Rare leptonic B and D decays

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6th International Workshop on the CKM Unitarity Triangle
University of Warwick, 06-10 September 2010

Contents

- Why rare leptonic decays
- Standard Model
- New Physics

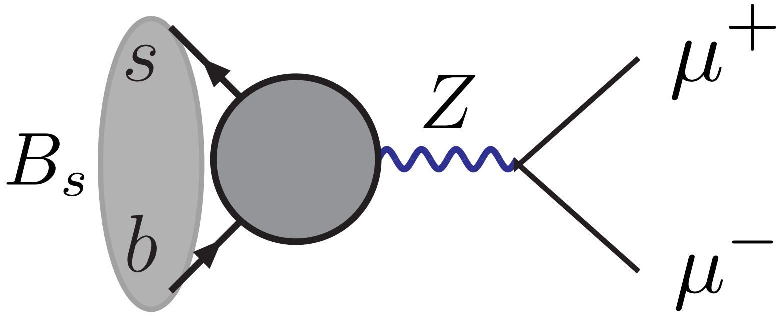
Why rare leptonic decays ?

Meson decays are the simpler, the fewer hadrons there are in the final state. Here “simple” refers to theory, particularly QCD

decay type	strong dynamics	# observables
Leptonic $B \to l\nu$, $B \to l^+ l^-$	decay constant $\langle 0 \| j^\mu \| B \rangle \propto f_B$	O(1)
semileptonic, radiative $B \to K^* l\nu$, $K^*\gamma$	form factors $\langle \pi \| j^\mu \| B \rangle \propto f^{B\pi}(q^2)$	O(10)
Nonleptonic 2-body $B \to \pi\pi$, πK, $\rho\rho$, ...	full matrix element $\langle \pi\pi \| Q_i \| B \rangle$	O(100)

Decay constants are accessible by first principle methods (lattice QCD). Price to pay: small branching fractions, few observables

Leptonic decay, NP and LHC

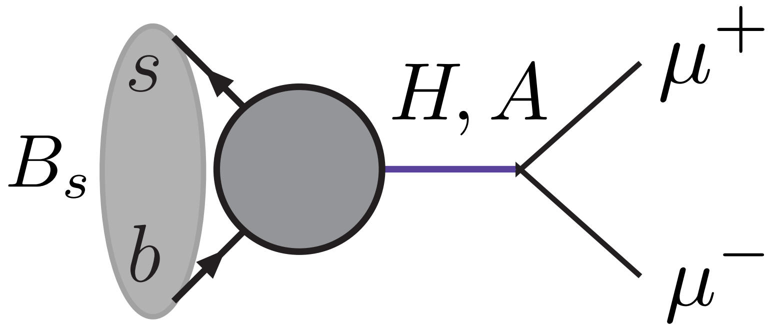


$$\propto \frac{m_\mu^2}{M_W^2}$$

loop and helicity
suppressed in SM

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

Buras et al 2010

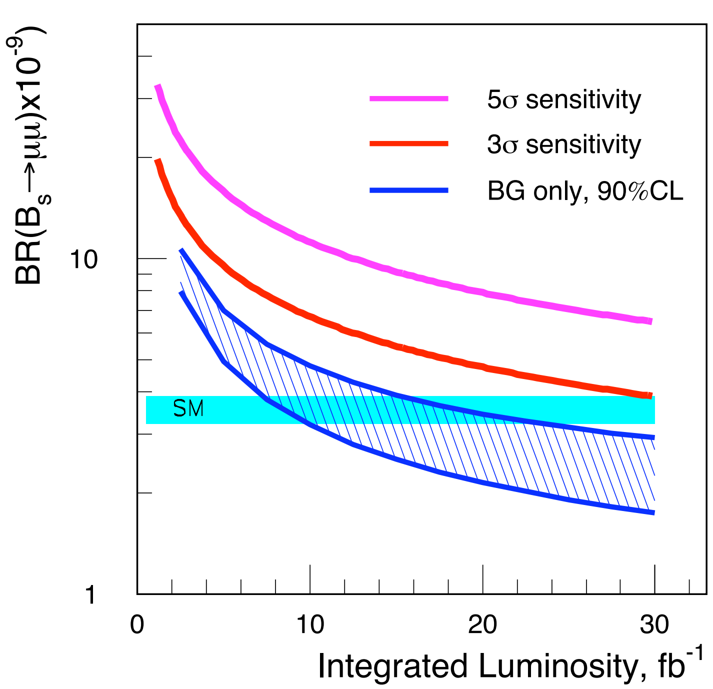


$$\propto \frac{m_b^2 m_\mu^2}{M_W^4} \tan^6\beta$$

Yukawa suppressed in SM

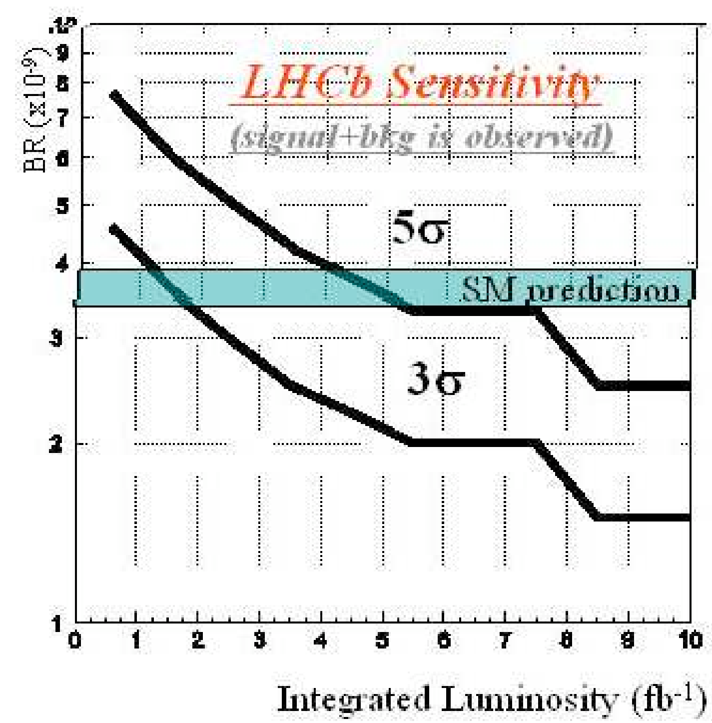
in 2HDM (or MSSM) Yukawas
can be very large

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



ATLAS/CMS

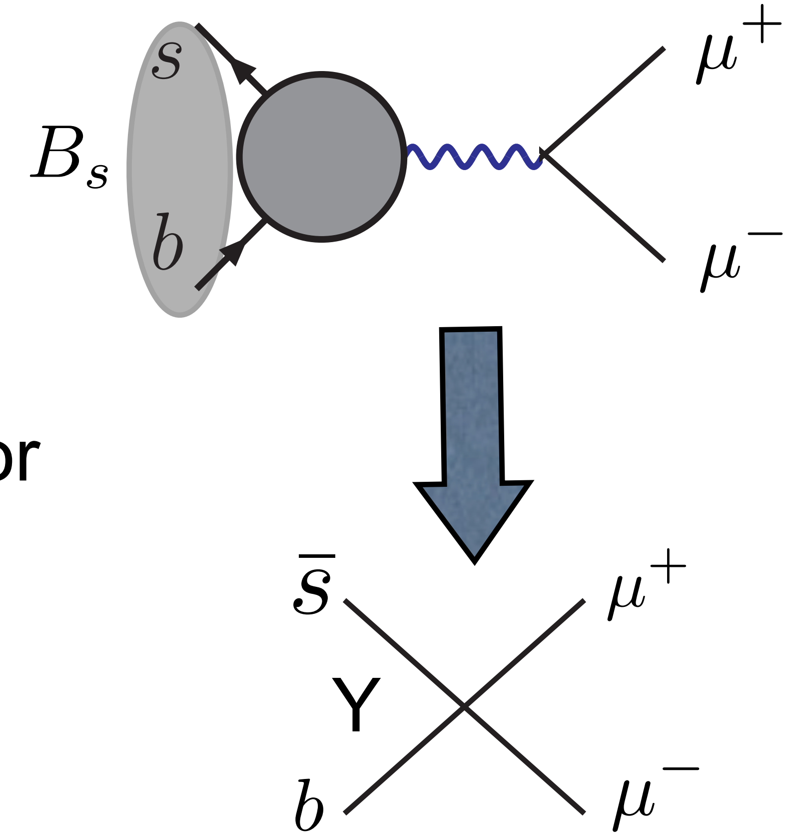
[Artuso et al 0801.1833]



LHCb

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

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2 \theta_W} V_{tb}^* V_{tq} Y Q_A$$

$$Y\left(\bar{m}_t(m_t)\right) = \quad 0.9636 \left[\frac{80.4 \text{ GeV}}{M_W} \frac{\overline{m}_t}{164 \text{ GeV}} \right]^{1.52}$$

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

(approximates NLO to <10^{-4})

[Buchalla&Buras 93,
Misiak&Urban 99;
Artuso et al 0801.1833]

higher orders negligible

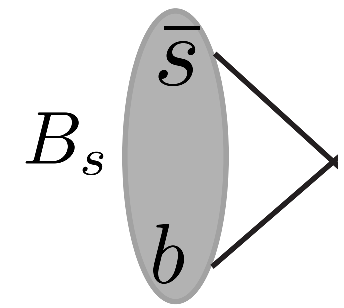
- branching fraction

$$B(B_s \to l^+ l^-) = \tau(B_s) \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2 \Theta_W} \right)^2 F_{B_s}^2 m_l^2 m_{B_s} \sqrt{1 - 4 \frac{m_l^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 \, Y^2$$

main uncertainties: decay constant, CKM
for D or K decays long-distance contributions are important

Standard Model

- F_{Bs} = (238.8 ± 9.5) MeV
  Lunghi, Laiho, van de Water 2009
  lattice QCD average



- error can be reduced by normalizing to $B_s - \bar{B}_s$ mixing

$$B(B_q \to \ell^+\ell^-) = C\frac{\tau_{B_q}}{\hat{B}_q}\frac{Y^2(\overline{m}_t^2/M_W^2)}{S(\overline{m}_t^2/M_W^2)}\Delta M_q$$

Buras 2003

where S is the ΔF=2 box function and C a numerical const
and in the bag factor $\hat{B}_{B_s} = 1.33 \pm 0.06$,
some systematic uncertainties cancel. Then

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

Buras et al 2010

- Very precise test of SM from hadronic observables at LHC!

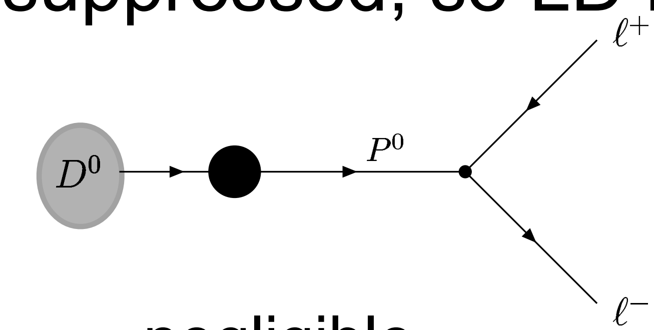
- same trick for B_d➔$\mu^+\mu^-$, $B_{s,d}$➔e^+e^- , $e^+\mu^-$, etc

- not for D➔$\mu^+\mu^-$ or K➔$\mu^+\mu^-$ as mixing is not calculable

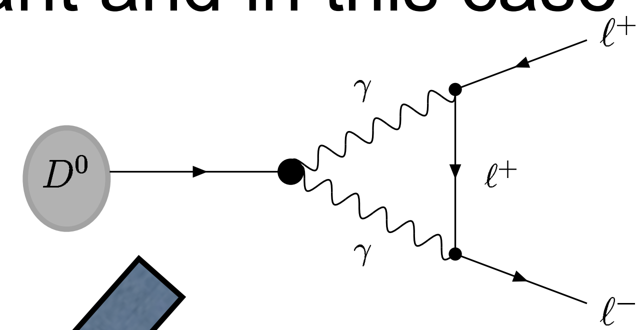
Long distance

see earlier talk by Stamou

- For $B_{s,d} \to \mu^+\mu^-$ long distance effects are CKM suppressed
- for $D \to \mu^+\mu^-$ (or $K \to \mu^+\mu^-$), short-distance itself GIM suppressed, so LD relevant and in this case dominant



negligible



Burdman et al 2001

Paul et al 2010

$$\mathcal{B}r^{(\gamma\gamma)}_{D^0\to\mu^+\mu^-} \simeq 2.7\times 10^{-5}\,\mathcal{B}r_{D^0\to\gamma\gamma} \sim 10^{-13}$$

- “background” effects such as undetected soft photons are not included in uncertainties quoted before and are traditionally left to experimentalists... see arXiv:0801.1833 sect. 3.4.

Experiment

- present upper bounds

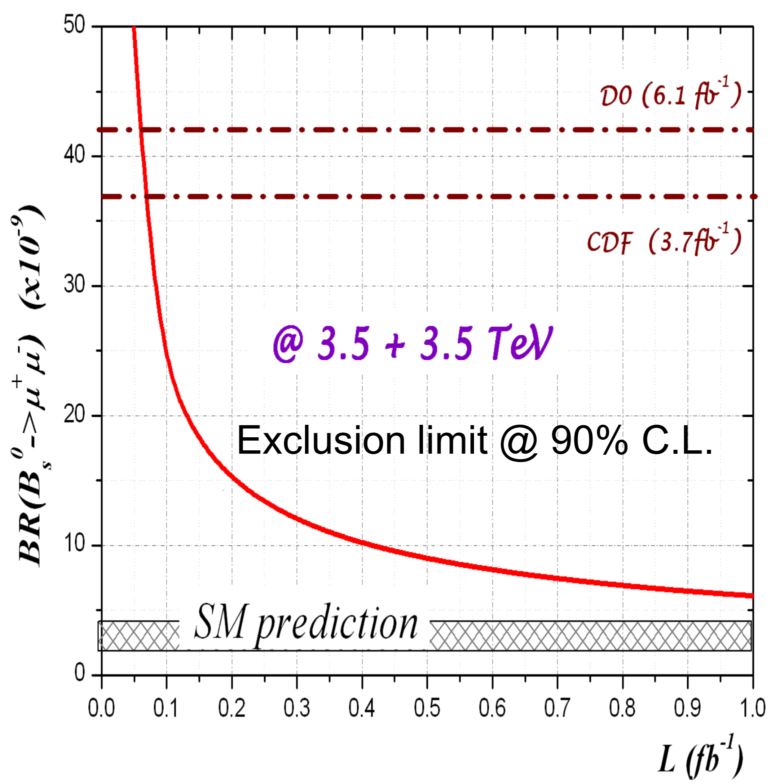
	CDF	D0	SM theory
$B_s \rightarrow \mu^+\mu^-$	$4.3\ 10^{-8}$ 95% CL	$5.2\ 10^{-8}$ 95% CL	$(3.2\pm0.2)\ 10^{-9}$
$B_d \rightarrow \mu^+\mu^-$	$7.6\ 10^{-9}$ 95% CL		$(1.0\pm0.1)\ 10^{-10}$
$D \rightarrow \mu^+\mu^-$	$3.0\ 10^{-7}$ 95% CL		$\sim 10^{-13}$

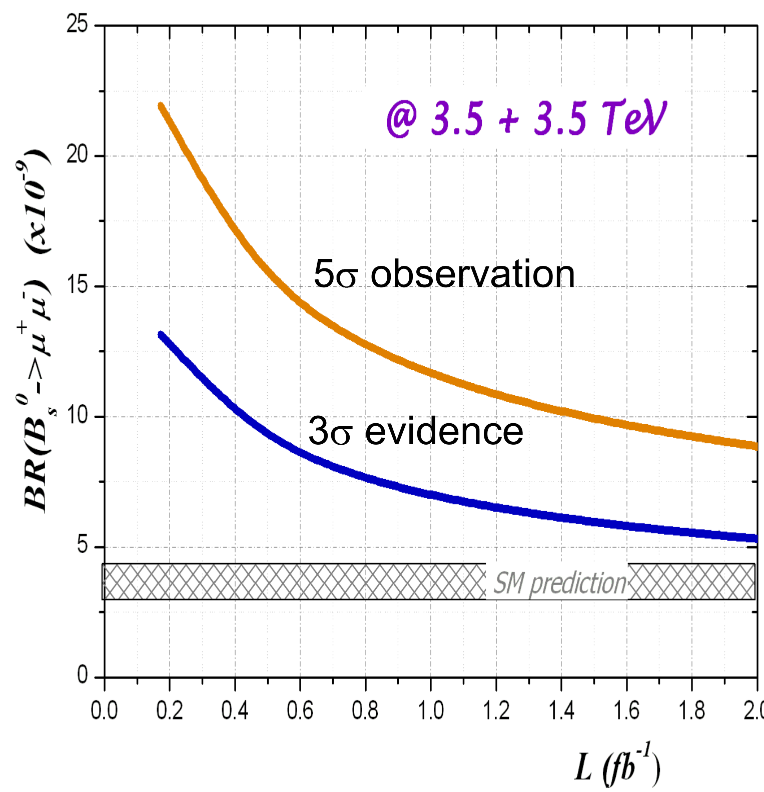
CDF public note 9892 D0 arXiv:1006.3469 D0 arXiv:1008.5077

Kreps arXiv:1008.0247 Buras et al arXiv:1007.1993

Burdman et al 2001

- early LHCb prospects



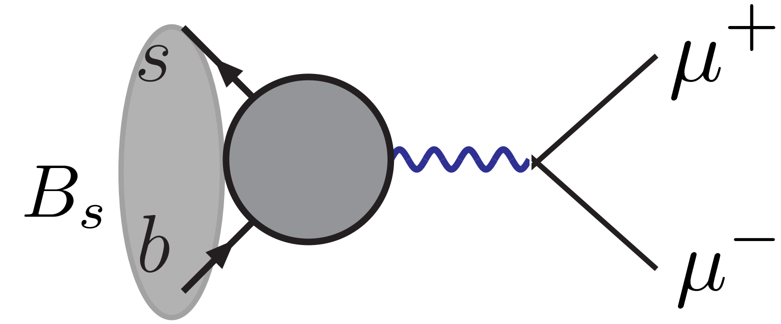


(Guy Wilkinson's plenary talk at this conference)

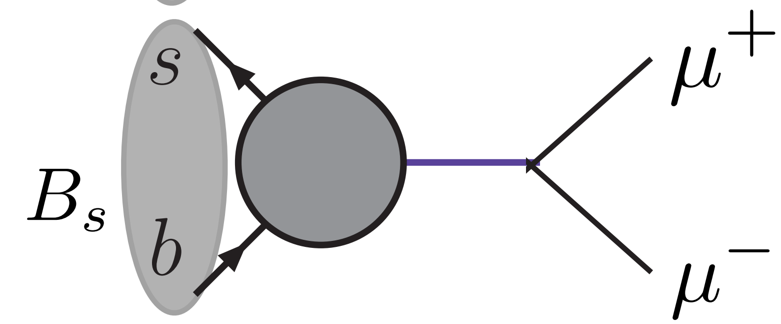
...I look forward to the following, experimental talks !

Beyond the SM

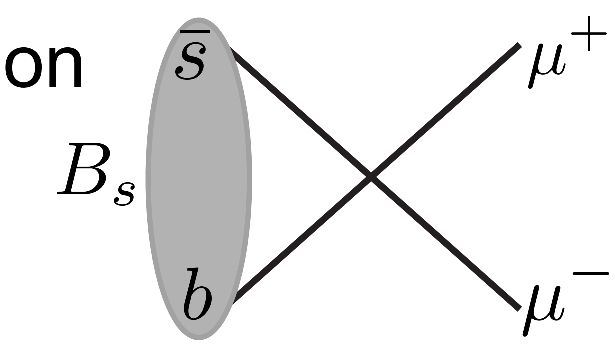
- New physics can modify the Z penguin ....



... induce a Higgs penguin ...



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



could also violate lepton flavour

- most general effective hamiltonian

$$\frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2 \theta_W} V_{tb}^* V_{tq} \left[C_S Q_S + C_P Q_P + C_A Q_A \right]$$

$$B\left(B_q \to \ell^+ \ell^-\right) = \frac{G_F^2\, \alpha^2}{64\, \pi^3 \sin^4 \theta_W} \left|V_{tb}^* V_{tq}\right|^2 \tau_{B_q} M_{B_q}^3 f_{B_q}^2 \sqrt{1 - \frac{4 m_\ell^2}{M_{B_q}^2}} \times \left[\left(1 - \frac{4 m_\ell^2}{M_{B_q}^2}\right) M_{B_q}^2\, C_S^2 + \left(M_{B_q} C_P - \frac{2 m_\ell}{M_{B_q}} C_A\right)^2 \right]$$

could violate lepton flavour !

MSSM - large tan β

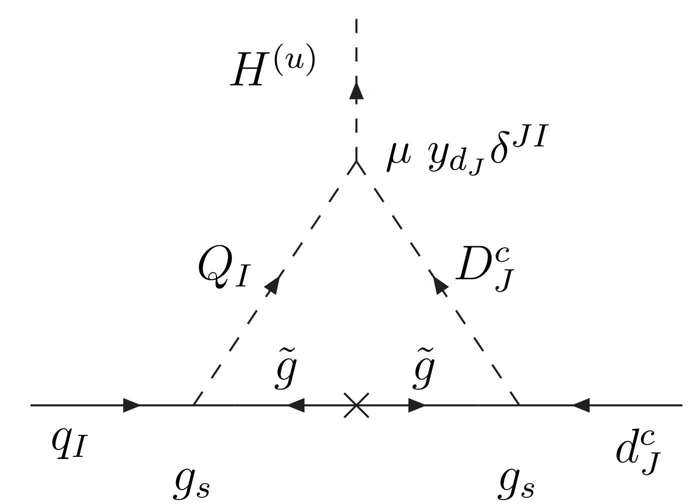
In SM, higgs couplings flavour diagonal
(proportional mass matrix)

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

MSSM - large tan β

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

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



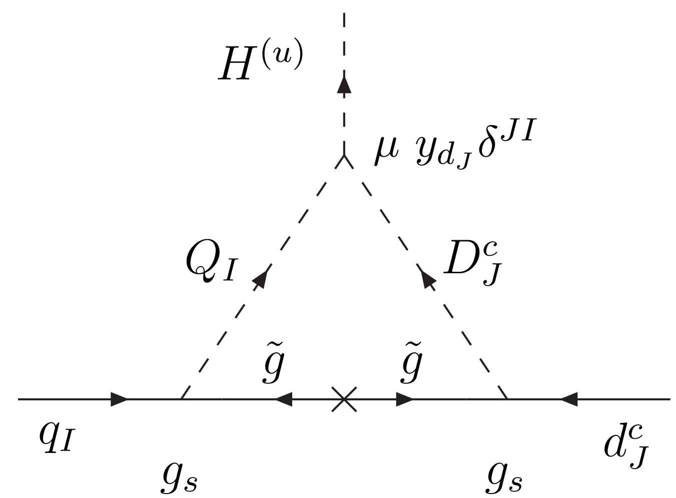
In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

MSSM - large tan β

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

parametrically
large if $v_u \gg v_d$

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



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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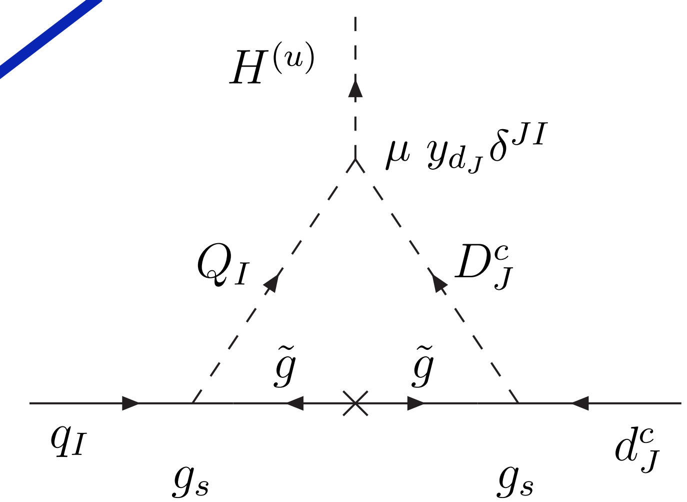
parametrically large if $v_u \gg v_d$

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



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

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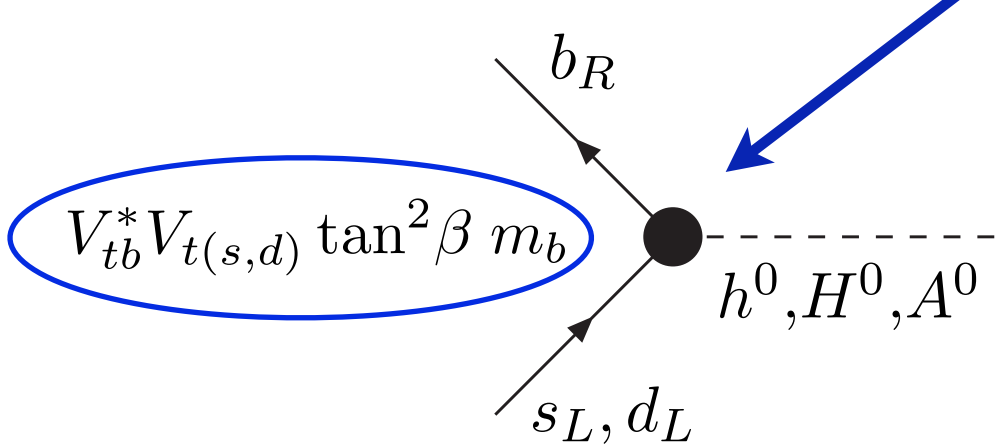
Yukawa becomes flavour-violating



MSSM - large tan β

In SM, higgs couplings flavour diagonal
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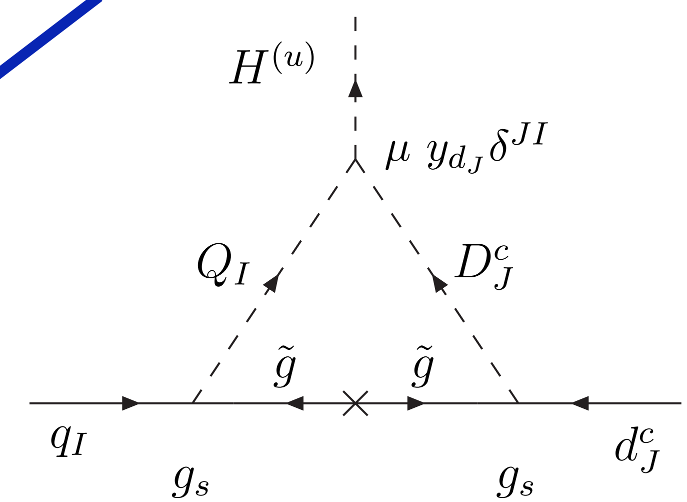


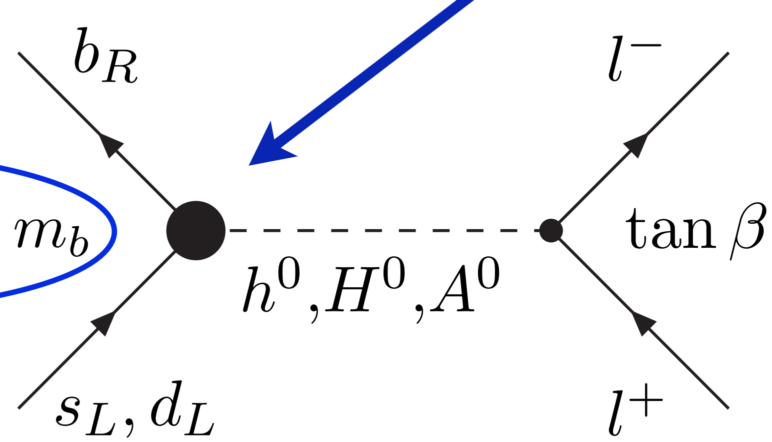
In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

tan $\beta = v_u/v_d$

Yukawa becomes flavour-violating

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

(for minimal flavour violation)



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

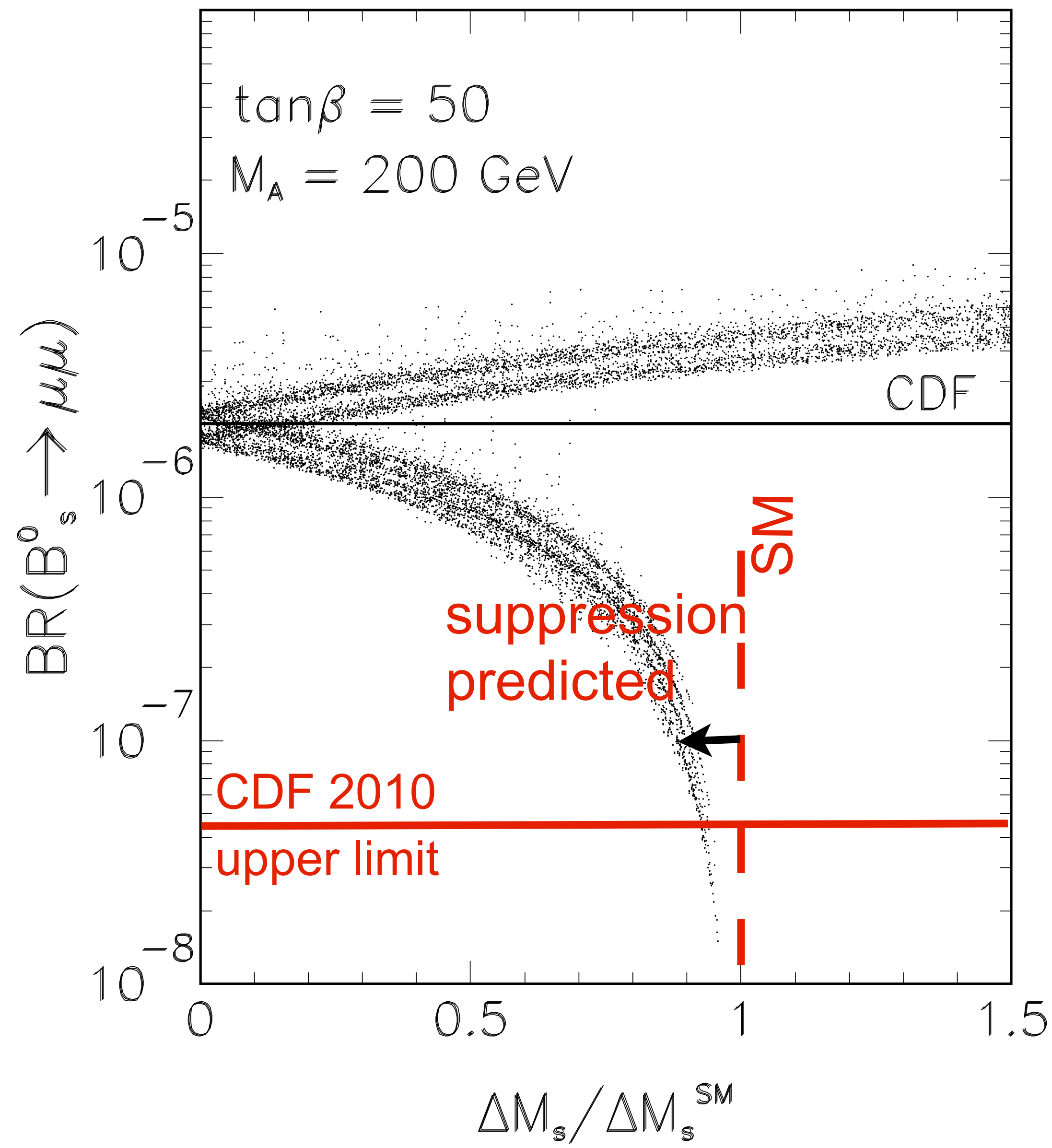
[Choudhury&Gaur 99; Hamzaoui, Pospelov, Toharia 99; Babu, Kolda 99; Isidori, Retico; Buras et al 02; Foster et al 04-06,...]

MSSM - large tan β - MFV

- huge rates possible, even for minimal flavour violation

- correlation (for MFV) [Buras et al 2002] with ΔM_{B_s} [Gorbahn, SJ, Nierste, Trine 2009]

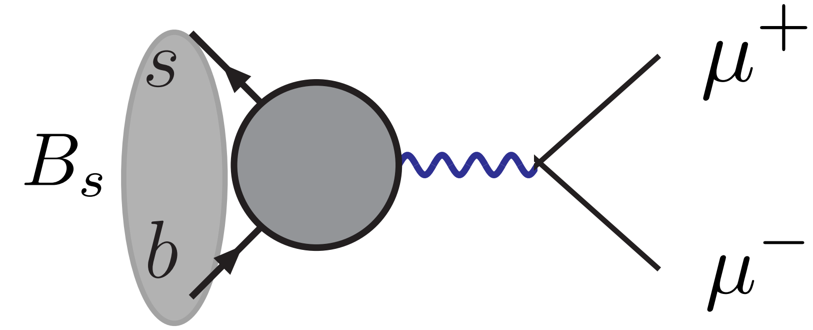
  bound on BR($B_s \rightarrow \mu^+\mu^-$) in these models implies closeness of ΔM_{B_s} to SM. In turn, ΔM_{B_s} at present does not constrain $B_s \rightarrow \mu^+\mu^-$



- beyond MFV, no correlations !
  not necessarily suppression of $B_d \rightarrow \mu^+\mu^-$ with respect to $B_s \rightarrow \mu^+\mu$

MSSM - small tan β

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

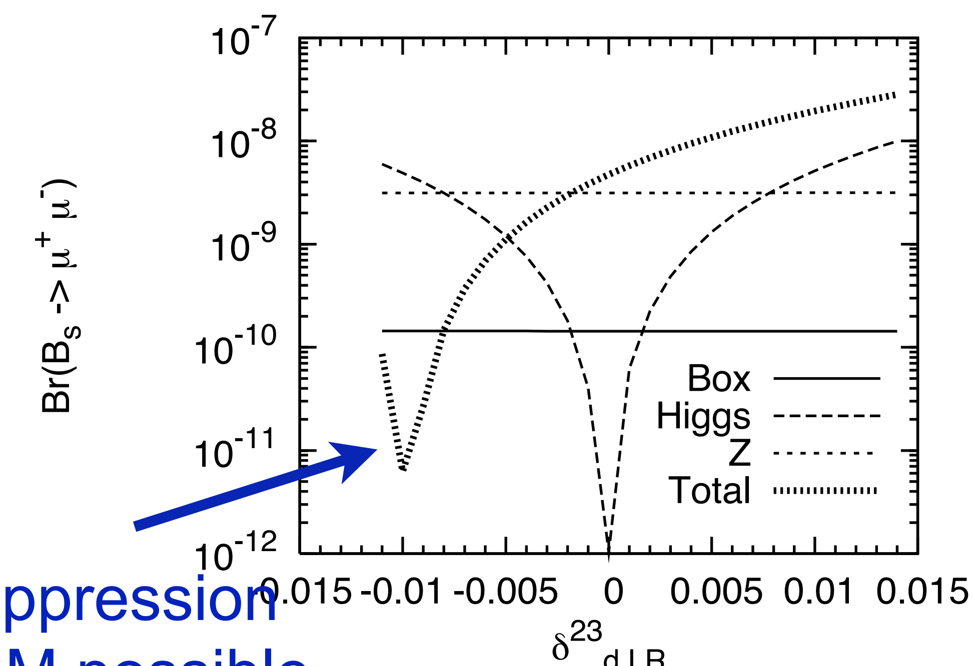


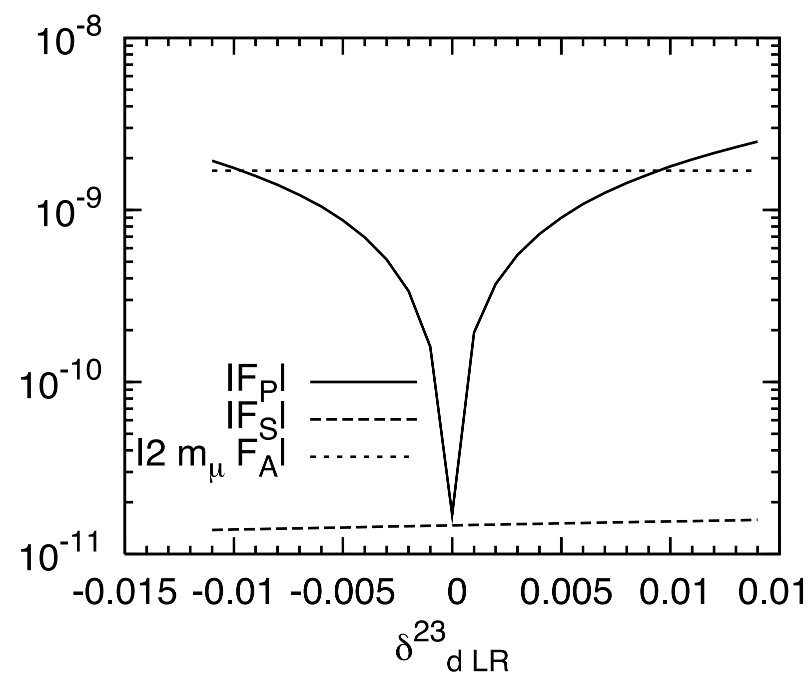
complete 1-loop calculation in general MSSM

[Dedes, Rosiek, Tanedo 2008]

implemented in public computer program “SUSY_FLAVOR”

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



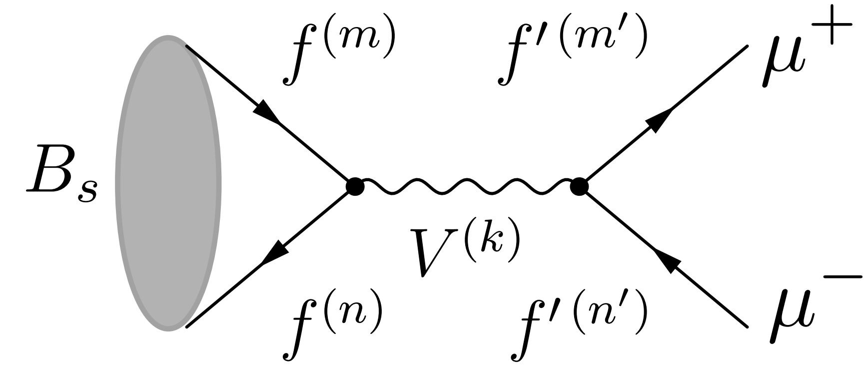


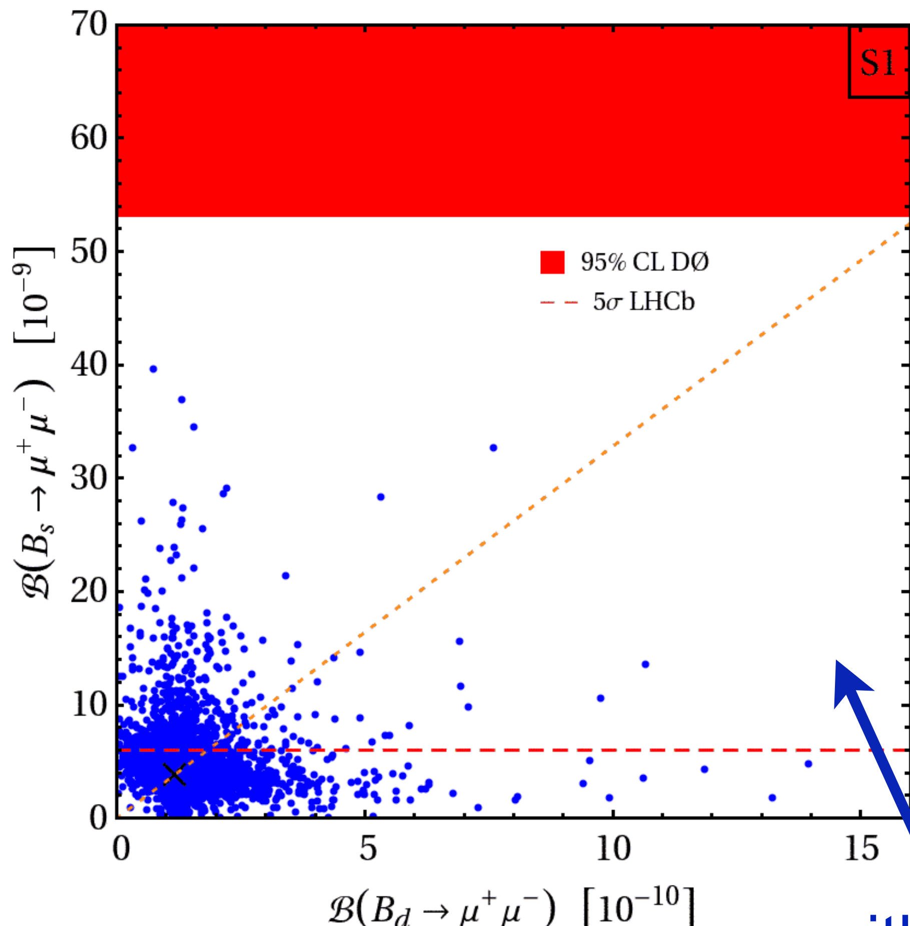
even suppression below SM possible

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

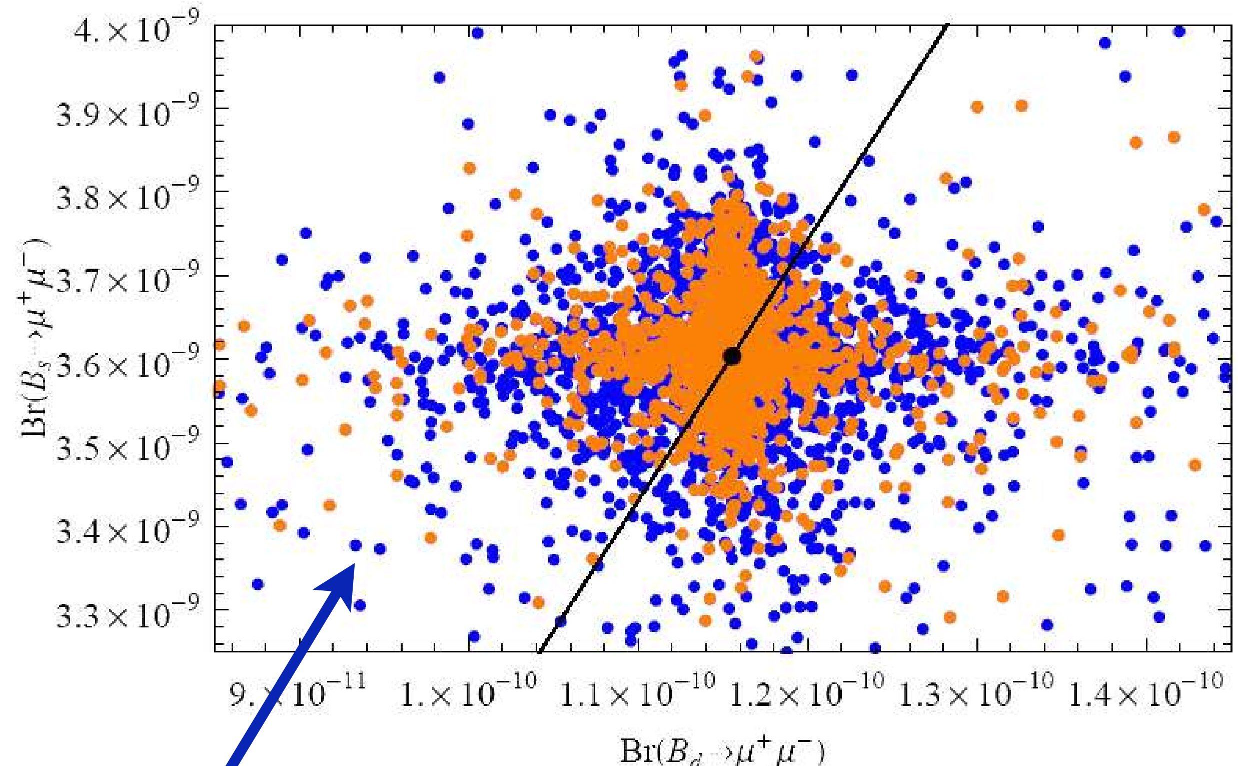
Randall-Sundrum

- 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

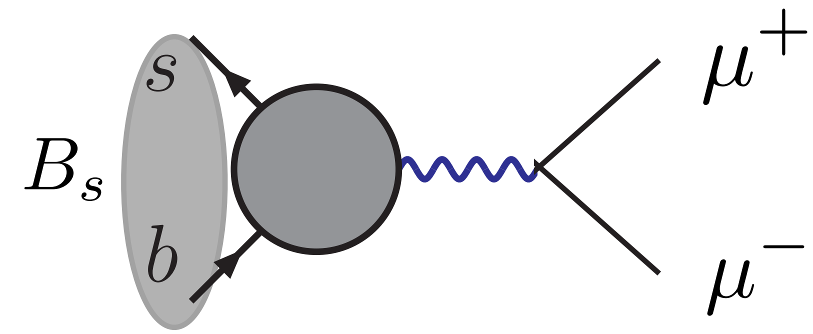


Blanke et al, arXiv:0812.3803v3

without / with custodial protection
higgs on IR brane

Little(st) Higgs (with T parity)

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

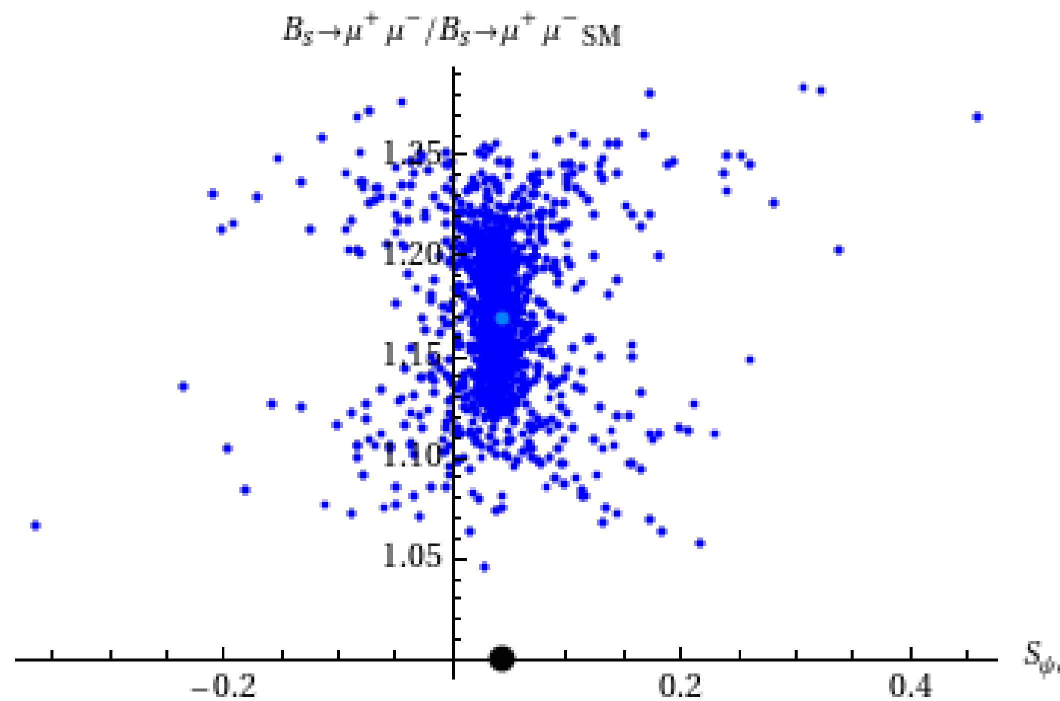


- enter at 1 loop through Z penguin, finite calculable contribution

[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



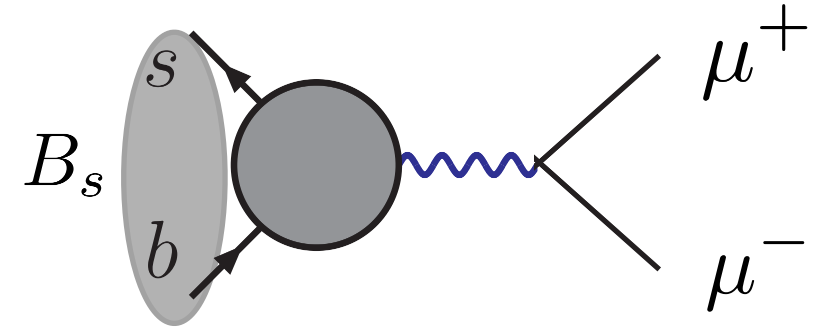
[Blanke et al 0906.5454]

- no observable effects in $D \to \mu^+\mu^-$

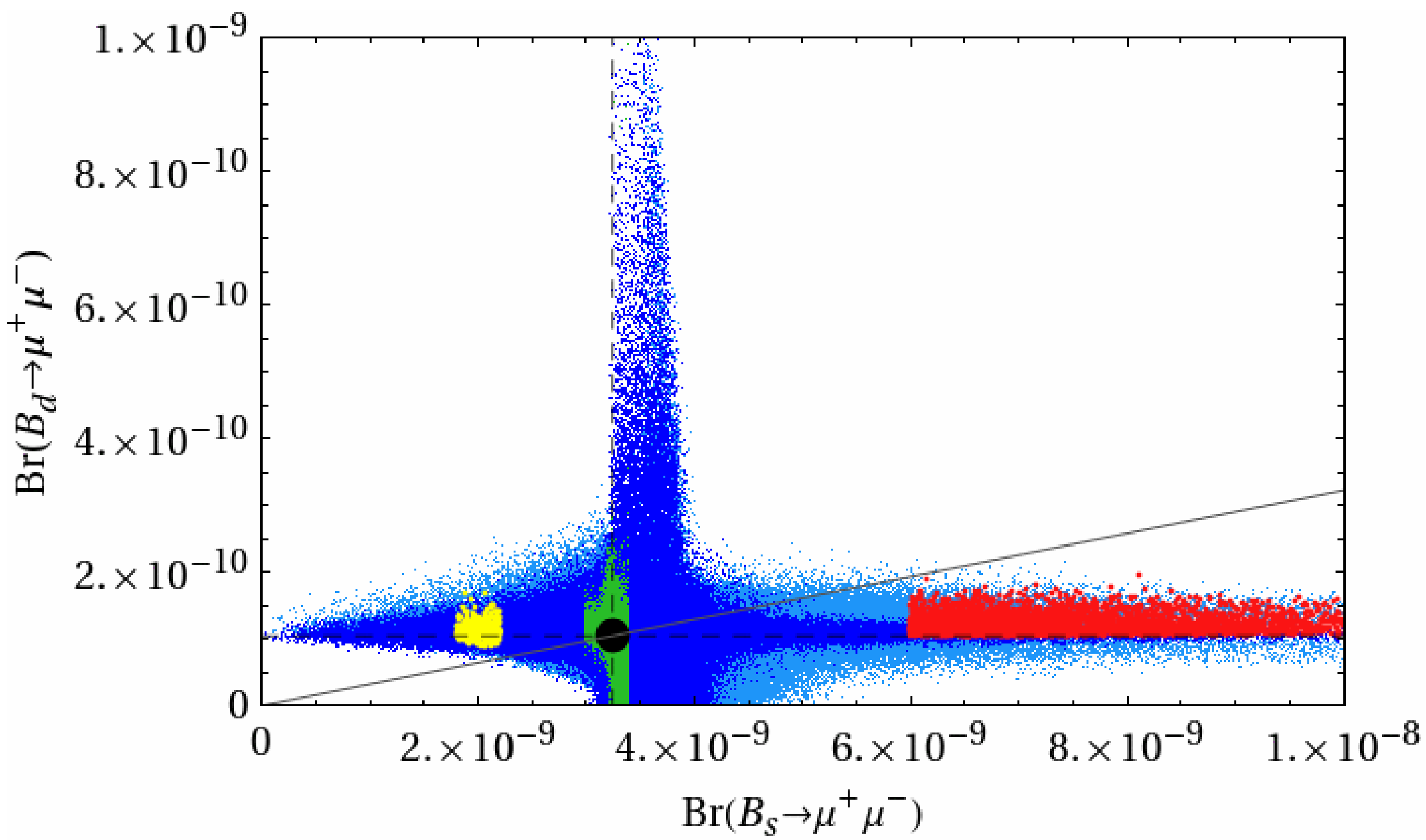
[Paul et al 1008.3141]

Fourth generation

- (in simplest form:)
  one extra family of fermions
  with SM quantum numbers
  same diagrams as in SM
  extra masses and “CKM” elements provide rich non-minimal source of flavour violation



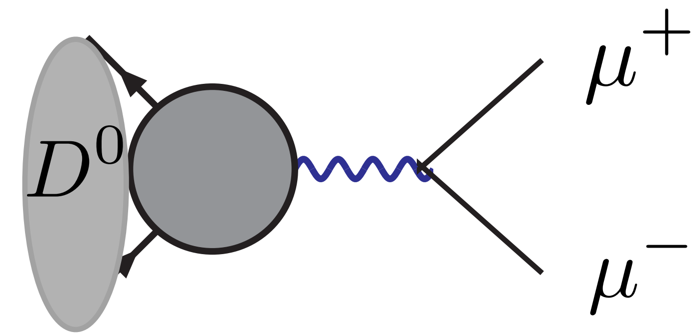
[eg Hou and Ma, 1004.2186]



[Buras et al arXiv:1004.4565]

$D \to \mu^+\mu^-$

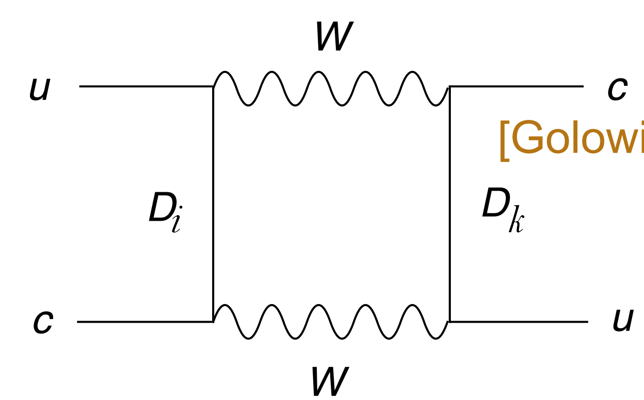
- Generically, this receives contributions from a Z penguin (negligible in SM due to GIM) which might not be small; Z' etc would also contribute



- Generic discussion and correlation with D mixing in BR($D \to \mu^+\mu^-$) of up to 10^{-9} in some scenarios [Golowich et al 0903.2830]

- However, analysis in LHT model shows unobservably small effects, reason are constraints in B and K physics (for any values of NP masses and mixings) [Paul et al 1008.3141]
  The authors ask whether this might be generically so.

  (why) is e.g. this diagram (not) accompanied by a contribution to neutral Kaon mixing ?



[Golowich et al 0903.2830]

- I think depending on experimental prospects this deserves further study

Conclusions

- Rare leptonic decays are theoretically clean
- They can be new physics dominated
- and LHCb can measure BR($B_s \rightarrow \mu^+\mu^-$) down to the SM value (and below)
- 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
- I encourage experimenters to look beyond $B_s \rightarrow \mu^+\mu^-$ where feasible (μ^+e^-, e^+e^- ? B_d !). (If encouragement is needed.)
- if $D^0 \rightarrow \mu^+\mu^-$ were observed in an experiment, it would be an unambiguous new physics discovery and/or measurement