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Finding New Physics with B decays: Prospects for $B \to K^* \mu^+ \mu^-$

Aoife Bharucha with W. Altmannshofer, Patricia Ball, A.J. Buras, D. Straub and M. Wick (arXiv:0811.1214 [hep-ph])
also with William Reece

IPPP

Seminar, Liverpool, 17th February 2010

Just launched expedition to 14 TeV

Just launched expedition to 14 TeV

Some Structure

- New sources of Flavour in B decays
- Theoretical Predictions for $B \to K^* \mu^+ \mu^-$
- Prospects at LHCb for $B \to K^* \mu^+ \mu^-$
- Constraints on NP at LHCb

Source of all Flavour in the SM

$$\mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}}$$

respects the Flavour Symmetry $SU(3)^3_q \times SU(3)^2_\ell$, under which

$$Q_L \to V_Q Q_L, \quad U_R \to V_U U_R, \quad D_R \to V_D D_R,$$

and

$$L_L \to V_L L_L, \quad E_R \to V_E E_R,$$

where the V_i are unitary matrices.
The Yukawa interactions

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\ \bar{Q}_{Li} \phi D_{Rj} + Y^u_{ij}\ \bar{Q}_{Li} \tilde{\phi} U_{Rj} + Y^e_{ij}\ \bar{L}_{Li} \phi E_{Rj} + \text{h.c.}.$$

BREAK the global symmetry, resulting in Flavour Violation...

CP Violation via the CKM Matrix

Choosing

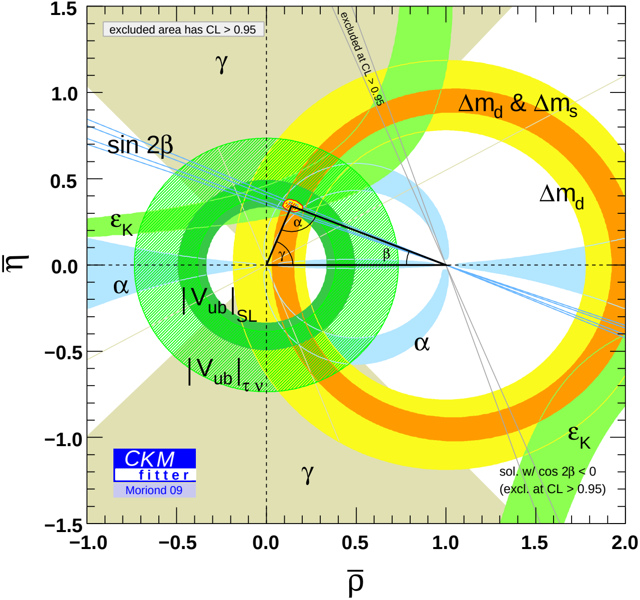
$$Y^d = \lambda_d, \quad Y^u = V^\dagger \lambda_u,$$

where $\lambda_{d,u}$ are diagonal,

CKM matrix V using the Wolfenstein Parameterization

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$\lambda = 0.2257 \pm 0.001$ and $A = 0.814 \pm 0.022$


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|_SL
|V_ub|_τν
CKM fitter
Moriond 09
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0

Current status of B decays and prospects at future colliders[1]

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$\lvert V_{ub}\rvert$ $[B \to \pi \ell \nu]$	input	$10\% \to 5\%_{\rm Latt}$	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \to \psi \phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \to \phi \phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \to K^* \gamma}$	few $\times$ 0.01	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \to \phi \gamma}$	few $\times$ 0.01	0.01	—	0.05	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \to \tau\nu)$	1×10^{-4}	$20\% \to 5\%_{\rm Latt}$	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu\nu)$	4×10^{-7}	$20\% \to 5\%_{\rm Latt}$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu^+\mu^-)$	3×10^{-9}	$20\% \to 5\%_{\rm Latt}$	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \to \mu^+\mu^-)$	1×10^{-10}	$20\% \to 5\%_{\rm Latt}$	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{\rm FB}(B \to K^* \mu^+ \mu^-)_{q_0^2}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \to K \nu \bar{\nu}$	4×10^{-6}	$20\% \to 10\%_{\rm Latt}$	$< 1.4 \times 10^{-5}$	20%	Super-B

[1] G. Isidori, Y. Nir and G. Perez, "Flavor Physics Constraints for Physics Beyond the Standard Model," arXiv:1002.0900 [hep-ph]

NP in B Decays

Can be model dependent or model independent..
Use an Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda_{\text{NP}}^{(d-4)}} O_i^{(d)}(\text{SM fields})$$

Flavour Changing Neutral Currents

- Suppressed at tree level by V_{ij} and M_W
- Big effects if Λ_{NP} provides similar suppression

Model Independent

MFV

Strictest bounds from $B \to X_s \gamma \Rightarrow$ Assume Flavour Violating Structure Beyond the SM linked to known SM Yukawas

- FCNC's suppressed even for $\Lambda \sim$ few TeV
- Naturally implementable in $\mathcal{L}_{\text{eff}}$
- Not a theory of flavour
- Difficult to prove but might be easy to disprove : $B \to X_s l^+ l^-$ / $B \to l^+ l^-$?

EXTENSIONS:

- MFV with **additional Higgs doublet**/ large $\tan\beta$
- MFV with **additional flavour diagonal phases**

Model Dependent

SUSY

Provides a well motivated model for various MFV scenarios

- Flavour Structure determind by **SUSY breaking soft mass terms** and **Trilinear couplings**
- **Flavour Blind MSSM** (FBMSSM): MFVMSSM modified by some flavour conserving but CP-violating phases in the soft SUSY breaking trilinear couplings
- **General MSSM** (GMSSM): No MFV, and generic flavour- and CP-violating soft SUSY-breaking terms allowed

Looking for NP in $B \to K^*\mu^+\mu^-$

- No. of events seen at Belle is 230
  $\Rightarrow B \to K^*\mu^+\mu^-$ is one of the rarest B decays ever observed
- LHCb predicts 7200 signal events with $2\text{fb}^{-1} \Leftrightarrow$ 1 year's data.
- FCNC, but bounds much weaker than for $B \to X_s\gamma$
- SM CP violation is doubly Cabibbo suppressed, NP CPV more visible
- 4 body decays, many angular observables, sensitive to NP

Experiment	BaBar	Belle	CDF
$\mathcal{B}(B \to K^*\mu^+\mu^-) \times 10^7$	$11.1 \pm 1.9 \pm 0.7$	$10.8^{+1.0}_{-1.0} \pm 0.9$	$8.1 \pm 3.0 \pm 1.0$
# of $B\bar{B}$ events	384×10^6	657×10^6	–

A B Physicists Tool Box

Effective Field Theories

$$\mathcal{L} = \sum_i C_i O_i$$

Contain short distance effects and possibly NP

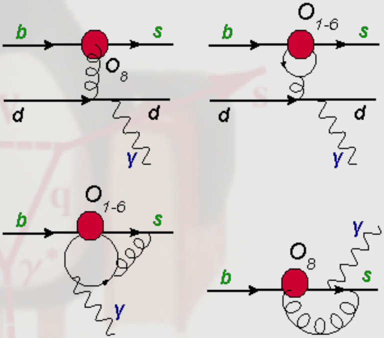
Hard Spectator Effects

For $B \to K^* \mu^+ \mu^-$ QCD factorization/ SCET/ HQET...

Hadronic Matrix Elements

e.g. $\langle B | J | K^* \rangle$

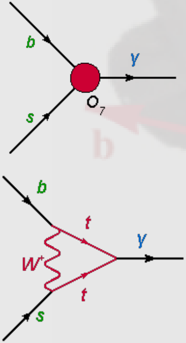
Described by Form Factors

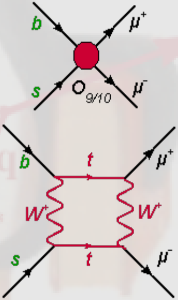


Relating Observables to NP: EFTs

For $B \to K^*$ decays, important Operators are..

Electromagnetic Dipole O_7 Vector/Axial Current $O_{9(10)}$

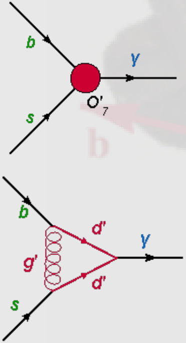




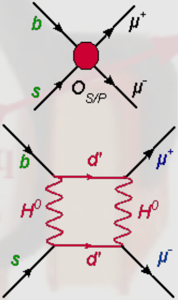
Relating Observables to NP: EFTs

For $B \to K^*(\to K^- \pi^+)\mu^+\mu^-$, important NP O's are..

Spin-Flipped EM Dipole O_7'



Scalar/Pseudoscalar $O_{S(P)}$



Brief Interlude-Form Factors

Matrix elements responsible for $B \to K^* l^+ l^-$ can be expressed as:

8 Full form factors (FF's)

$$\langle K^*(p)|\bar{s}\gamma_\mu\gamma_L b|\bar{B}(p_B)\rangle = -ie^*_\mu(m_B + m^*_K)\mathbf{A_1}(q^2) + i(p_B + p)_\mu e^*.q\frac{\mathbf{A_2}(q^2)}{m_B + m^*_K}$$

$$+ iq_\mu(e^*.q)\frac{2m_{K^*}}{q^2}\left(\mathbf{A_3}(q^2) - \mathbf{A_0}(q^2)\right) + \epsilon_{\mu\nu\rho\sigma}e^{*\nu}p^\rho_B p^\sigma \frac{2\mathbf{V}(q^2)}{m_B + m^*_K}$$

$$\langle K^*(p)|\bar{s}\sigma_{\mu\nu}q^\nu\gamma_L b|\bar{B}(p_B)\rangle = i\epsilon_{\mu\nu\rho\sigma}e^{*\nu}p^\rho_B p^\sigma 2\mathbf{T_1}(q^2) + \mathbf{T_2}(q^2)e^*_\mu(m^2_B - m^2_{K^*})$$

$$- \mathbf{T_2}(q^2)(e^*.q)\,(p_B + p)_\mu + \mathbf{T_3}(q^2)(e^*.q)\left\{q_\mu - \frac{q^2}{m^2_B - m^2_{K^*}}(p_B + p)_\mu\right\}$$

Form Factor Predictions

Theoretical Prections:

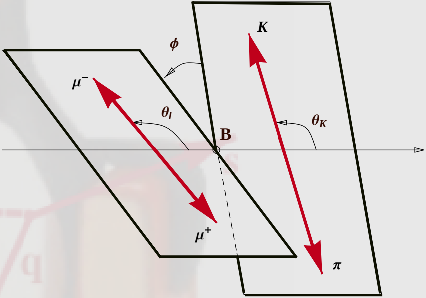
- **Lattice**: High q^2, Unstable particles eg. K^* difficult
- **Light Cone Sum Rules**: Low q^2

Range of Form Factors:

- Kinematic Range: $0 \leq q^2 \leq 20\text{GeV}^2$
- QCDF Range for $B \to K^* \mu^+ \mu^-$: $1 \leq q^2 \leq 6\text{GeV}^2$

Angular Observables for $B \to K^*\mu^+\mu^-$

Choosing a good place to look..



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

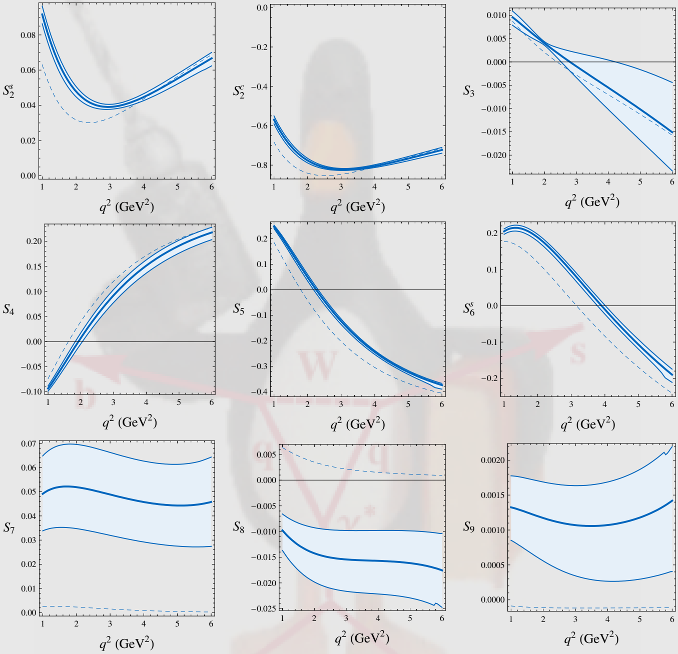
..where $I(q^2, \theta_l, \theta_K, \phi) = \sum_{i=1}^{9} I_i^{(s/c)}(q^2)\, \omega_i(\theta_l, \theta_K, \phi)$

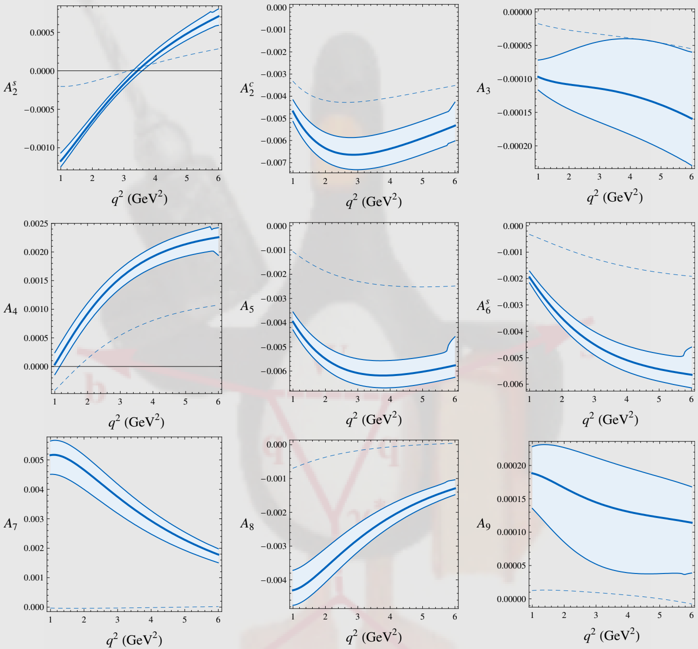
Emphasize CP conserving and CP violating[2] effects

$$S_i^{(a)} = \frac{I_i^{(a)} + \bar{I}_i^{(a)}}{\mathrm{d}(\Gamma + \bar{\Gamma})/\mathrm{d}q^2}$$

$$A_i^{(a)} = \frac{I_i^{(a)} - \bar{I}_i^{(a)}}{\mathrm{d}(\Gamma + \bar{\Gamma})/\mathrm{d}q^2}$$

[2] Also considered in C. Bobeth, G. Hiller and G. Piranishvili arXiv:0805.2525


S_2^s
S_2^c
S_3
S_4
S_5
S_6^s
S_7
S_8
S_9
q^2 (GeV^2)

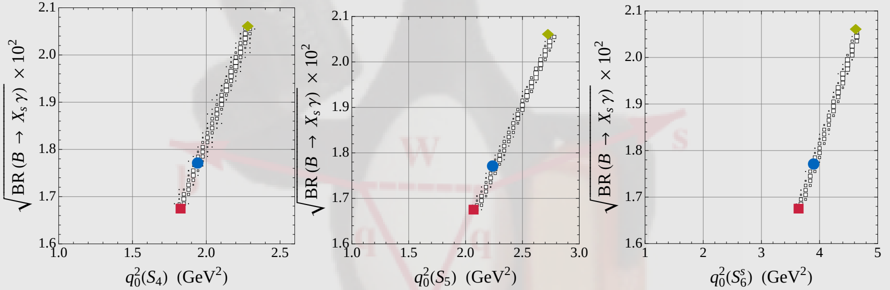

A_2^s
A_2^c
A_3
A_4
A_5
A_6^s
A_7
A_8
A_9
q^2 (GeV^2)

Model Independent Analysis

Observable	Most affected by
$S_1^s,\ S_1^c,\ S_2^s,\ S_2^c$	$C_7,\ C_7',\ C_9,\ C_9',\ C_{10},\ C_{10}'$
S_3	$C_7',\ C_9',\ C_{10}'$
S_4	$C_7,\ C_7',\ C_{10},\ C_{10}'$
S_5	$C_7,\ C_7',\ C_9,\ C_{10}'$
S_6^s	$C_7,\ C_9$
A_7	$C_7,\ C_7',\ C_{10},\ C_{10}'$
A_8	$C_7,\ C_7',\ C_9,\ C_9',\ C_{10}'$
A_9	$C_7',\ C_9',\ C_{10}'$
S_6^c	$C_S - C_S'$

Theoretical Predictions: Specific Scenarios

Correlate zeros of S_4, S_5, S_6^s with $B(b \to s\gamma)$



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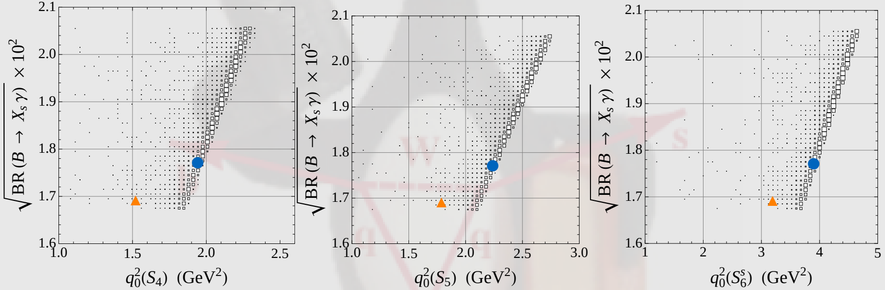
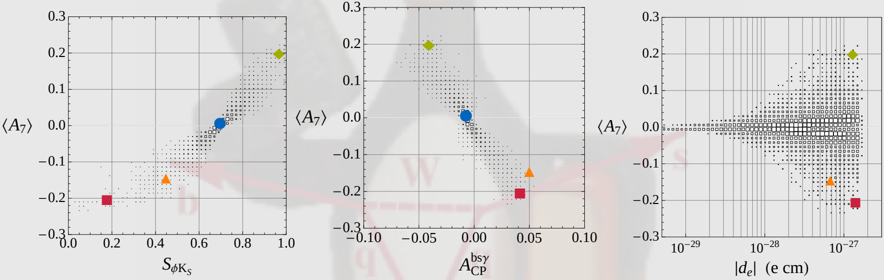
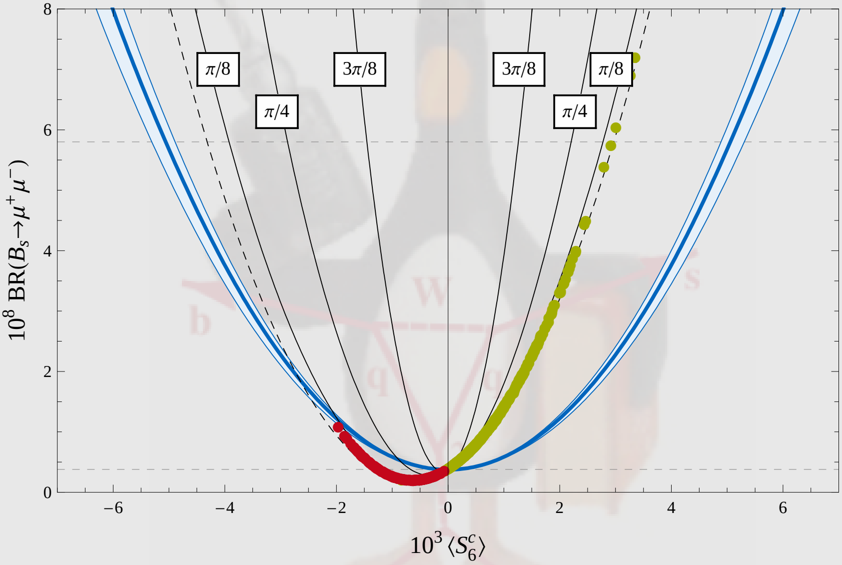


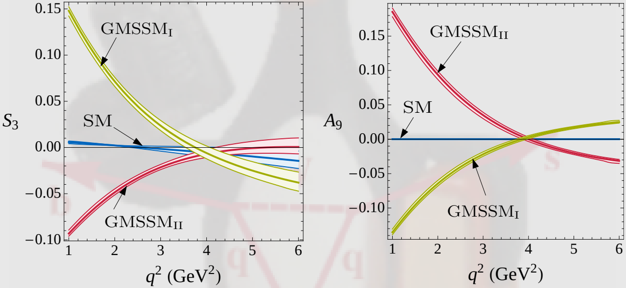
Theoretical Predictions: Specific Scenarios



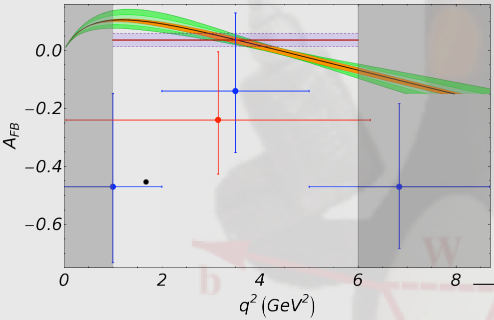
Correlations at large tanβ



General MSSM: No MFV constraints



Current Status/Prospects at LHCb



- Belle (2008) - ICHEP
  200 events
- BaBar (2008) 0804.4412
  100 events
- LHCb $< 0.1\,\text{fb}^{-1}$ 100 events
  $2\,\text{fb}^{-1}$ 7200 events
  $q^2 < m^2_{J/\psi}$, 3900 events[a]

[a] J. Dickens, V. Gibson, C. Lazzeroni and M. Patel, CERN-LHCB-2007-038

- EvtGen Model for $B \to K^* \mu^+ \mu^-$ at NLO
- Includes trigger studies, acceptance effects
- Finds sets of allowed WCs using current experimental constraints

Observables for early measurement

Using S's and A's reconstruct standard observables e.g. forward-backward asymmetry, $A_{\rm FB}$, longtitudinal polarization fraction, $F_{\rm L}$:

$$A_{\rm FB} = \frac{3}{8}(2S_6^s + S_6^c) \qquad \text{and} \qquad {\rm F_L} = -{\rm S_2^c}.$$

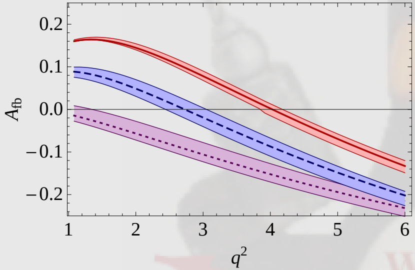
Extract by counting in angular bins:

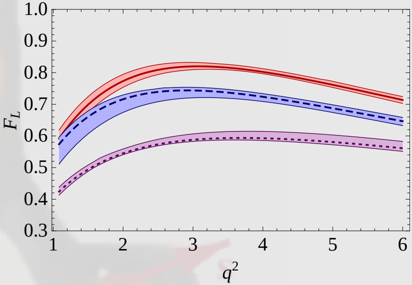
$$A_{\rm FB} = \frac{4}{3}\left(\int_0^1 - \int_{-1}^0\right) {\rm d}\theta_{\rm l} \frac{{\rm d}^2(\Gamma+\bar\Gamma)}{{\rm dq}^2\,{\rm d}\theta_{\rm l}} \Big/ \frac{{\rm d}(\Gamma+\bar\Gamma)}{{\rm dq}^2}$$

$$F_{\rm L} = \frac{1}{9}\left(16\int_{-1/2}^{1/2} \frac{{\rm d}(\Gamma+\bar\Gamma)}{{\rm dq}^2\,{\rm d}\cos\theta_{\rm K^*}} \Big/ \frac{{\rm d}(\Gamma+\bar\Gamma)}{{\rm d}q^2} - 11\right)$$

$$S_5 = \frac{4}{3}\left(\int_0^{\pi/2} + \int_{3\pi/2}^{2\pi} - \int_{\pi/2}^{3\pi/2}\right) {\rm d}\phi \left(\int_0^1 - \int_{-1}^0\right) {\rm d}\cos\theta_{\rm K^*} \frac{{\rm d}^3(\Gamma-\bar\Gamma)}{{\rm dq}^2\,{\rm d}\cos\theta_{\rm K^*}\;{\rm d}\phi} \Big/ \frac{{\rm d}(\Gamma+\bar\Gamma)}{{\rm dq}^2}$$

Sensitivity to New Physics

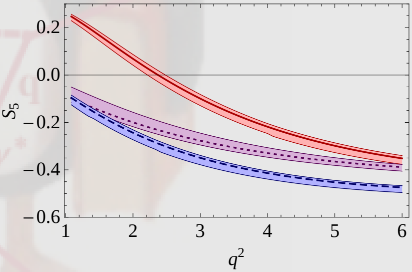




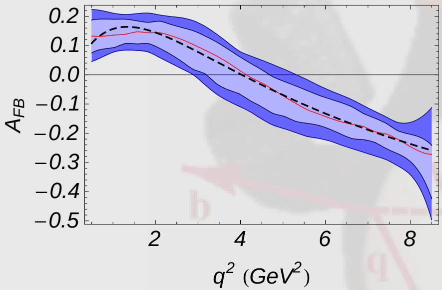
At Leading Order:

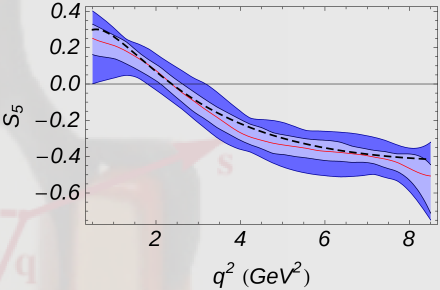
$$q_0^2(A_{\rm FB}) = -2 m_B\, m_b \frac{C_7^{\rm eff}}{C_9^{\rm eff}}$$

$$q_0^2(S_5) = \frac{-m_B\, m_b (C_7^{\rm eff} + C_7^{\prime\rm eff})}{C_9^{\rm eff} + \hat{m}_b (C_7^{\rm eff} + C_7^{\prime\rm eff})}$$



$A_{\rm FB}$ and S_5 at LHCb





Experimental Sensitivities

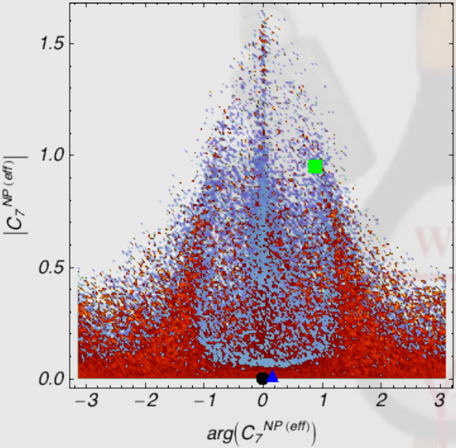
Observable	$2\mathrm{fb}^{-1}$	$1\mathrm{fb}^{-1}$	$0.5\mathrm{fb}^{-1}$
$\langle A_{\mathrm{FB}} \rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.03}_{-0.04}$	$^{+0.05}_{-0.03}$	$^{+0.08}_{-0.06}$
$\langle F_{\mathrm{L}} \rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.02}_{-0.02}$	$^{+0.04}_{-0.03}$	$^{+0.04}_{-0.06}$
$\langle S_5 \rangle_{1-6\,\mathrm{GeV}^2}$	$^{+0.07}_{-0.08}$	$^{+0.09}_{-0.11}$	$^{+0.16}_{-0.15}$
$q_0^2(A_{\mathrm{FB}})$	$^{+0.56}_{-0.94}$	$^{+1.27}_{-0.97}$	–
$q_0^2(S_5)$	$^{+0.27}_{-0.25}$	$^{+0.53}_{-0.40}$	–

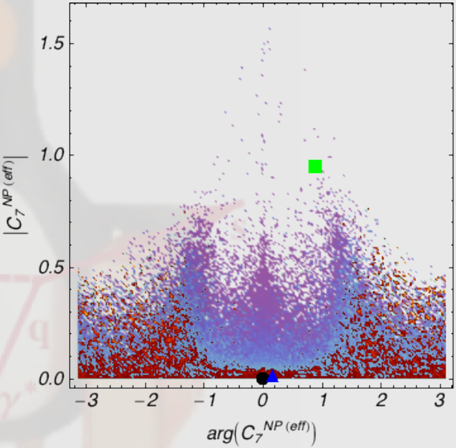
$$\langle V \rangle_{1-6\,\mathrm{GeV}^2} = \int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} \mathrm{d}q^2 \left(V(q^2) \frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2} \right) \Bigg/ \int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} \mathrm{d}q^2 \frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}$$

Existing Constraints for $b \longrightarrow s$

Observable	Experiment	SM Theory
$\mathcal{B}(B_s \to \mu^+ \mu^-)$	$3.6 \cdot 10^{-8}$	$(3.70 \pm 0.31) \cdot 10^{-9}$
$\mathcal{B}(B \to X_s l^+ l^-)_{1-6\,\mathrm{GeV}^2}$	$(1.60 \pm 0.51) \cdot 10^{-6}$	$(1.97 \pm 0.11) \cdot 10^{-6}$
$\mathcal{B}(B \to X_s \gamma)$	$(3.52 \pm 0.23 \pm 0.09) \cdot 10^{-9}$	$(3.28 \pm 0.25) \cdot 10^{-4}$
$S(B \to K^* \gamma)$	$(-1.6 \pm 2.2) \cdot 10^{-1}$	$(-0.26 \pm 0.05) \cdot 10^{-1}$
$\langle A_{\mathrm{FB}} \rangle_{1-6\,\mathrm{GeV}^2}$	-0.26 ± 0.29	0.04 ± 0.03
$\langle F_L \rangle_{1-6\,\mathrm{GeV}^2}$	0.67 ± 0.24	0.76 ± 0.08

Constraints on C_7 and C_7'





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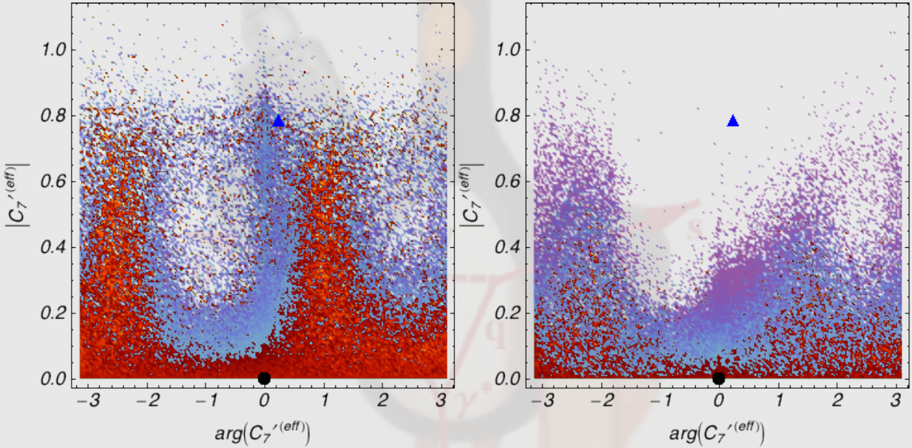
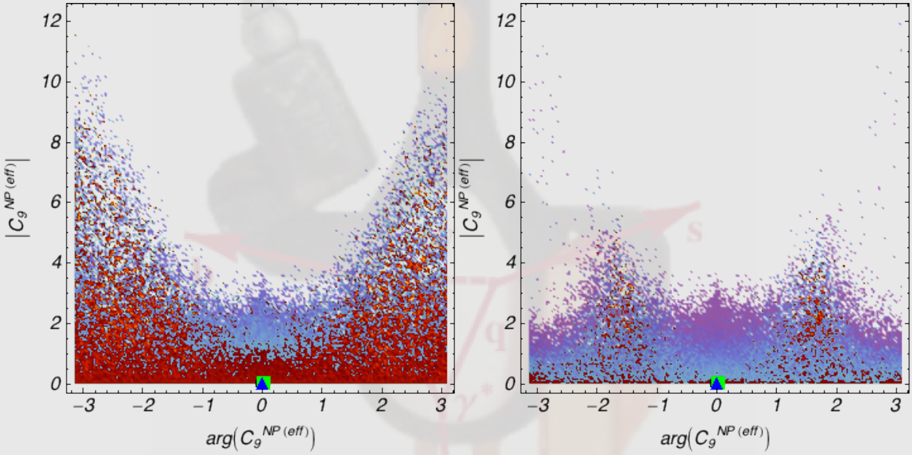


Constraints on C_9 and C'_{10}



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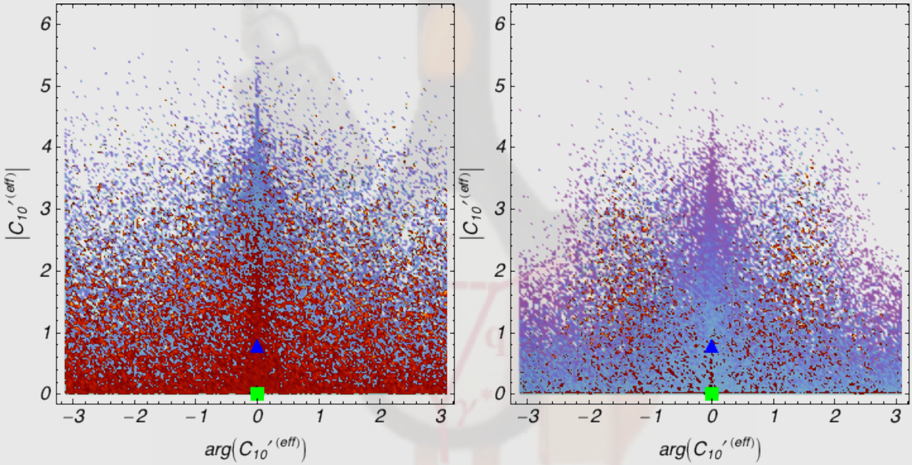

Summary

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