Left-right models and flavor patterns

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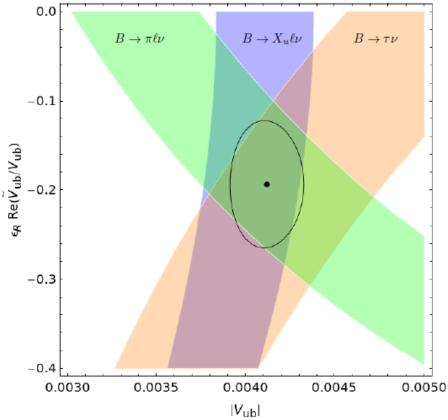
Different values for CKM element $|V_{ub}|$ from different channels:



$$\begin{aligned} |V_{ub}|_{B\to\pi\ell\nu} &= 3.38(36)\cdot 10^{-3} \\ |V_{ub}|_{B\to X_u\ell\nu} &= 4.27(38)\cdot 10^{-3} \\ |V_{ub}|_{B^+\to\tau\nu} &= 4.70(56)\cdot 10^{-3} \end{aligned}$$

right-handed charged currents can resolve tension

Crivellin (2009)

Buras, Gemmler, Isidori (2010)

➢ **Does this solution hold in a concrete left-right model?**

Basics of a general left-rght model

- based on the **gauge group** (gauge couplings g_s, g_L, g_R, g')

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- new heavy gauge bosons W', Z' and new heavy charged and neutral Higgs particles
- quark flavor mixing matrices $V^L = V_{\text{CKM}}$ and V^R describing left- and right-handed charged current interactions

Already

- known for almost 40 years
- studied extensively by many authors starting from scenarios with exact LR symmetry up to more general frameworks

PATI, SALAM, MOHAPATRA, SENJANOVIC... (1974-2011)

➢ So what is new here?

In a nutshell

MB, Buras, Gemmler, Heidsieck, JHEP 03 (2012) 024

Simultaneous analysis of the most important electroweak precision and flavor constraints on a **general left-right model**

EWP constraints
+
collider bounds

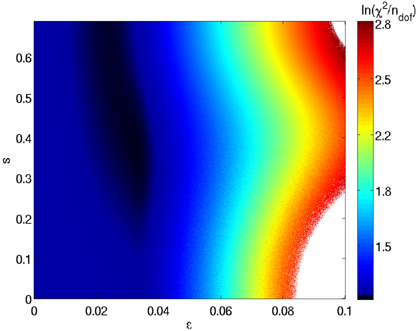
tree level decays
meson anti-meson mixing
$B \to X_{s,d}\gamma$

- ➢ determine **allowed parameter space**
- ➢ **identify patterns** in flavor violating effects
- ➢ address **tensions** in flavor data ($|V_{ub}|$ etc.)
- ➢ derive **bound on heavy Higgs masses**

Electroweak precision and collider constraints

full fit of ~ 40 EWP observables

HSIEH, SCHMITZ, YU, YUAN (2010)



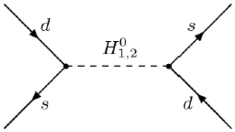
Our strategy:

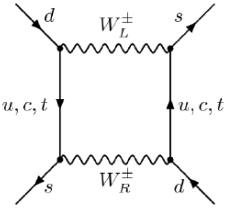
- apply the results of Hsieh et al. & perform χ^2 fit for the most constraining observables
- identify a set of EW benchmark parameters in the best fit region

➢ $M_{W'} = 2.6$ TeV in agreement with present collider bounds
$M_H \simeq 16$ TeV on the edge of perturbativity

New LR contributions to meson-antimeson mixing

- main impact from LR operators (QCD enhancement!)



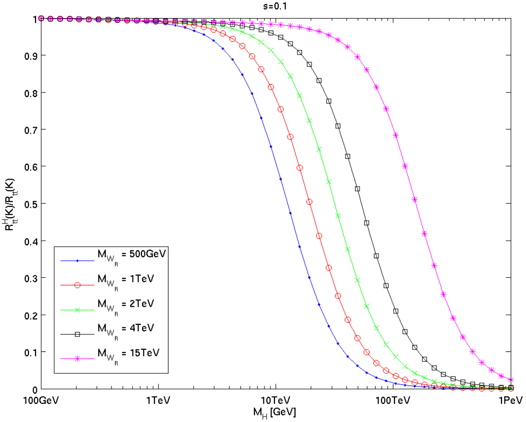


- dominant NP contribution to mixing amplitude

$$(M_{12}^q)_{\mathrm{LR}} \sim \sum_{i,j=u,c,t} \left[\lambda_i^{\mathrm{LR}}(q)\lambda_j^{\mathrm{RL}}(q)\right]^* R_{ij}(q) \qquad (q = K, d, s)$$

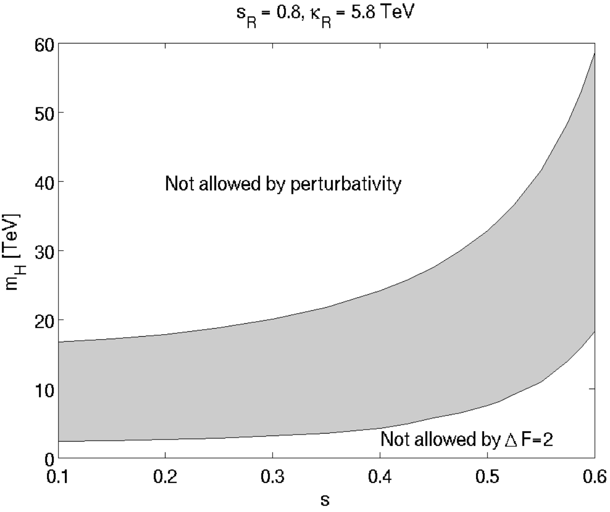
$\lambda_i^{\mathrm{LR,RL}}(q)$	relevant combination of V^L and V^R elements
$R_{ij}(q)$	loop integral / tree level propagator + QCD effects

Relative size of neutral Higgs contribution



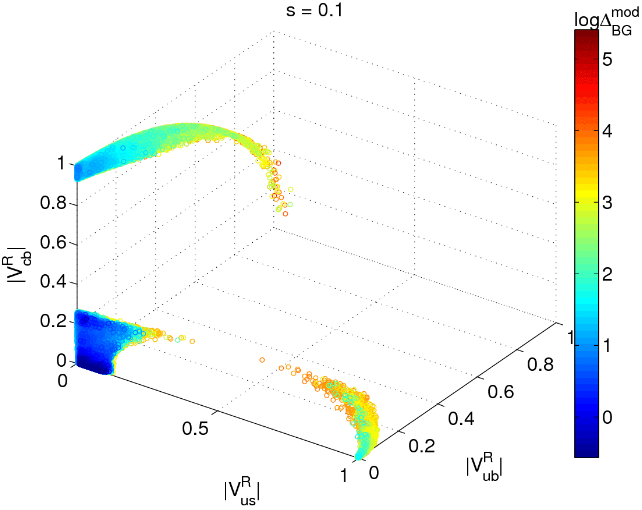
- Higgs contribution dominant even for $M_H \sim 20\,\text{TeV}$
- increases further with increasing s (Higgs sector parameter)

Bound on the heavy Higgs mass



Allowed ranges for V^R

V^R parameter space consistent with tree level and $\Delta F = 2$ constraints:



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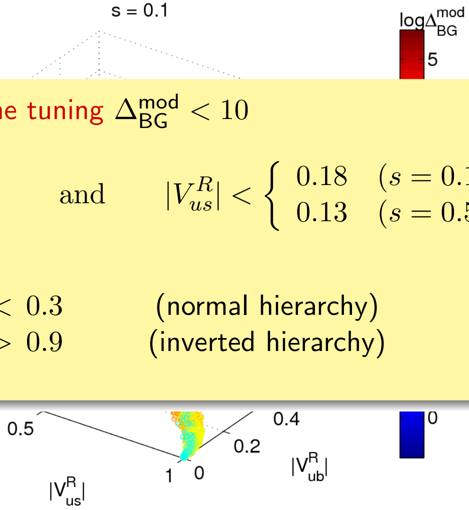


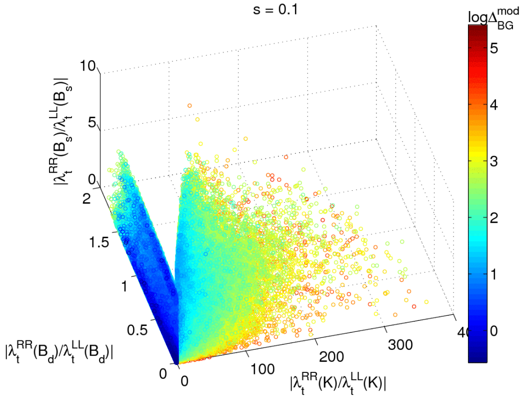
for points with small fine tuning $\Delta_{BG}^{\text{mod}} < 10$

$$|V_{td}^R| < 1.2 \cdot 10^{-2} \qquad \text{and} \qquad |V_{us}^R| < \begin{cases} 0.18 & (s = 0.1) \\ 0.13 & (s = 0.5) \end{cases}$$

$$\begin{aligned} |V_{cb}^R| &< 0.3 \qquad \text{(normal hierarchy)} \\ |V_{cb}^R| &> 0.9 \qquad \text{(inverted hierarchy)} \end{aligned}$$

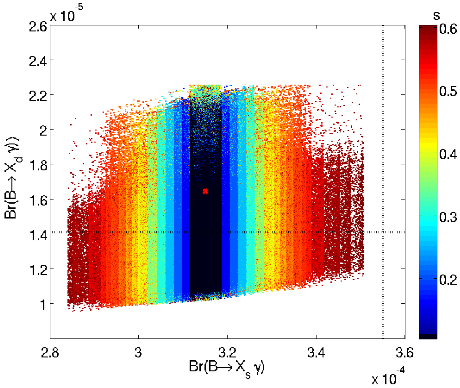
Relative size of effects in K, B_d and B_s systems

$\lambda_t^{\rm RR}(q)/\lambda_t^{\rm LL}(q)$: relative size of LR effects in $q = K, B_d, B_s$ decays



largest effect in K physics, but associated to large fine tuning in ε_K

The $B \to X_{s,d}\gamma$ decays

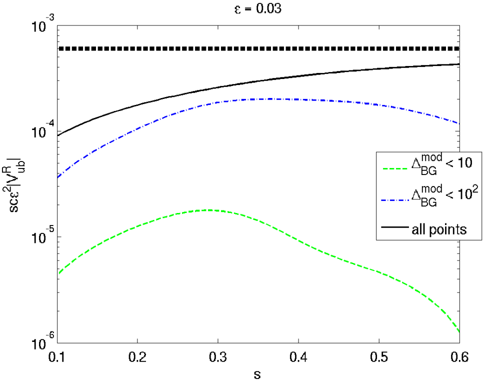


$B \to X_{s,d}\gamma$ constraints relevant for $s > 0.5$ due to enhancement of charged Higgs contribution

Revisiting the $|V_{ub}|$ problem

Recall: inconsistency in $|V_{ub}|$ determinations

➢ solution requires RH contribution $sc\epsilon^2|V_{ub}^R| \sim 6 \cdot 10^{-4}$



$\Delta F = 2$ constraints preclude solution of $|V_{ub}|$ problem
in particular if low fine tuning is required

Conclusions

LR model confronting flavor data:

- strong constraints from meson antimeson mixing, in particular ε_K
  - dominated by tree level Higgs exchange
  - very hierarchical structure for V^R required
- LR model can be made consistent with electroweak precision and flavor constraints for low W' masses well in the reach of the LHC
- $|V_{ub}|$ problem cannot be solved

Backup slides

More details on the LR model

- **fermion representations**

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim \left(3, 2, 1, \frac{1}{3}\right) \qquad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim \left(3, 1, 2, \frac{1}{3}\right)$$

$$L_L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix} \sim (1, 2, 1, -1) \qquad L_R = \begin{pmatrix} \nu_R \\ l_R \end{pmatrix} \sim (1, 1, 2, -1)$$

- **extended Higgs sector**

$$\phi \sim (1, 2, 2, 0) \qquad \Delta_R \sim (1, 1, 3, 2) \qquad \Delta_L \sim (1, 3, 1, 2)$$

- **electroweak symmetry breaking in two steps**

1. $\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ \kappa_R & 0 \end{pmatrix}$ breaks $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$
2. $\langle \phi \rangle = \begin{pmatrix} cv & 0 \\ 0 & sv \end{pmatrix}$ breaks $SU(2)_L \times U(1)_Y \to U(1)_Q$

here $\epsilon = v/\kappa_R \ll 1$

New flavor violating interactions in the LR model

- quark masses generated by **Yukawa couplings**

$$\mathcal{L}_{\mathsf{Yuk}} = -y_{ij}\overline{Q}_{Li}\phi Q_{Rj} - \tilde{y}_{ij}\overline{Q}_{Li}\tilde{\phi}Q_{Rj} + \text{h.c.}$$

➢ flavor changing heavy neutral Higgs couplings
➢ charged Higgs contributes to FCNCs at the loop level

- **right-handed charged currents** mediated by $W^\pm$ and $W'^\pm$

$$\bar{u}_R^i d_R^j W^+ \propto sc\epsilon^2 V_{ij}^R \qquad \bar{u}_R^i d_R^j W'^+ \propto V_{ij}^R$$

- new **right-handed mixing matrix V^R** in addition to CKM matrix
  ➢ three new mixing angles and six complex phases

On explicit parity (or charge conjugation symmetry)

- most studies assume explicit parity or charge conjugation symmetry at the TeV scale

> ➢ $g_L = g_R$
>
> ➢ $|V_{ij}^R| = |V_{ij}^L|$

- very predictive framework for flavor phenomenology

> ➢ $M_{W'} > 4\,$TeV from $K - \bar{K}$ mixing
>
> ➢ $|V_{ub}|$ problem cannot be solved

➢ **We do not assume a discrete LR symmetry!**

- lower mass scales possible
- much richer flavor phenomenology (arbitrary V^R)

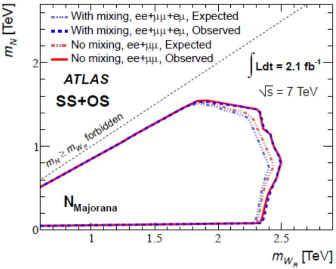
Collider constraints on the LR model

- W' searches in lepton+MET

  $M_{W'} > 2.5$ TeV — only applies if ν_R escapes detection

- combined W' and heavy ν_R search
  - $W' \to \ell\nu_R \to \ell\ell jj$
  - 2D exclusion contour

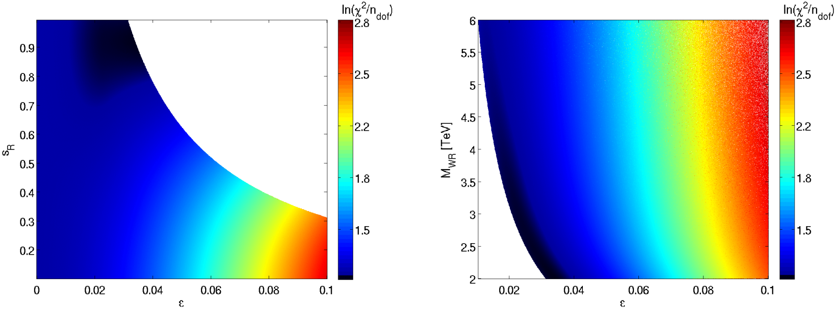
  $M_{W'} > 2.2$ TeV for wide range of M_{ν_R}



- for $M_{\nu_R} > M_{W'}$, W' decays dominantly to quarks

  ➢ dijet resonance search: $M_{W'} > 1.5$ TeV

More details on the EWP fit



benchmark parameters for our flavor analysis:

$$\epsilon = 0.03 \qquad g_R/g_L = 0.7 \qquad 0.1 < s < 0.6$$
$$M_H = 16\,\text{TeV}/\sqrt{1-2s^2}$$

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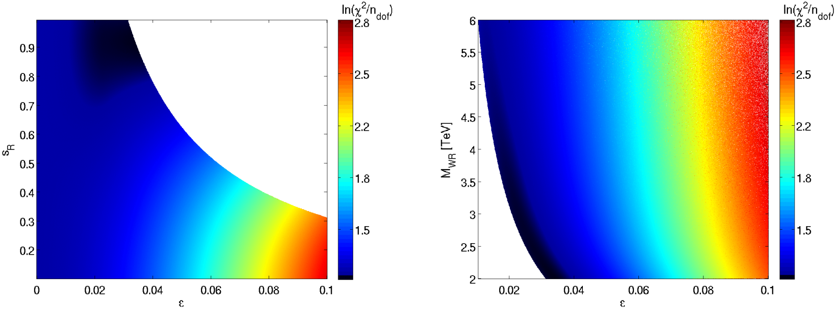

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Tree level constraints on flavor mixing

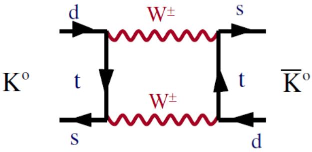
different transition measure different combinations of V_{ij}^L and V_{ij}^R

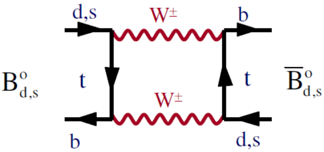
$$|V_{ij}|_V \equiv |V_{ij}^L + sc\epsilon^2 V_{ij}^R| \qquad |V_{ij}|_A \equiv |V_{ij}^L - sc\epsilon^2 V_{ij}^R|$$

transition	considered decay	$\lvert V_{ij}^L \rvert$	$\lvert V_{ij} \rvert_V$	$\lvert V_{ij} \rvert_A$
$u \to d$	superallowed $0^+ \to 0^+$	-	0.97425(22)	-
	$\pi^+ \to \mu^+ \nu$	-	-	0.981(13)
$u \to s$	$K \to \pi \ell \nu$	-	0.2257(12)	-
	$K \to \mu \nu$	-	-	0.2268(32)
$c \to d$	$D \to K \ell \nu$ and $D \to \pi \ell \nu$	-	0.229(25)	-
	νN charm production	-	-	0.230(11)
$c \to s$	semileptonic D decays	-	0.98(10)	-
	$D_s \to \tau^+ \nu$	-	-	0.978(31)
$b \to u$	$B \to X_u \ell \nu$	$4.27(38) \cdot 10^{-3}$	-	-
	$B \to \pi \ell \nu$	-	$3.38(36) \cdot 10^{-3}$	-
	$B \to \tau \nu$	-	-	$4.70(56) \cdot 10^{-3}$
$b \to c$	$B \to X_c \ell \nu_\ell$	$41.54(73) \cdot 10^{-3}$	-	-
	$B \to D \ell \nu$	-	$39.4(17) \cdot 10^{-3}$	-
	$B \to D^* \ell \nu$	-	-	$39.70(92) \cdot 10^{-3}$
$t \to b$	$Br(t \to bW)/Br(t \to qW)$	0.95(5)	-	-

Particle antiparticle mixing — the main actors

- mediated by box diagrams in the Standard Model



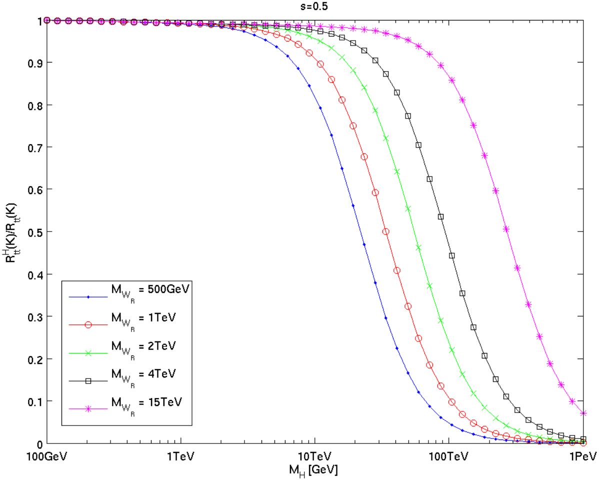


- characterized by mass differences ΔM_K, $\Delta M_{d,s}$ (CP conserving)
- CP violating observables

$K-\bar{K}$: ε_K (indirect CP violation in $K\to\pi\pi$ decays)
$B_d-\bar{B}_d$: time dependent CP asymmetry $S_{\psi K_S}$ in $B_d\to J/\psi K_S$
$B_s-\bar{B}_s$: time dependent CP asymmetry $S_{\psi\phi}$ in $B_s\to J/\psi\phi$

+ semileptonic asymmetries $A^{d,s}_{\text{SL}}$ (➢ dimuon charge asymmetry)

Contributions to $\Delta F = 2$ — $s = 0.5$



Fine tuning measure

- **Barbieri-Giudice measure of fine tuning**

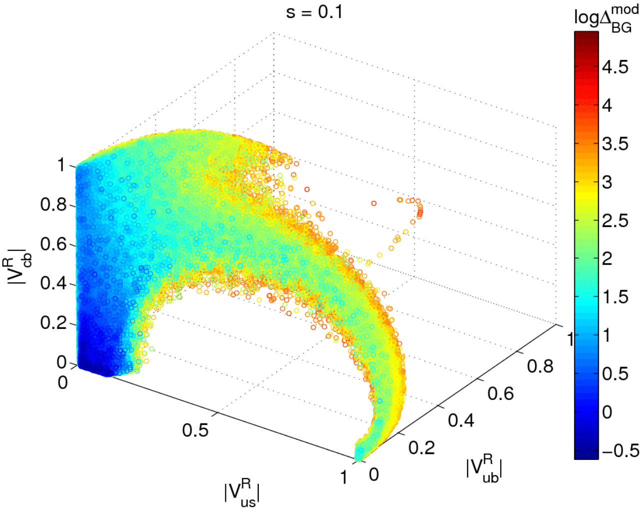
$$\Delta_{\mathsf{BG}}(O) = \max_i \left| \frac{p_i}{O} \frac{\partial O}{\partial p_i} \right|$$

measures sensitivity of observable O
to small variations in paramteres p_i

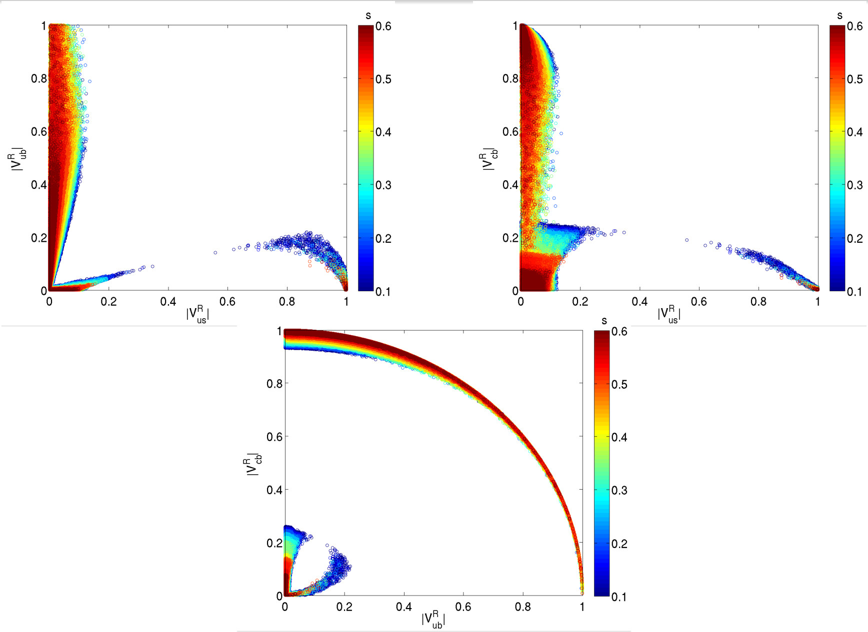
- **modified Barbieri-Giudice measure**

$$\Delta_{\mathsf{BG}}^{\mathsf{mod}} = \sum_{j=1}^{N_{\mathsf{Obs}}} \Delta_{\mathsf{BG}}(O_j)$$

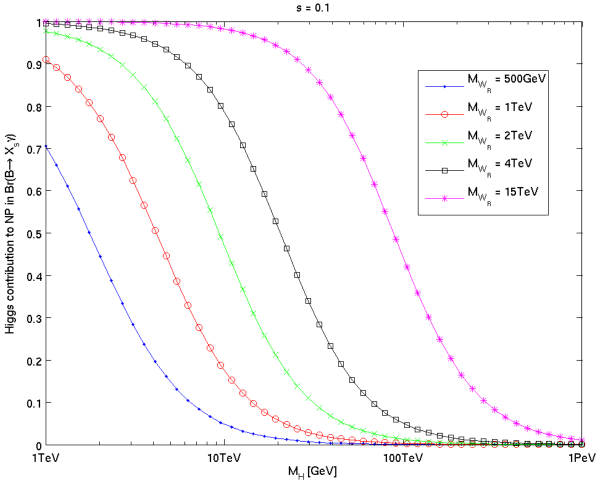
Omitting Higgs contributions



Allowed ranges for V^R — s dependence



Charged Higgs contribution to $B \to X_s\gamma$



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