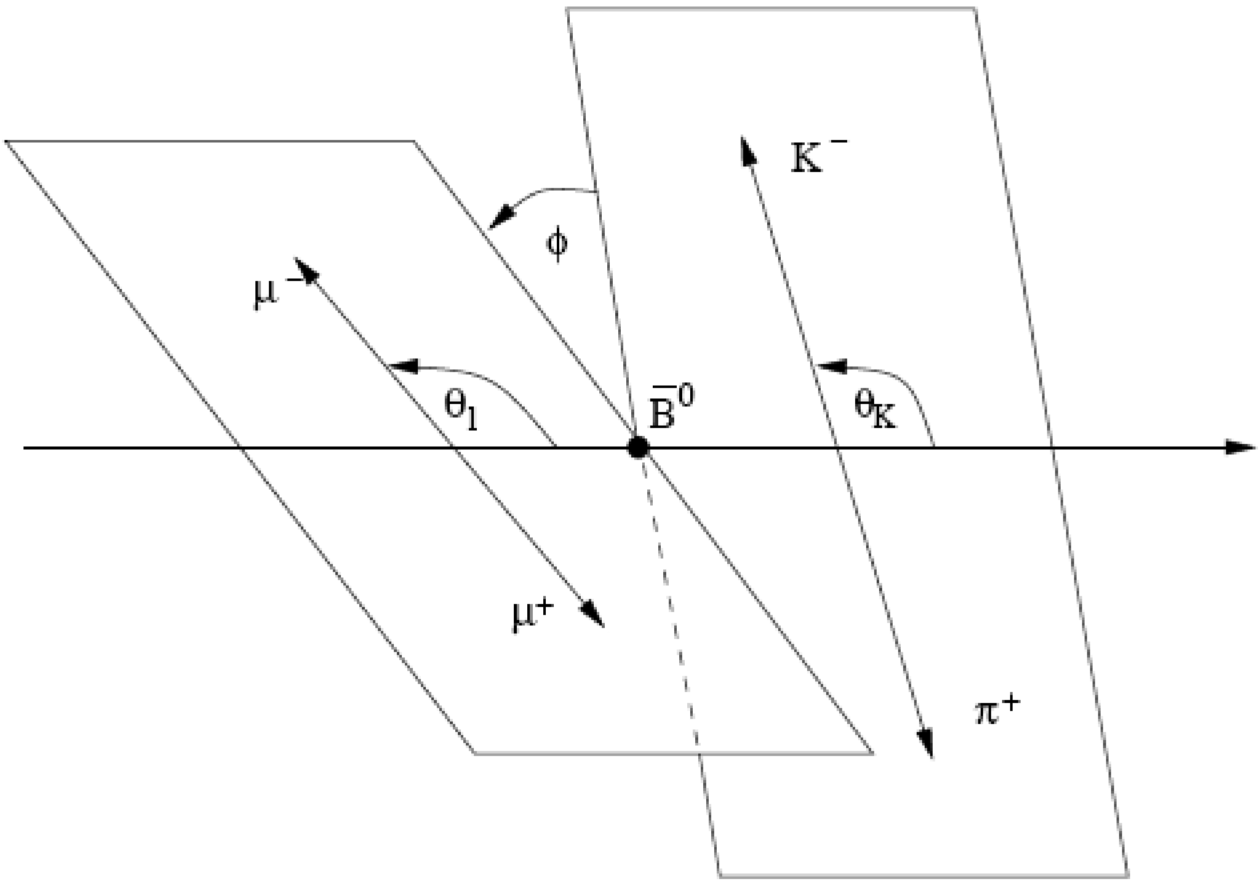
  this uncertainty fully dominant

- Input parameters:

m_B	$5.27950 \pm 0.00033\,\mathrm{GeV}$	λ	0.2262 ± 0.0014
m_K	$0.896 \pm 0.040\,\mathrm{GeV}$	A	0.815 ± 0.013
M_W	$80.403 \pm 0.029\,\mathrm{GeV}$	$\bar{\rho}$	0.235 ± 0.031
M_Z	$91.1876 \pm 0.0021\,\mathrm{GeV}$	$\bar{\eta}$	0.349 ± 0.020
$\hat{m}_t(\hat{m}_t)$	172.5 ± 2.7 GeV	$\Lambda_{\mathrm{QCD}}^{(n_f=5)}$	$220 \pm 40\,\mathrm{MeV}$
$m_{b,\mathrm{PS}}(2\,\mathrm{GeV})$	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
$f_{K^*,\perp}(1\,\mathrm{GeV})$	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	$\lambda_{B,+}(1.5\mathrm{GeV})$	$0.485 \pm 0.115\,\mathrm{GeV}$
$\xi_{K^*,\perp}(0)$¶	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

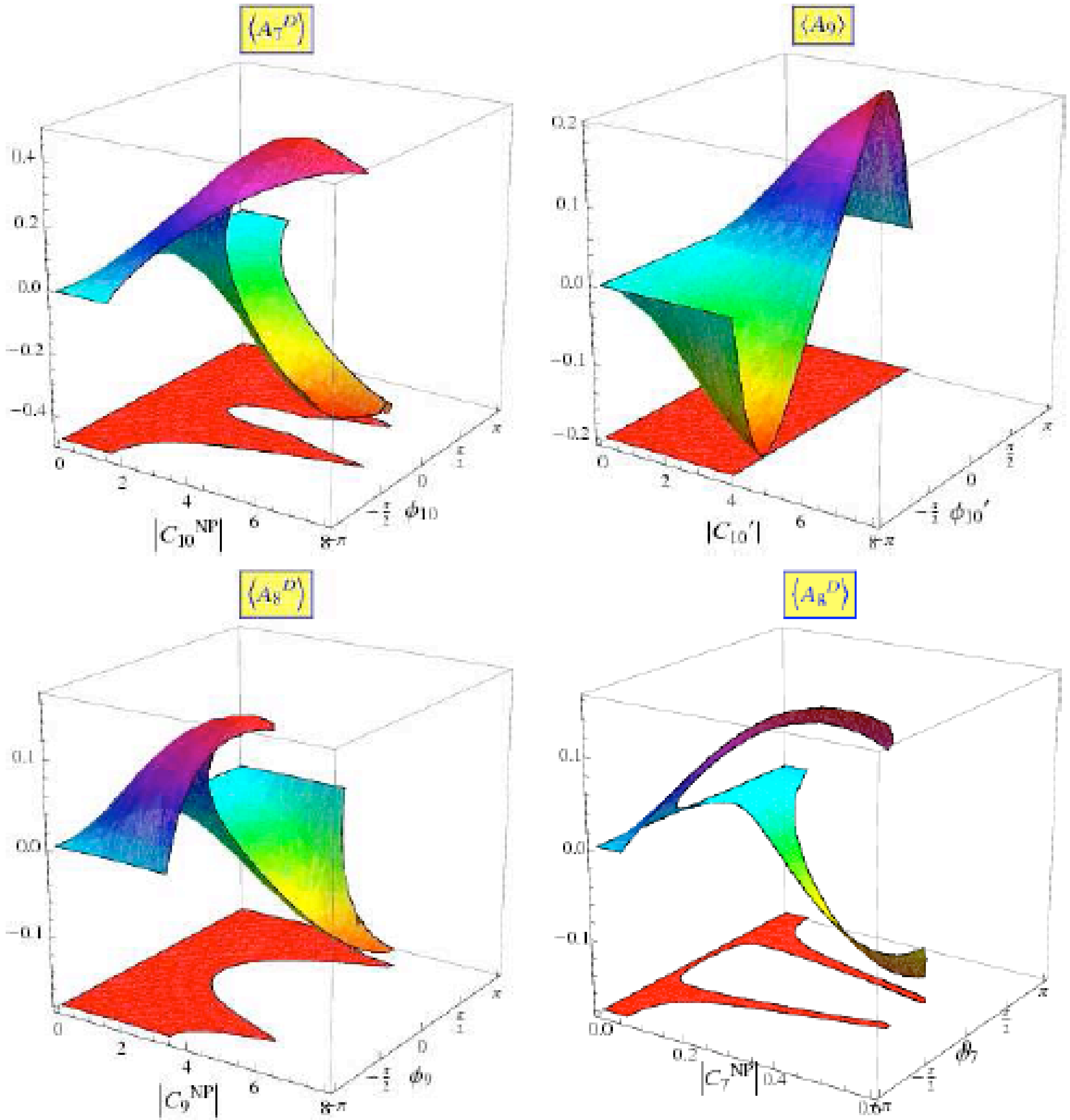
θ_K : Angle between K^- and **z** axis in anti-K^* rest frame

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)

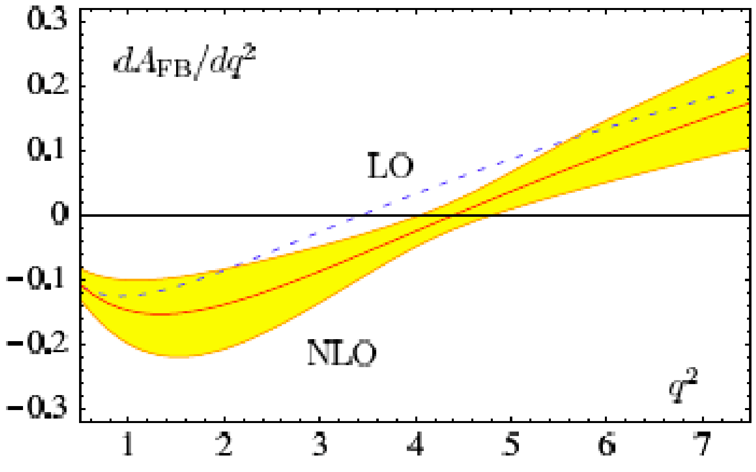
- Region $s \leq 1GeV^2$
  - corresponds to information which is tested out by the $b \to s\gamma$ mode
  - lower resonances complicate the theoretical description
  - longitudinal amplitude generates a logarithmic divergence in the limit $s \to 0$ indicating problems in the theoretical description

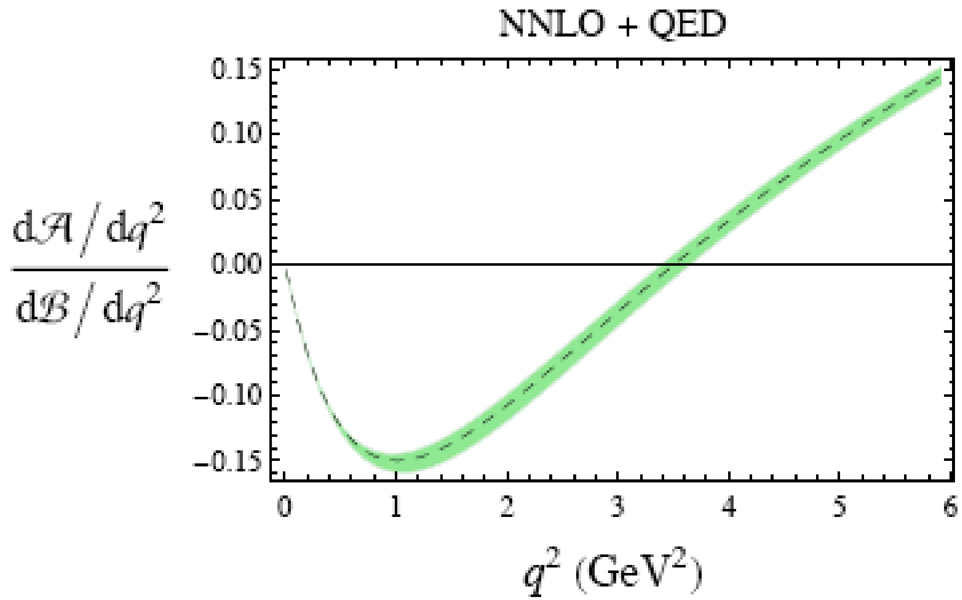
    transversal amplitude however is fine, so observables based on it free from this theoretical problem
  - electron modes preferable (lower cut)

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

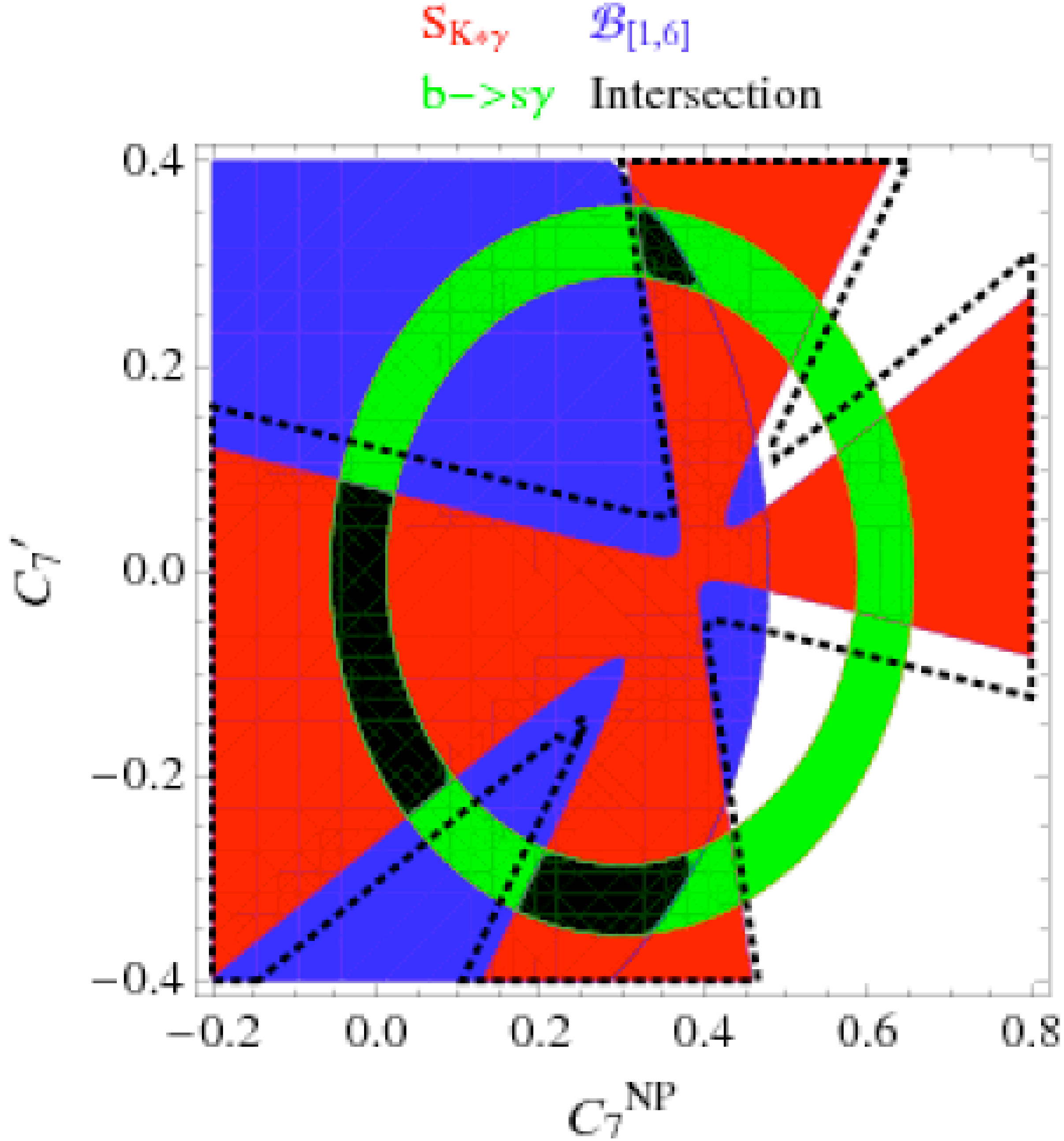
Inclusive Zero:

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

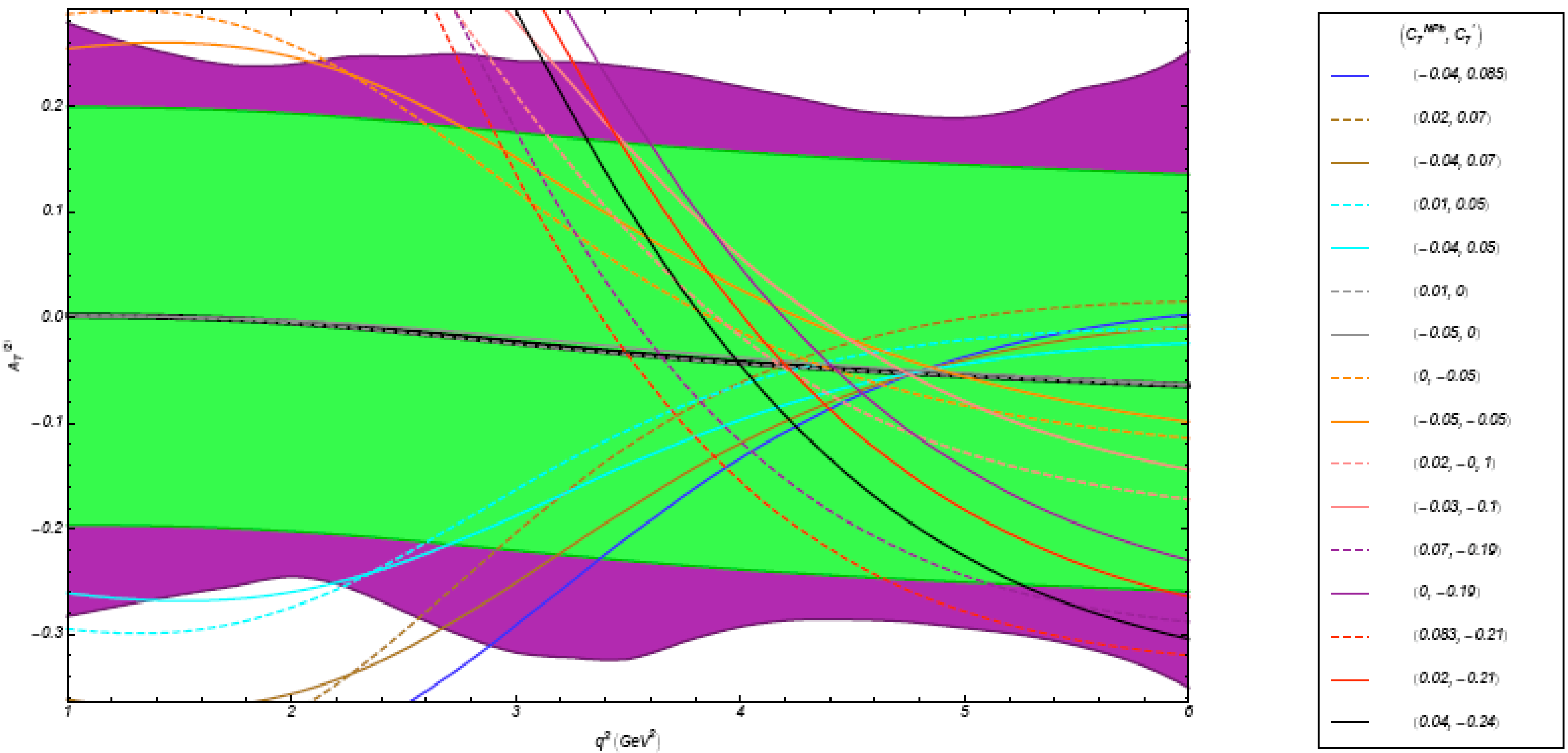
Present bounds on C_7 and C_7':

Bobeth et al, arXiv:0805.2525



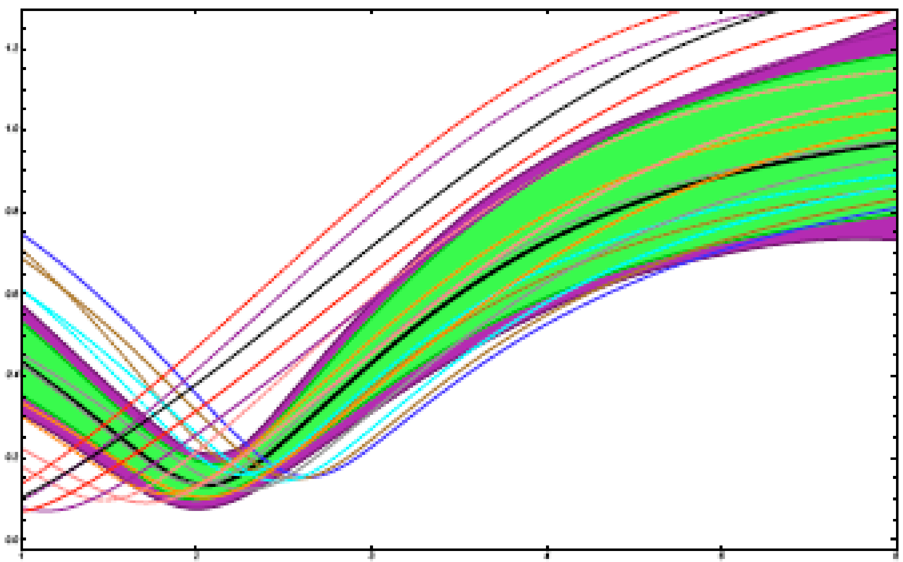
Test of allowed region around $C_7' = 0$ in the C_7 and C_7' plane

$A_T^{(2)}$

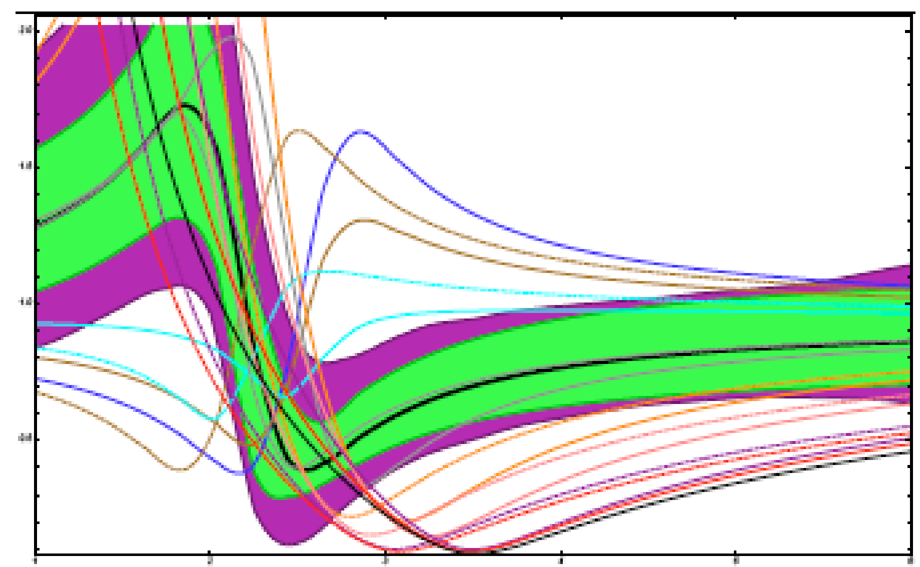


new observables

$A_T^{(3)}$

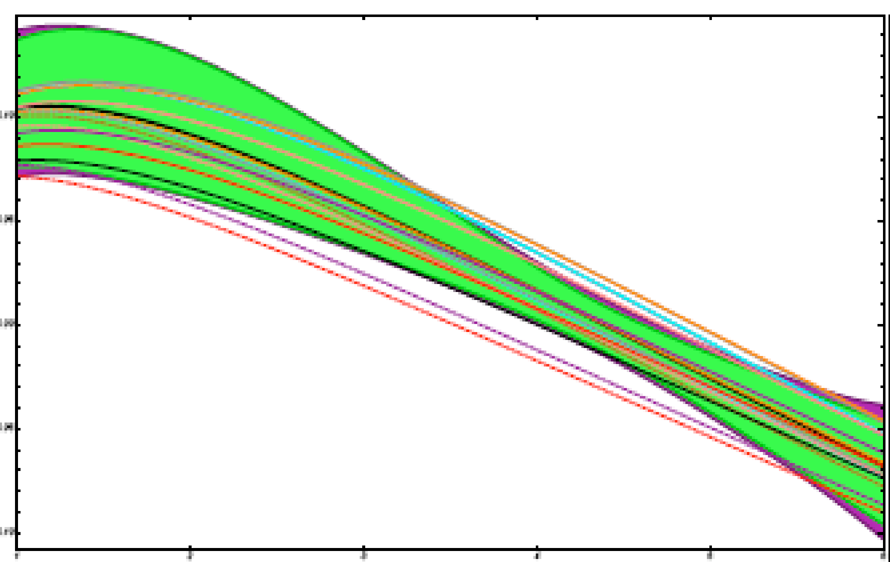


$A_T^{(4)}$

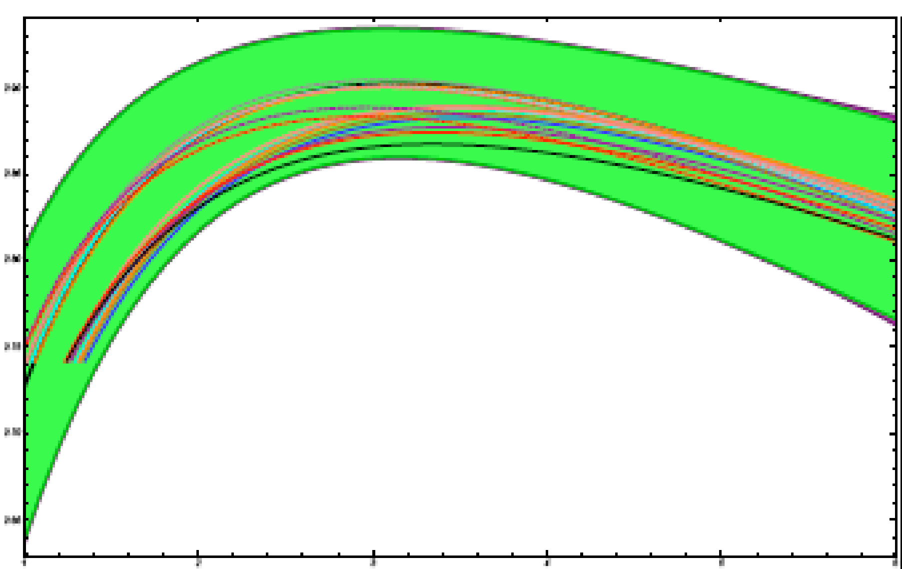


old observables

A_{FB}



F_L



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

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

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