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Probing Universal Extra Dimensions through rare B and Λ_b decays

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Outline

- Introduction to Extra Dimensions
- The ACD model with a single Universal Extra Dimension
- Rare B and Λ_b decays in the ACD scenario

based on **Phys. Rev. D73 (2006)**
and **Phys. Rev. D74 (2006)**

Why Extra Dimensions?

- quantization of gravitational interactions (string theory)
- hierarchy problem
- dark matter
- …

Physical implications of compact EDs

Let us consider a single extra-dimension compactified on a circle of radius R.

$$F(x,y) = F(x, y + 2\pi R) \xrightarrow[\text{expansion}]{\text{Fourier}} F(x,y) = \sum_{n=-\infty}^{n=+\infty} F_n(x) e^{iny/R}$$

$$\underset{M=0,1,2,3,5}{\partial_M} \partial^M F(x,y) = 0 \longrightarrow \left(\underset{\mu=0,1,2,3}{\partial_\mu} \partial^\mu + \frac{n^2}{R^2} \right) F_n(x) = 0 \qquad \frac{n^2}{R^2} = m_n^2$$

Kaluza-Klein excitations

There are various models with extra-dimensions, differing by the space-time geometry and by the fields which are allowed to propagate in the EDs.

- **Braneworld models:** the SM fields are confined to our 4-dimensional world (**brane**).
  - Arkani-Hamed, Dimopoulos, Dvali (ADD) model
  - Randall Sundrum (RS) models

- **Universal Extra Dimensions (UEDs):** all the SM fields are allowed to propagate in the extra dimensions.

Appelquist-Cheng-Dobrescu (ACD) model with a single UED

Single new parameter: the compactification radius R

KK parity conservation $(-1)^j$ (j=KK number)

- First level KK particles cannot be singly produced
- The lightest KK particle (LKP) is stable (good dark matter candidate)

Bounds from Tevatron:

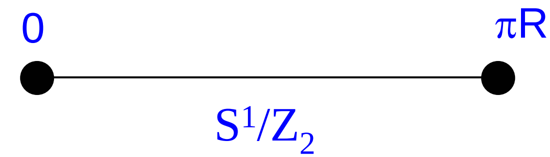
$$\frac{1}{R} > 250\,\mathrm{GeV} \qquad (\text{if} \quad M_H > 250\,\mathrm{GeV})$$

$$\frac{1}{R} > 300\,\mathrm{GeV} \qquad (\text{if} \quad M_H < 250\,\mathrm{GeV})$$

ACD model may have interesting predictions for collider phenomenology.

Orbifold compactification in the ACD model with a single UED

Let us consider a single extra-dimension compactified on S^1/Z_2



$$\phi(x,y)=\frac{1}{\sqrt{2\pi R}}\left[\phi_0(x)+\sqrt{2}\sum_{n=1}^{+\infty}\left(\phi_n^{(1)}(x)\cos\left(\frac{ny}{R}\right)+\phi_n^{(2)}(x)\sin\left(\frac{ny}{R}\right)\right)\right]$$

SM field

KK excitations

SM fields are identified with zero-modes.

It is assumed that fields have definite properties under the reflection $y \to -y$:

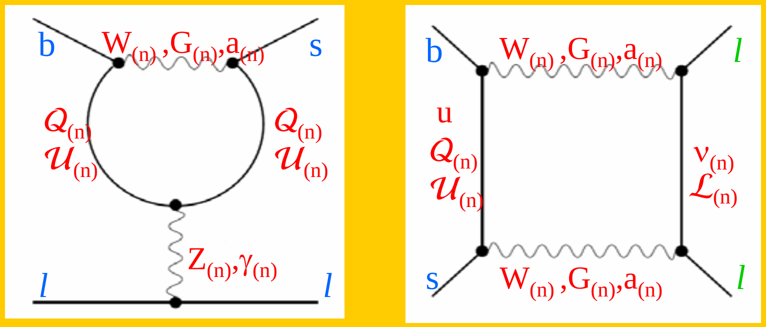
even: $\phi(x,y)=\phi(x,-y) \longrightarrow \phi_n^{(2)}=0$ ← fields which have a correspondent in the SM

odd: $\phi(x,y)=-\phi(x,-y) \longrightarrow \phi_0=0, \quad \phi_n^{(1)}=0$ ← fields having no SM partner (for example fermions with unwanted chirality or the fifth component of gauge fields)

FCNC rare decays can be used to constrain the ACD scenario

Their investigation allows to probe indirectly high energy scales of the theory, since the loop-contributions from high energy modes could be non negligible.

KK modes could contribute to processes induced by $b \to s$ transition.



It is possible to establish a lower bound on 1/R by comparing theoretical predictions with experimental data.

The following decays will be considered:

$$B \to K^{(*)} l^+ l^-$$
$$B \to K^{(*)} \nu \bar{\nu}$$
$$B \to K^* \gamma$$

(BR, differential widths, A_{FB})

$$B \to X_s \tau^+ \tau^-$$
$$B \to K^{(*)} \tau^+ \tau^-$$

(BR, τ polarization asymmetries, K^* helicity fractions)

$$B_s \to \phi \gamma$$
$$B_s \to \phi \nu \bar{\nu}$$

$$\Lambda_b \to \Lambda \gamma$$
$$\Lambda_b \to \Lambda \nu \bar{\nu}$$

(BR, differential widths)

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

$$H_W = 4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

Minimal Flavour Violation
(no new operators; CKM matrix)

current-current operators

$$O_1 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})(\bar{c}_{L\beta}\gamma_\mu c_{L\beta})$$
$$O_2 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})(\bar{c}_{L\beta}\gamma_\mu c_{L\alpha})$$

long distance effects (neglected)

$$q_{R,L} = \frac{1 \pm \gamma_5}{2} q$$
$$\sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

QCD penguin operators

$$O_3 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})[(\bar{u}_{L\beta}\gamma_\mu u_{L\beta}) + \ldots + (\bar{b}_{L\beta}\gamma_\mu b_{L\beta})]$$
$$O_4 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})[(\bar{u}_{L\beta}\gamma_\mu u_{L\alpha}) + \ldots + (\bar{b}_{L\beta}\gamma_\mu b_{L\alpha})]$$
$$O_5 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})[(\bar{u}_{R\beta}\gamma_\mu u_{R\beta}) + \ldots + (\bar{b}_{R\beta}\gamma_\mu b_{R\beta})]$$
$$O_6 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})[(\bar{u}_{R\beta}\gamma_\mu u_{R\alpha}) + \ldots + (\bar{b}_{R\beta}\gamma_\mu b_{R\alpha})]$$

small Wilson coefficients

magnetic penguin operators

$$\boxed{O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_{L\alpha}\sigma^{\mu\nu} b_{R\alpha}) F_{\mu\nu}}$$
$$O_8 = \frac{g_s}{16\pi^2} m_b \left[\bar{s}_{L\alpha}\sigma^{\mu\nu}\left(\frac{\lambda^a}{2}\right)_{\alpha\beta} b_{R\beta}\right] G^a_{\mu\nu}$$

semileptonic EW penguin operators

$$\boxed{O_9 = \frac{e^2}{16\pi^2}(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\ \bar{\ell}\gamma_\mu \ell}$$
$$\boxed{O_{10} = \frac{e^2}{16\pi^2}(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\ \bar{\ell}\gamma_\mu\gamma_5 \ell}$$

main contributions come from these operators

We only need the coefficients C_7, C_9, C_{10}.

In the ACD model:

$$\boxed{C\left(x_t, \frac{1}{R}\right) = C_0(x_t) + \sum_{n=1}^{\infty} C_n(x_t, x_n)} \longrightarrow x_n = \frac{m_n^2}{m_W^2}, \quad m_n = \frac{n}{R}$$

SM

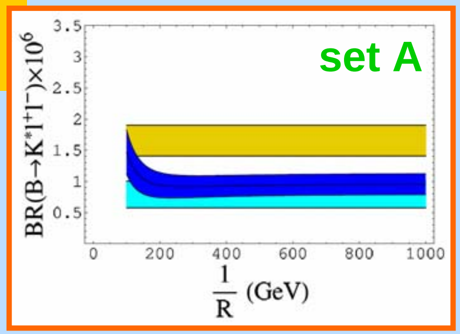
computed by Buras et al.

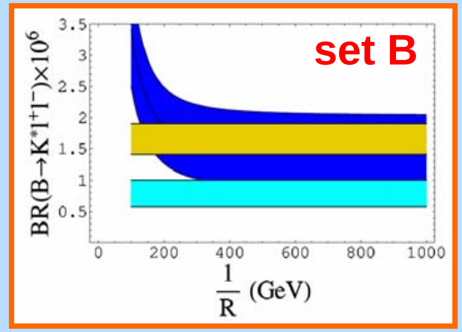
$B \to K^* l^+ l^-$

We choose two sets of **form factors**:

set A: 3-point QCD sum rules
set B: light cone QCD sum rules

Branching Ratio



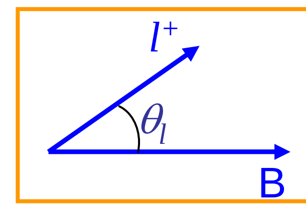


Belle $\left(16.5^{+2.3}_{-2.2} \pm 0.9 \pm 0.4\right) \times 10^{-7}$

BaBar $\left(7.8^{+1.9}_{-1.7} \pm 1.2\right) \times 10^{-7}$

Forward Backward Asymmetry

$$A_{fb}(q^2) = \frac{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\vartheta_l} d\cos\vartheta_l - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\vartheta_l} d\cos\vartheta_l}{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\vartheta_l} d\cos\vartheta_l + \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\vartheta_l} d\cos\vartheta_l}$$

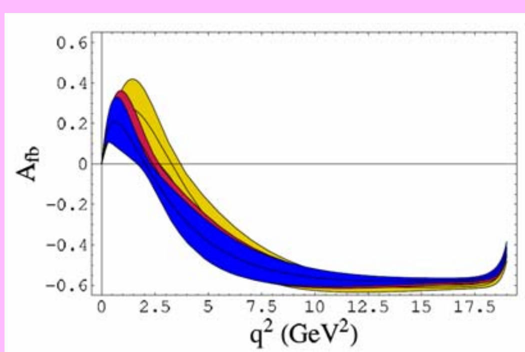


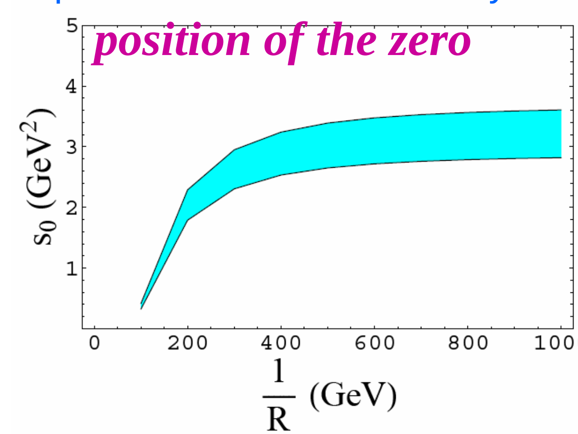
The presence and the position of the zero could distinguish among SM predictions and models beyond SM.

$\frac{1}{R} = 200\ \text{GeV}$

$\frac{1}{R} = 250\ \text{GeV}$

SM

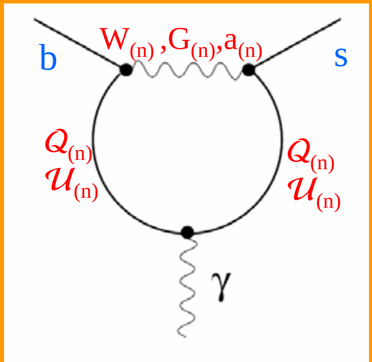


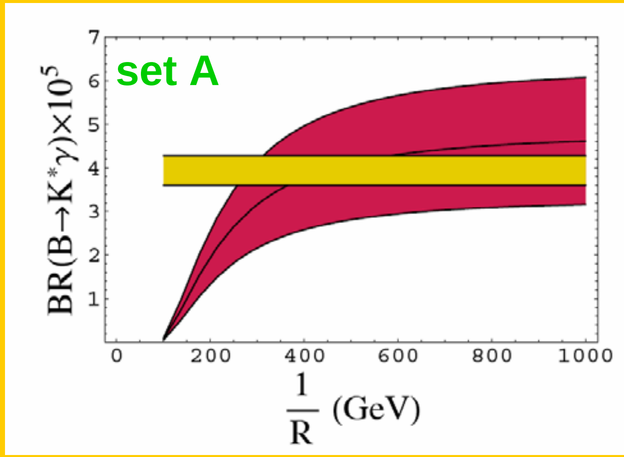


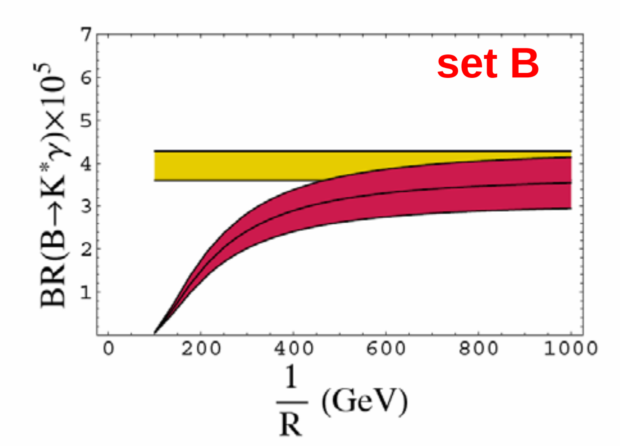
$B \to K^* \gamma$

Branching Ratio

Mode	Belle Collab.	BaBar Collab.
$B^0 \to K^{*0}\gamma$	$(4.01 \pm 0.21 \pm 0.17) \times 10^{-5}$	$(3.92 \pm 0.20 \pm 0.24) \times 10^{-5}$
$B^- \to K^{*-}\gamma$	$(4.25 \pm 0.31 \pm 0.24) \times 10^{-5}$	$(3.87 \pm 0.28 \pm 0.26) \times 10^{-5}$







set **A** allows to put

$$\frac{1}{R} > 300 \ \text{GeV}$$

set **B** allows to put

$$\frac{1}{R} > 400 \ \text{GeV}$$

Lepton polarization asymmetries in $b(p) \to s(p')\tau^-(k_1)\tau^+(k_2)$

τ^- lepton rest frame:

$$s_L = \left(0, \overrightarrow{e_L}\right) = \left(0, \frac{\overrightarrow{k_1}}{\left|\overrightarrow{k_1}\right|}\right)$$

$$s_N = \left(0, \overrightarrow{e_N}\right) = \left(0, \frac{\overrightarrow{p'} \wedge \overrightarrow{k_1}}{\left|\overrightarrow{p'} \wedge \overrightarrow{k_1}\right|}\right)$$

$$s_T = \left(0, \overrightarrow{e_T}\right) = \left(0, \overrightarrow{e_N} \wedge \overrightarrow{e_L}\right)$$

lepton pair rest frame:

$$s_L = \frac{1}{m_\tau}\left(\left|\overrightarrow{k_1}\right|, 0, 0, E_1\right)$$

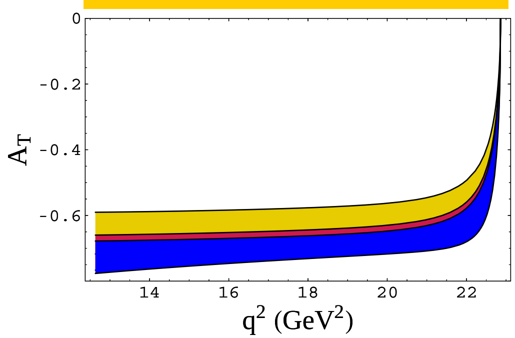
$$A_M\left(q^2\right) = \frac{\frac{d\Gamma}{dq^2}(s_M) - \frac{d\Gamma}{dq^2}(-s_M)}{\frac{d\Gamma}{dq^2}(s_M) + \frac{d\Gamma}{dq^2}(-s_M)}$$

polarization asymmetries

$M = L, N, T$

transverse asymmetry

$B \to K\tau^+\tau^-$

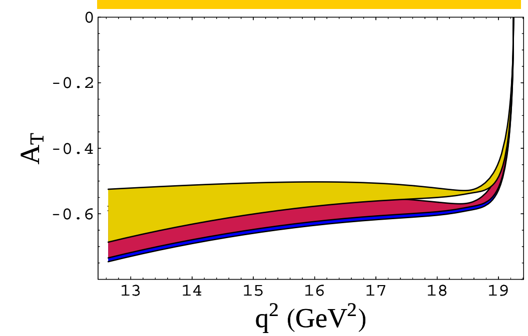


$\frac{1}{R} = 200GeV$

$\frac{1}{R} = 500GeV$

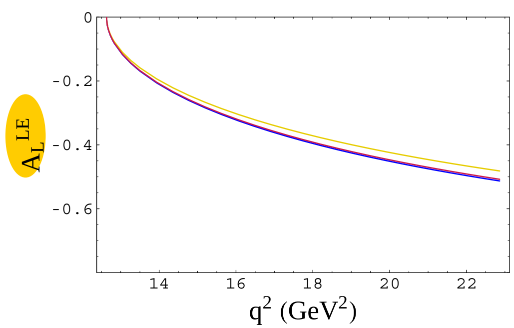
SM

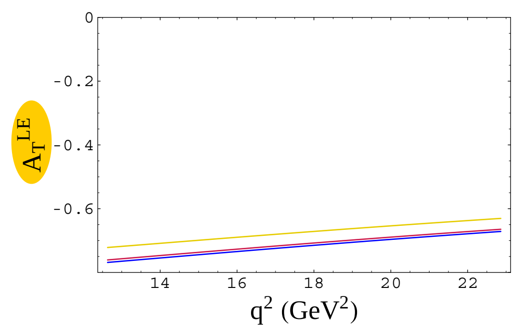
$B \to K^*\tau^+\tau^-$



LARGE ENERGY LIMIT

In the large energy limit of the final light meson the form factors are tied by some relations.
As a consequence, the dependence of the asymmetries on form factors disappears.





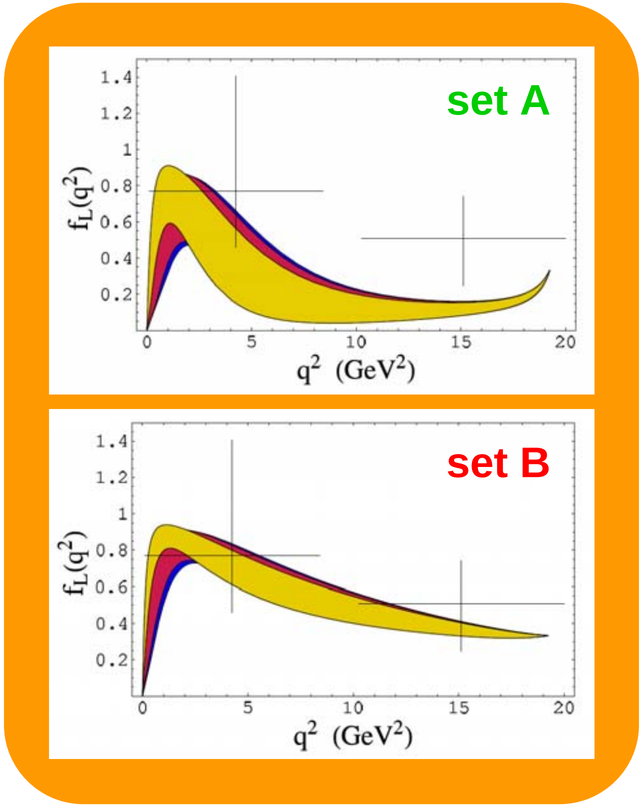
K^* helicity fractions in $B \to K^* l^+ l^-$

$$f_L(q^2) = \frac{d\Gamma_L(q^2)/dq^2}{d\Gamma(q^2)/dq^2}$$ ← *longitudinal fraction*

$$f_\pm(q^2) = \frac{d\Gamma_\pm(q^2)/dq^2}{d\Gamma(q^2)/dq^2}$$

$$f_T(q^2) = f_+(q^2) + f_-(q^2)$$ ← *transverse fraction*

longitudinal fraction



$\frac{1}{R} = 200 GeV$

$\frac{1}{R} = 500 GeV$

SM

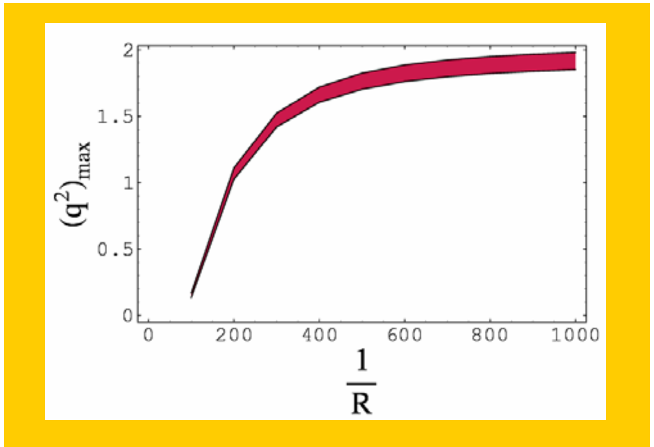
BaBar results:

$$f_L = 0.77^{+0.63}_{-0.30} \pm 0.07 \qquad 0.1 \le q^2 \le 8.41 \ \ GeV^2$$

$$f_L = 0.51^{+0.22}_{-0.25} \pm 0.08 \qquad q^2 \ge 10.24 \ \ GeV^2$$

The longitudinal helicity fraction has an interesting feature:
the value of q^2 where f_L has a maximum is sensitive to R.

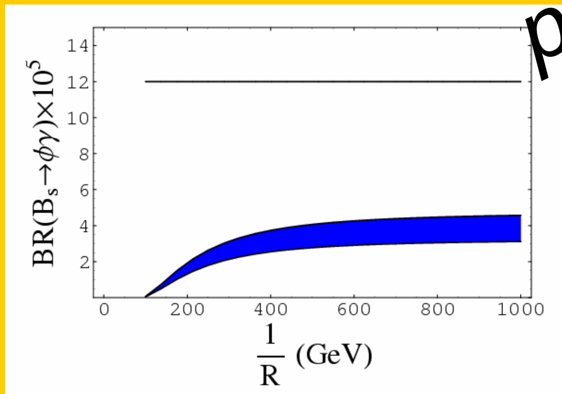
position of the maximum of f_L as a function of 1/R

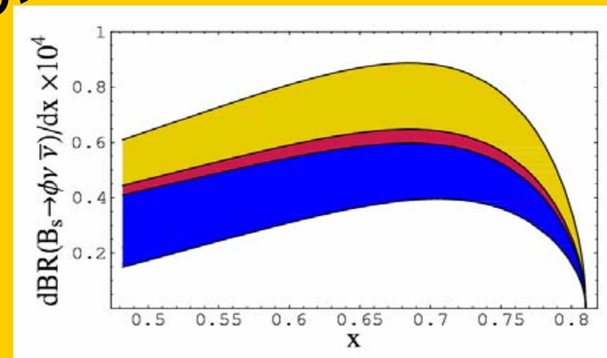


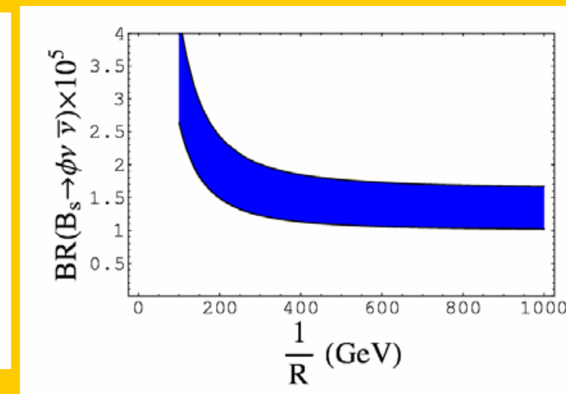
$B_s \to \phi\gamma$

preliminary

$B_s \to \phi\nu\bar{\nu}$



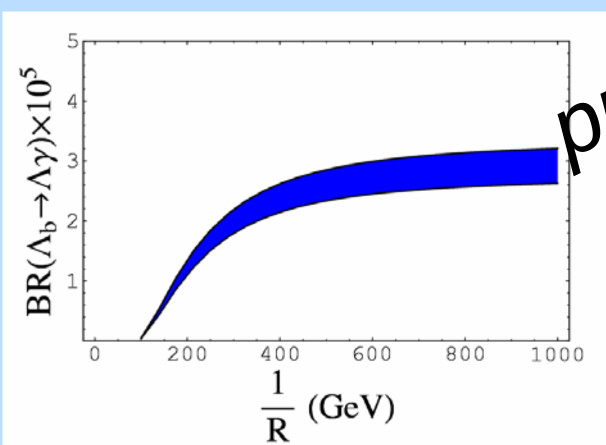


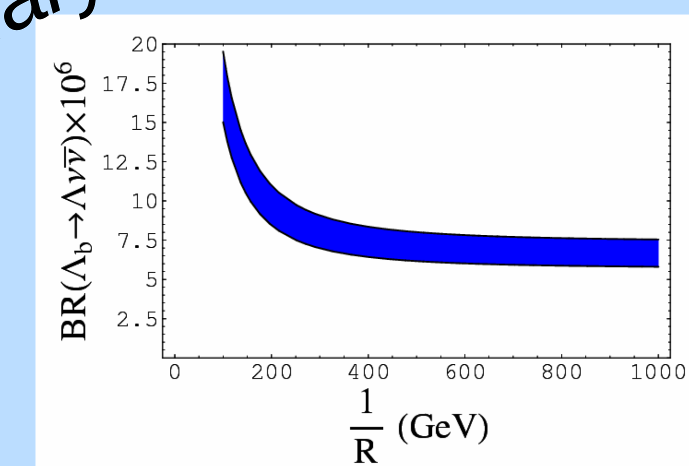


$\Lambda_b \to \Lambda\gamma$

preliminary

$\Lambda_b \to \Lambda\nu\bar{\nu}$





Other analysis of decays induced by $b \to s$ in the ACD model

Inclusive modes:

$For \ \frac{1}{R} = 300 \ \ GeV$

Buras et al., Nucl. Phys. B 660 (2003)
Nucl. Phys. B 678 (2004)

$br(B \to X_s \nu \bar{\nu})$ ↑ $+21\%$

$br(B \to X_d \nu \bar{\nu})$ ↑ $+12\%$

$br(B \to X_s \gamma)$ ↓ -20%

$br(B \to X_s gluon)$ ↓ -40%

$br(B \to X_s \mu^+ \mu^-)$ ↑ $+12\%$

Bound from $\bar{B} \to X_s \gamma$: $\frac{1}{R} > 600$ GeV

Haisch et al., hep-ph/0703064

Exclusive modes:

$B_s \to \phi l^+ l^-$

$B_s \to l^+ l^- \gamma$

Mohanta et al., Phys. Rev. D75 (2007)

$B_s \to \gamma\gamma$

Devidze et al., Phys. Lett. B 634 (2006)

$\Lambda_b \to \Lambda l^+ l^-$

Aliev et al., Eur. Phys. J. C50 (2007)

Conclusions

In the ACD model with a single UED the following rare decays have been analyzed:

- the exclusive rare $B \to K^{(*)} l^+ l^-$, $B \to K^{(*)} \nu \bar{\nu}$ and $B \to K^* \gamma$ decays, with their ***BR***, ***differential widths***, and the ***FB asymmetry*** in the $B \to K^* l^+ l^-$ case.
  The strongest limit on R comes from $B \to K^* \gamma$: $1/R > 300\ GeV$
  It is noticeable that the zero of the FB asymmetry in the $B \to K^* l^+ l^-$ channel is sensitive to the value of R.

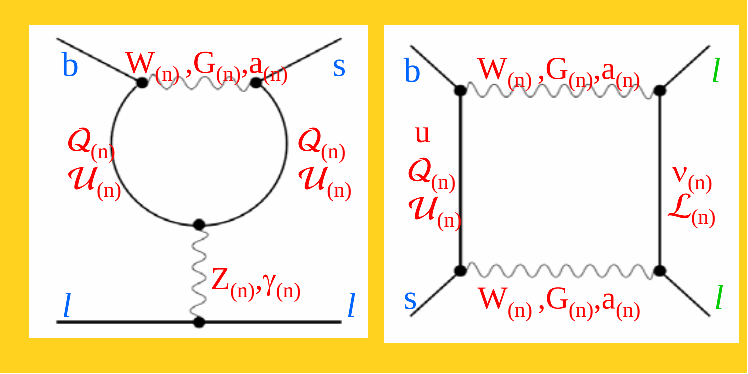
- the inclusive $B \to X_s \tau^+ \tau^-$ and the exclusive $B \to K^{(*)} \tau^+ \tau^-$ decays, with the analysis of the τ ***polarization asymmetries***. The transverse asymmetry is the most sensitive to the value of R.
  In the large energy limit, hadronic uncertainties disappear.
  In the ***K* helicity fractions*** of $B \to K^* l^+ l^-$: the value of q^2 where the longitudinal fraction has a maximum is sensitive to R.

- *preliminary* the exclusive $B_s \to \phi \gamma$, $B_s \to \phi \nu \bar{\nu}$ and $\Lambda_b \to \Lambda \gamma$, $\Lambda_b \to \Lambda \nu \bar{\nu}$ decays, with their ***BR*** and ***differential widths***.

With the improved experimental data and the theoretical uncertainties reduced, it could be possible in the future to distinguish the predictions of the ACD model from the SM ones, and to establish more stringent constraints on 1/R.

Back-up slides

$B \to K l^+ l^-$

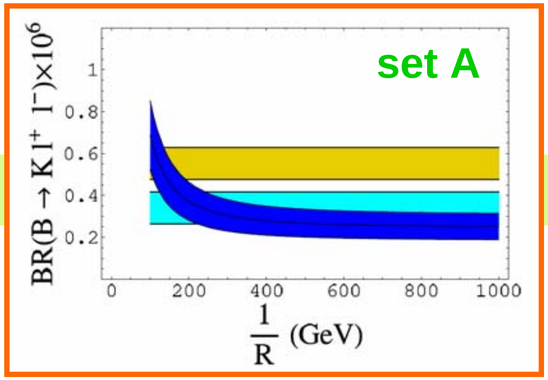


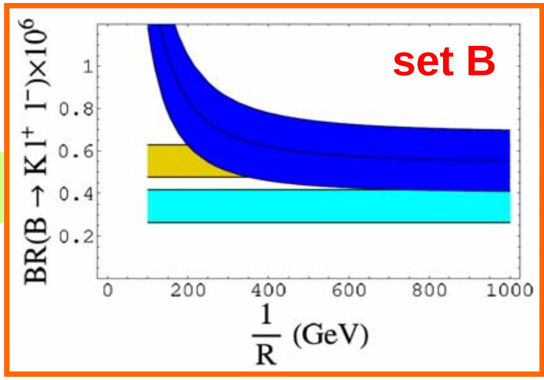
$B \to K l^+ l^-$

branching ratio

Belle $\left(5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02\right) \times 10^{-7}$

BaBar $\left(3.4 \pm 0.7 \pm 0.3\right) \times 10^{-7}$





$B \to K^* l^+ l^-$

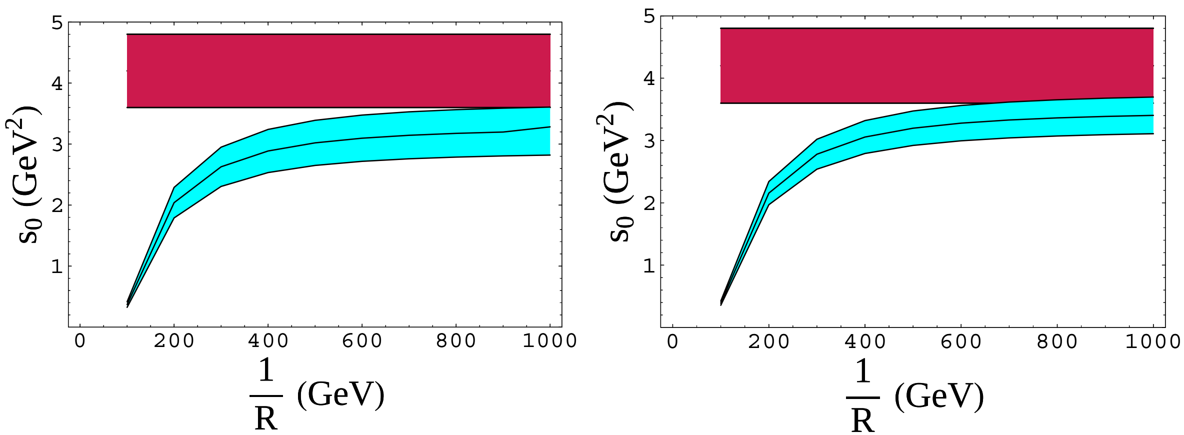
Forward-Backward Asymmetry

Zero position:

$$\mathrm{Re}(C_9) + \frac{2m_b}{q^2} C_7 \left[\left(M_B + M_{K^*} \right) \frac{T_1(q^2)}{V(q^2)} + \left(M_B - M_{K^*} \right) \frac{T_2(q^2)}{A_1(q^2)} \right] = 0$$

•Large Energy Limit relations:

$$\frac{T_1(E)}{V(E)} = \frac{1}{2} \frac{M_B}{M_B + M_{K^*}} \qquad \frac{T_2(E)}{A_1(E)} = \frac{M_B + M_{K^*}}{2M_B}$$



zero position

in the Large Energy Limit

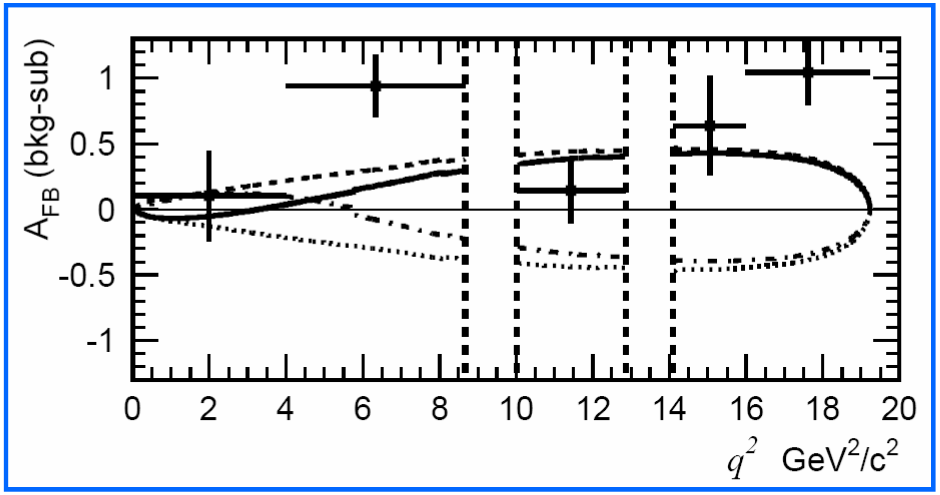
Beneke et al

$B \to K^* l^+ l^-$

Large forward-backward asymmetry is observed

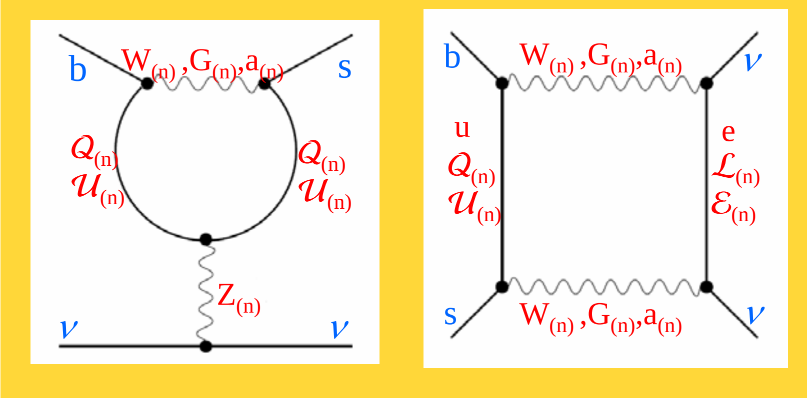
The analysis performed by Belle Collaboration indicates that the relative sign of the Wilson coefficients C_7 and C_9 is negative, confirming that A_{fb} should have a zero. Its accurate measurement is within the reach of current experiments.

Belle hep-ex/0603018



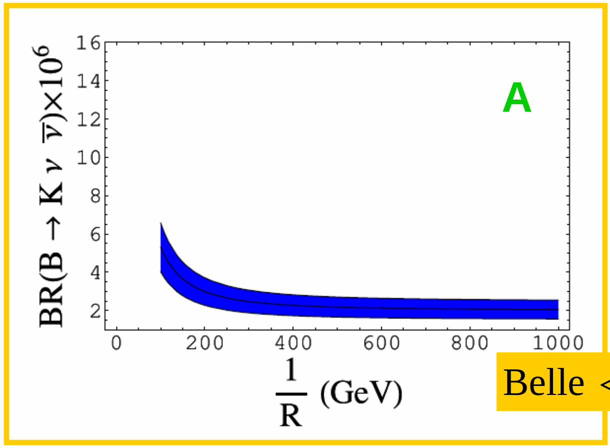
$B \to K^{(*)} \nu \bar{\nu}$

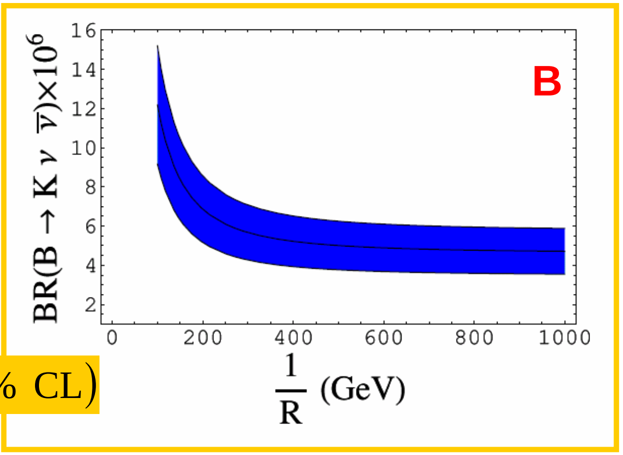
Only a single penguin operator (theoretically clean channel).
Long distance effects are absent.



Branching Fractions

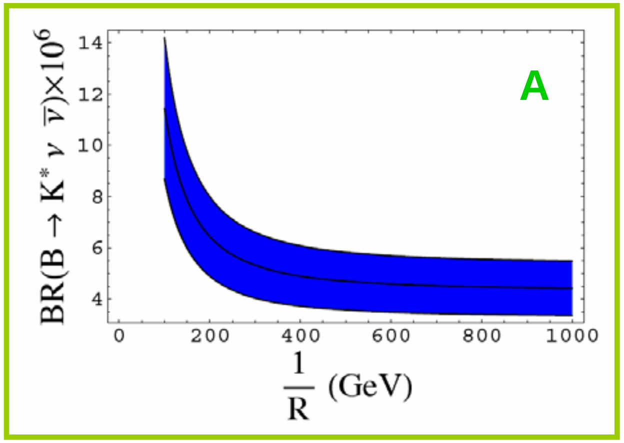
$B \to K \nu \bar{\nu}$

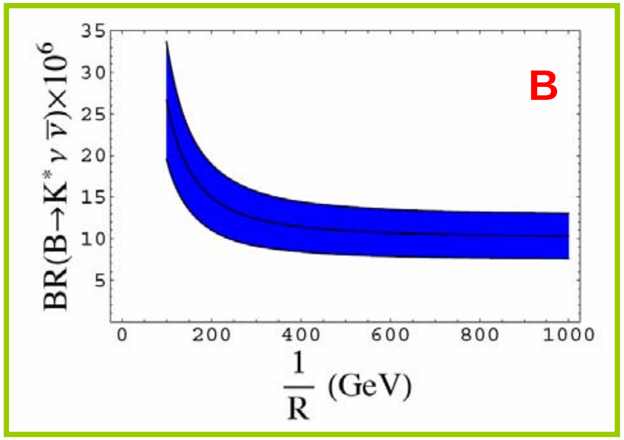




Belle $< 3.6 \times 10^{-5}$ (90% CL)

$B \to K^* \nu \bar{\nu}$





$B \to X_s \tau^+ \tau^-$