Flavour physics

M. Beneke (TU München)

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Outline

- Introduction
- Unitarity triangle
- B_s (mixing, $B_s \to \mu^+\mu^-$, non-leptonic)
- Electroweak penguin decays
- Flavour-violating Higgs couplings
- Loops and flavour violation in RS

Flavour and CP violation in the SM

$SU(3) \times SU(2) \times U(1)_{\rm Y}$
Field content and gauge charges

$$-y_i^d (\bar{Q}_L' V_{CKM}^\dagger)_i \Phi d_{Ri} - y_i^u \bar{Q}_{Li}' \tilde{\Phi} u_{Ri}$$
$$- y_i^l \bar{L}_i \Phi e_{Ri} + \text{h.c.}$$

Only charged current.
No Higgs FCNC $\Rightarrow$ little direct impact of Higgs discovery on SM flavour physics.

$$-\frac{f_{ij}}{\Lambda} [(\bar{L}^T \epsilon)_i i\sigma^2 \Phi] \, [\Phi^T i\sigma^2 L_j] + \text{h.c.}$$

$\sin\theta_{13}$ measured $\Rightarrow$ CPV measurements in neutrino sector possible.

FV in the SM is natural and predictive (especially CPV) ...

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FV in the SM is natural and predictive (especially CPV) ...

- What is $y_i^{u,d}$, $V_{\rm CKM}$? Is $V_{\rm CKM}$ complex? Why is $y_i^{u,d}$, $V_{\rm CKM}$ what it is?
  (Origin of flavour hierarchies)
- Is this all there is? If not, what is it? Why didn't we see it already?
  (The other flavour problem)
- Baryogenesis? Leptogenesis? Strong CP problem, absence of EDMs.

The gauge hierarchy-flavour problem

SM presumably valid only below some scale Λ

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm dim\,4} - \frac{\Lambda^2}{2}\Phi^\dagger\Phi + \sum_i \frac{1}{\Lambda^2}\,(\bar{q}q\bar{q}q)_i + \ldots$$

- Scalar mass term is the only dimensionful parameter in the renormalizable part of the Lagrangian.
  Sets the electroweak scale.

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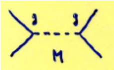
- Scalar mass term receives large quantum corrections is there is another scale Λ.
  Electroweak physics requires $\Lambda \leq M_W/g \approx$ few hundred GeV.
- But flavour physics restricts the scale of dimension-6 operators to

$$\Lambda \geq 10^{4-5}\,\text{TeV} \quad (\bar{s}d)(\bar{s}d) \qquad \Lambda \geq 10^3\,\text{TeV} \quad (\bar{b}d)(\bar{b}d)$$



unless it is special (weak coupling, loop suppression, CKM-like suppressions).
Generic scale far beyond reach of LHC!

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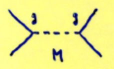

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Difficult to construct natural models.
But the argument may simply be wrong because nature may not care about naturalness ...

Flavour in the LHC Era

LHCb (indirect)

- B_s physics
- Electroweak penguins
- γ from $B \to DK$s
- Charm

LHC ("high-p_T")

- Higgs flavour
- top flavour
- Direct production

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Interplay?

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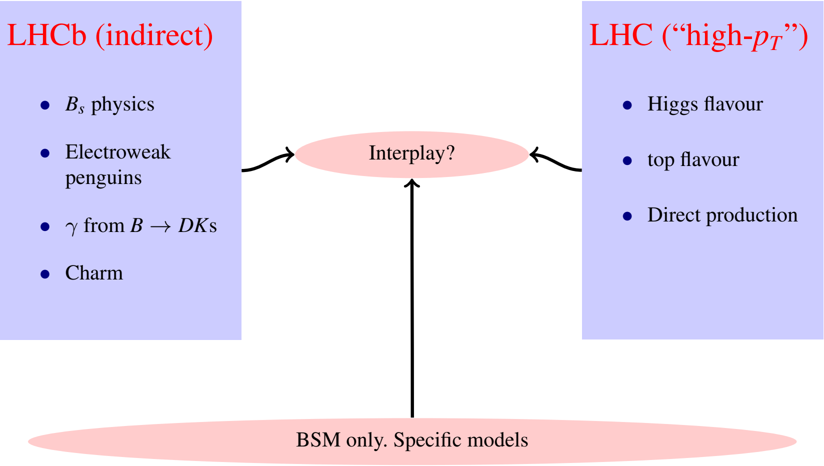
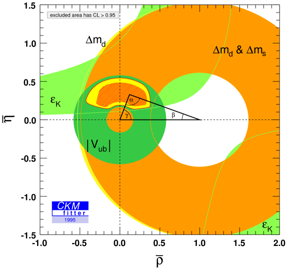
Flavour in the LHC Era

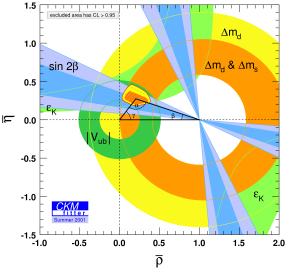


The Unitarity Triangle

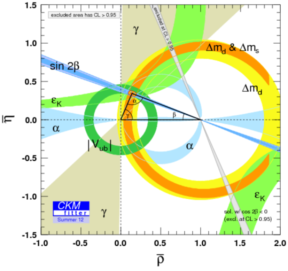
1995 (top discovery)



2001 (B factory turn-on)



2013 (Precision flavour physics)



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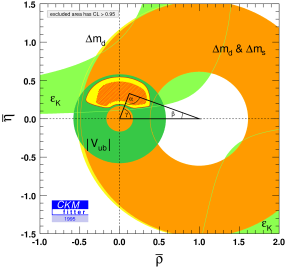

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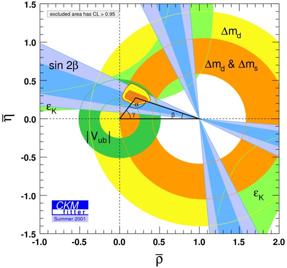

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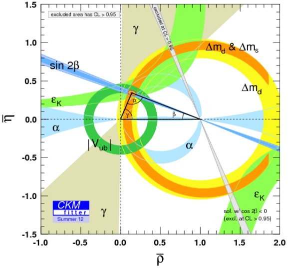

- Anomalies disappeared ($B \to \tau\nu$) or became implausible (Di-muon asymmetry $A^s_{\rm SL}$).
- Never before as consistent and precise $\to$ MFV paradigm
- UT triangle fit no longer an adequate representation of all tests of the SM flavour sector.
- Non-standard flavour physics can still be hidden.

$|V_{ub}|$ problem

Inclusive $B \to X_u \ell \nu$

$$|V_{ub}| = (4.41 \pm 0.15_{\rm exp}{}^{+0.15}_{-0.17}{}_{\rm th}) \cdot 10^{-3}$$

Kinematic constraints due to charm background.
HQE + resummation.

Exclusive $B \to \pi \ell \nu$

$$|V_{ub}| = (3.23 \pm 0.31) \cdot 10^{-3}$$

Lattice QCD
QCD sum rules
analyticity

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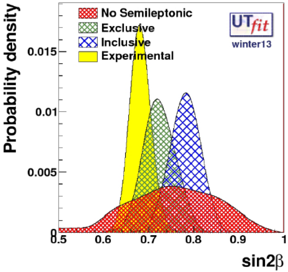

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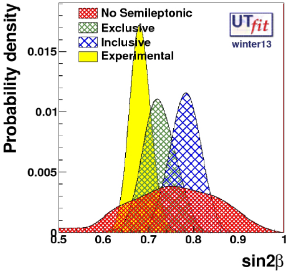
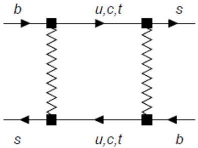


- V_{ub} – $\sin 2\beta$ – ϵ_K connection
- Bet on exclusive ...
- Some two-loop results for inclusive (fully differential (Brucherseifer, Caola, Melnikov, 2012); hard coefficient for resummation (Bonciani, Ferroglia; Asatrian, Greub, Pecjak; MB, Huber, Li; Bell, 2008)) not yet implemented.

B_s lifetime difference and mixing phase

$$i\frac{d}{dt}\begin{pmatrix}|B_s(t)\rangle\\|\bar{B}_s(t)\rangle\end{pmatrix} = \left(\mathrm{M}^s - \frac{i}{2}\,\Gamma^s\right)\begin{pmatrix}|B_s(t)\rangle\\|\bar{B}_s(t)\rangle\end{pmatrix}$$



Three observables related to mixing:

- $\Delta m_s/\Gamma_s$ large $\rightarrow$ many oscillations per lifetime

$$M_{12} \propto (V_{ts}^* V_{tb})^2$$

- $\Delta\Gamma_s$ ($|\Gamma^s_{12}|$) relevant. Significant fraction of common final states from $b \rightarrow c\bar{c}s$.

$$\frac{\Delta\Gamma}{\Gamma} = (1,\alpha_s) \times 16\pi^2\frac{\Lambda^3}{m_b^3} + 16\pi^2\frac{\Lambda^4}{m_b^4} + \ldots \quad \Longrightarrow \quad \Delta\Gamma_s = (0.090 \pm 0.018)\,\mathrm{ps}^{-1}$$

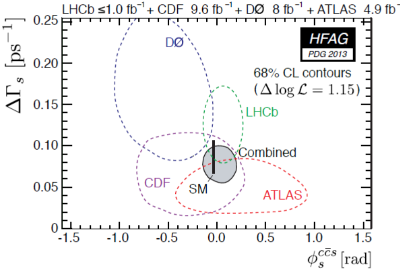
[Lenz-Nierste update, 1102.4274]

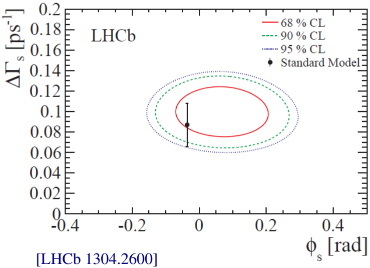
OPE+HQE [MB, Buchalla, Dunietz, 1996; MB et al., 1998] + Lattice

- Phase [MB et al, 1998, 2003; Ciuchini et al., 2003]

$$\phi_s = \arg\left(-\frac{M^s_{12}}{\Gamma^s_{12}}\right) = 0.22^\circ \pm 0.06^\circ \qquad 2\beta_s = 2\arg\left(-V_{tb}^* V_{ts}/(V_{cb}^* V_{cs})\right) = 2.1^\circ \pm 0.1^\circ$$

$\Delta\Gamma_s$ and β_s from $B_s \to J/\psi\phi$ and related





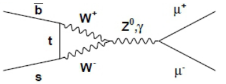
[LHCb 1304.2600]

- Last loophole for large NP in $B_{d,s}$ mixing closed
- HQE and Quark-Hadron Duality works in $b \to c\bar{c}s$.
- No effect large expected in MFV models.
- Generic models would affect B_d mixing more than B_s due to stronger CKM suppression. But quark flavour mixing may be related to lepton neutrino mixing.
- To complete the picture

$$a_{\rm sl} = \frac{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)}{\Gamma(\bar{B}_s \to \ell^+ X) + \Gamma(B_s \to \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\Phi_s$$

Anomaly in D0 measurement.

$B_s \to \mu^+\mu^-$



$$\mathrm{Br}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + \frac{2m_\mu}{m_{B_s}}(C_{10} - C_{10}')\right|^2 \right\}$$

- SM only C_{10} $\Rightarrow$ helicity suppression
  Sensitive to scalar couplings.

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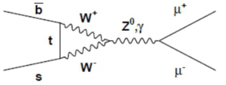

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- Width difference correction [De Bruyn et al., 2012]

$$\langle \Gamma(B_s(t) \to f) \rangle \equiv \Gamma(B_s(t) \to f) + \Gamma(\bar{B}_s(t) \to f) = R_H^f e^{-\Gamma_H^s t} + R_L^f e^{-\Gamma_L^s t}$$

$$\mathrm{BR}(B_s \to f)_{\mathrm{obs}} = \frac{1}{2}\int_0^\infty dt\, \langle \Gamma(B_s(t) \to f) \rangle = \underbrace{\frac{\tau_{B_s}}{2}(R_H^f + R_L^f)}_{\text{theory calculation}} \underbrace{\left[\frac{1+\mathcal{A}_{\Delta\Gamma}^f y_s}{1-y_s^2}\right]}_{+10\%\ \text{correction}}$$

$$y_s = \Delta\Gamma_s/(2\Gamma_s) \approx 0.1$$

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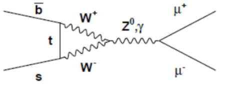

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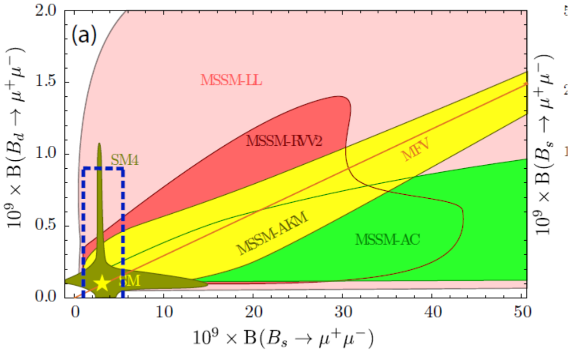
- LHCb [1211.2674]: $(3.2^{+1.5}_{-1.2}) \times 10^{-9}$ vs. Theory [Buras et al., 1208.0934]: $(3.54 \pm 0.30) \times 10^{-9}$

$B_s \to \mu^+\mu^-$ model killing

[Straub, 1205.6094]



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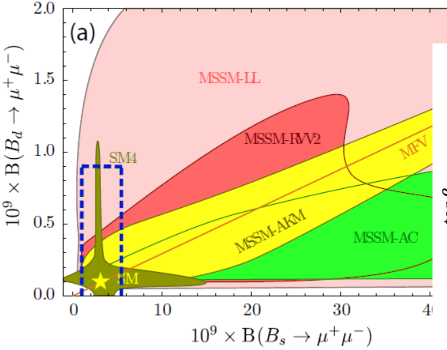
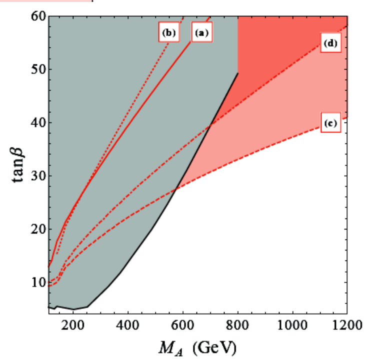


[Altmannshofer, 1306.0022]



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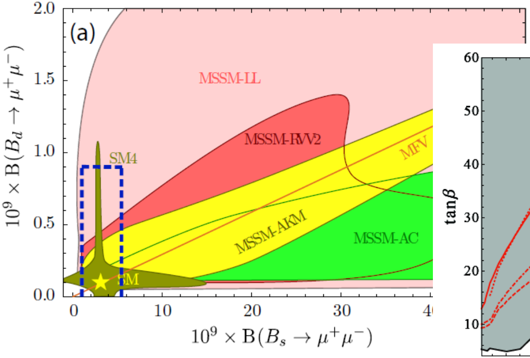

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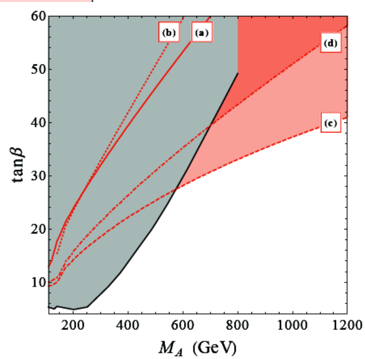


- Scalar FCNC cannot play an important role in non-helicity-suppressed amplitudes.
- Suppression relative to SM possible for pseudoscalar Higgs interfering with SM axial-vector contribution.

Hadronic matrix elements

HQE/OPE, lattice, (QCD sum rules)

QCD factorization, (flavour symmetries)

None – pure quantum interference

$\langle 0|\mathcal{O}|B\rangle$
$\langle B|\mathcal{O}|B\rangle$

$\langle M|\mathcal{O}|B\rangle$

$\langle M_1 M_2|\mathcal{O}|B\rangle$

Increasingly difficult

Hadronic matrix elements

HQE/OPE, lattice, (QCD sum rules) — over $\langle 0|\mathcal{O}|B\rangle$, $\langle B|\mathcal{O}|B\rangle$, $\langle M|\mathcal{O}|B\rangle$

QCD factorization, (flavour symmetries) — over $\langle M_1 M_2|\mathcal{O}|B\rangle$

None – pure quantum interference	$\langle 0\|\mathcal{O}\|B\rangle$ $\langle B\|\mathcal{O}\|B\rangle$	$\langle M\|\mathcal{O}\|B\rangle$		$\langle M_1 M_2\|\mathcal{O}\|B\rangle$

→ Increasingly difficult

γ from $B \to DK$ [and related methods] $2\beta_{B_s}$	$B \to \tau\nu_\tau$ $B_s \to \mu^+\mu^-$ $\Delta M_{B_d,B_s}$ $\Delta\Gamma_{B_s}$	$B \to D\tau\nu_\tau$ $\|V_{ub}\|$ $B \to K\nu\bar{\nu}$	$B \to \rho\gamma$ $B \to K^{(*)}\ell\ell$	Direct CP asym $B_s \to \pi K, KK, \ldots$ $B_s \to \pi\pi$ $B_s \to \phi\phi, K^{*0}\bar{K}^{*0}$

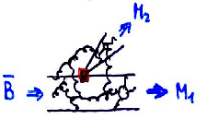
Many new LHCb results

Hadronic matrix elements from QCD factorization

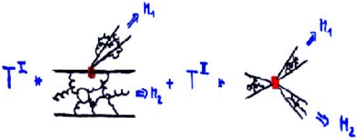
[BBNS, 1999-2003]

Heavy quark limit: $m_b \gg \Lambda_{\rm QCD}$
Large-energy limit: $E_M \approx m_b/2 \gg \Lambda_{\rm QCD}$
Scales: m_b, $\sqrt{m_b \Lambda_{\rm QCD}}$, $\Lambda_{\rm QCD}$, $(M_{\rm EW}, \Lambda_{\rm NP})$

$\mu \approx m_b$



$\mu \approx 1$ GeV



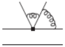
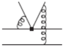
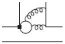
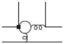
- Reduces $\langle M_1 M_2|\mathcal{O}|B\rangle$ to simpler $\langle M|\mathcal{O}|B\rangle$ (form factors), $\langle 0|\mathcal{O}|B\rangle$, $\langle 0|\mathcal{O}|M\rangle$ (decay constants and distribution amplitudes).
- Calculation from first principles, but limited accuracy by $\Lambda_{\rm QCD}/m_b$ corrections.

Status of NNLO radiative calculations

$$\langle M_1 M_2 | C_i O_i | \bar{B} \rangle_{\mathcal{L}_{\text{eff}}} = \sum_{\text{terms}} C(\mu_h) \times \Big\{ F_{B\to M_1} \times \underbrace{T^{\text{I}}(\mu_h, \mu_s)}_{1+\alpha_s+\ldots} \star f_{M_2} \Phi_{M_2}(\mu_s)$$

$$+ f_B \Phi_B(\mu_s) \star \Big[\underbrace{T^{\text{II}}(\mu_h, \mu_I)}_{1+\ldots} \star \underbrace{J^{\text{II}}(\mu_I, \mu_s)}_{\alpha_s+\ldots} \Big] \star f_{M_1} \Phi_{M_1}(\mu_s) \star f_{M_2} \Phi_{M_2}(\mu_s) \Big\}$$

$$+ 1/m_b\text{-suppressed terms}$$

Status	2-loop vertex corrections (T_i^I)	1-loop spectator scattering (T_i^{II})
Trees	 [GB 07, 09] [Beneke, Huber, Li 09]	 [Beneke, Jäger 05] [Kivel 06] [Pilipp 07]
Penguins	 in progress	 [Beneke, Jäger 06] [Jain, Rothstein, Stewart 07]

from G. Bell [FPCP 2010]

Tree-dominated decays complete at NNLO.
Other non-leptonic and $B \to (M, \gamma)(\gamma, \ell^+\ell^-, \ell\nu)$ at NLO (= partly 2-loop).
No NNLO result yet on direct CP asymmetries: $A_{\text{CP}} = [c \times \alpha_s]_{\text{NLO}} + \mathcal{O}(\alpha_s^2, \Lambda/m_b)$

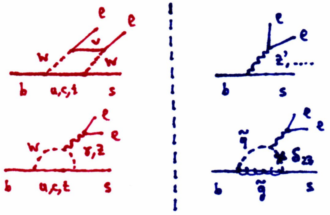
Electroweak penguin decay $B \to K^*(\to K\pi)\ell^+\ell^-$ [and related]

- Sensitive to TeV scale new particles in a cleaner environment than purely hadronic processes.

$$\mathcal{O}_7^{(\prime)} = -\frac{g_{\rm em}\hat{m}_b}{8\pi^2}\,\bar{s}\sigma^{\mu\nu}(1\pm\gamma_5)bF_{\mu\nu}$$

$$\mathcal{O}_{9,10}^{(\prime)} = \frac{\alpha_{\rm em}}{2\pi}\,(\bar{\ell}\ell)_{V,A}\,(\bar{s}b)_{V\pm A}$$

$$\mathcal{O}_{S,P,T}$$



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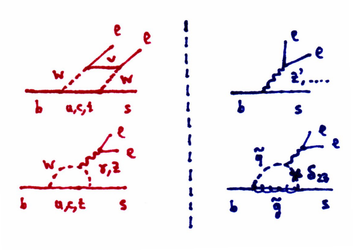
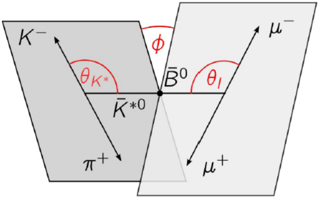


- Powerful diagnostic due to access to different tensor structures and chiralities through kinematic distributions and asymmetries

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

12 (10,8) angular coefficients $I_i(q^2)$ + CP conjugates.



Theory description

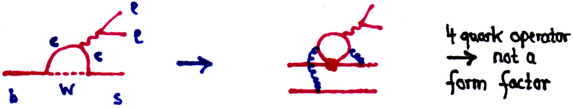
- $B \to K^*$ form factors not enough. Charm loops introduce a "hadronic component" of the virtual photon, as well as resonances.

- Amplitude has two components

$$\langle K^* \ell\ell | H_{\rm eff} | B\rangle = \underbrace{\sum_i a_i(C^{(\prime)}_{7,9,10},\ldots)\, F_i^{B\to K^*}}_{} + \underbrace{\frac{ie^2}{q^2}\langle \ell\ell|\bar{l}\gamma_\mu l|0\rangle \int d^4x\, e^{iq\cdot x}\,\langle K^*|T(j^\mu_{\rm em}(x) H^{\rm had}_{\rm eff}(0)|B\rangle}_{}$$

Electroweak penguins;
local;
sensitive to new physics

QCD;
non-local;
NP constrained by non-leptonics;
photon pole, charmonium resonances



Lepton invariant mass spectrum and theoretical approaches

- QCD factorization for $q^2 \leq 6\,\mathrm{GeV}^2$ [MB, Feldmann, Seidel, 2001; 2004]

$$\langle \ell\ell K^* | \mathcal{O}_i | \bar{B} \rangle = C_i \xi + \Phi_B \otimes T_i \otimes \Phi_{K^*} + \mathcal{O}(\Lambda/m_b)$$

QCD factorization

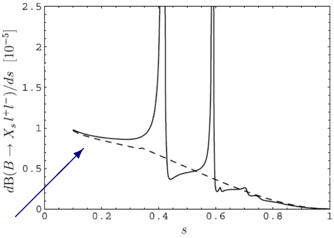


Fig. 2 Differential $B \to X_s l^+ l^-$ branching fraction as a function of $s = q^2/m_b^2 \equiv m_{l^+l^-}^2/m_b^2$, including the effect of charm resonances in

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- OPE and HQE for $q^2 \geq 15\,\text{GeV}^2$ [Grinstein, Pirjol, 2004; Beylich et al., 2011]

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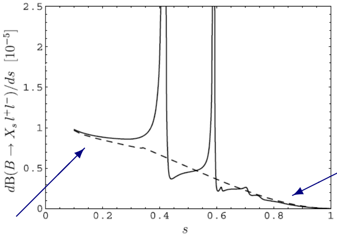
Power corrections and duality violation (integrated) estimated below 2%.



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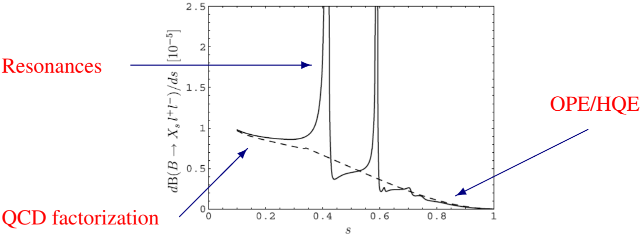
- Charmonium resonance region e.g. [Khodjamirian et al., 2010, 2012]. No quark-hadron duality in this region [MB, Buchalla, Neubert, Sachrajda, 2009]



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Form factors and "effective Wilson coefficients"

- Key point at large recoil: only two independent form factors due to helicity and parity conservation of the strong interaction – up to calculable α_s corrections [Charles et al., 1998, MB, Feldmann, 2000], e.g.,

$$\langle K^*(\lambda = \pm 1)|\bar{s}P_{R/L}\Gamma b|\bar{B}\rangle \quad \Rightarrow \quad \xi_\perp(q^2)$$

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- Double differential distribution with "effective Wilson coefficients"

$$\frac{d^2\Gamma}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{ts}^* V_{tb}|^2}{128\pi^3} M_B^3 \, \lambda(q^2, m_{K^*}^2)^3 \left(\frac{\alpha_{\rm em}}{4\pi}\right)^2 \times \Bigg[(1+\cos^2\theta) \, \frac{2q^2}{M_B^2} \, \xi_\perp(q^2)^2 \left(|\mathcal{C}_{9,\perp}(q^2)|^2 + C_{10}^2 \right)$$

$$+ (1-\cos^2\theta) \left(\frac{E\, \xi_\parallel(q^2)}{m_{K^*}}\right)^2 \left(|\mathcal{C}_{9,\parallel}(q^2)|^2 + C_{10}^2 \, \Delta_\parallel(q^2)^2 \right) - \cos\theta \, \frac{8q^2}{M_B^2} \, \xi_\perp(q^2)^2 \, {\rm Re}(\mathcal{C}_{9,\perp}(q^2)) \, C_{10} \Bigg]$$

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$$\mathcal{C}_{9,\perp}(q^2) \equiv C_9 + \frac{2m_b M_B}{q^2}\,\frac{\mathcal{T}_\perp(q^2)}{\xi_\perp(q^2)} = C_9 + Y(q^2) + \frac{2m_b M_B}{q^2}\,C_7^{\rm eff} + \ldots$$

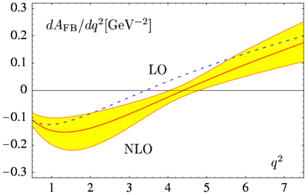
$$\mathcal{C}_{9,||}(q^2) \equiv C_9 - \frac{2m_b}{M_B}\,\frac{\mathcal{T}_{||}(q^2)}{\xi_{||}(q^2)} = C_9 + Y(q^2) + \frac{2m_b}{M_B}\,C_7^{\rm eff} - e_q\,\frac{4M_B}{m_b}\,(\bar{C}_3 + 3\bar{C}_4)$$
$$\times\,\frac{\pi^2}{N_c}\,\frac{f_B f_{K^*}}{M_B(E/m_{K^*})\xi_{||}(q^2)}\int d\omega\,\frac{M_B\Phi_{B,-}(\omega)}{M_B\omega - q^2 - i\epsilon} + \ldots$$

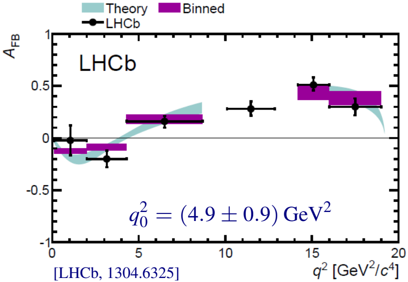
$$\mathcal{T}_a = \xi_a\left(C_a^{(0)} + \frac{\alpha_s C_F}{4\pi}\,C_a^{(1)}\right) + \frac{\pi^2}{N_c}\,\frac{f_B f_{K^*,a}}{M_B}\,\Xi_a\sum_\pm\int\frac{d\omega}{\omega}\,\Phi_{B,\pm}(\omega)\int_0^1 du\,\Phi_{K^*,a}(u)\,T_{a,\pm}(u,\omega)$$

Forward backward asymmetry zero: $\mathrm{Re}(\mathcal{C}_{9,\perp}(q_0^2)) = 0$

- Zero arises if C_9 and C_7 have different sign.
  Almost free from hadronic uncertainties (protected from form factor uncertainty)
  [Burdman, 1997; Ali et al, 1999; MB, Feldmann, Seidel, 2001,2004]

$$q_0^2[K^{*0}] = 4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2 \qquad q_0^2[K^{*+}] = 4.15 \pm 0.27\,\mathrm{GeV}^2$$ [MB, Feldmann, Seidel, 2004]





[LHCb, 1304.6325]

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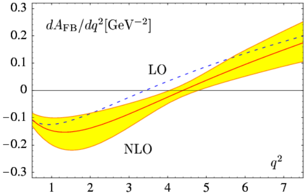

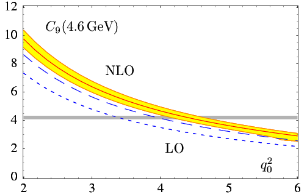

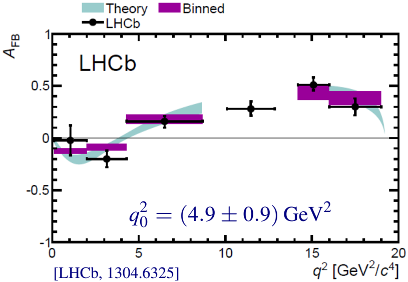

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$$C_9 = -\frac{2M_B m_b}{q_0^2}\,C_7^{\mathrm{eff}} - \mathrm{Re}\,Y(q_0^2) + \text{known NLO correction}$$

Full angular analysis

- $A_{FB}(q^2)$ is protected from form factor uncertainty only at one point. Can do much better, when angular amplitudes $I_i(q^2)$ are measured. [Egede et al. 2008, 2009, 2010; Altmannshofer et al. 2008; Bobeth et al. 2008; Bobeth, Hiller, van Dyk, 2010, 2011; Matias et al., 2012; Beaujean et al., 2012; Descotes-Genon et al., 2012; Jäger, Martin Camalich, 2012]

- Basic idea: Construct (most) I_i such that

$$I_i(q^2) \propto |\xi_\perp(q^2)|^2 \quad \text{or} \quad |\xi_\parallel(q^2)|^2 \quad \text{or} \quad \xi_\perp(q^2)\xi_\parallel(q^2)$$

and take ratios such that form factors cancel. “Theoretically clean” for all q^2.

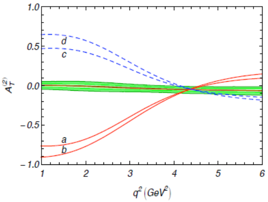
$$P_i(q^2) = a_i(q^2) + \frac{\alpha_s}{\xi_a(q^2)} \times \text{spectator scattering} + O\left(\frac{\Lambda}{m_b}\right)$$

- Example: Transversity amplitude is protected for all q^2.

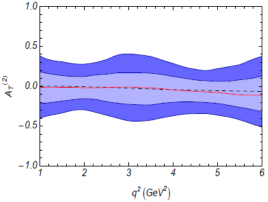
$$A_T^{(2)}(q^2) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

Full angular analysis

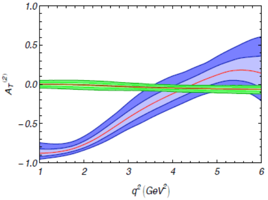
[Figure from Egede et al., 2008]



Theoretical error including Λ/m_b and SUSY scenarios (1 TeV masses)



Experimental sensitivity, 10 fb^{-1} at LHCb.



Experimental sensitivity for SUSY scenario b.

- Unique flavour laboratory: The set of all angular observables allows one to determine magnitude, phase and chirality of the magnetic penguin and electroweak penguin coefficients. [Example: $A_T^{(2)}(q^2)$ is negligible in the SM, and proportional to $C_7^{(\prime)}$ BSM.]
- Starts being measured at LHCb $\Rightarrow$ Egede's talk
- Primary application of factorization to LHCb physics.

Summary on “traditional” flavour physics

- Only the beginning of flavour physics at LHCb ... SuperKEKB to come (2016)
- B_s mixing, scalar FCNCs, electroweak penguins, charm, ... flavour physics looks more SM-like than ever

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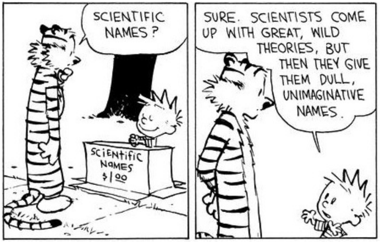
- SM could be valid to very high scales ...

"There is a theory in physics that explains, at the deepest level, nearly all of the phenomena that rule our daily lives [...] It surpasses in precision, in universality, in its range of applicability from the very small to the astronomically large, every scientific theory that has ever existed. This theory bears the unassuming name 'The Standard Model of Elementary Particles' [...] It deserves to be better known, and it deserves a better name. I call it 'The Theory of Almost Everything'."

(Robert Oerter, The Theory of Almost Everything: The Standard Model, the Unsung Triumph of Modern Physics, 2006)



Two new players on the field

Top

- Low-energy phenomenology determined by $V_{ts}, V_{td} \ll 1$: Meson-mixing, down-type quark FCNC
- Collider phenomenology (top decay, single top production) dominated by $V_{tb} \sim 1$.
- FCNC strongly GIM suppressed

$$\mathrm{Br}(t \to c\gamma) \sim |V_{cb}|^2 \times \frac{\alpha}{16\pi^3} \times \left(\frac{m_b^2}{m_t^2}\right)^2 \sim 10^{-13}$$

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Top and Higgs flavour physics is BSM physics

Flavour-changing couplings of the Higgs boson

$SU(3) \times SU(2) \times U(1)_{\mathrm{Y}}$ effective Lagrangian [Buchmüller, Wyler, 1985; Grzadkowski et al., 2010]

$$\mathcal{L} = -\lambda^L_{ij}\bar{L}_i \phi e_{Ri} - \frac{\lambda'^L_{ij}}{\Lambda^2}\bar{L}_i \phi e_{Ri}\,(\phi^\dagger \phi) + \phi^\dagger i \overleftrightarrow{D} \phi\,(\bar{\psi}\psi) \text{ operators}$$
$$+ \text{quark operators}$$

$$\sqrt{2}m = \lambda + \frac{v^2}{2\Lambda^2}\lambda' \qquad \sqrt{2}Y = \lambda + \frac{3v^2}{2\Lambda^2}\lambda'$$

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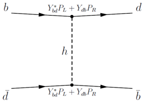
Misalignment generates Higgs FCNC

$$\mathcal{L}_Y = -Y_{\mu\tau}\bar{\mu}_L\tau_R H - Y_{\tau\mu}\bar{\tau}_L\mu_R H + \text{h.c.} + \ldots \qquad Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\left[V_L\lambda' V_R^\dagger\right]_{ij}$$

- No tuning between λ and λ' if $|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$ etc. [Cheng, Sher, 1987]
- Present in many BSM models: multi-Higgs, RS (see below), ...

Low- and high-energy constraints

[Blankenburg et al., 2012; Harnik et al., 2012; Atwood et al., 2013; ...]



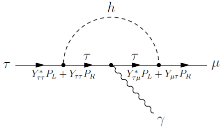
Low energy

- Quark couplings: meson (K, D, B) mixing
- Neutron EDM
- Lepton couplings: radiative penguins
- $\ell_i \to \ell_j\gamma$, $\ell_i \to \ell_j\ell\ell$, μe conversion, $(g-2)_\ell$, ℓEDM

Direct observation in FV Higgs decay?
$H \to \ell_i\ell_j$,
$H \to t^*(\to bW)q$

High energy

- Single top production
- Same-sign tt production
- (LEP)
- $t \to h + \text{jet}$



Limits on $Y_{f_i f_j}$

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc} Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db} Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb} Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut} Y_{ct}\rvert$, $\lvert Y_{tu} Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu} Y_{ct}\rvert$, $\lvert Y_{ut} Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut} Y_{tu} Y_{ct} Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut} Y_{tu})$	$< 4.4 \times 10^{-8}$

[Harnik et al., 1209.1397v2]

Limits on $Y_{f_i f_j}$

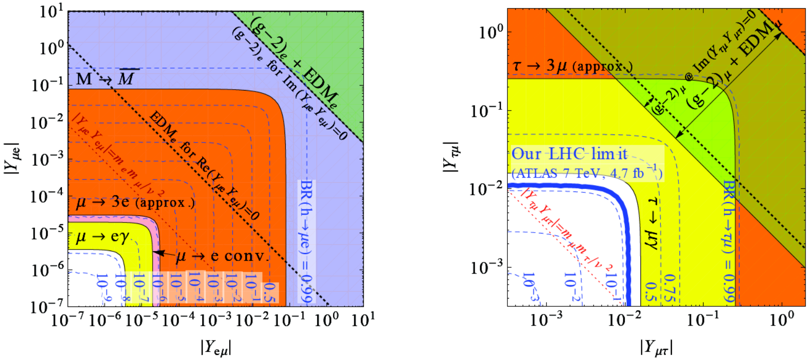
Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc} Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db} Y_{bd}\rvert$	$< 3.3 \times$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times$
	$\lvert Y_{sb} Y_{bs}\rvert$	$< 2.5 \times$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6]$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6]$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6]$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8]$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	$< 3.$
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	$< 1.$
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.3
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.3
D^0 oscillations [48]	$\lvert Y_{ut} Y_{ct}\rvert$, $\lvert Y_{tu} Y_{tc}\rvert$	$< 7.6 \times$
	$\lvert Y_{tu} Y_{ct}\rvert$, $\lvert Y_{ut} Y_{tc}\rvert$	$< 2.2 \times$
	$\lvert Y_{ut} Y_{tu} Y_{ct} Y_{tc}\rvert^{1/2}$	$< 0.9 \times$
neutron EDM [37]	$\mathrm{Im}(Y_{ut} Y_{tu})$	$< 4.4 \times$

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert \mathrm{Im}(Y_{e\mu} Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 4.6 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y_{e\mu}^*\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert \mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu} Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau} Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

[Harnik et al., 1209.1397v2]

Limits on $Y_{f_i f_j}$

[Figure from Harnik et al., 1209.1397v2]

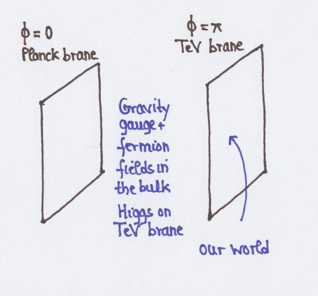


- Indirect constraints preclude any collider signatures except in the τ and top sector.
- Br $(H \to \tau\mu) \sim 10\%$ and Br $(H \to \tau e) \sim 10\%$ still possible [Blankenburg et al., 2012]
  Could be excluded by dedicated LHC searches [Harnik et al., 2012]
- Caveat: LFV penguins can be generated at the scale Λ.

Penguin transitions in the (minimal) RS model

Slice of AdS_5 in interval $[0, \pi]$ ($[1/k, 1/T]$ in conformal coordinates)
Minimal RS model: All SM fields except the Higgs in the bulk.
Potentially a theory of flavour.

- Higgs FCNC at tree-level due to mixing with KK excitations [Agashe, Perez, Soni, 2006; Azatov et al., 2009]
- Lepton- and quark penguin transitions [Csaki et al., 2010; Blanke et al., 2012], with WCHC [Delaunay et al., 2012]
- Complete 5D calculation of gauge-boson contribution to $g_\mu - 2$, and Higgs-exchange induced LFV. [MB, Dey, Rohrwild, 2012]



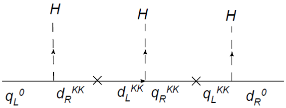
Wrong-chirality Higgs couplings (WCHC)

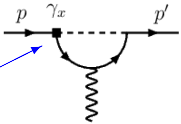
$$\int d^4x \; [(\bar{L}\Phi)E + \text{h.c.}]_{|z=1/T} = \int d^4x \; [(\bar{L}_L\Phi)E_R + (\bar{L}_R\Phi)E_L + \text{h.c.}]_{z=1/T}$$

The WCHC $(\bar{L}_R\Phi)E_L$ vanishes for a brane-localized Higgs due to the boundary condition. Too naive!

Higgs FCNC and dipole operators

$$\mathcal{L} = \frac{ce}{8\pi^2}\,\bar{\tau}\sigma_{\mu\nu}\mu F^{\mu\nu} + \text{h.c.} \qquad \Gamma(\tau\to\mu\gamma) = \frac{\alpha m_\tau^5 |c|^2}{64\pi^4}$$





Electroweak scale loop (anarchic 5D Yukawa) [Azatov et al., 2009]

$$c \sim \frac{Y_{\tau\tau}Y^*_{\tau\mu}}{12 m_H^2} \sim Y_*^2 \frac{\sqrt{m_\mu m_\tau}}{12 T^2} \times \frac{m_\tau^2}{m_H^2}$$

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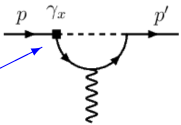

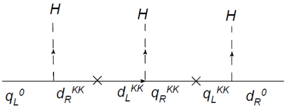

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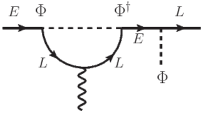

KK scale loop generates dim-6 $\bar{L}_i \Phi \sigma_{\mu\nu} E_j F^{\mu\nu}$ operator (narrow bulk Higgs profile) [MB, Dey, Rohrwild, 2012]

$$c \sim Y_*^2 \frac{\sqrt{m_\mu m_\tau}}{12 T^2}$$

Dominant. Decouples low-energy constraints from LFV Higgs decays.

Summary

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II As do null searches at high-energy colliders supports the idea that the SM could be valid to very high scales

III Even if there is no new fundamental physics (yet) there is lots of fascinating physics

IV 20% NP effects often possible. Precision is important for flavour physics at LHCb and SuperBelle

V Constraints from flavour physics perhaps more important than ever though would have hoped for guidance from LHC discoveries

VI Top and Higgs add extra dimensions to flavour

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