New physics sensitivity of the rare decay mode $b \to s\ell^+\ell^-$

Tobias Hurth

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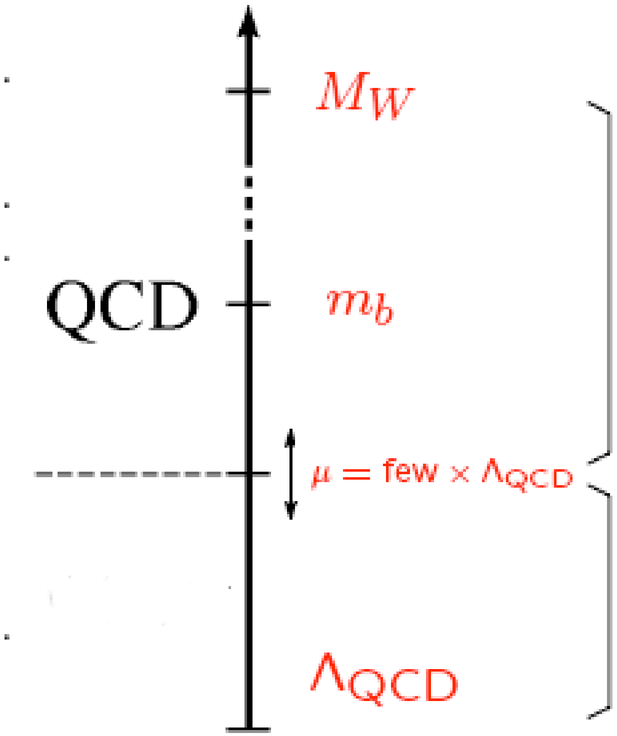
JHEP 0811:032,2008, arXiv:0807.2589 [hep-ph] and arXiv:1005.0571



QCD effects in B decays

short-distance physics
perturbative

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

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

- $\mu^2 \approx M_{New}^2 >> M_W^2$: 'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

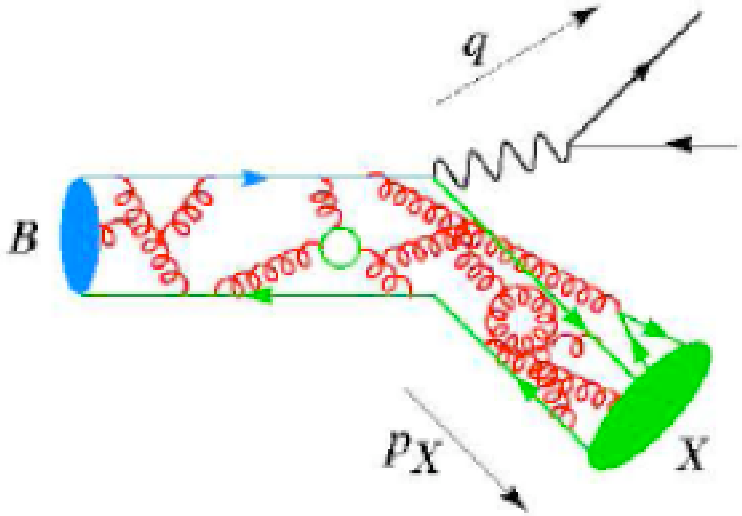
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

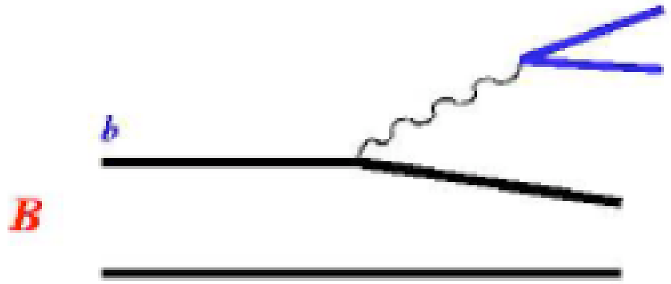
Inclusive modes $B \to X_s\gamma$ or $B \to X_s\ell^+\ell^-$

- Heavy mass expansion for inclusive modes:

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

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





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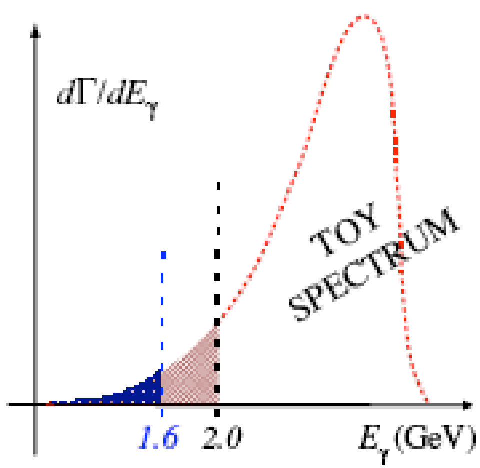
– More sensitivities to nonperturbative physics due to kinematical cuts: shape functions; multiscale OPE (SCET) with $\Delta = m_b - 2E_\gamma^0$

Becher,Neubert,hep-ph/0610067



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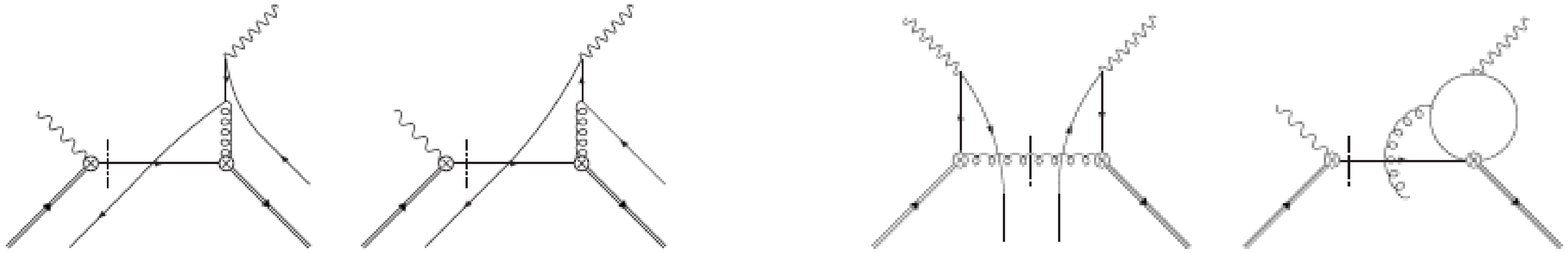
– If one goes beyond the leading operator ($\mathcal{O}_7$, $\mathcal{O}_9$):

breakdown of local expansion

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

Benzke,Lee,Neubert,Paz,arXiv:1003.5012



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

Naive approach:

Parametrize the hadronic matrix elements in terms of form factors

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

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

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 $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

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

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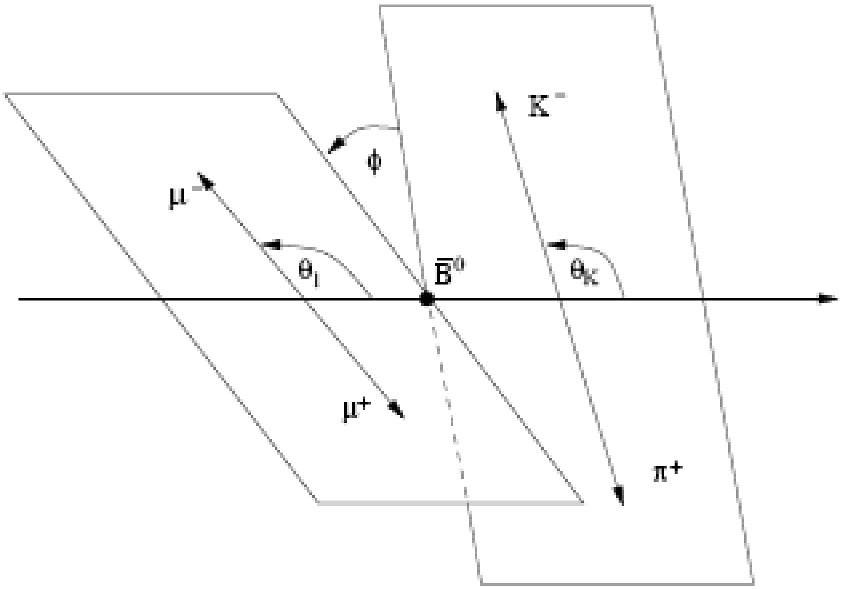
Opportunities in $B \to K^*(\to K\pi)\ell^+\ell^-$: angular distributions

Kinematics

- 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:

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



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

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

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

However: Subleties in measuring the 12 coefficients J_i

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

$$J_i = J_i(A_{\perp L/R}, A_{\parallel L/R}, A_{0L/R}) \qquad A_{\perp,\parallel} = (H_{+1} \mp H_{-1})/\sqrt{2}, \quad A_0 = H_0$$

- By inspection one finds: $J_{1s} = 3J_{2s}, \quad J_{1c} = -J_{2c}$

Moreover, $J_{6c} = 0$ for $m_{lepton} = 0$

12 theoretical independent amplitudes A_j

?

$\Leftrightarrow$ 9 independent coefficient functions J_i

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Symmetries of $J_i = J_i(A_{\perp L/R}, A_{\| L/R}, A_{0L/R})$

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 $F(J_i)$ are also invariant under these 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)

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)

Additional symmetry

Observation -correlations in the Monte-Carlo fit between different A_i-
guided us to fourth symmetry:

$$n_i' = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i,$$

where θ and $\tilde{\theta}$ can be varied independently.

$$n_1 = (A_\parallel^L, A_\parallel^{R*})$$
$$n_2 = (A_\perp^L, -A_\perp^{R*})$$
$$n_3 = (A_0^L, A_0^{R*})$$

There is an additional non-trivial relationship between the angular distributions J_i

$$J_{1s} = 3J_{2s} \qquad J_{1c} = -J_{2c} \qquad J_{1c} = 6\frac{(2J_{1s} + 3J_3)\left(4J_4^2 + J_7^2\right) + (2J_{1s} - 3J_3)\left(J_5^2 + 4J_8^2\right)}{16J_1^{s\,2} - 9\left(4J_3^2 + J_6^{s\,2} + 4J_9^2\right)}$$
$$- 36\frac{J_{6s}(J_4J_5 + J_7J_8) + J_9(J_5J_7 - 4J_4J_8)}{16J_{1s}^2 - 9\left(4J_3^2 + J_{6s}^2 + 4J_9^2\right)}.$$

If ignored by experiments they will reduce their sensitivity

Number of symmetries depend on assumptions:

Case	Coefficients	Dependencies	Amplitudes	Symmetries
$m_\ell = 0,\ A_S = 0$	11	3	6	4
$m_\ell = 0$	11	2	7	5
$m_\ell > 0,\ A_S = 0$	11	1	7	4
$m_\ell > 0$	12	0	8	4

Theoretical framework

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

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

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

QCDf/SCET analysis

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

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

Form factor relations broken by α_s and Λ/m_b corrections

- 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

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

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

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

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

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

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

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

Contruct observables where universal form factors cancel at LO

Careful design of observables

- Good sensitivity to NP contribitions, i.e. to $C_7^{eff'}$
- Good experimental resolution
- 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
    syst. errors due to QCD sum rules almost eliminated

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    syst. errors due to QCD sum rules almost eliminated
  - 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 ±10% and also of ±5%
    illustrates effect without making assumption about level

    CP violating observables:

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

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

  - Scale dependence of NLO result

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Benchmark points in MSSM

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

Specific model:

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

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

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}.

New observables

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

- sensitive to $C_7^{eff'}$
- invariant under $R-L$ symmetries
- theoretical clean
- 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

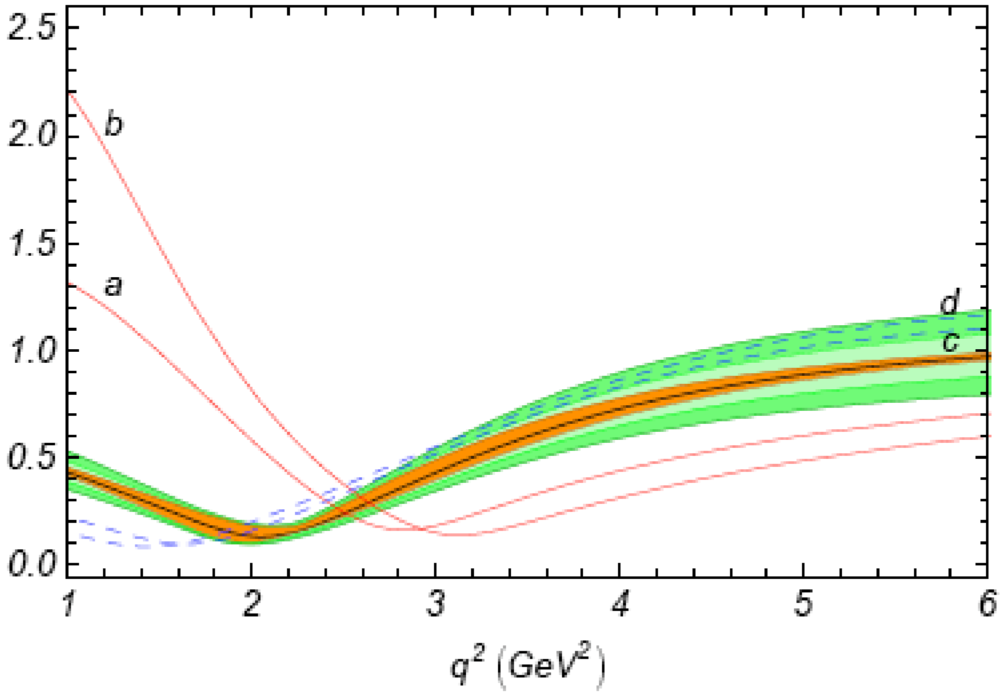
Different sensibility to $C_7^{eff'}$ via A_0 in $A_T^{(3)}$, $A_T^{(4)}$

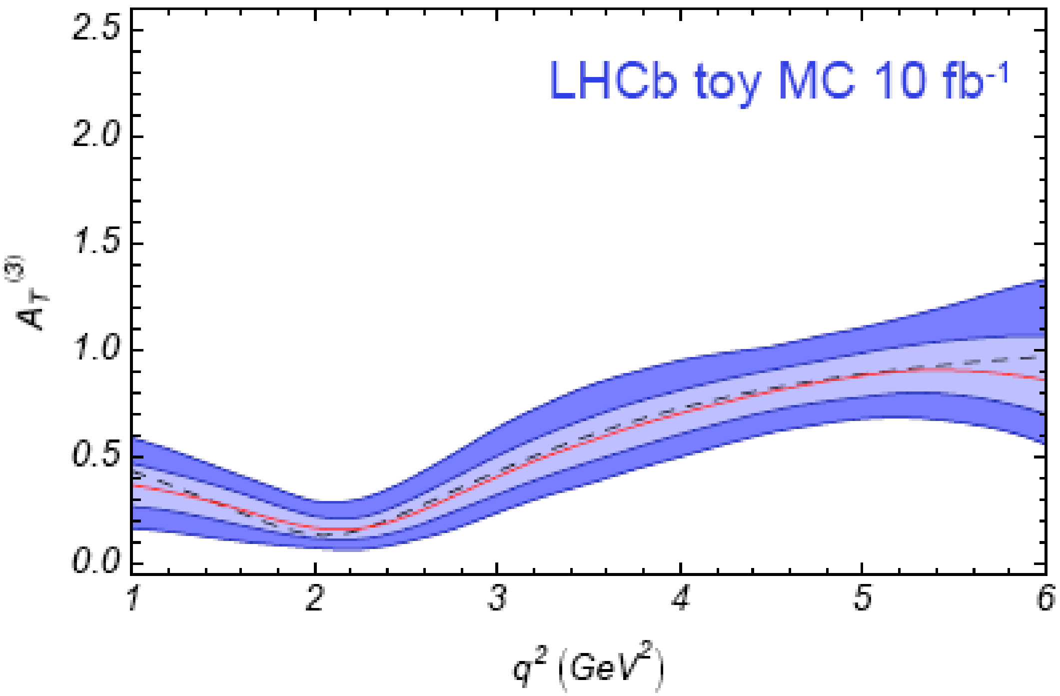
Next step: design of observables sensitive to other new physics operators

(see also Buras et al. 2008)

Results

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





Theoretical sensitivity

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

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

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

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

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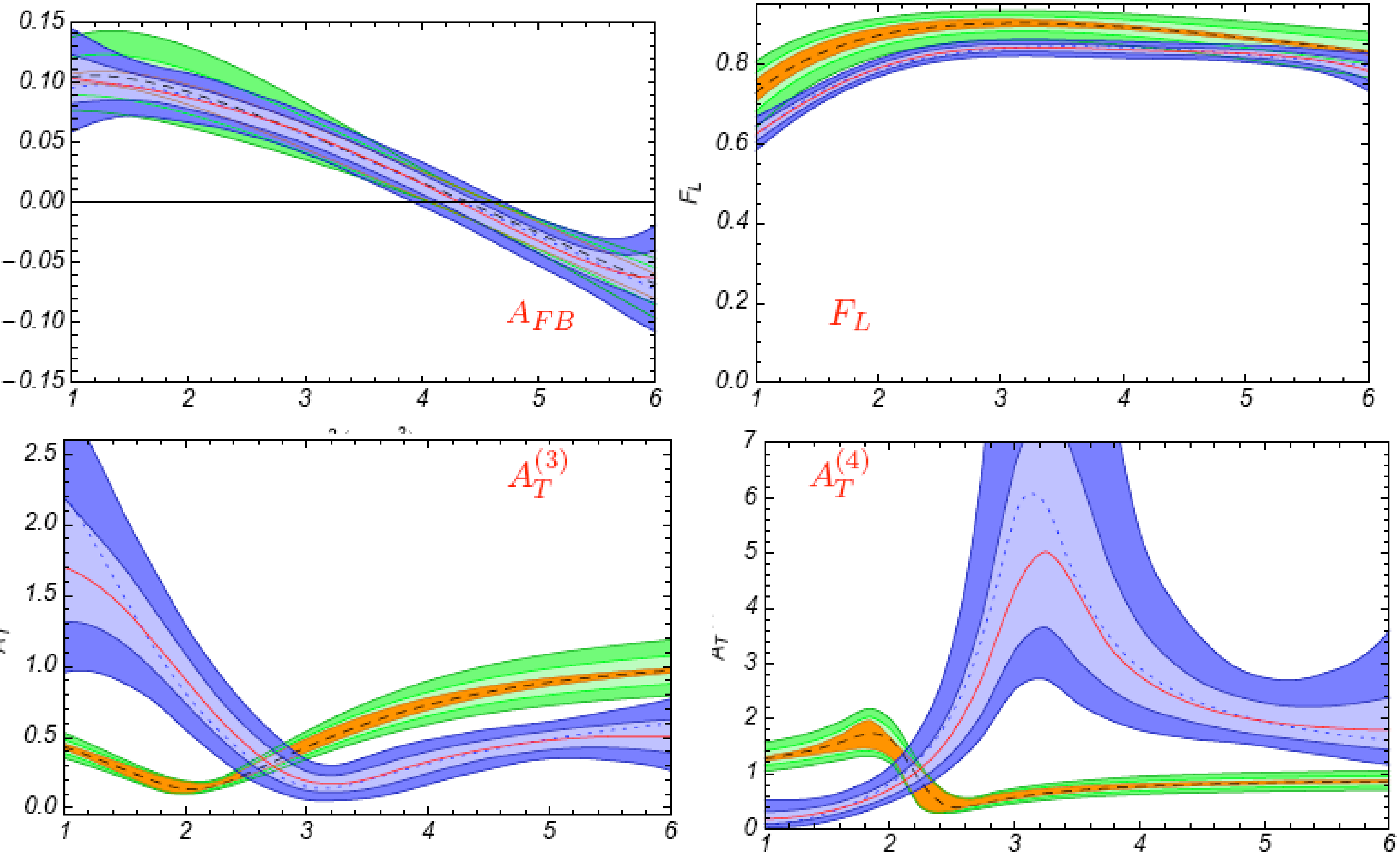
Comparison between old and new observables



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

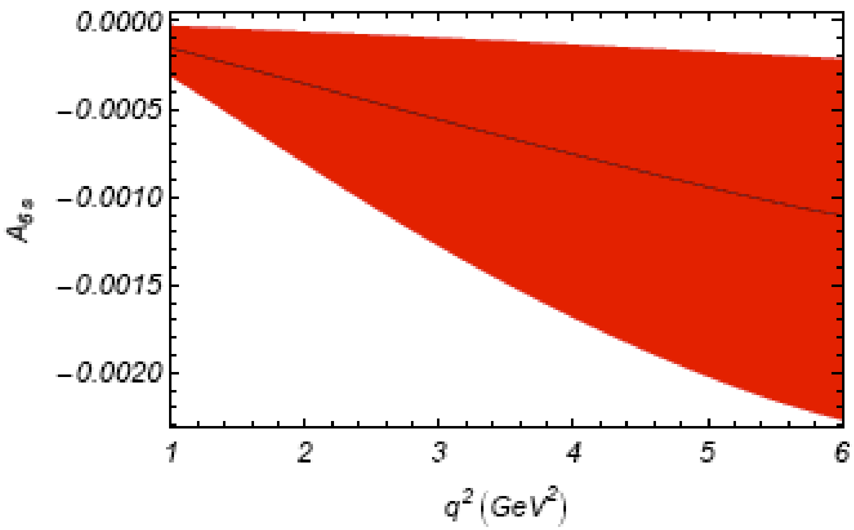
- Angular distributions allow for the measurement of 7 CP asymmetries
  (Krüger,Seghal,Sinha[2] 2000,2005)
- NLO (α_s) corrections included: scale uncertainties reduced
  (however, some CP asymmetries start at NLO only)
  (Bobeth,Hiller,Piranishvili 2008)
- New CP-violating phases in C_{10},C'_{10}, 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)

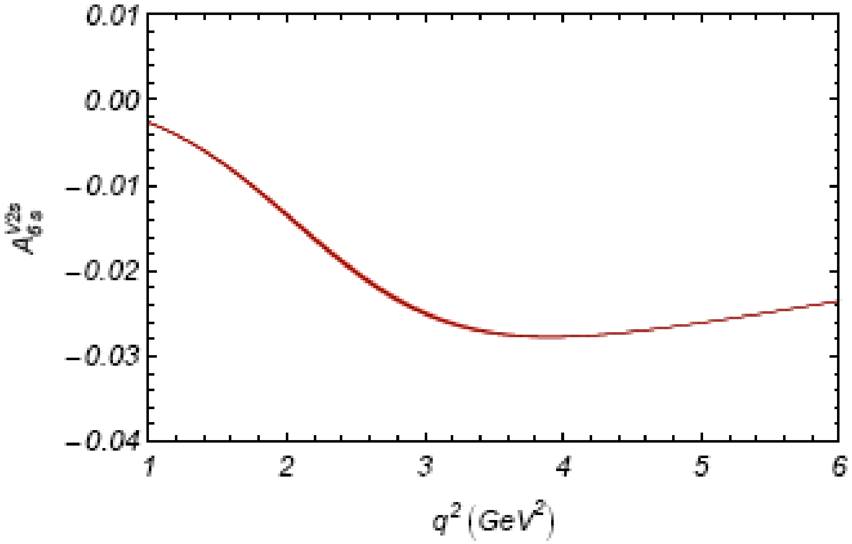
- New physics reach of CP-violating observables of the angular distributions depends on the theoretical and experimental uncertainties:
  - soft/QCD formfactors
  - other input parameters
  - scale dependences
  - Λ/m_b corrections
  - experimental sensitivity in the full angular fit

Appropriate normalization eliminates the uncertainty due to form factors

Example

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





Red bands: conservative estimate of uncertainty due to formfactors only

Relative error drops dramatically

However:

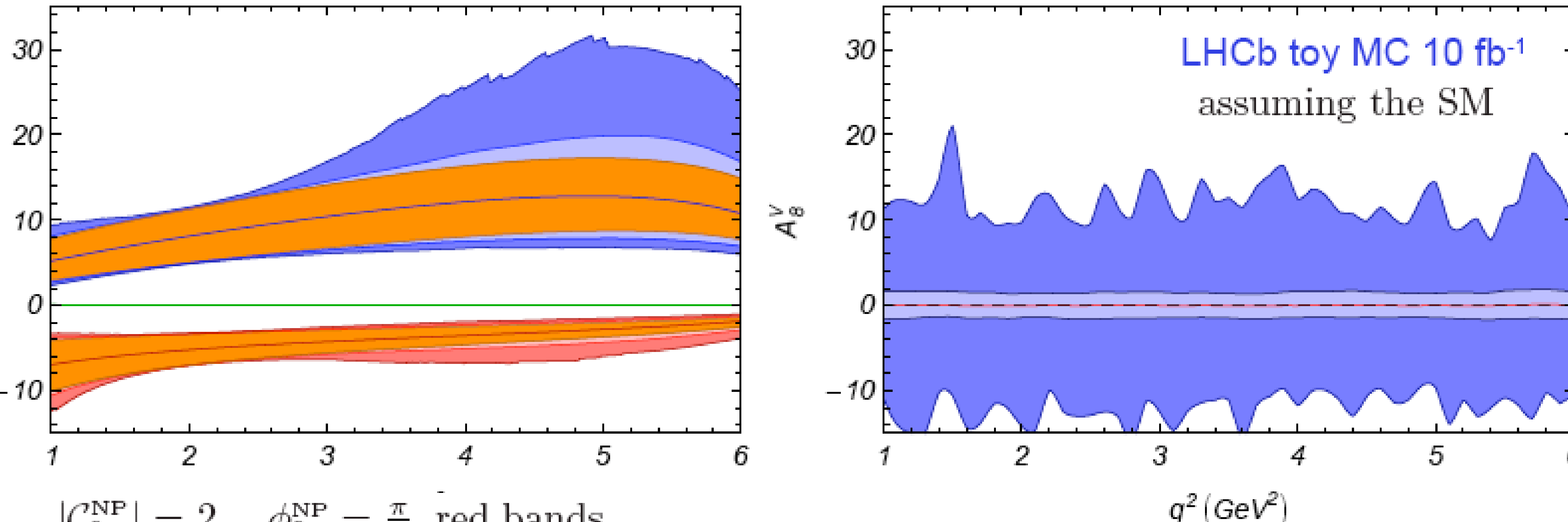
Λ/m_b corrections very small in SM due to small weak SM phase

but sizeable if NP CPV effects are large!

In addition poor experimental uncertainty !

$$A_8^V = \frac{J_8 - \bar{J}_8}{J_8 + \bar{J}_8}$$

Hard to see these will ever be useful observables



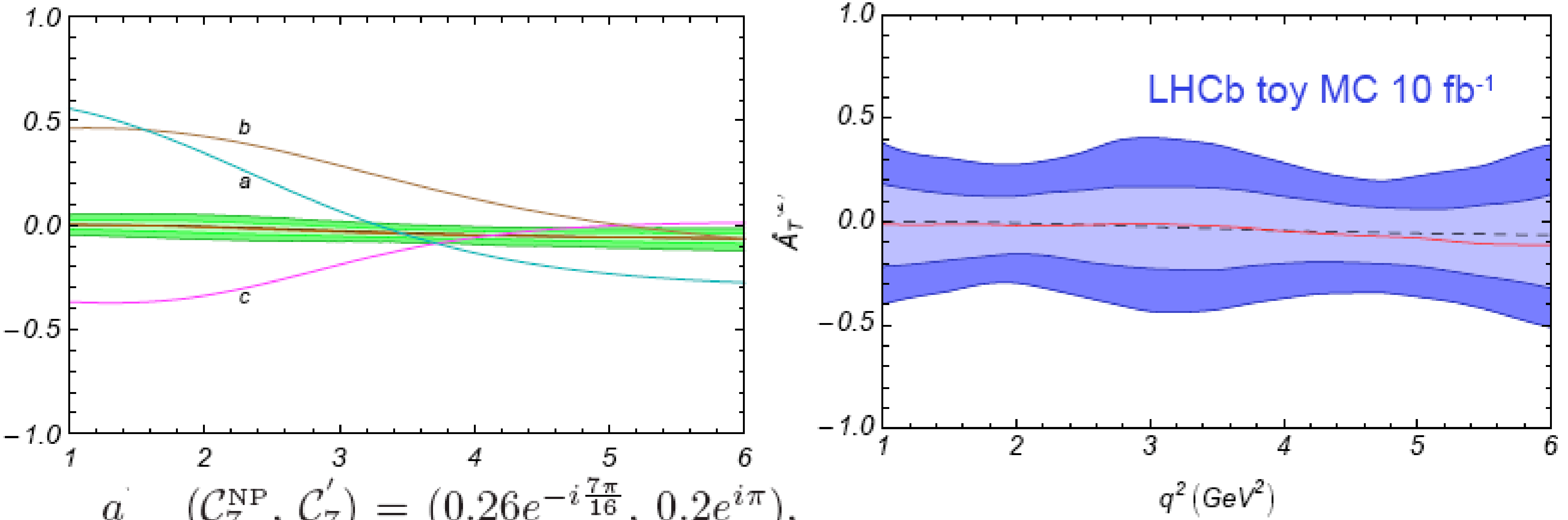
$|C_9^{\rm NP}| = 2, \quad \phi_9^{\rm NP} = \frac{\pi}{2}$, red bands

$|C'_{10}| = 3, \; \phi'_{10} = \frac{\pi}{2}$, blue bands

Note: poor experimental sensitivity NOT due to normalisation !

CP conserving $A_T^{(i)}$ observables more sensitive to complex phases

$A_T^{(2)}$

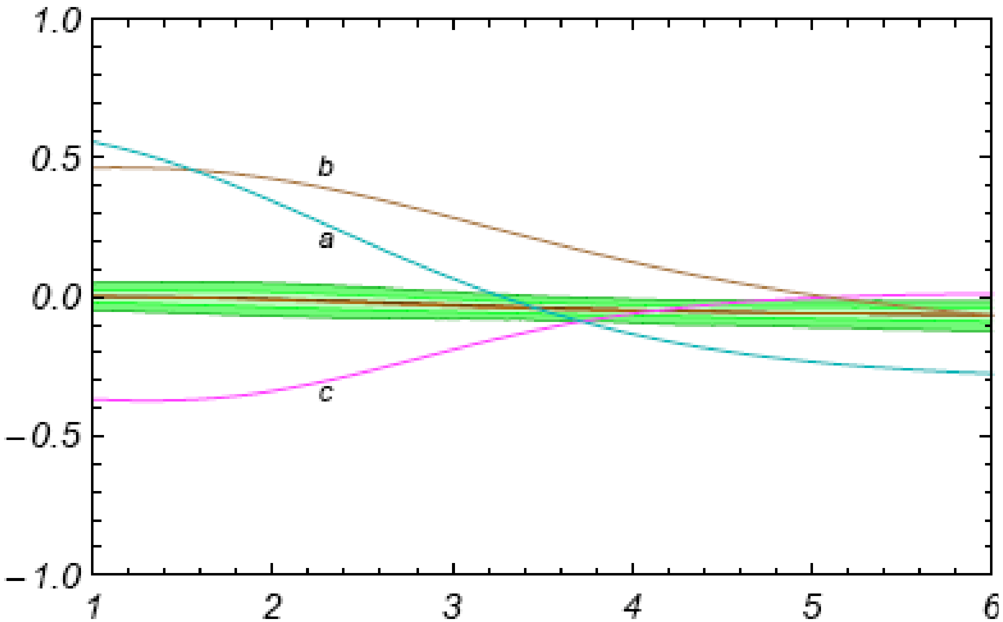


$$
\begin{aligned}
&a \quad (\mathcal{C}_7^{\rm NP}, \mathcal{C}_7^{'}) = (0.26e^{-i\frac{7\pi}{16}}, 0.2e^{i\pi}),\\
&b \qquad\qquad\qquad\quad (0.07e^{i\frac{3\pi}{5}}, 0.3e^{i\frac{3\pi}{5}})\\
&c \qquad\qquad\qquad\quad (0.03e^{i\pi}, 0.07)
\end{aligned}
$$

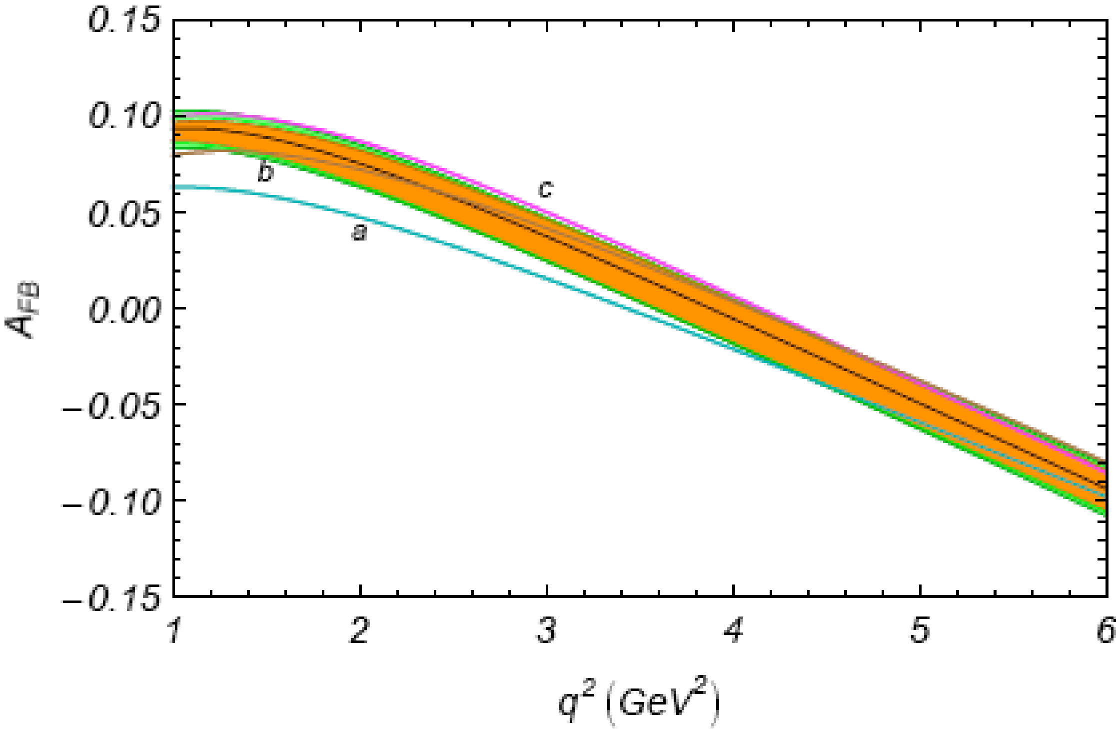
All benchmarks currently experimentally allowed

CP conserving $A_T^{(i)}$ observables more sensitive to complex phases

$A_T^{(2)}$



A_{FB}



$a \quad (\mathcal{C}_7^{\mathrm{NP}}, \mathcal{C}_7') = (0.26e^{-i\frac{7\pi}{16}}, 0.2e^{i}$

$b \quad (0.07e^{i\frac{3\pi}{5}}, 0.3e^{i\frac{3\pi}{5}})$

$c \quad (0.03e^{i\pi}, 0.07)$

All benchmarks currently experimentally allowed

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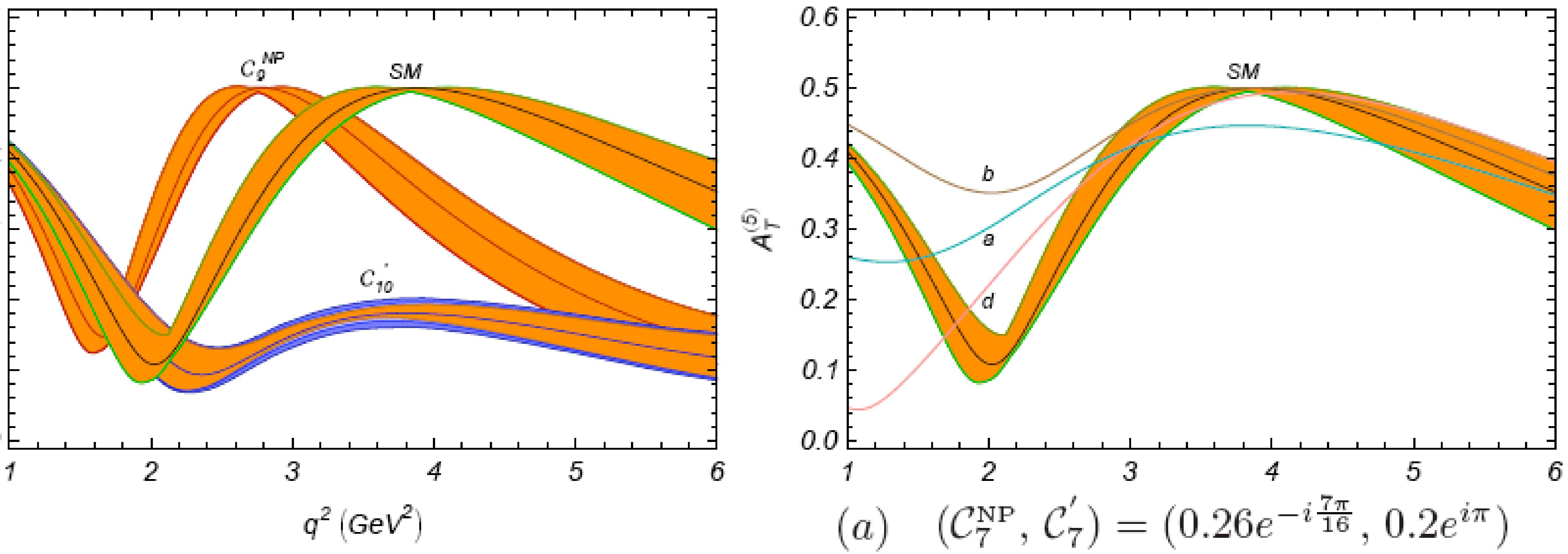
$A_T^{(5)}$

$$A_{\rm T}^{(5)} = \frac{\left|A_\perp^L A_\parallel^{R*} + A_\perp^{R*} A_\parallel^L\right|}{\left|A_\perp^L\right|^2 + \left|A_\perp^R\right|^2 + \left|A_\parallel^L\right|^2 + \left|A_\parallel^R\right|^2} \qquad A_{\rm T}^{(5)}\Big|_{m_\ell=0} = \frac{\sqrt{16 J_1^{s\,2} - 9 J_6^{s\,2} - 36(J_3^2 + J_9^2)}}{8 J_1^s}$$



NP in $\mathcal{C}_{10}' = 3e^{i\frac{\pi}{8}}$ and $\mathcal{C}_9^{\rm NP} = 2e^{i\frac{\pi}{8}}$

(a) $(\mathcal{C}_7^{\rm NP}, \mathcal{C}_7') = (0.26 e^{-i\frac{7\pi}{16}}, 0.2 e^{i\pi})$

(b) $(0.07 e^{i\frac{3\pi}{5}}, 0.3 e^{i\frac{3\pi}{5}})$

(d) $(0.18 e^{-i\frac{\pi}{2}}, 0)$

Very different behaviour for different NP contributions

Conclusions

When making measurements in $B \to K^* \ell^+ \ell^+$ great care has to be taken to

Minimise theoretical errors due formfactors and Λ/m_b corrrections

Design observables that satisfy symmetries and that have optimised specific NP sensitivity

Framework developed for how to get such observables

Theoretical and experimental errors estimated

CPV observables have no experimental sensitivity

Most important pending issue for NP sensitivity

Getting bounds on Λ/m_b corrections

Highly relevant for LHCb measurements

Further work:

Above results are valid in the kinematic region in which

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

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

Charm loops — Khodjamirian et al. 2010

Going for region with $q^2 > 6GeV^2$ requires better understanding of charm loops

Soft recoil region (high-q^2) — Bobeth et al. 2010

Use HQET framework as applied by Grinstein and Pirjol (2004)

Observables constructed in a similar way to us

Extra

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

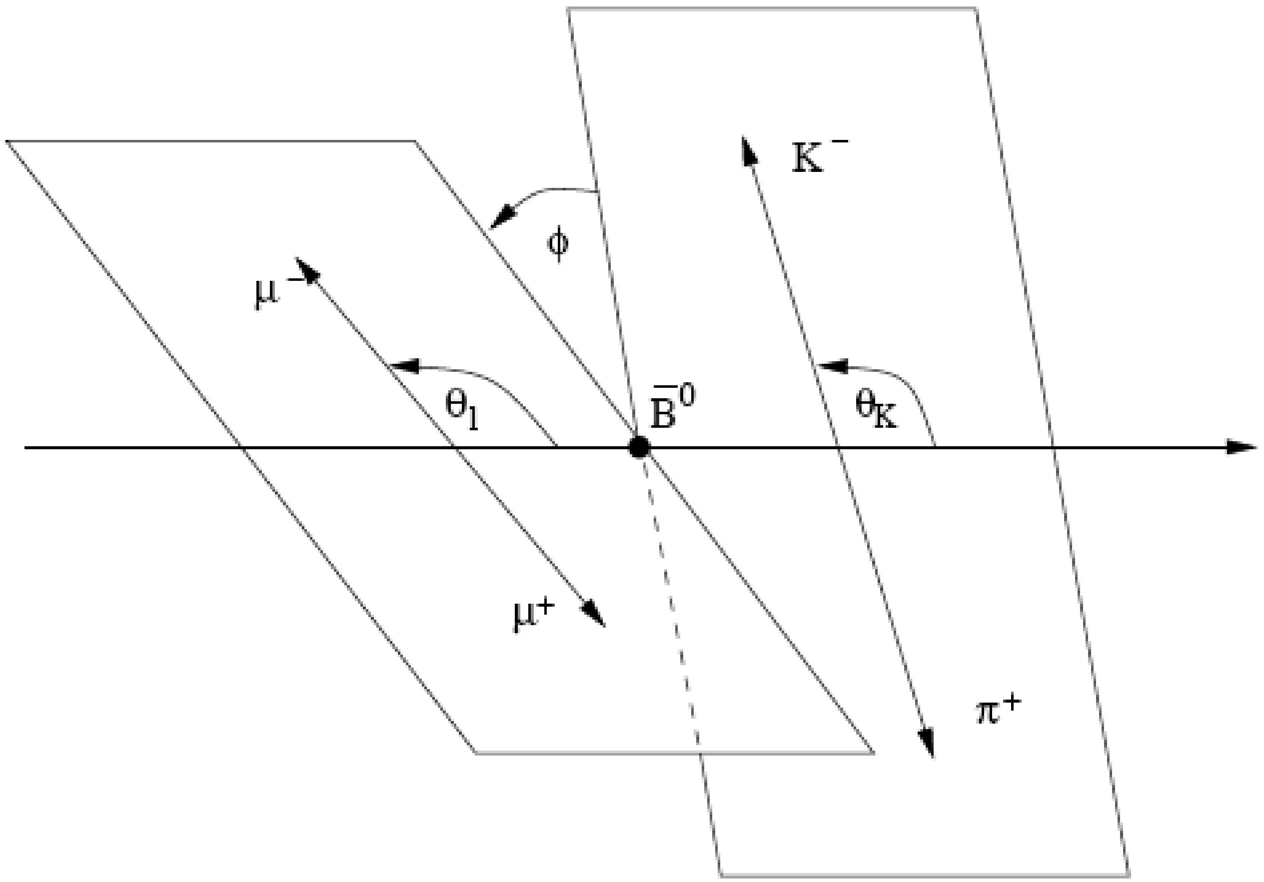
  this uncertainty fully dominant

- 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 μμ rest frame

θ$_K$: Angle between K^- and **z** axis in anti-K* rest frame

φ : Angle between the anti-K* and μμ decay planes

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

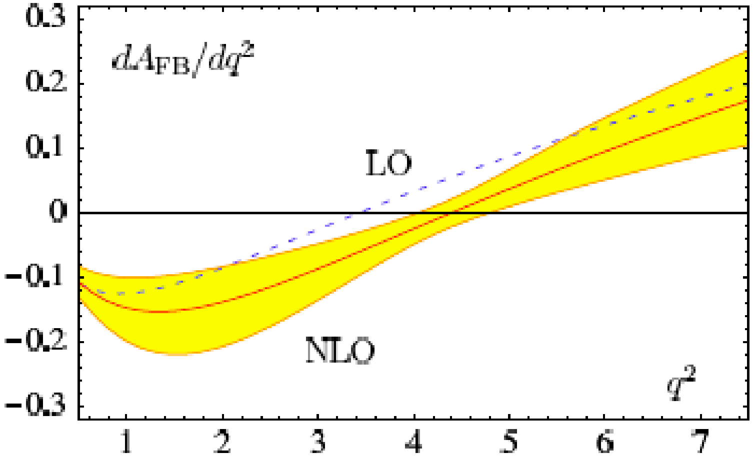
$$\cos\theta_l = \frac{\mathbf{q}_{\mu^-} \cdot \mathbf{e}_z}{|\mathbf{q}_{\mu^-}|}, \quad \cos\theta_K = \frac{\mathbf{r}_{K^-} \cdot \mathbf{e}_z}{|\mathbf{r}_{K^-}|}, \quad \sin\phi = (\mathbf{e}_l \times \mathbf{e}_K) \cdot \mathbf{e}_z, \quad \cos\phi = \mathbf{e}_K \cdot \mathbf{e}_l$$

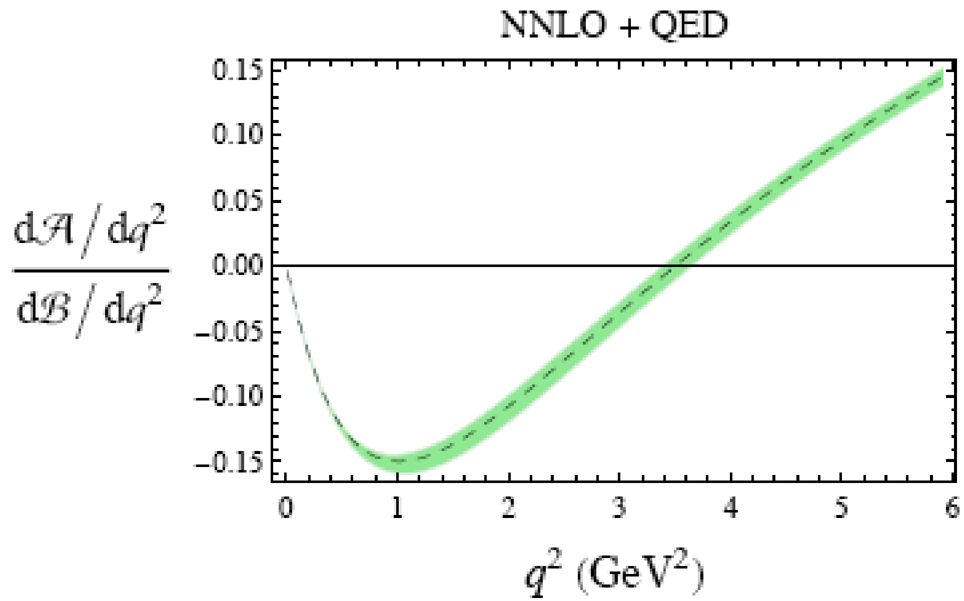
Error budget in inclusive and exclusive modes

SLHCb versus SFF   Important role of Λ/m_b corrections

Measurement of inclusive modes restricted to e^+e^- machines.
(S)LHC experiments: Focus on theoretically clean exclusive modes necessary.

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





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

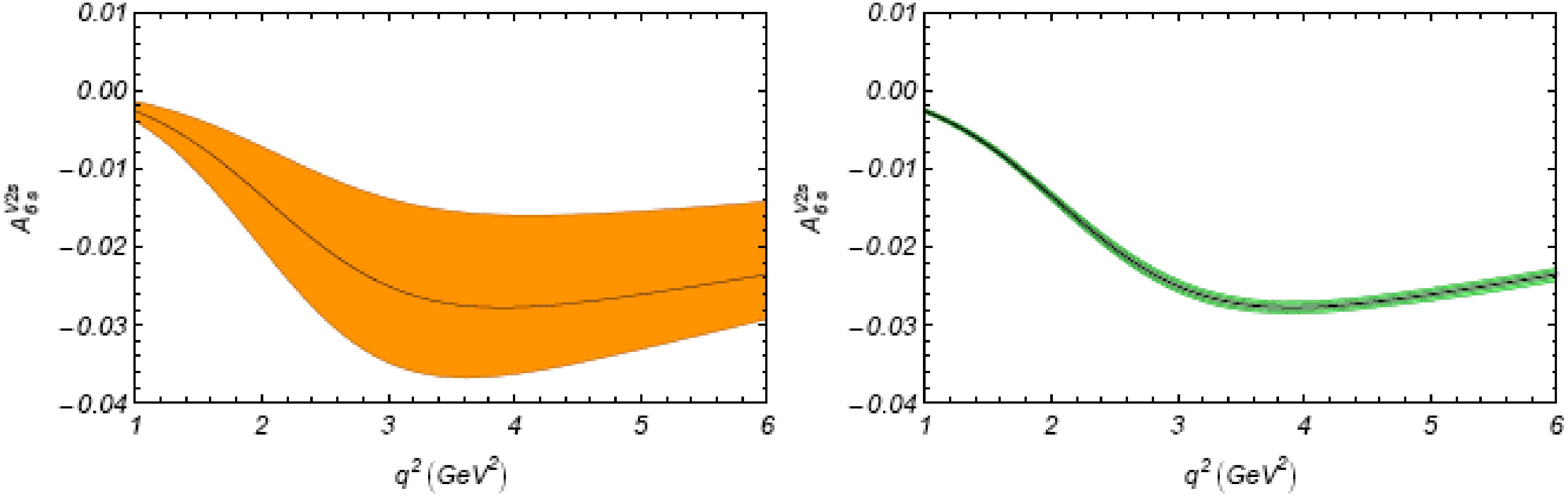
Inclusive Zero:

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

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

$$A^{6s}_{V2s} = \frac{I^{6s} - \bar{I}^{6s}}{I^{2s} + \bar{I}^{2s}}$$



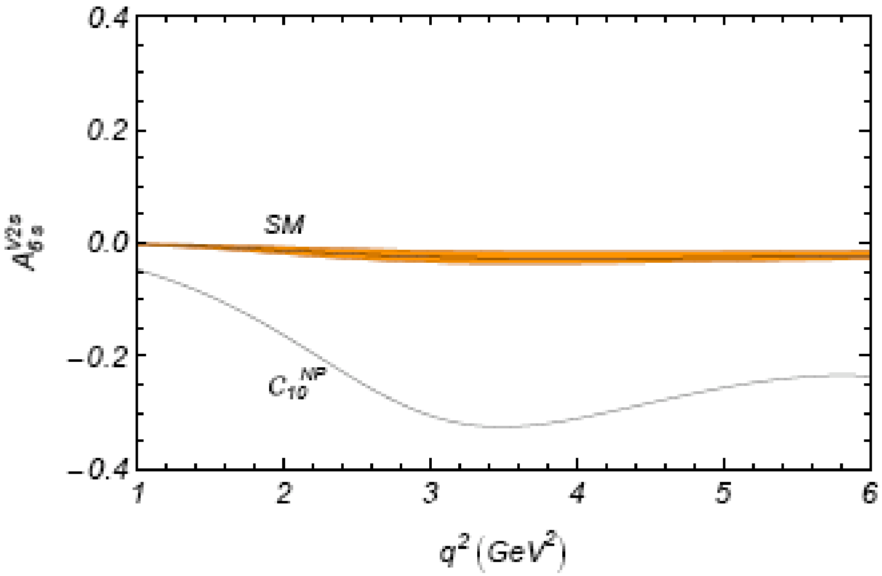
Uncertainty due Λ/m_b corrections significantly smaller than error due to input parameters

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

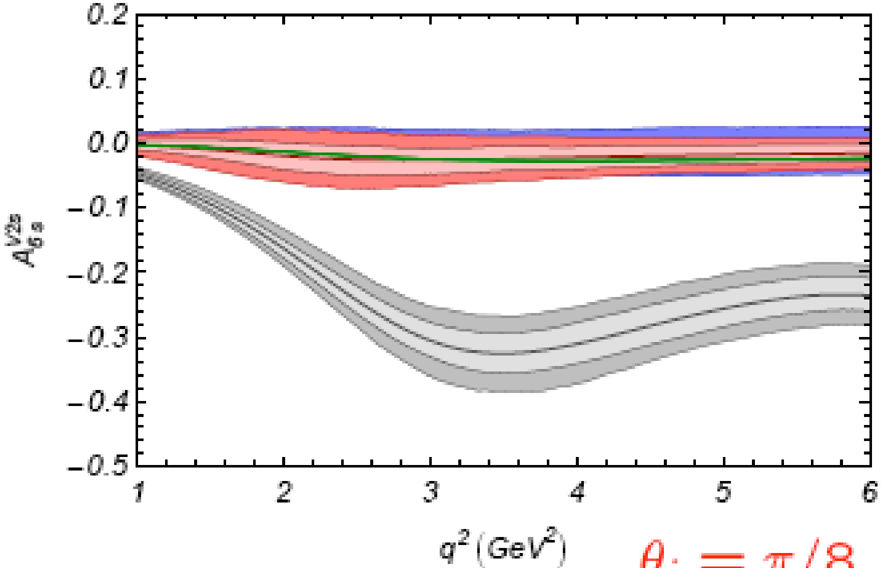
NP benchmarks



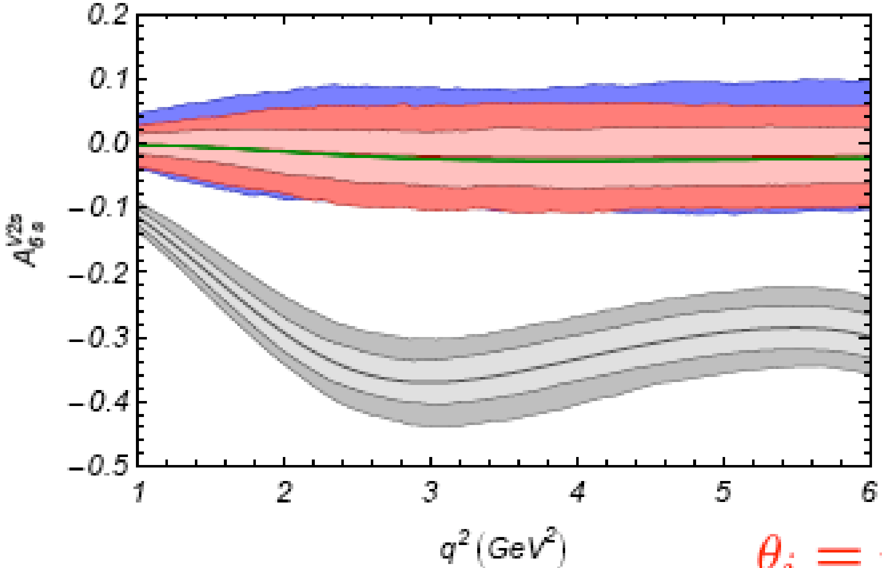
1. $|C_9^{\rm NP}| = 2.$ and $\theta_9^{\rm NP} = \pi/8, \pi/2, \pi$

2. $|C_{10}^{\rm NP}| = 1.5.$ and $\theta_{10}^{\rm NP} = \pi/8, \pi/2, \pi$

3. $|C_{10}'| = 3.$ and $\theta_{10}' = \pi/8, \pi/2, \pi$



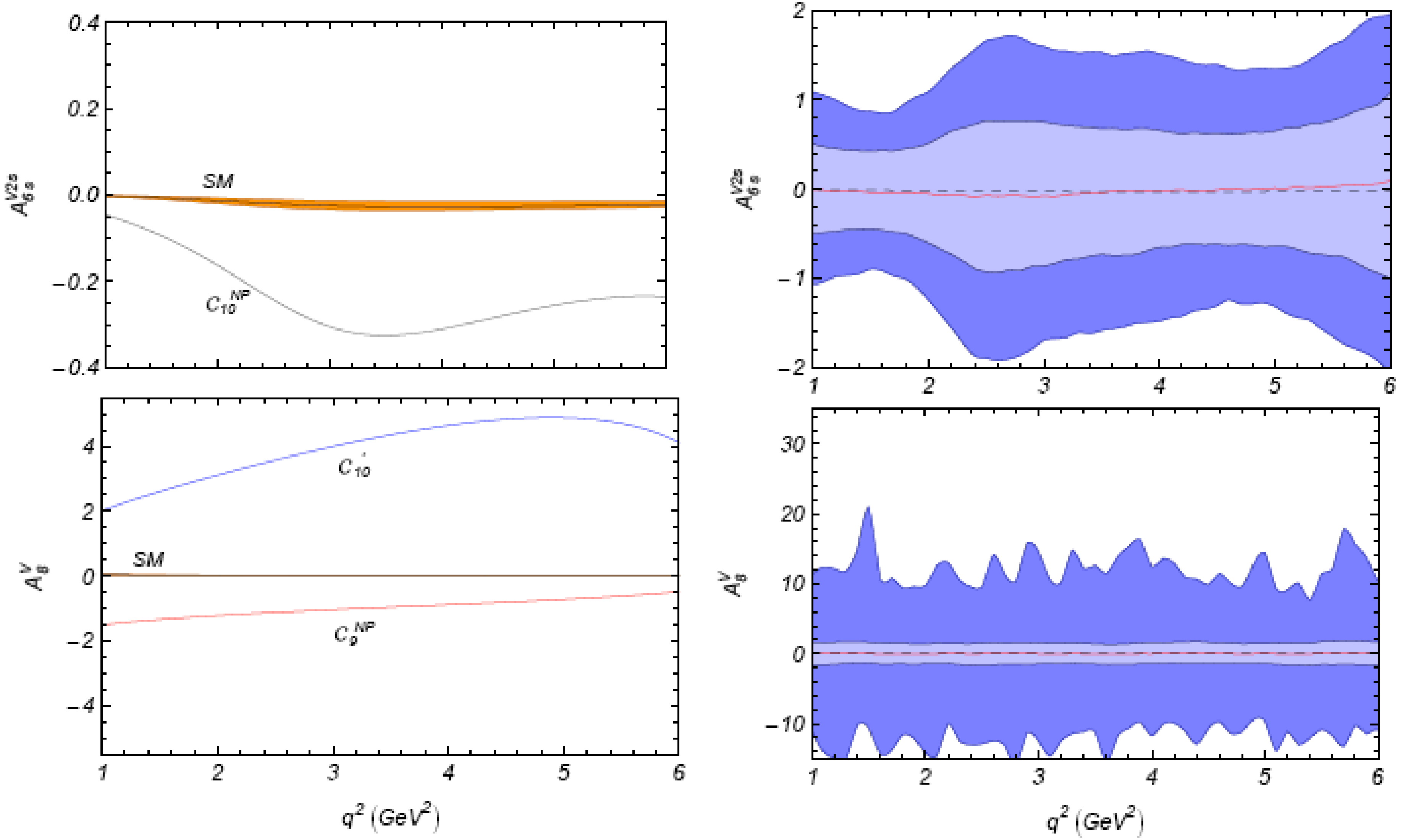
$\theta_i = \pi/8$



$\theta_i = \pi/2$

Λ/m_b corrections

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.

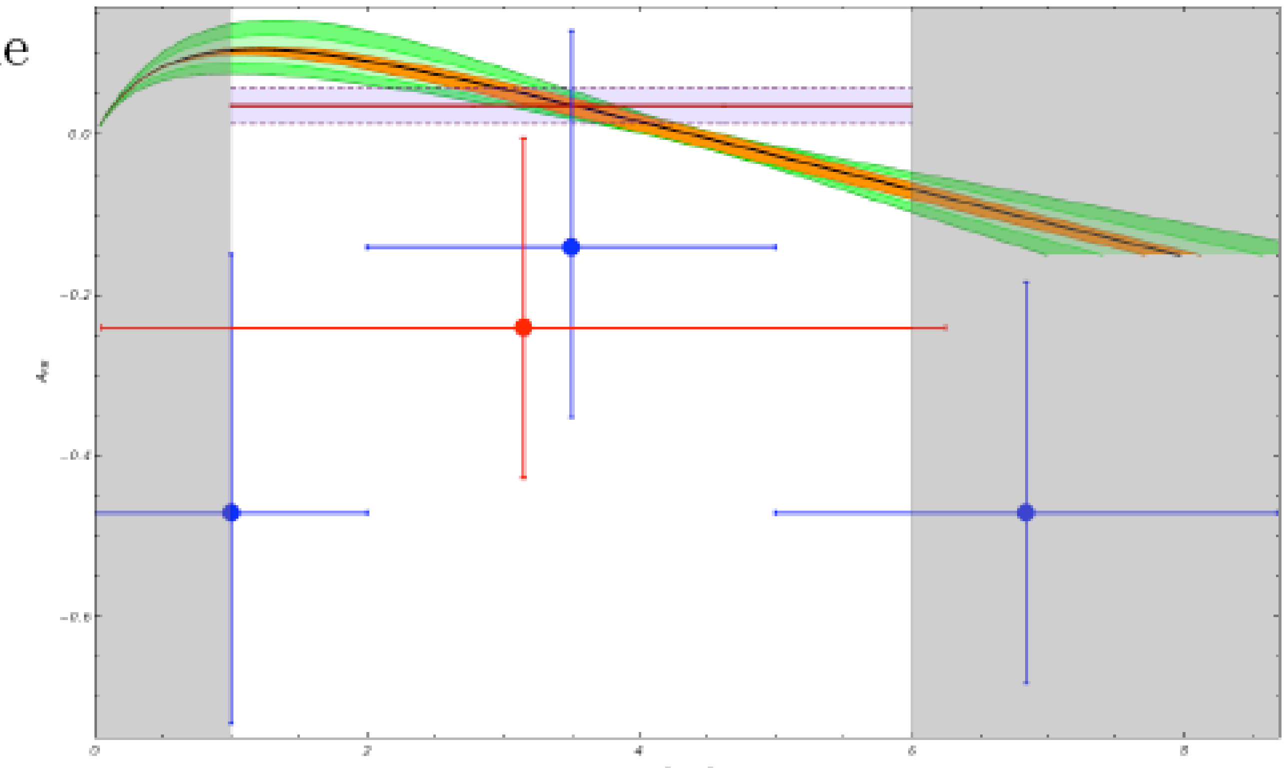
However, all phases ($0 \to 2\pi$) are compatible with the present data

In contrast to observables like A_T^i, CP observables call for Super-LHCb old observables : data available

Babar FPCP 2008

Belle ICHEP 2008

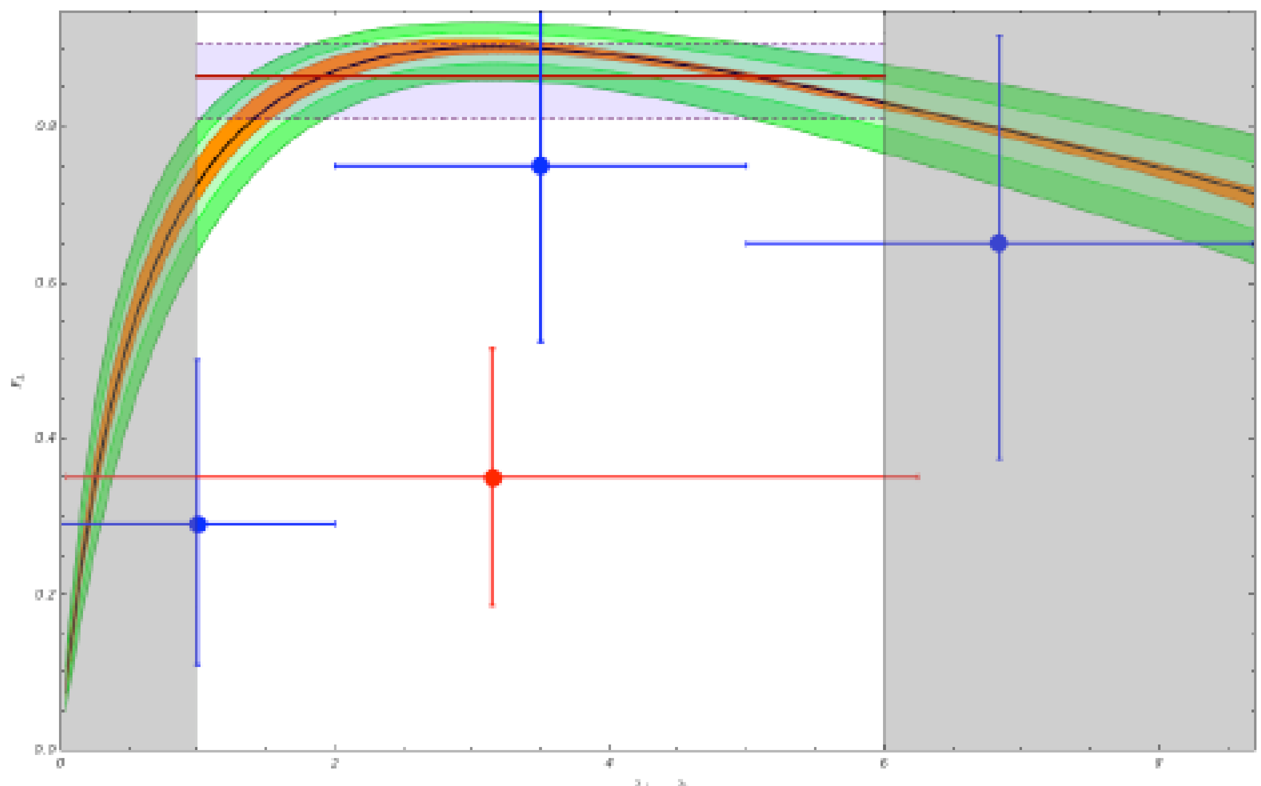
$$A_{\rm FB} = \frac{3}{2}\frac{{\rm Re}(A_{\parallel L}A^*_{\perp L}) - {\rm Re}(A_{\parallel R}A^*_{\perp R})}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$



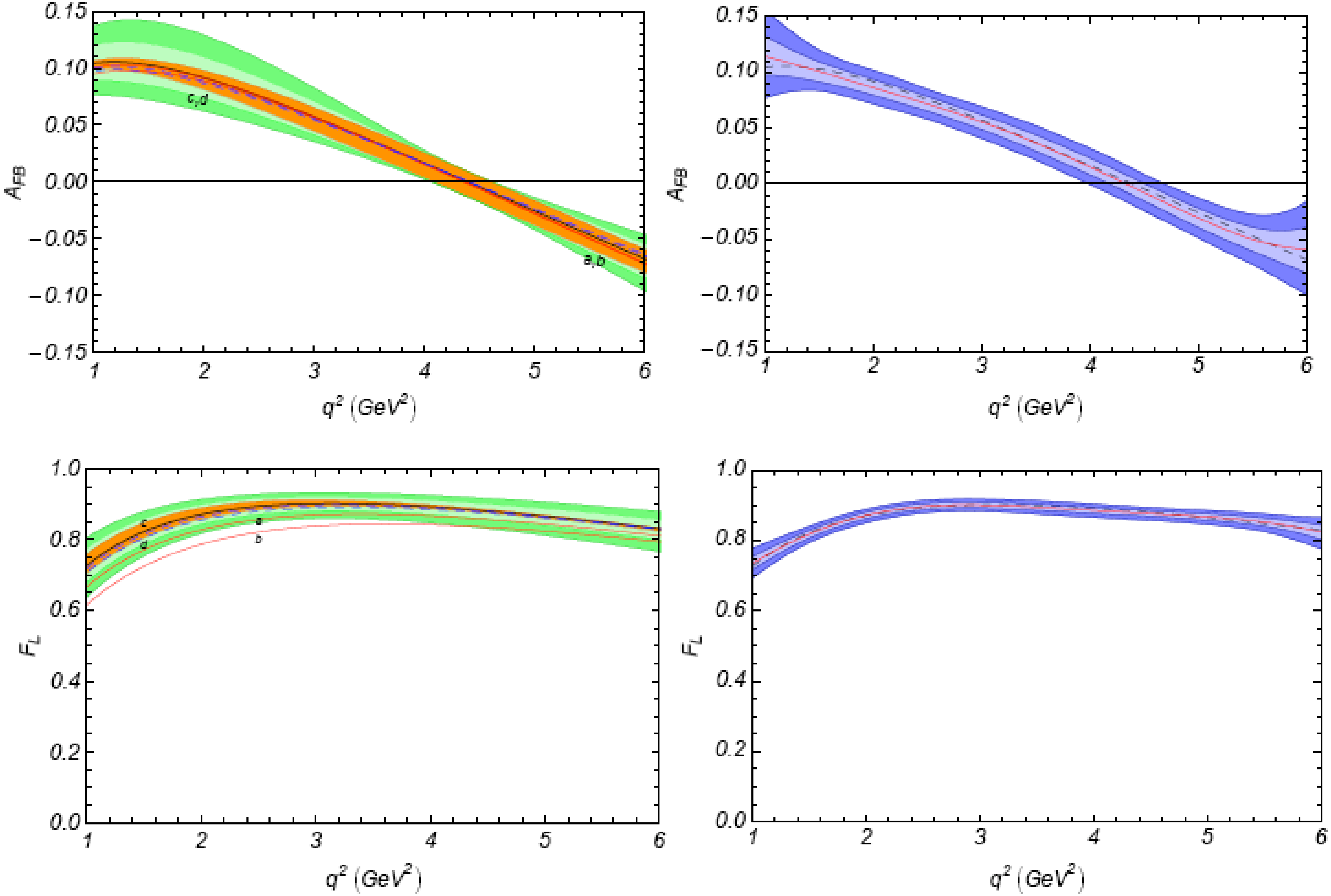
Babar FPCP 2008

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



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 $(\succ 2fb^{-1})$

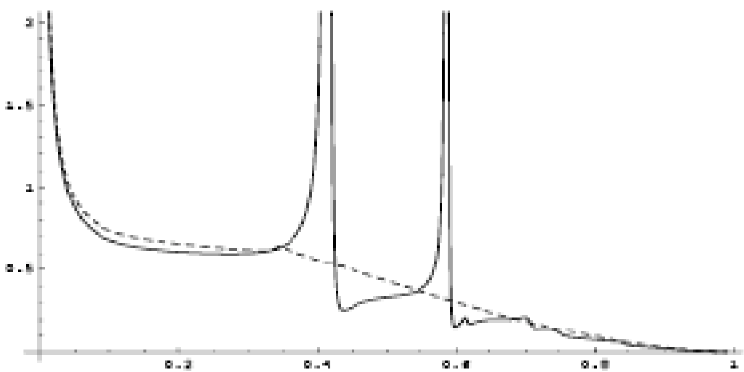
much better resolution (factor 3 even in $A_T^{(2)}$)

New observables are available

Unbinned analysis, q^2 dependence parametrised by polynomial

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

$\frac{d}{d\hat{s}} BR(\bar{B} \to X_s l^+ l^-) \times 10^{-5}$



$\hat{s} = q^2/m_b^2$

NNLL prediction of $\bar{B} \to X_s \ell^+\ell^-$: dilepton mass spectrum
Asatryan, Asatrian, Greub, Walker, hep-ph/0204341;
Ghinculov, Hurth, Isidori, Yao hep-ph/0312128:

NNLL QCD corrections $q^2 \in [1GeV^2, 6GeV^2]$
central value: -14%, perturbative error: $13\% \to 6.5\%$

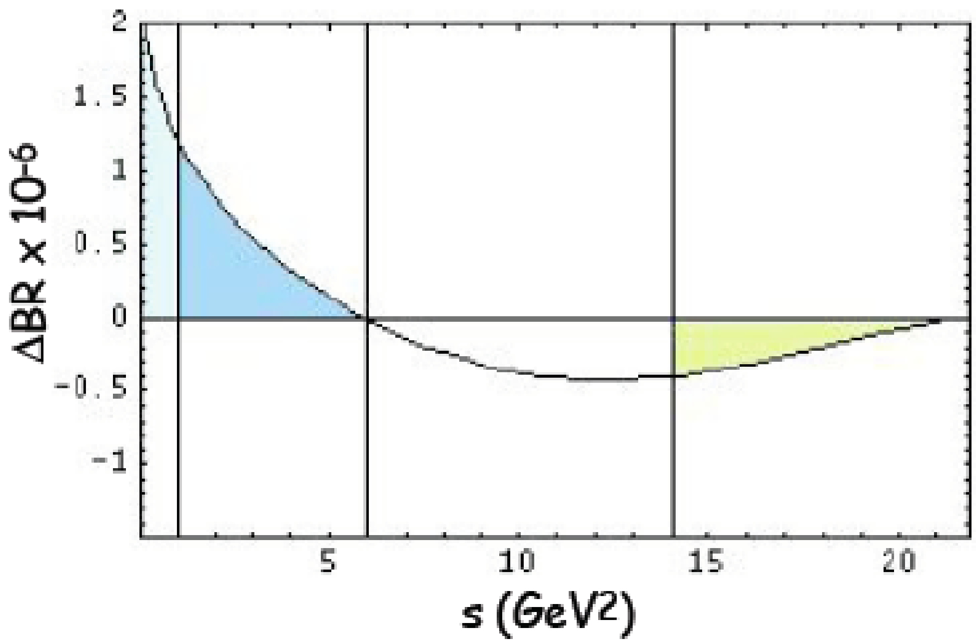
NNLL prediction of $\bar{B} \to X_s \ell^+\ell^-$: forward-backward-asymmetry (FBA)
Asatrian, Bieri, Greub, Hovhannisyan, hep-ph/0209006;
Ghinculov, Hurth, Isidori, Yao, hep-ph/0208088, hep-ph/0312128:

Update with electromagnetic corrections for dilepton mass spectrum
and FBA including the high-q^2 region Huber, Hurth, Lunghi arXiv/0712.3009[hep-ph]

Electromagnetic corrections

Huber, Hurth, Lunghi arXiv/0712.3009[hep-ph]

- Focus on corrections to the Wilson coefficients which are enhanced by a large logarithm $\alpha_{em} Log(m_W/m_b)$
- Corrections to matrix elements lead to large collinear logarithm $Log(m_b/m_\ell)$ which survive intregration if a restricted part of the dilepton mass spectrum is considered
  - $+2\%$ effect in the low-q^2 region for muons, for the electrons the effect depends on the experimental cut parameters:
  - Note that the coefficient of this logarithm vanishes when integrated over the whole spectrum



$\Rightarrow$ Relative effect of this logarithm in the high-q^2 region much larger : we find -8% !

- Our theory predictions correspond to a Super-B measurement not to the present Babar/Belle set-up see Huber, Hurth, Lunghi, arXiv:0807.1940 [hep-ph]

Further refinements:

Recent proposal: normalization to semileptonic $B \to X_u \ell \nu$ decay rate with the same cut reduces the impact of $1/m_b$ corrections in the high-q^2 region significantly. Ligeti, Tackmann, hep-ph/0707.1694

Hadronic invariant-mass cut is imposed in order to eliminate the background like $b \to c\,(\to s e^+ \nu) e^- \bar{\nu} = b \to s e^+ e^- +$ missing energy Lee, Stewart, hep-ph/0511334

Third independent combination of Wilson coefficents in $\bar{B} \to X_s \ell^+ \ell^-$ ($z = cos\theta$)

$$\frac{d^2\Gamma}{dq^2\,dz} = 3/8\,\left[(1+z^2)\,H_T(q^2) + 2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right]$$

$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2)\,, \qquad \frac{dA_{\rm FB}}{dq^2} = 3/4\,H_A(q^2)$$

Huber,Hurth,Lunghi arXiv/0712.3009[hep-ph]

- Each of the brackets gets fully expanded in all couplings, but no overall expansion

$$[\frac{A_{FBbs\ell\ell}(q^2)}{\Gamma_u}] \, / \, [\frac{\Gamma_{bs\ell\ell}(q^2)}{\Gamma_u}]\,; \quad m_{b,\text{pole}} \leftrightarrow m_{b,\overline{\text{MS}}} \leftrightarrow m_{b,1\text{S}}$$

	1S	$\overline{\text{MS}}$	pole
μ	3.50	3.47	3.52
e	3.38	3.34	3.41

- Residual μ-dependence also for the Zero of the AFB a good estimate of the perturbative error

- Additional $O(5\%)$ uncertainty due to nonlocal power corrections $O(\alpha_s \Lambda/mb)$

$$A_{\text{FB}} \approx \quad \left\{-\,6\,\text{Re}(\tilde{C}^{eff}_{7,FB}\tilde{C}^{*\,eff}_{10,FB}) - 3\hat{s}\,\text{Re}(\tilde{C}^{eff}_{9,FB}\tilde{C}^{*\,eff}_{10,FB}) + A^{brems}_{FB}\right\}$$