New physics via $B_s \rightarrow \mu^+\mu^-$ and related decays

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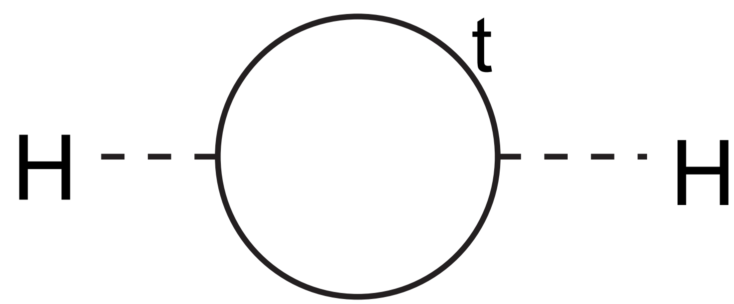
Workshop "Flavour of New Physics in b➔s transitions"
Institut Henri Poincare', 2-3 June 2014

Contents

- New physics and where to look for it
- Appraisal of $B_s \rightarrow \mu^+\mu^-$ et al
- Constraints & predictions of BSM physics (selection)

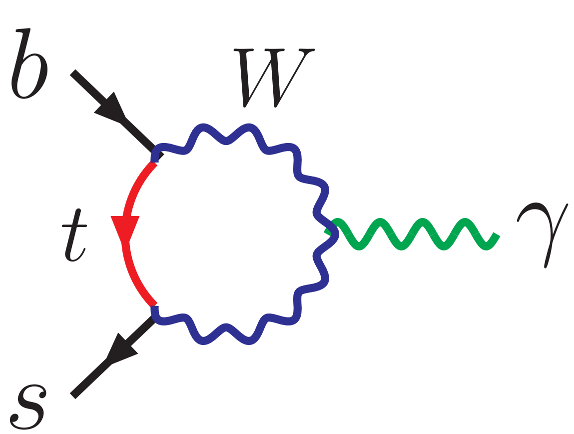
Why rare B decays

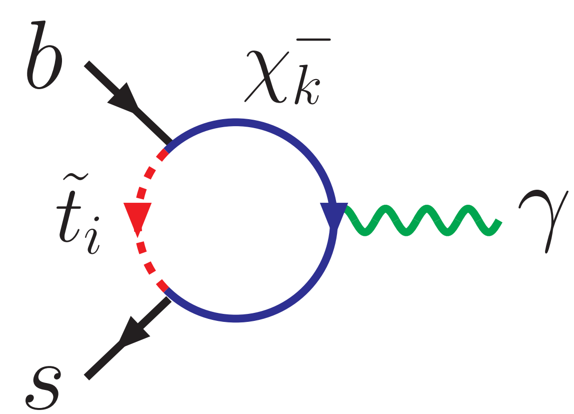
Solutions to the hierarchy problem must bring in particles to cut off the top contribution to the weak scale (Higgs mass parameter).



$$\propto y_t^2 \Lambda_{\mathrm{UV}}^2$$

The new particles' couplings tend to break flavour (they do in all the "natural" proposals for TeV physics)





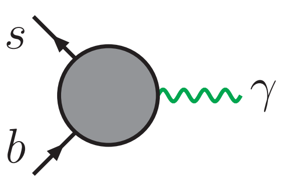
At least they will have CKM-like flavour violations (minimal flavour violation), so will always affect rare decays

weak ΔB=ΔS=1 Hamiltonian

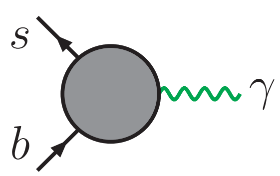
= EFT for ΔB=ΔS=1 transitions (up to dimension six)

$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3\ldots6} C_i P_i + C_{8g} Q_{8g} \right] \qquad C_i \sim g_{\rm NP} \frac{m_W^2}{M_{\rm NP}^2}$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}' + C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T' \Big].$$

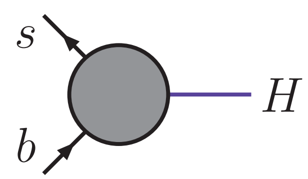


$$\mathcal{O}_7 = \frac{e}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \,,$$



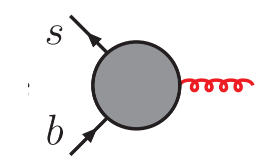
$$\mathcal{O}_V = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l) \,,$$

$$\mathcal{O}_S = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} l) \,,$$

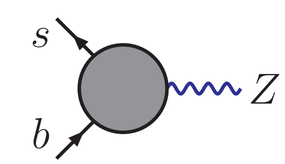


$$\mathcal{O}_T = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s}\sigma_{\mu\nu} P_R b)(\bar{l}\sigma^{\mu\nu} P_R s) \,,$$

$$\mathcal{O}_8 = \frac{g_s}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b \,,$$



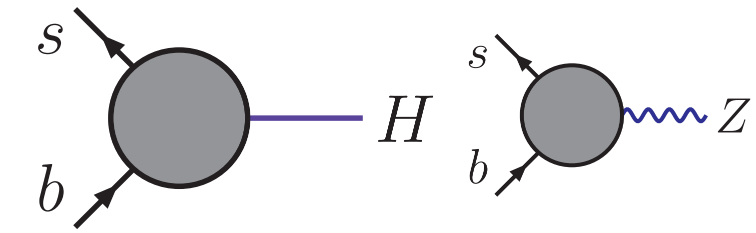
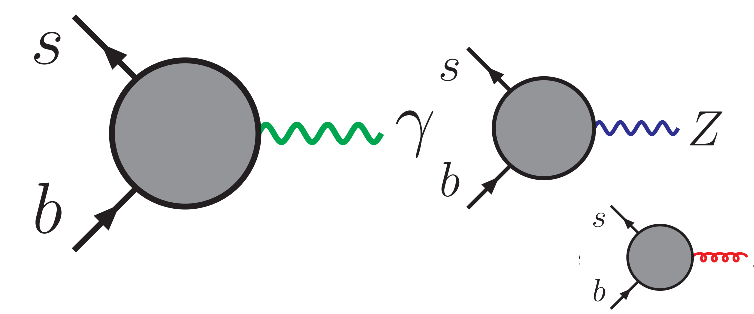
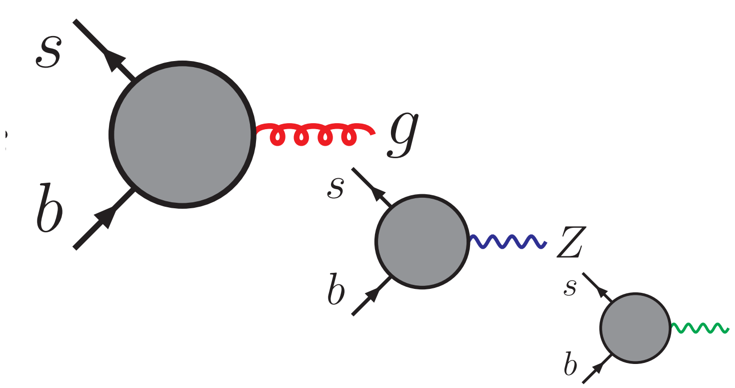
$$\mathcal{O}_A = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma^5 l)_A$$



$$\mathcal{O}_P = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l}\gamma^5 l) \,,$$

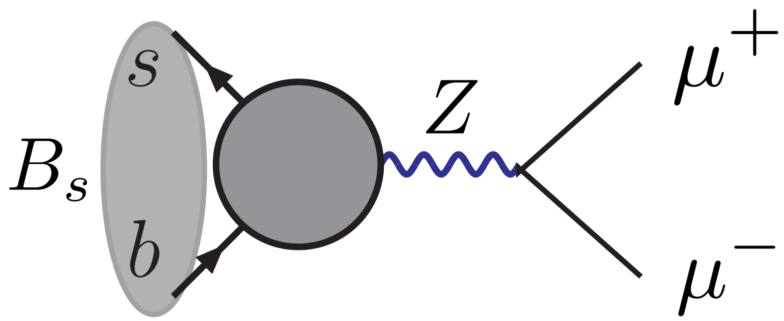
look for observables sensitive to C_i's, specifically those that are suppressed in the SM

Exclusive decays at LHCb

final state	strong dynamics	#obs	NP enters through
Leptonic $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-$, $K^* \gamma$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi$, πK, $\phi\phi$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

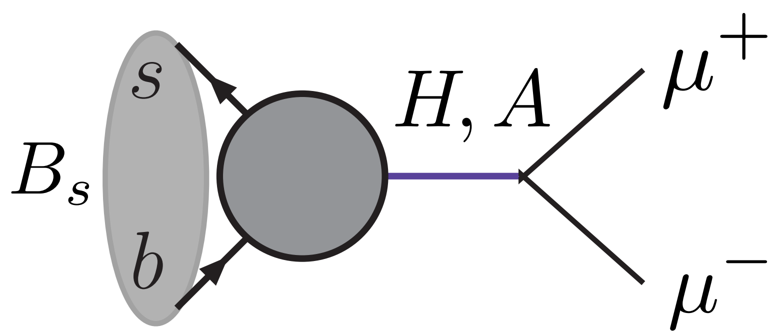
Decay constants and form factors accessible by QCD sum rules and, increasingly, by lattice QCD. Lattice in particular for the decay constants; price to pay: small branching fractions, few observables

Leptonic decay, NP and LHC



$$\propto \frac{m_\mu^2}{M_W^2}$$

loop and helicity suppressed in SM



$$\propto \frac{m_b^2 m_\mu^2}{M_W^4} \tan^6 \beta$$

Yukawa suppressed in SM

in 2HDM (or MSSM) Yukawas can be (very) large

Loop suppression and possible removal of helicity/Yukawa suppression imply strong sensitivity to new physics

$$BR(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$BR(B_d^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

SM theory (time-averaged) Bobeth et al 2013

$$BR(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

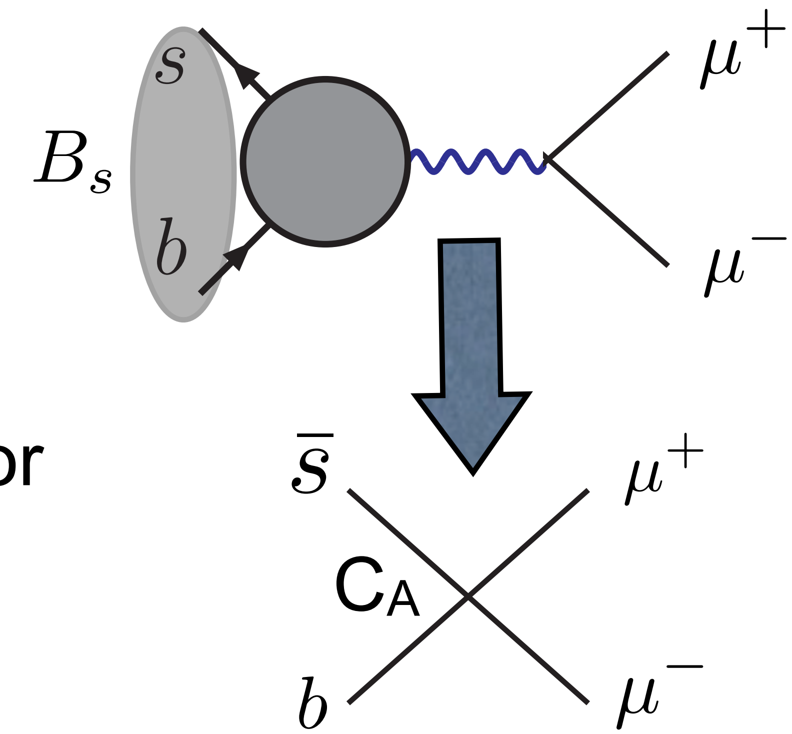
$$BR(B_d^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

CMS/LHCb average (2013)

more SM theory: D Guadagnoli talk

Standard Model

- Mediated by short-distance
  Z penguin and box - long distance
  strongly CKM / GIM suppressed



- including QCD corrections, matches onto single relevant effective operator

$$Q_A = \bar{b}_L \gamma^\mu q_L \, \bar{\ell} \gamma_\mu \gamma_5 \ell$$

$$\overline{\mathcal{B}}_{q\ell} = \frac{|N|^2 M_{B_q}^3 f_{B_q}^2}{8\pi \, \Gamma_H^q} \beta_{q\ell} \, r_{q\ell}^2 \, |C_A(\mu_b)|^2 + \mathcal{O}(\alpha_{em})$$

[Buchalla&Buras 93, Misiak&Urban 99; De Bruyn et al 2012; Guadagnoli & Isidori 2012; Buras et al 2012,2013; Bobeth et al 2013]

- includes: NNLO QCD, NLO EW (matching); photon bremsstrahlung; time-averaging

- nonperturbative QCD in decay constant and O(α_{em}) only
  main uncertainties: decay constant, CKM

more SM theory: D Guadagnoli talk

How does it compare?

- Leptonic decay is
  + NP QCD only through a (lattice-accessible) decay constant; unless multi-photon exchanges considered
  + free from long-distance photon penguins, photon cannot create a spin-0 lepton-antilepton pair.

- For comparison, semileptonic $B \rightarrow K^* l^+ l^-$
  + kinematically rich 4-body final state, much richer source of information in principle
  - but involves 7 form-factors *and* long-distance sensitivity from photon penguins
  + at leading power in Λ/m_b (only), FF and LD drop out/ controllable in suitable angular observables
  - power corrections can have sizable effect on some angular observables in some q^2 ranges

  dedicated session in afternoon

- Hadronic observables: even larger in number
  - even more complicated theory (more reliance on heavy-quark expansions, or else “plausible” dynamical assumptions
  + sheer number is large: data-driven modelling of LD?

Heavy-quark limit and corrections

At most 1-2% over entire 0..6 GeV^2 range -> ignore

$$F(q^2) = F^\infty(q^2) + a_F + b_F q^2/m_B^2 + \mathcal{O}([q^2/m_B^2]^2)$$

heavy quark limit

Power corrections - parameterise

form factors in helicity basis

Bharucha et al 2011
SJ, Martin Camalich 2012

$$F^\infty(q^2) = F^\infty(0)/(1 - q^2/m_B^2)^p + \Delta_F(\alpha_s; q^2)$$

$p = 2$ for $\lambda = -1$
$p = 3$ for $\lambda = 0$

(Charles et al) (Beneke, Feldmann)

For alpha s=0, q^2 dependence constrained from heavy-quark limit [?] (argument relies on properties of vector light-cone DA)

$V_+^\infty(0) = 0$ $T_+^\infty(0)=0$
$V_-^\infty(0) = T_-^\infty(0)$
$V_0^\infty(0) = T_0^\infty(0)$

from heavy-quark/ large energy symmetry

Corrections are calculable in terms of perturbation theory, decay constants, light cone distribution amplitudes

$V_+^\infty(q^2) = 0$ $T_+^\infty(q^2)=0$

hence

$$T_+(q^2) = \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b)$$
$$V_+(q^2) = \mathcal{O}(\Lambda/m_b).$$

[SJ @ LHCb 2013, Aspen 2014, ...]

- **"naively factorizing" part of the helicity amplitudes $H_{V,A}^+$ strongly suppressed** as a consequence of chiral SM weak interactions
- We see the suppression is **particularly strong** near low-q^2 endpoint
- Form factor relations imply reduced uncertainties in suitable observables

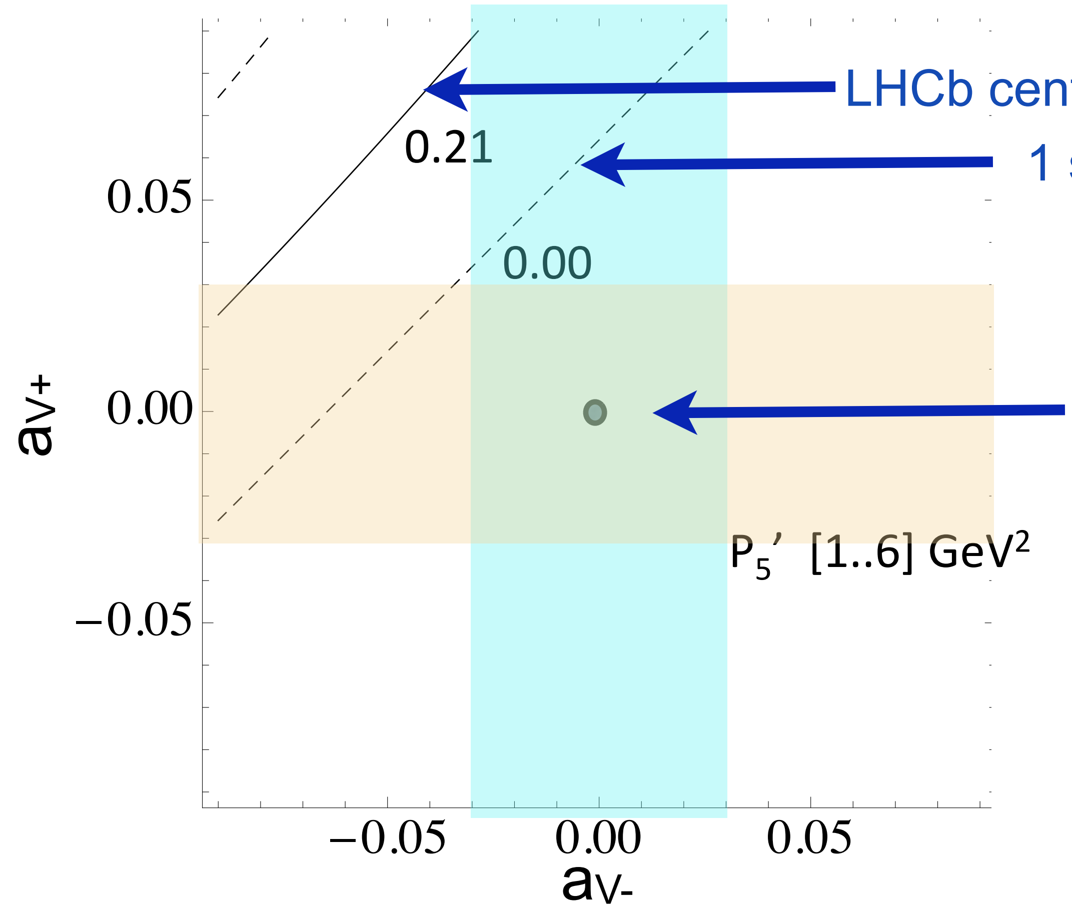
Burdman, Hiller 1999 (quark picture)

P_5' power-correction dependence

plot in plane of two form factor power correction parameters

relating to V_+ and V_-, respectively

(there are 10 power-correction parameters to order q^2/m_B^2)



[SJ, J Martin Camalich JHEP 1305 (2013) 043, arXiv:1212.2263; SJ @LHCb 10/2013, Aspen 2014, etc; SJ, J Martin Camalich, to appear]

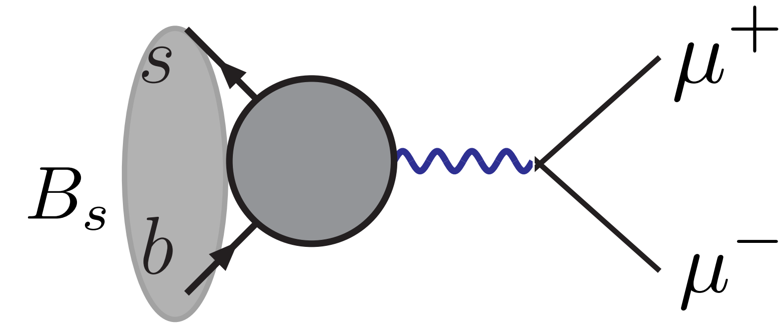
~ +/- 0.03 for either power correction parameter corresponds to a 10% power correction & is sufficient to bring data in agreement with SM theory

Drawing conclusions based on this observable requires **sufficient accuracy on the form factor calculations** (not even considering nonfactorizable long-distance effects yet).

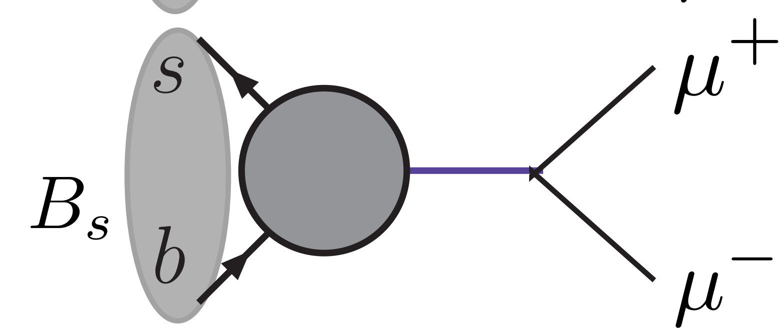
Argument relies only on the functional dependence of P_5' on form factors and holds **irrespectively** of statistical treatments, assumptions on soft form factors at $q^2=0$, etc.

Beyond the SM

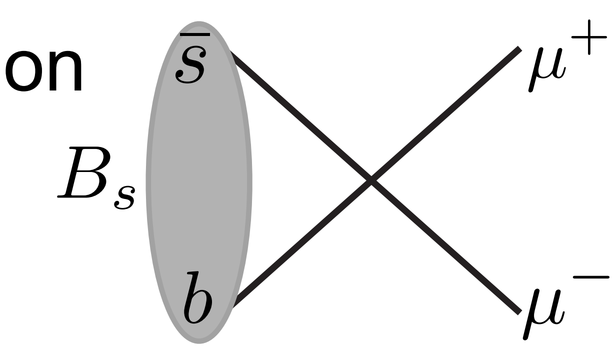
- New physics can modify the Z penguin ....



  ... induce a Higgs penguin ...



  ... or induce (or comprise) four-fermion contact interactions directly



could also violate lepton flavour

- for the most general effective Hamiltonian,

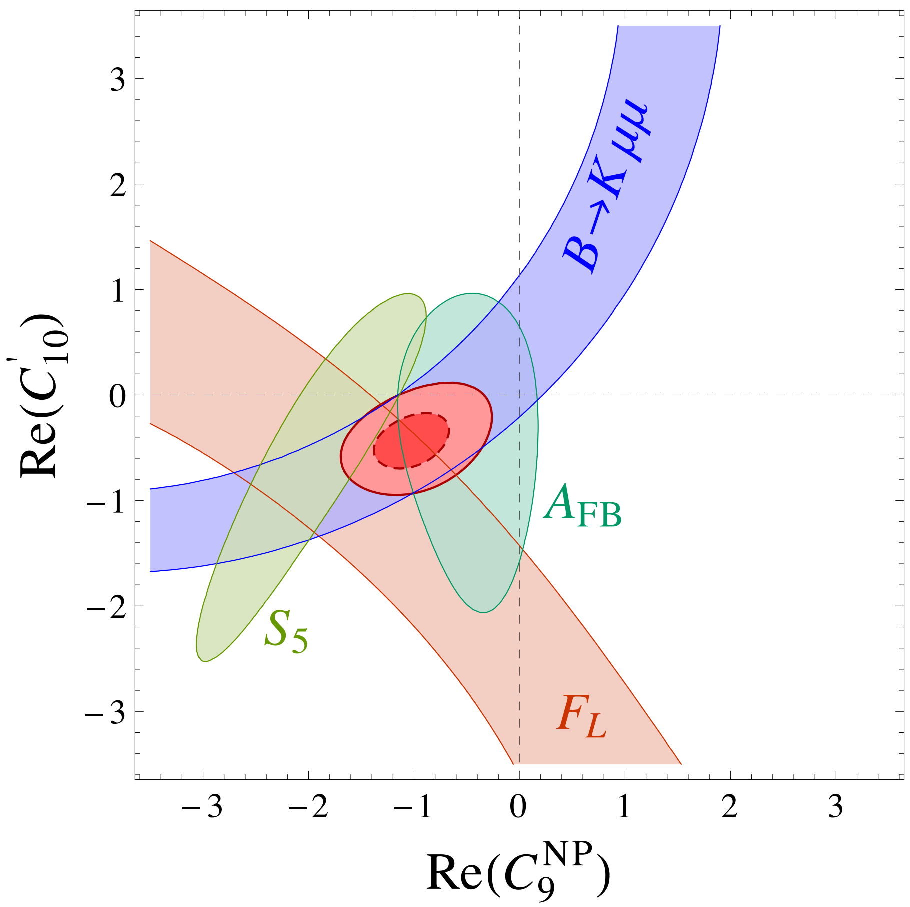
$$\mathcal{B}\left(\bar{B}_q \to \mu^+\mu^-\right) = \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 \tau_{B_q}}{64\pi^3} |V_{tb}V_{tq}^*|^2 \sqrt{1-4\hat{m}_\mu^2} \left\{ (1-4\hat{m}_\mu^2)|F_S|^2 + |F_P + 2\hat{m}_\mu F_A|^2 \right\}$$

where $$F_{S,P} = M_{B_q}\left[\frac{c_{S,P} m_b - c'_{S,P} m_q}{m_b + m_q}\right], \quad F_A = c_{10} - c'_{10}$$

[Bobeth, Ewerth, Kruger, Urban 2002]

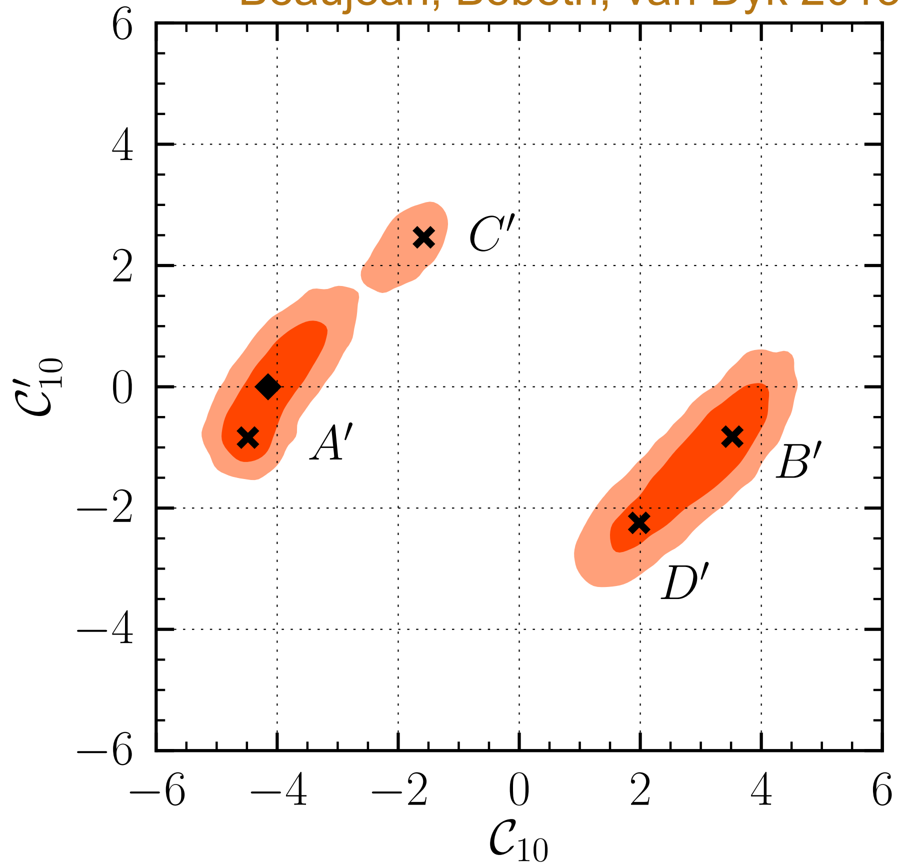
Global fits

[Altmannshofer, Paradis, Straub 2012;
Altmannshofer, Straub 2013;
Bobeth, Hiller, van Dyk 2011-2012;
Beaujean, Bobeth, van Dyk 2013, ...]



Altmannshofer, Paradisi 2013

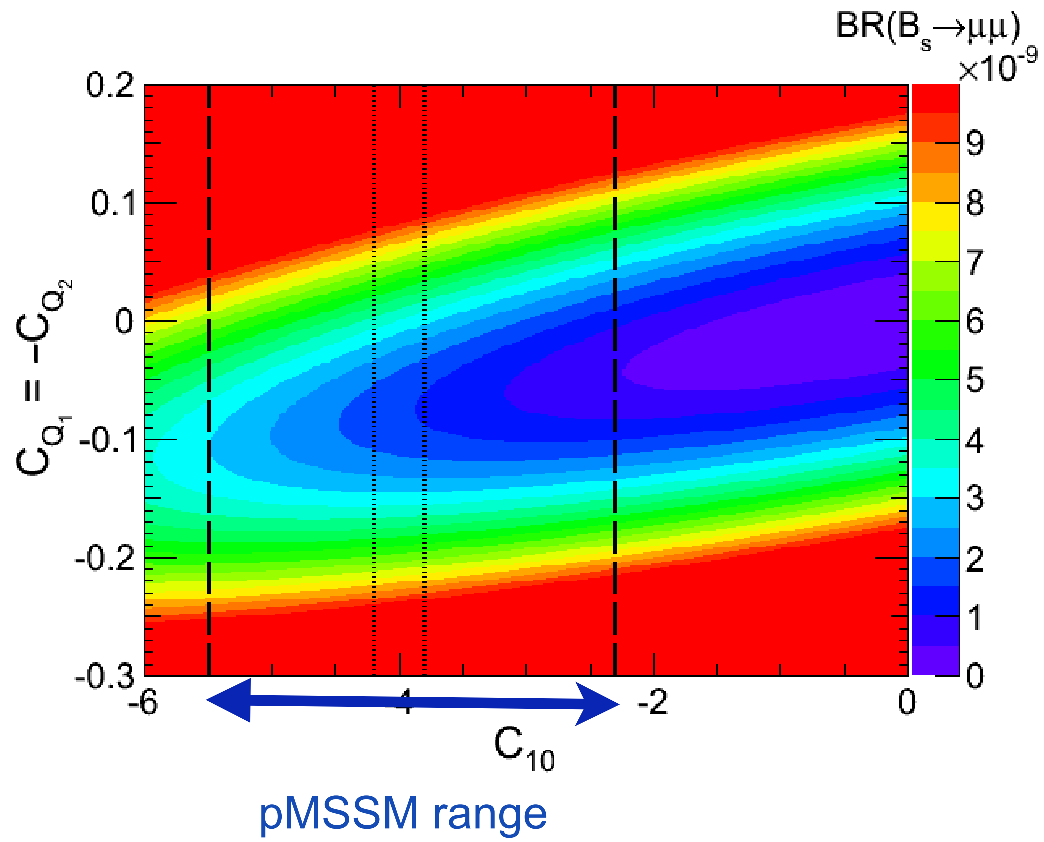
Beaujean, Bobeth, van Dyk 2013



- Outside the scalar operators, $B_s \to \mu^+\mu^-$ not a competitive constraint

- Patterns in data ("LHCb anomaly"), not (in my opinion) significant

Impact of $B_s \rightarrow \mu^+\mu^-$



Arbey, Battaglia, Mahmoudi, Martinez Santos 1212.4887

- $B_s \rightarrow \mu^+\mu^-$ provides strong constraints on scalar/pseudoscalar operators

  [$C_{Q1} = m_b C_S$, $C_{Q2} = m_b C_P$]

- in other words, basically fully complementary to semileptonic decays

MSSM - large tan β

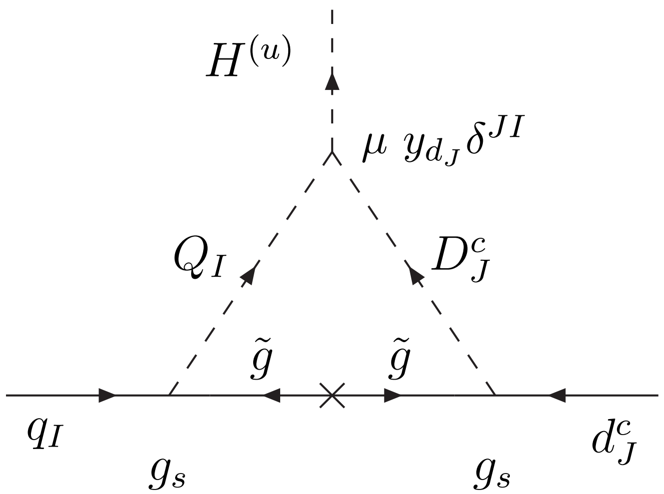
In SM, higgs couplings flavour diagonal
(proportional mass matrix)

$$M^d_{ij} = v \ Y^d_{ij}$$

MSSM - large tan β

In SM, higgs couplings flavour diagonal
(proportional mass matrix)

$$M^d_{ij} = v_d Y^d_{ij} + v_u \Delta_{ij}$$



In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

MSSM - large tan β

parametrically large if $v_u \gg v_d$

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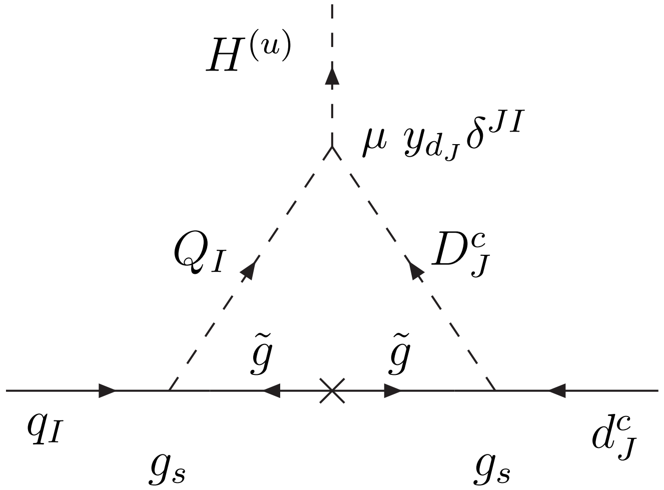

In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

tan $\beta = v_u / v_d$

MSSM - large tan β

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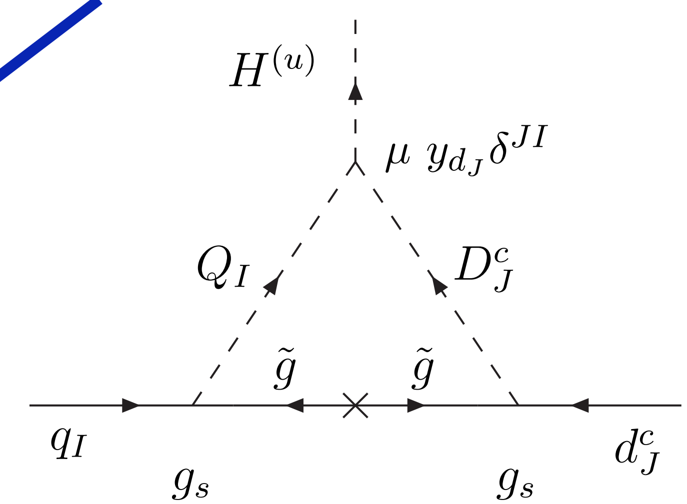
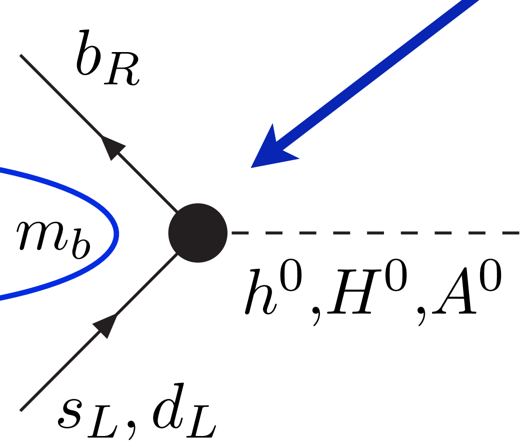


In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

tan $\beta = v_u/v_d$

Yukawa becomes flavour-violating

$$V^*_{tb} V_{t(s,d)} \tan^2\beta\, m_b$$



MSSM - large tan β

In SM, higgs couplings flavour diagonal
(proportional mass matrix)

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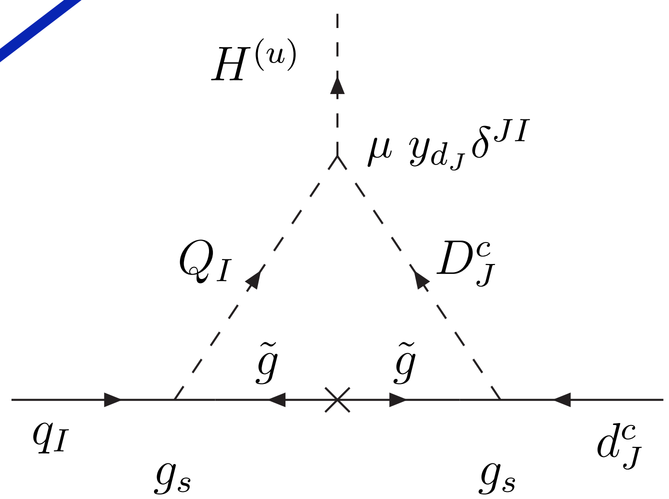

In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

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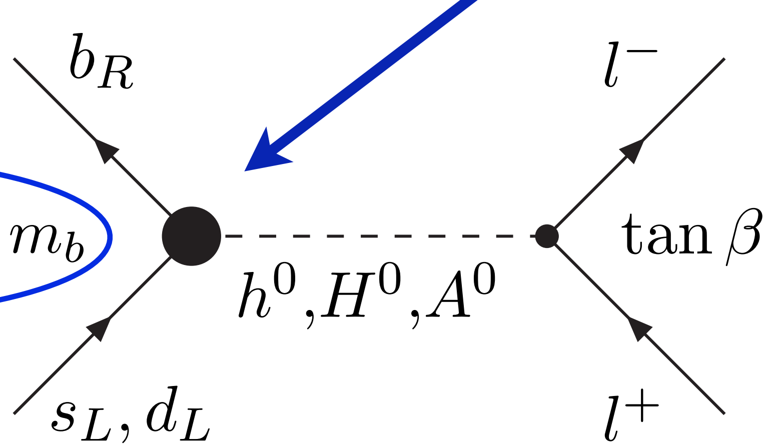
$V^*_{tb} V_{t(s,d)} \tan^2\beta\, m_b$

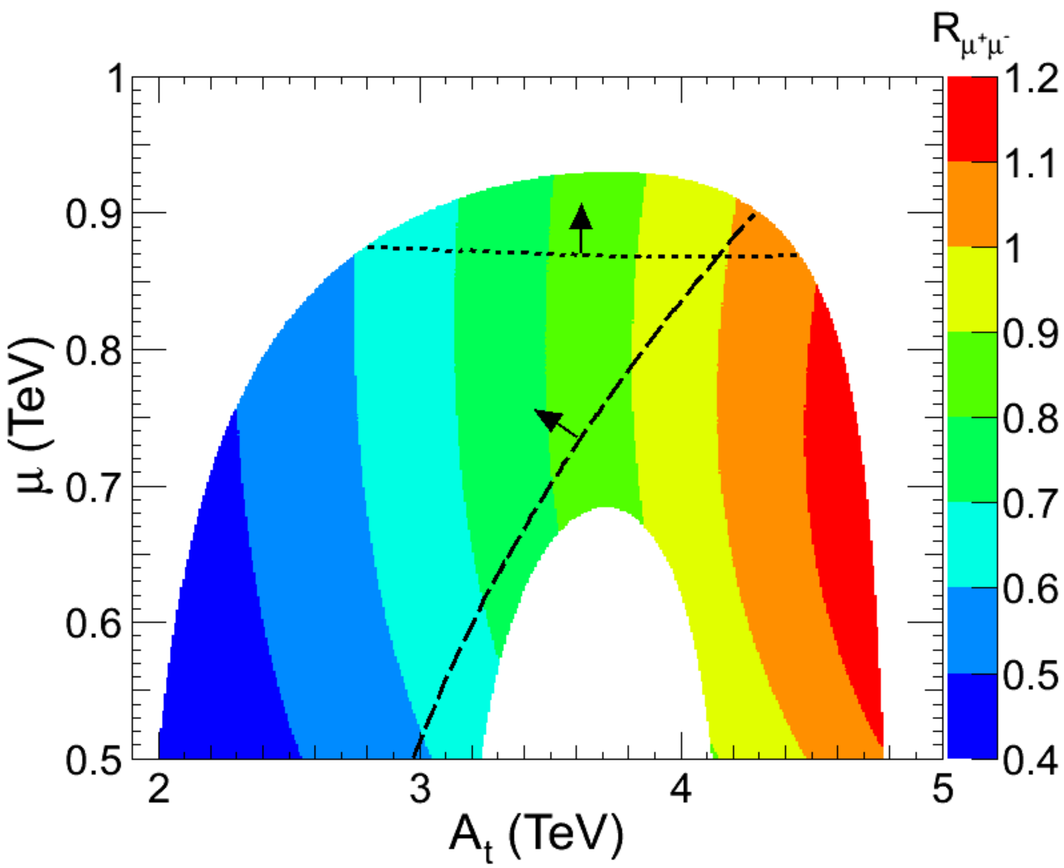
(for minimal
flavour violation)



$$BR(B_s \to \mu\mu) \propto \tan^6\beta$$

[Choudhury&Gaur 99; Hamzaoui, Pospelov, Toharia 99; Babu, Kolda 99; Isidori, Retico; Buras et al 02; Foster et al 04-06,...]

$B_s \rightarrow \mu^+\mu^-$: MSSM, large tan β



Haisch, Mahmoudi 1210.7806

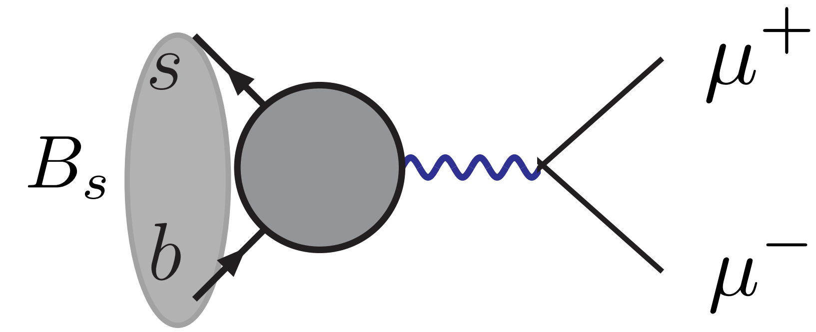
also Altmannshofer, Carena et al 12

tanβ= 60; dashed line: B->X_s gamma favoured

- Both enhancement or suppression possible. Due to SM-BSM interference .

MSSM - small tan β

- Z penguin contributions now relatively more important and interference effects possible

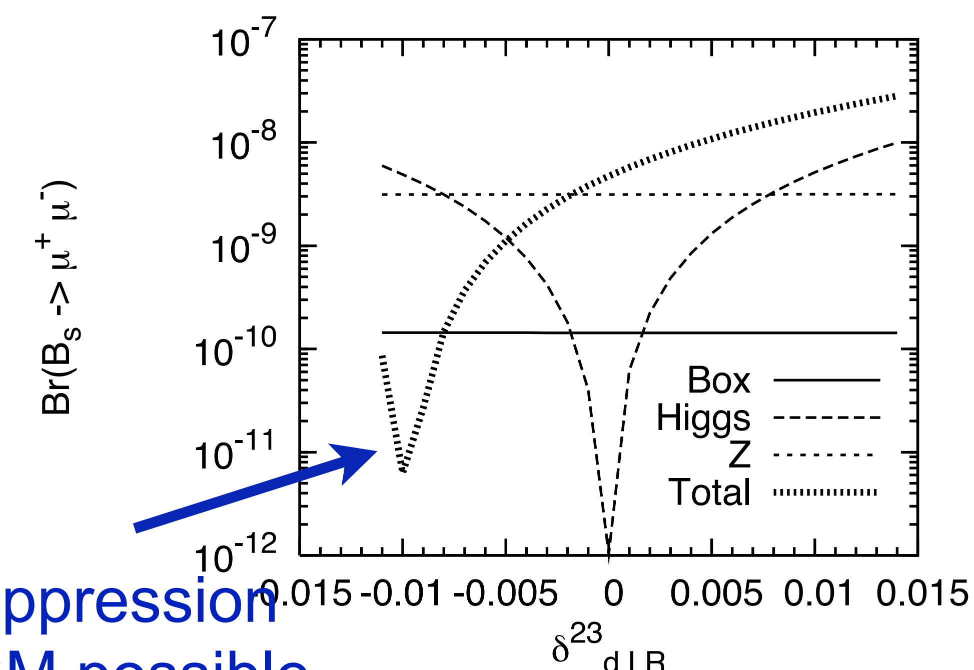


complete 1-loop calculation in general MSSM

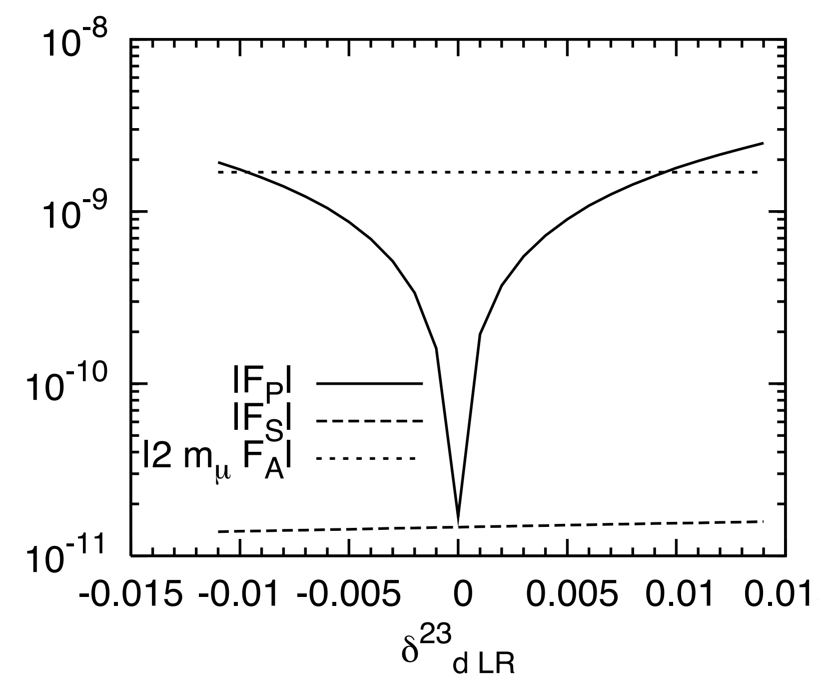
[Dedes, Rosiek, Tanedo 2008]

implemented in public computer program “SUSY_FLAVOR”

[Rosiek, Chankowski, Dedes, SJ, Tanedo 2010]



even suppression below SM possible

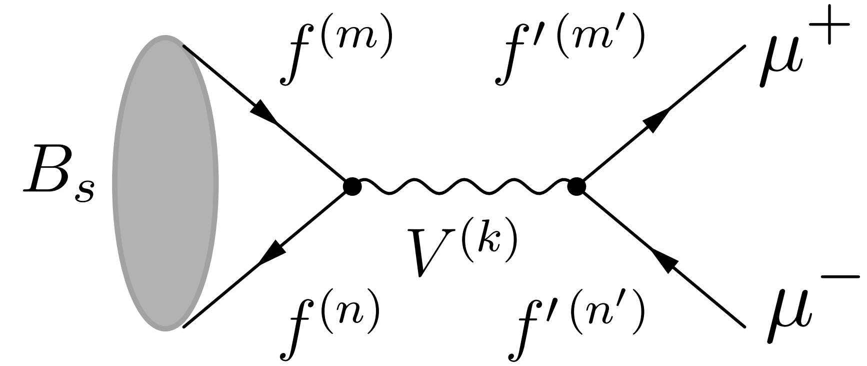


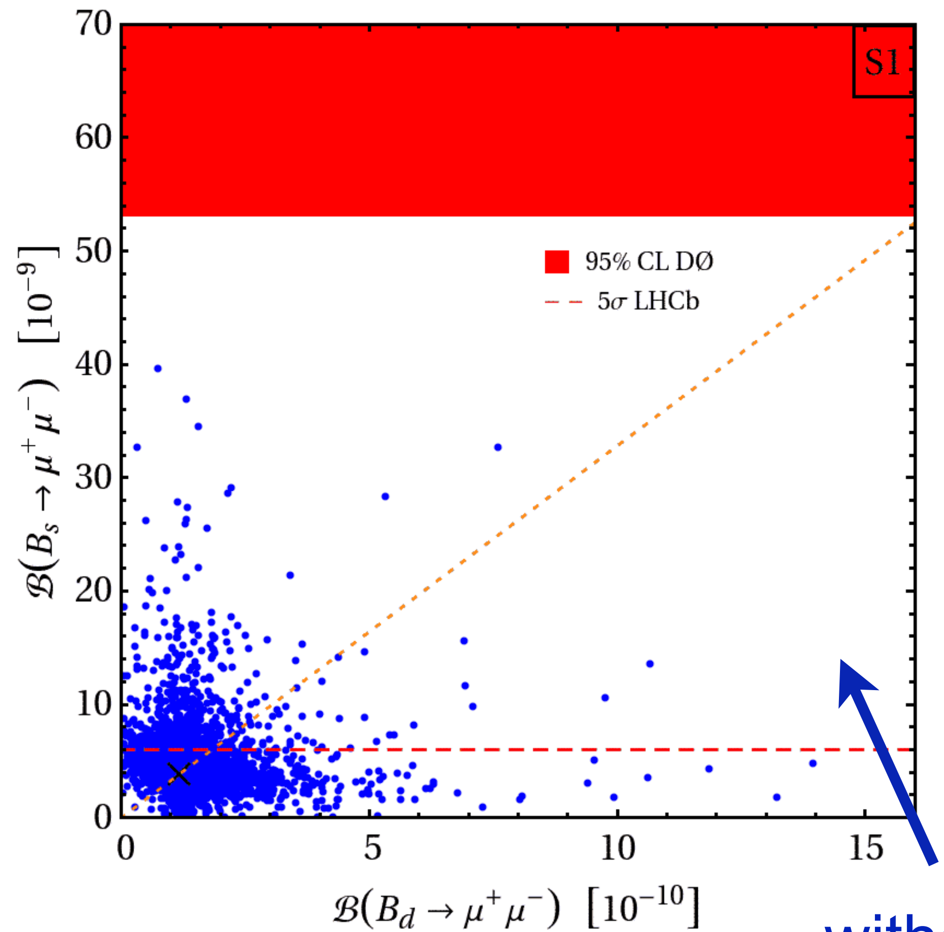
(in this plot the Z penguin does not receive large contributions, in general it can)

(numerics outdated post Higgs discovery; see references on previous slide)

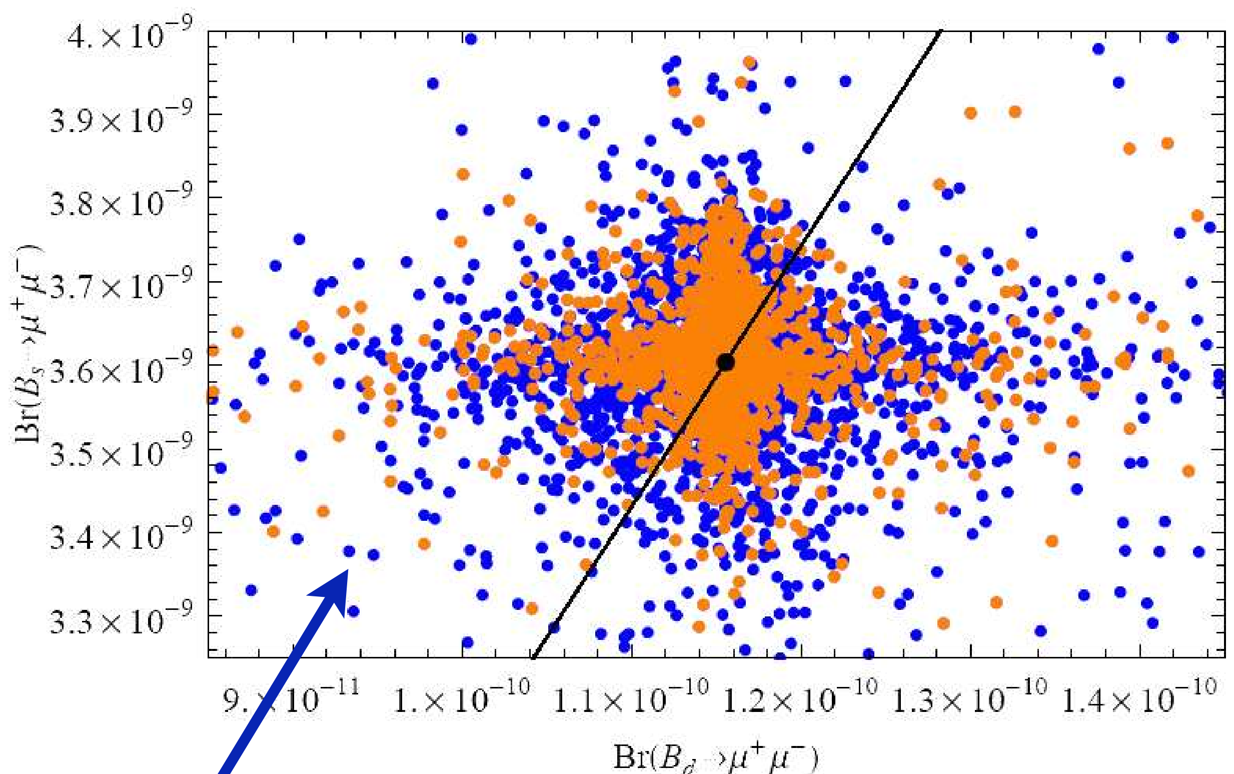
Randall-Sundrum

- Warped extra-dimensional models "explain" SM flavour structure by localizing the SM degrees of freedom differently in the extra dimension. Higher Kaluza-Klein states of the gauge bosons have tree-level FCNC couplings to the SM particles





Casagrande et al, arXiv:0912.1625

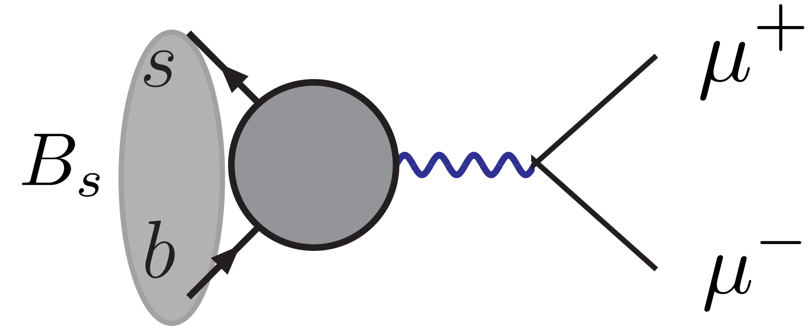


Blanke et al, arXiv:0812.3803v3

without / with custodial protection
higgs on IR brane

(should apply post Higgs discovery)

Little(st) Higgs (with T parity)



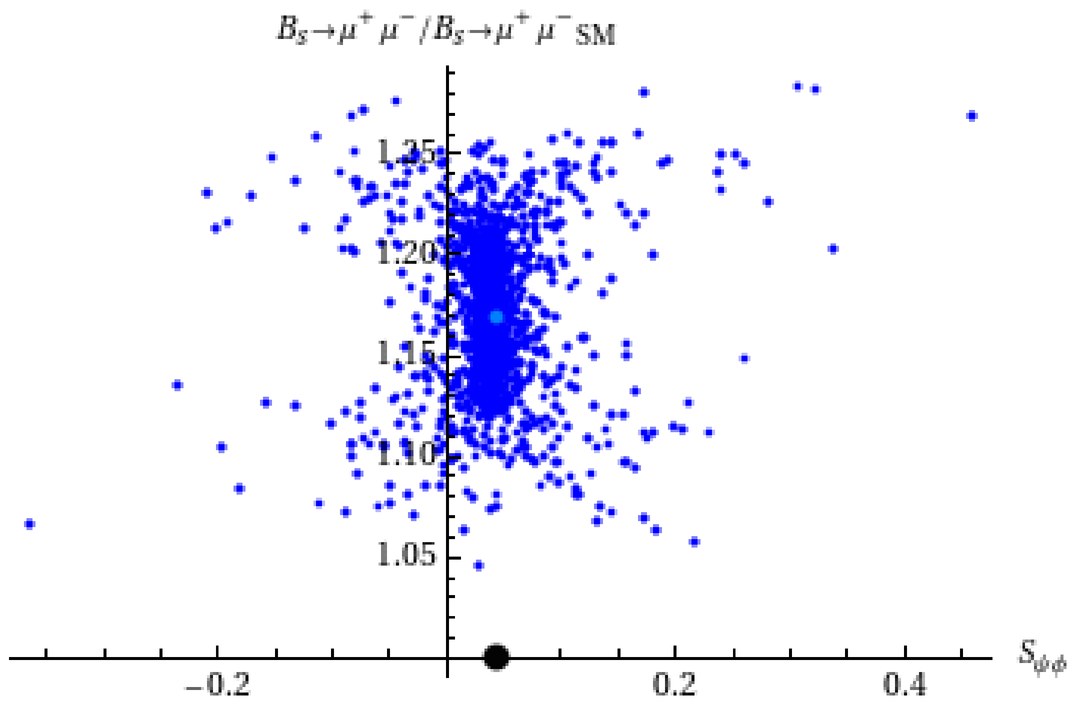
- Higgs is pseudo-Goldstone boson. Implies new particles with non-MFV couplings

- enter at 1 loop through Z penguin, finite calculable contribution

[Goto et al 0809.4753]

[de Aguila et al 0811.2891]

- effect less pronounced than in MSSM or RS but should be distinguishable from Standard Model



[Blanke et al 0906.5454]

(should apply post Higgs discovery)

Conclusions

- Rare leptonic decays are NP-sensitive and theoretically clean; followed by the kinematically rich rare semileptonic decays
- $B_{s,d} \rightarrow \mu^+\mu^-$ stand out clearly from theory clean-ness, price to pay is few observables and tiny rates
- They can still have O(1) new physics contributions in spite of constraints from elsewhere.
- and CMS/LHCb appear sensitive to both BR($B_{s,d} \rightarrow \mu^+\mu^-$) down to the SM value
- Without a theory of flavour, we *cannot* predict hierarchies between BR($B_s \rightarrow \mu^+\mu^-$) and BR($B_d \rightarrow \mu^+\mu^-$), or even between lepton-flavour-conserving and violating modes
- Should also look beyond $B_s \rightarrow \mu^+\mu^-$ where feasible (μ^+e^-, e^+e^- ? B_d !). (If encouragement is needed.)

Backup

Form factors

Helicity amplitudes naturally involve helicity form factors

$$
\begin{aligned}
-im_B\tilde{V}_{L(R)\lambda}(q^2) &= \langle M(\lambda)|\bar{s}\not{\epsilon}^*(\lambda)P_{L(R)}b|\bar{B}\rangle,\\
m_B^2\tilde{T}_{L(R)\lambda}(q^2) &= \epsilon^{*\mu}(\lambda)q^\nu\langle M(\lambda)|\bar{s}\sigma_{\mu\nu}P_{R(L)}b|\bar{B}\rangle\\
im_B\tilde{S}_{L(R)}(q^2) &= \langle M(\lambda=0)|\bar{s}P_{R(L)}b|\bar{B}\rangle.
\end{aligned}
$$

~ Bharucha et al 2010

(& rescale helicity-0 form factors by kinematic factor.)

Can be expressed in terms of traditional "transversity" FFs

$$
\begin{aligned}
V_\pm(q^2) &= \frac{1}{2}\left[\left(1+\frac{m_V}{m_B}\right)A_1(q^2) \mp \frac{\lambda^{1/2}}{m_B(m_B+m_V)}V(q^2)\right],\\
V_0(q^2) &= \frac{1}{2m_V\lambda^{1/2}(m_B+m_V)}\left[(m_B+m_V)^2(m_B^2-q^2-m_V^2)A_1(q^2)-\lambda A_2(q^2)\right]\\
T_\pm(q^2) &= \frac{m_B^2-m_V^2}{2m_B^2}T_2(q^2) \mp \frac{\lambda^{1/2}}{2m_B^2}T_1(q^2),\\
T_0(q^2) &= \frac{m_B}{2\,m_V\lambda^{1/2}}\left[(m_B^2+3m_V^2-q^2)T_2(q^2)-\frac{\lambda}{(m_B^2-m_V^2)}T_3(q^2)\right],\\
S(q^2) &= A_0(q^2),
\end{aligned}
$$

The form factors satisfy two exact relations:

$$
\begin{aligned}
T_+(q^2=0) &= 0,\\
S(q^2=0) &= V_0(0)
\end{aligned}
$$

note - M can be multiparticle state. Eg for a two-pseudoscalar state

$$
\begin{aligned}
\tilde{V}_{L\lambda} &= -\eta(-1)^L\tilde{V}_{R,-\lambda} \equiv \tilde{V}_\lambda,\\
\tilde{T}_{L\lambda} &= -\eta(-1)^L\tilde{T}_{R,-\lambda} \equiv \tilde{T}_\lambda,\\
\tilde{S}_L &= -\eta(-1)^L\tilde{S}_R \equiv \tilde{S},
\end{aligned}
$$

L = angular momentum

η = intrinsic parity

\+ invariant mass dependence

SJ, J Martin Camalich 2012