THE BIRDS & THE Bs

in a Warped Extra dimension

The $b \to s\gamma$ penguin in Randall-Sundrum

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The next 13 minutes of your life

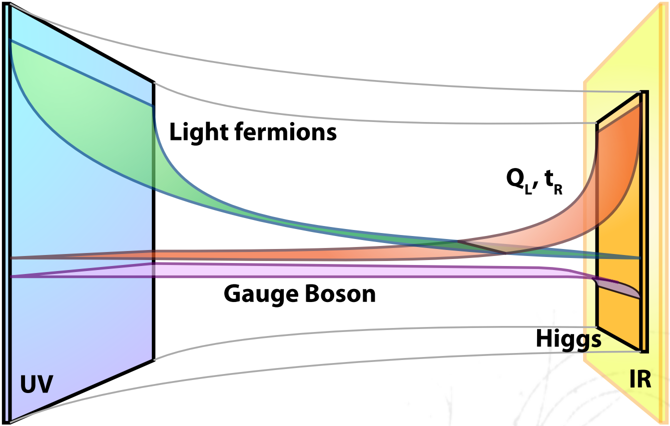
Warped flavor at loop level

5D calculation

Flavor phenomenology

Theory remarks

Warped flavor review



$$y_{ij} = f_i Y_{ij} f_j$$

Flavor-changing dipole operators

5D $\Rightarrow$ non-renormalizable theory, loop-level process:

$$y_{ij} H \cdot \bar{Q}_i \sigma^{\mu\nu} D_j$$

In fact: UV finite at loop-level

1. Gauge invariance (Ward identity)
2. Lorentz invariance

Effective theory with flavor-changing dipoles

$\boxed{\text{Calculate these in RS}}$

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tq}^* V_{tb} \left[C_7(\mu) \, \boxed{Q_7(\mu)} + C_7'(\mu) \, \boxed{Q_7'(\mu)} \right] + \text{h.c.}$$

$$\boxed{Q_7 = \frac{e}{4\pi^2} m_b (\bar{q}\sigma_{\mu\nu} P_R b) F^{\mu\nu}}$$

$$\boxed{Q_7' = \frac{e}{4\pi^2} m_b (\bar{q}\sigma_{\mu\nu} P_L b) F^{\mu\nu}}$$

Also analogous $C_8^{\prime}$ terms for gluon penguin.
Significant C_7–C_8 mixing from RG evolution: $M_{\text{KK}} \to m_b$

Structure of the amplitude

$$\boxed{\frac{-vR'^2}{8\,m_b\,G_F}(V_{tq}^* V_{tb})^{-1}}$$

$$\Delta C_7 = \boxed{\text{pre}} \sum_{ijk\ell} (U_{qi}^{D_L})^\dagger f_{Q_i^d} \left[\sum_{k,\ell} a_{k\ell} \boxed{Y_{ik}^{u\dagger} Y_{k\ell}^{u} Y_{\ell j}^{d\dagger}} + b_{ij} \boxed{Y_{ij}^{d\dagger}} \right] f_{D_j} U_{jb}^{D_R}$$

Anarchic

Misalignment

Misalignment: $f_i Y_{ij} f_j \propto m_{ij}$ wants to be diagonalized

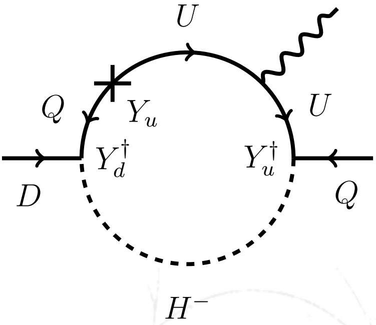
Non-zero contribution from b_{ij} (bulk masses)

5D formalism

- position/momentum space
- Sums entire KK tower
- Mass insertion approximation

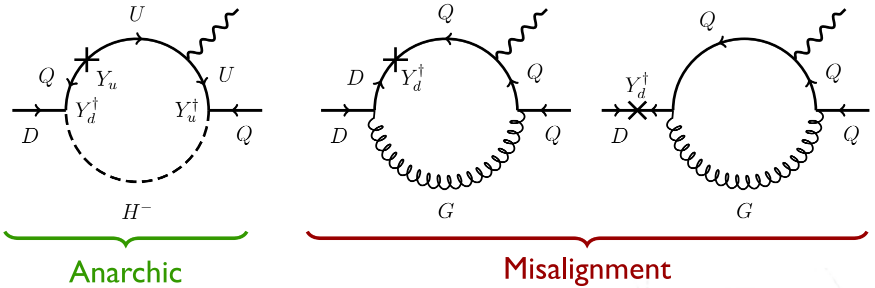
vs KK reduction

- Avoids ambiguities with 5D Lorentz-invariant loop integral
- Flavor structure manifest



Arrows denote zero-mode chirality

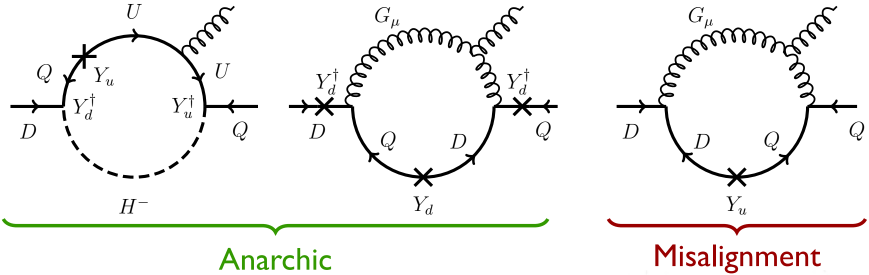
Dominant C_7 diagrams



- $H^{\pm}$ diagram: not in $\mu \to e\gamma$, no 'accidental' cancellations
- Gluon diagrams: enhanced by $\left(g_s^2 \ln \frac{R'}{R}\right) \approx 36$

Chirality flipped C_7' given by Hermitian conjugate

Dominant C_8 diagrams

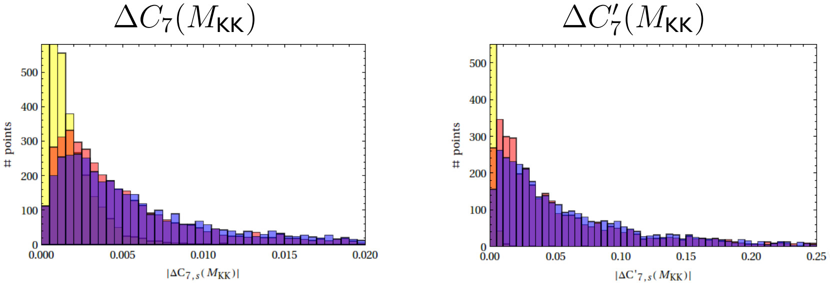


- (glue)^3 vertex enhanced over quark vertex by Dynkin factors
- Anarchic diagrams come with independent Yukawa structures, sum with arbitrary phase

Chirality flipped C_8' given by Hermitian conjugate

Large contributions to wrong-chirality dipole

Contributions to $\Delta C_7^{(\prime)}$ in the minimal and custodial models; also the misalignment contribution alone



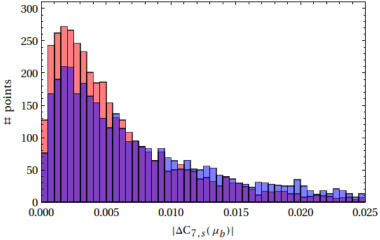
Note scale! $C_7' \gg C_7$ in RS. C' corresponds to $b_L \to s_R$, recall that b_L localized near IR brane. $C_8^{(\prime)}$ plots are similar, $\mathcal{O}(10)$ larger.

Scan over parameters that pass quark spectrum and CKM constraints

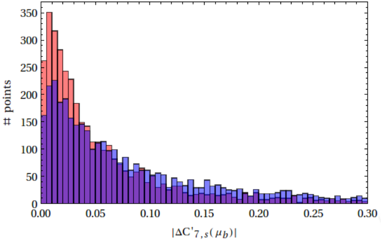
Magnetic dipole distribution at μ_b

Contributions to $\Delta C_7^{(\prime)}$ in the minimal and custodial models

$\Delta C_7(\mu_b)$



$\Delta C_7'(\mu_b)$



Note scale! $C_7' \gg C_7$ in RS.

Scan over parameters that pass quark spectrum and CKM constraints

Penguin phenomenology in RS

Inclusive $B \to X_s \gamma$

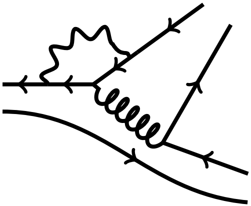
CP Asym. in $B \to K^* \gamma$

Semileptonic $B \to X_s \mu\mu$

Semileptonic $B \to K^* \mu\mu$

Forward-backward asymmetry

Transverse asymmetry



Scan over custodial model parameters that pass $\Delta F = 2$ tree-level bounds.

CP Asymmetry in $B^0(t) \to K^{*0}\gamma$

$$\frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)} = \boxed{S} \sin(\Delta M t) - C \cos(\Delta M t)$$

$$\boxed{S_{K^*\gamma} \simeq \frac{2}{|C_7|^2 + |C_7'|^2} \text{Im} \left(e^{-i\phi_d} C_7 C_7' \right)}$$

$S_{K^*\gamma}$ sensitive to new physics in C_7', where we expect large RS contributions. Current: $S^{\text{exp}}_{K^*\gamma} = -16\% \pm 22\%$

Transverse Asymmetry in $B \to K^* \mu\mu$

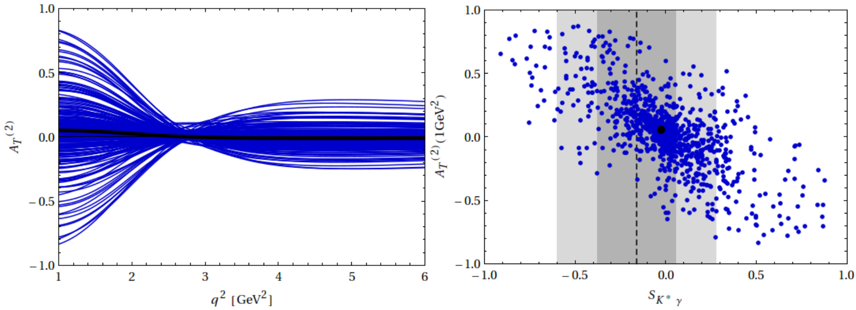
$A_T^{(2)}$ describes the linear polarization vectors of the K^* and $\mu\mu$ relative to one another: $F = 2m_b m_B / q^2$

$$= \frac{2\left[\text{Re}(C'_{10A}C^*_{10A}) + F^2\,\text{Re}(C'_7 C^*_7) + F\,\text{Re}(C'_7 C^*_{9V})\right]}{|C_{10A}|^2 + |C'_{10A}|^2 + F^2\left(|C_7|^2 + |C'_7|^2\right) + |C_{9V}|^2 + 2F\,\text{Re}(C_7 C^*_{9V})}$$

Depends only on short-distance physics & $C'_{\text{SM}} \approx 0 \Rightarrow A^{(2)}_{T,\text{SM}} \approx 0$.

Krüger et al. hep-ph/0502060

Transverse Asymmetry in $B \to K^* \mu\mu$

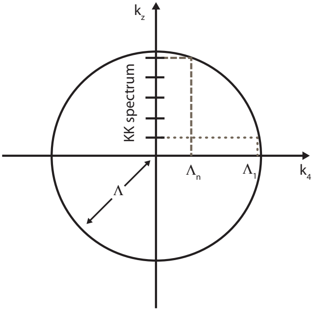


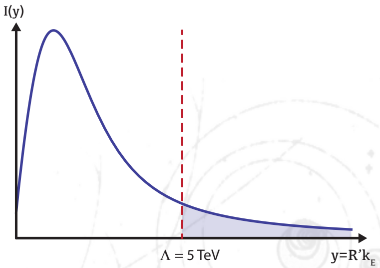
- Big enhancements possible for small q^2
- Weak correlation with $S_{K^*\gamma}$ due to C_7' sensitivity
  - $A_T^{(2)}$ is CP conserving while $S_{K^*\gamma}$ is CP violating
  - Correlation can be washed out depending on the phase

Matching 4D and 5D calculations

$$\mathcal{M} \sim \frac{1}{M_{\text{KK}}^2}\left[\left(\frac{n_f M_{\text{KK}}}{\Lambda}\right)^2 + \mathcal{O}\left(\frac{v^2}{M_{\text{KK}}^2}\right)\right]$$

Leading term vanishes if finite loop cutoff $\Lambda \to \infty$ without including all KK modes. Must match Λ with heaviest KK scale.





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Conclusions

- One loop penguin amplitudes are finite and calculable
- Main RS contributions appear in C_7': $b_L \to s_R\gamma$
- Good agreement with data
  - $B \to X_s\gamma$, $\quad B \to x_s\mu\mu$, $\quad A_{\text{FB}}(B \to K^*\mu\mu)$
- Distinctive signature at flavor factories
  - Time-dependent CP asymmetry in $B \to K^*\gamma$
  - Angular observables in $B \to K^*\mu\mu$
- Theory feature: Matching 4D KK EFT to 5D

Partial References

RS model building

Original: hep-ph/9905221. **Reviews:** hep-ph/0404096, hep-ph/0510275, 1008.2570. **Bulk fields:** hep-ph/9911262, hep-ph/9911294, hep-ph/9912408, hep-ph/0003129. **Custodial**: hep-ph/0308036.

RS Flavor

hep-ph/0002279, hep-ph/0408134, 0804.1954, 0807.4937, 0812.3803, 0903.2415, 0905.2318, 0912.1625

RS Penguins

NDA: hep-ph/0406101, hep-ph/0606021. **Calculation**: 1004.2037, 1203.6650

Penguin Flavor

hep-ph/9806471, 1104.3342, 1111.1257.