Title: Flavor Constraints on Left-right Models

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Abstract: Models with right-handed currents have recently attracted attention because of their potential ability to solve the discrepancy in various determinations of |V_{ub}|. We consider a minimal setup with an SU(2)_L x SU(2)_R x U(1)_{B-L} gauge symmetry, for which we perform a simultaneous analysis of the most important constraints from electroweak precision observables, particle anti-particle mixing and the B -> X_{s,d} gamma decays. The main goals of our analysis are the determination of allowed parameter space for the new right-handed mixing matrix and the possible solution of various anomalies in the current flavor data.

Flavor constraints on left-right models

Monika Blanke

Cornell University

Particle Physics Seminar
Perimeter Institute
March 27, 2012

Why left-right models?

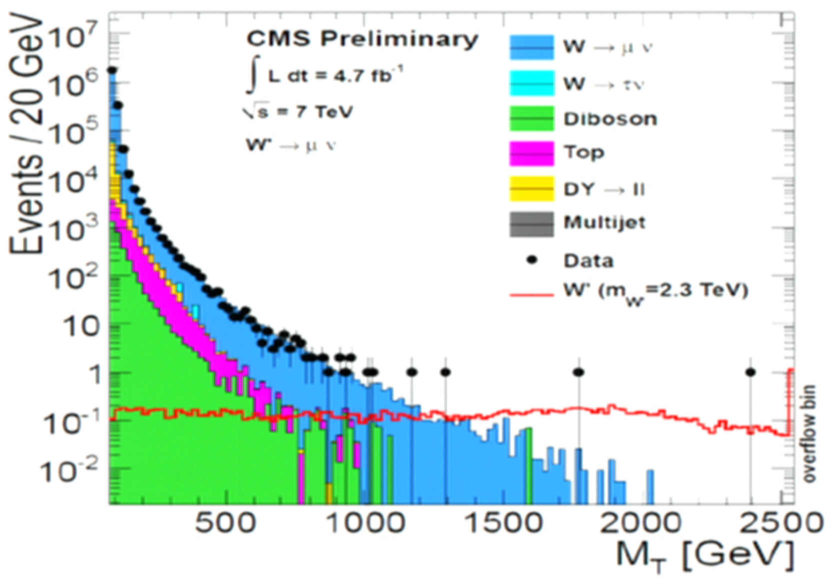
Weak interactions in the SM are left-handed

Why?!

Why left-right models?

- LR models allow to restore parity at high scale
- anomaly free with minimal fermion content
- embedding in $SO(10)$ possible
- CMS W' search: outlier event in $\mu + \not{E}_T$ with $M_T = 2.4$ TeV

EXO-11-024



The $|V_{ub}|$ problem

Crivellin (2009), Buras, Gemmler, Isidori (2010) (EFT approach)

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

decay	$\boldsymbol{|V_{ub}|}$ **value**
$B \to \pi \ell \nu$	$3.38(36) \cdot 10^{-3}$
$B \to X_u \ell \nu$	$4.27(38) \cdot 10^{-3}$
$B \to \tau \nu$	$4.70(56) \cdot 10^{-3}$

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

describes charged current interactions
($W^{\pm}$ boson couplings to left-handed quarks)

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decay	$\boldsymbol{|V_{ub}|}$ **value**	**with RH currents**
$B \to \pi\ell\nu$	$3.38(36) \cdot 10^{-3}$	$|L+R|^2$
$B \to X_u\ell\nu$	$4.27(38) \cdot 10^{-3}$	$|L|^2 + |R|^2$
$B \to \tau\nu$	$4.70(56) \cdot 10^{-3}$	$|L-R|^2$

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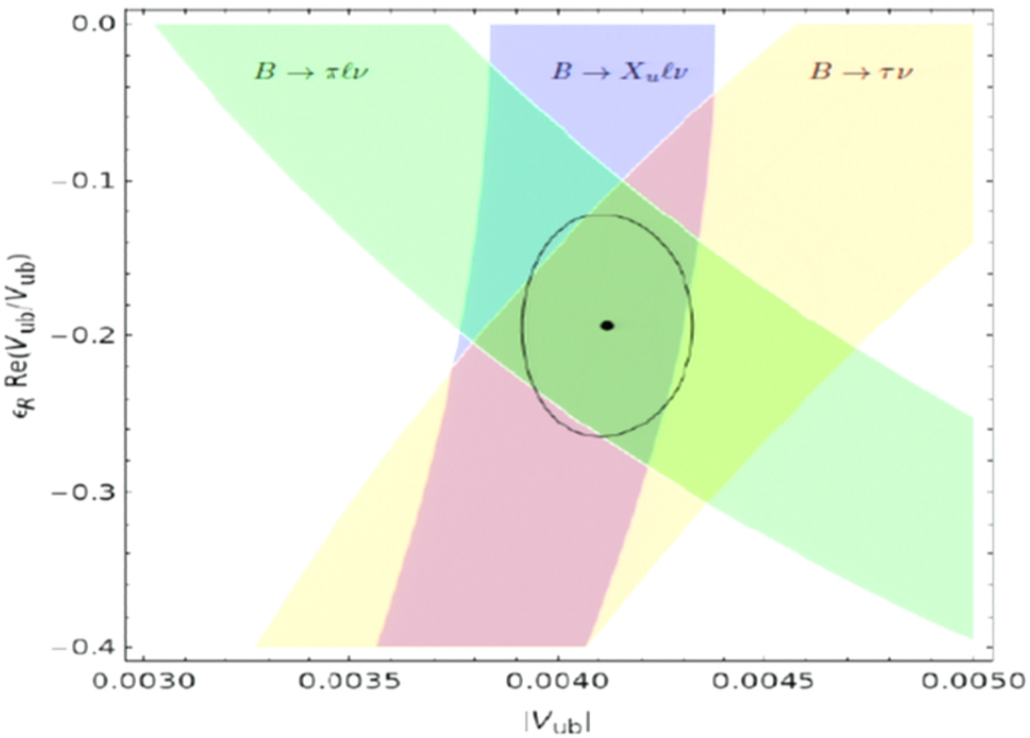

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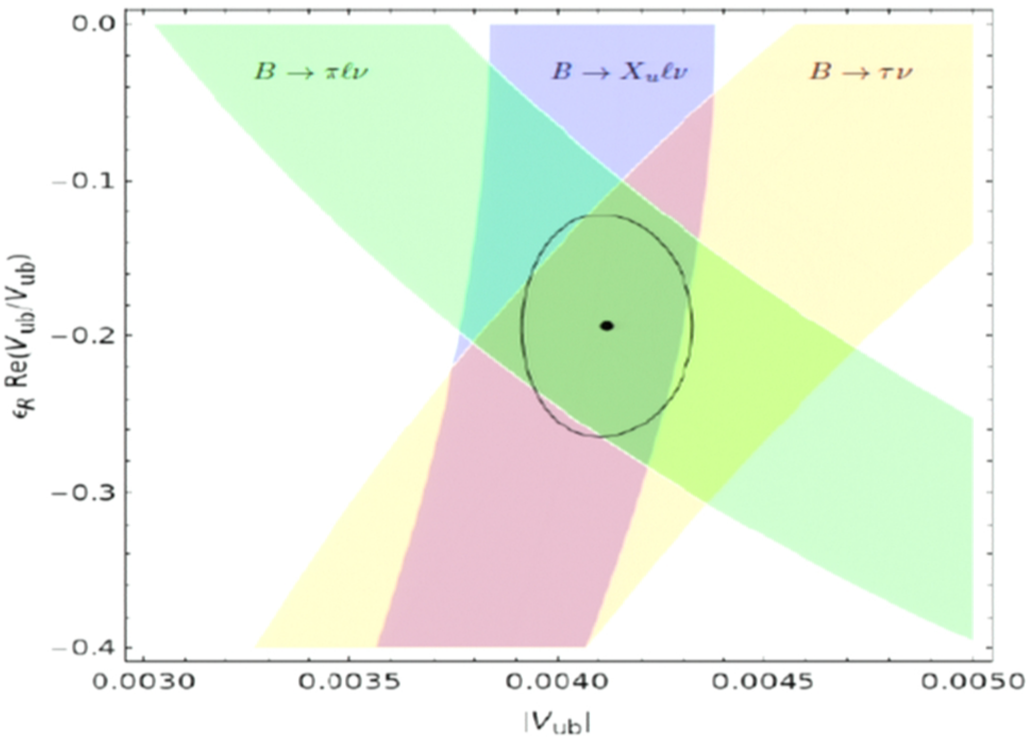

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RH charged currents affect decays in a different manner
➢ **elegant solution to $|V_{ub}|$ problem**

Does this solution hold in a concrete LR model?

Today on the menu

1. Amuse-gueule
2. Hors d'œuvre
   - The LR model
3. Potage
   - Collider & electroweak precision constraints
4. Plat principal
   - Flavor constraints on the LR model
   - Patterns in the LR flavor sector
5. Dessert

The chef and his staff

MB, A.J.Buras, K.Gemmler, T.Heidsieck, JHEP 03 (2012) 024 [arXiv:1111.5014]

Basic ingredients of the LR model

Pati, Salam, Mohapatra, Senjanovic, ...

- **extended gauge group** (gauge couplings g_s, g_L, g_R, g')

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

- **fermion representations**

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

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

- electric charge given by

$$Q = T_L^3 + \underbrace{T_R^3 + \frac{B-L}{2}}_{\text{'natural' origin of SM hypercharges}}$$

Higgs sector & symmetry breaking

- 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 heavy gauge bosons $W'^{\pm}$ and Z' with TeV-scale masses
  ➢ note: $M_{Z'} \geq 2M_{W'}$

- new heavy charged and neutral Higgs particles in addition to light SM-like Higgs

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New flavor violating interactions in the LR model

- quark masses generated by **Yukawa couplings**

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

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

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

$$\bar{u}^i_R d^j_R W^+ \propto sc\epsilon^2 V^R_{ij} \qquad \bar{u}^i_R d^j_R W'^+ \propto V^R_{ij}$$

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

A note on 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

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- lower mass scales possible
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Potage

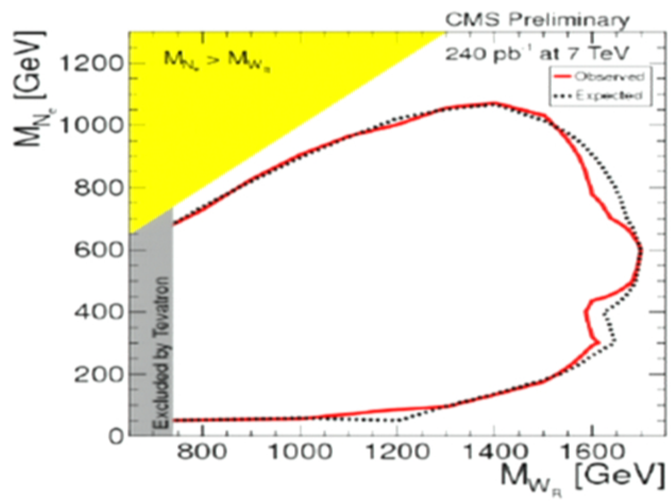
Collider constraints on the LR model

- W' searches in lepton+MET

  $M_{W'} > 2.5\,\text{TeV}$ — 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

  $M_{W'} > 1.6\,\text{TeV}$ for wide range of M_{ν_R}



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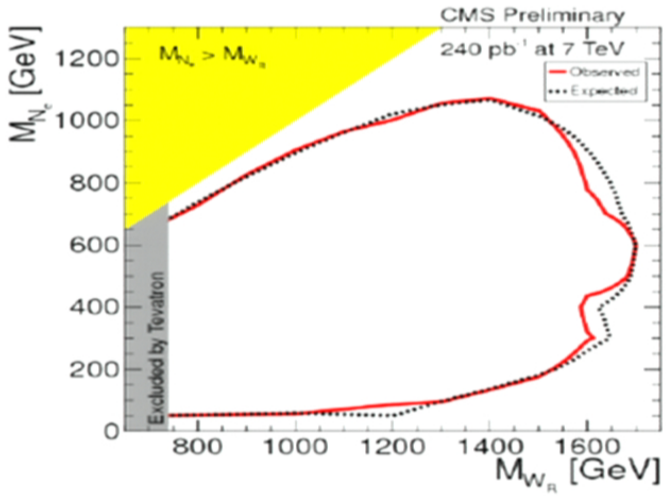

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In a nutshell

- bound on W' strongly dependent on ν_R mass
- all constraints based on simplifying assumptions, e. g. $g_L = g_R$
- all numbers lie in the ballpark $1.5 - 2\,\text{TeV}$

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(our EW benchmark point will satisfy $M_{W'} = 2.6\,\text{TeV}$)

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Electroweak precision constraints

HSIEH, SCHMITZ, YU, YUAN (2010)

- full fit of ~ 40 EWP observables yields constraints

$$M_{Z'} > 1.6\,\text{TeV} \qquad M_{W'} > 0.3\,\text{TeV}$$

- most stringent constraint from
  - partial branching fraction σ_{had} of $Z \to q\bar{q}$
  - forward-backward asymmetry A^b_{FB}
  - weak charge $Q_W(\text{Cs})$ of Cs-135
  - left-handed coupling $g_L^{\nu N}$ in νN scattering

our strategy:

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

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Result of the χ^2 fit

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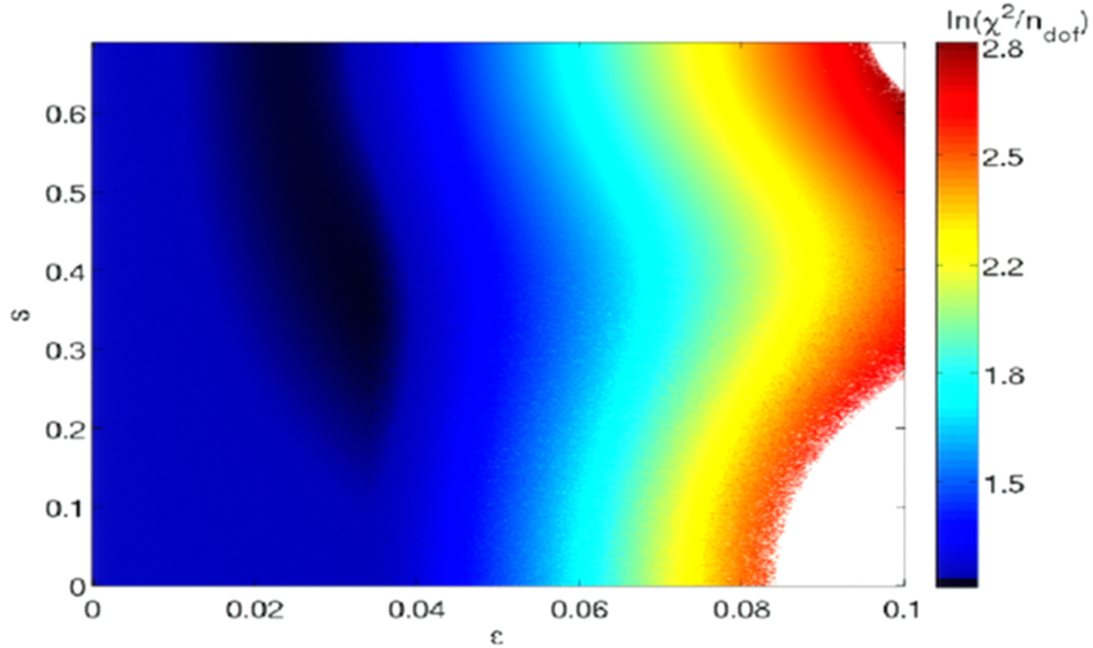

benchmark parameters for our flavor analysis:

$$\epsilon = 0.03 \qquad g_R/g_L = 0.7 \qquad 0.1 < s < 0.6$$

$$M_H = 16\,\text{TeV}/\sqrt{1-2s^2}$$

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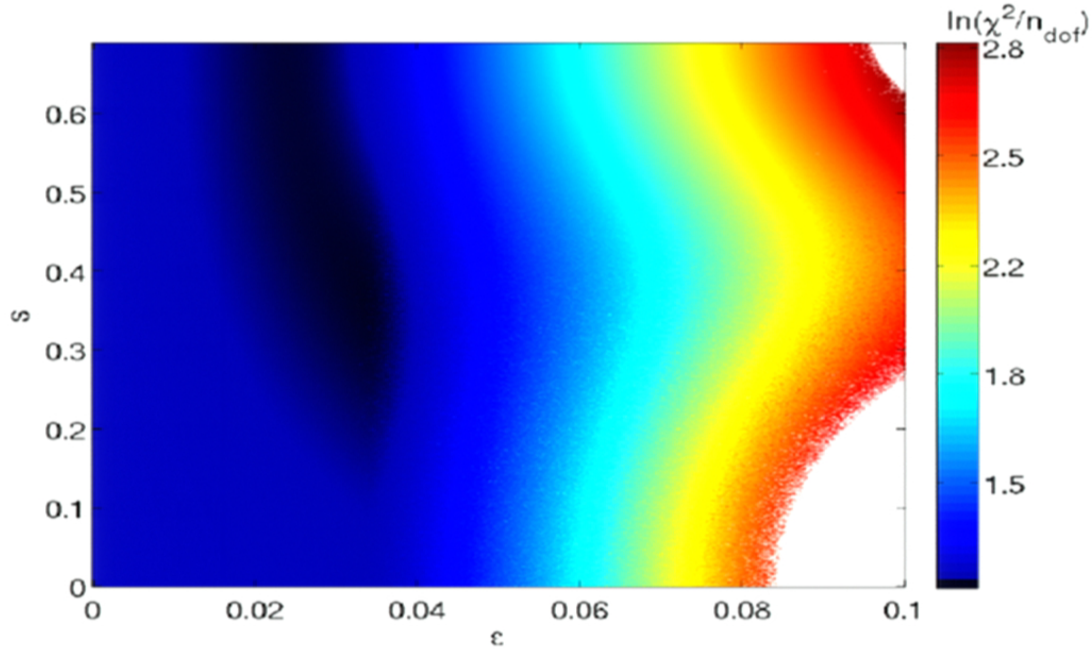

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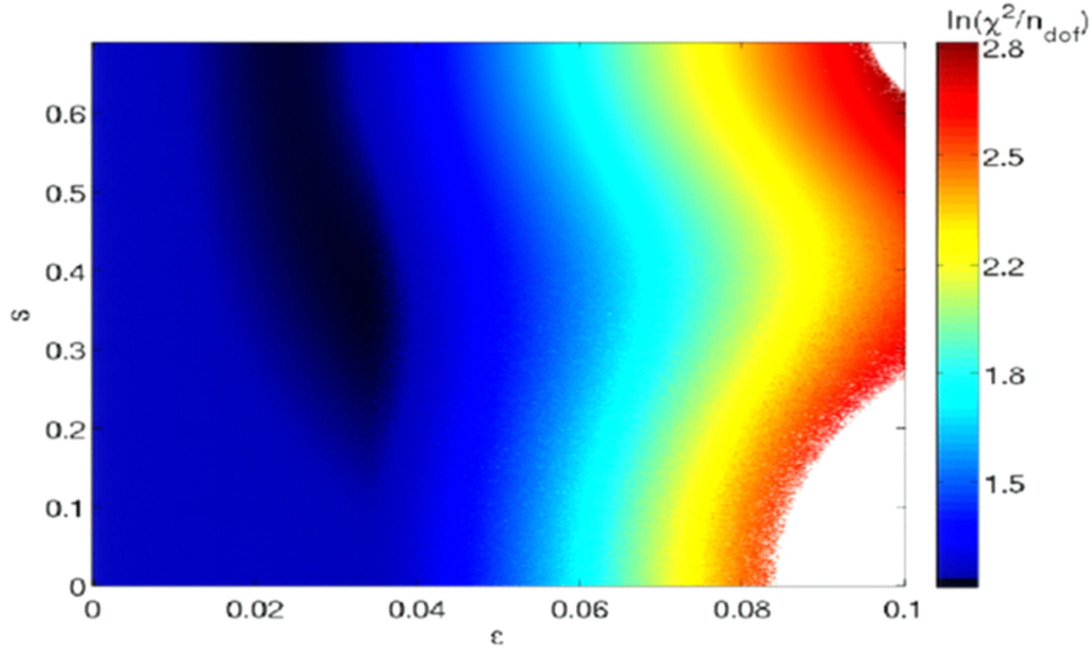

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Tree level constraints on flavor mixing

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)	-	-

➢ **we impose these constraints at the 2σ level**

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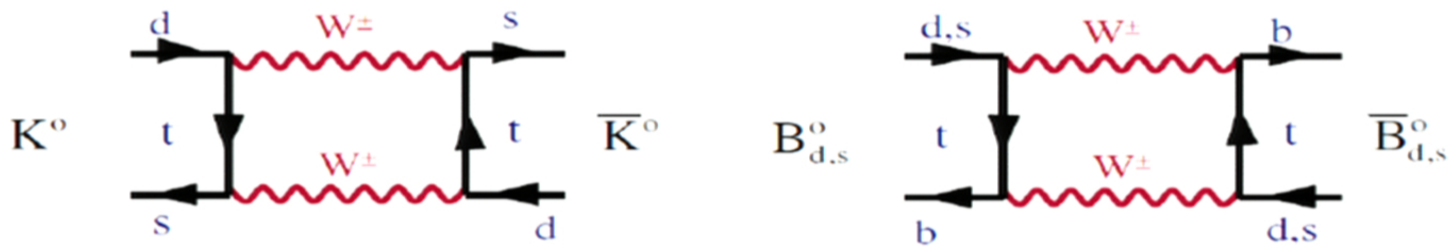
Particle antiparticle mixing — the main actors

- 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 $A_{\mathsf{SL}}^{d,s}$ (➢ dimuon charge asymmetry)

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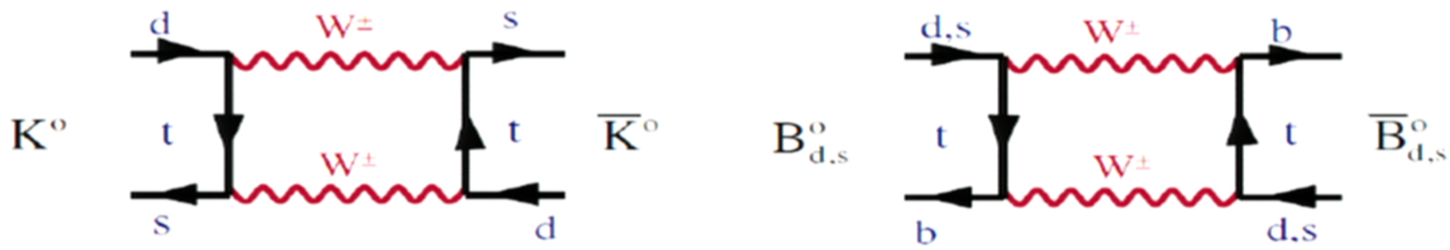

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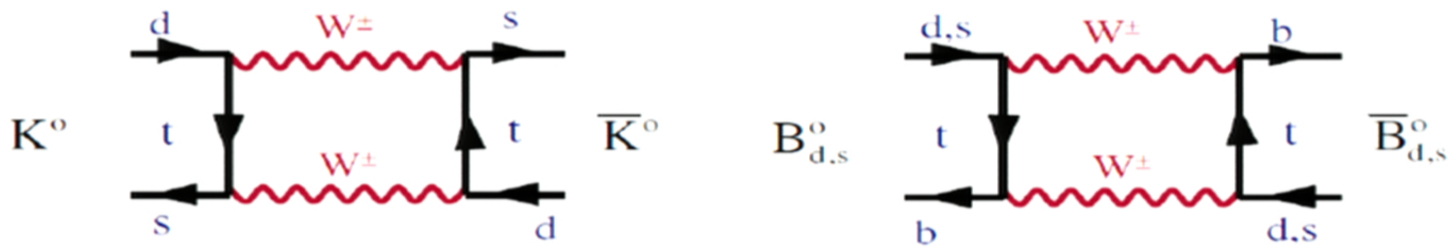

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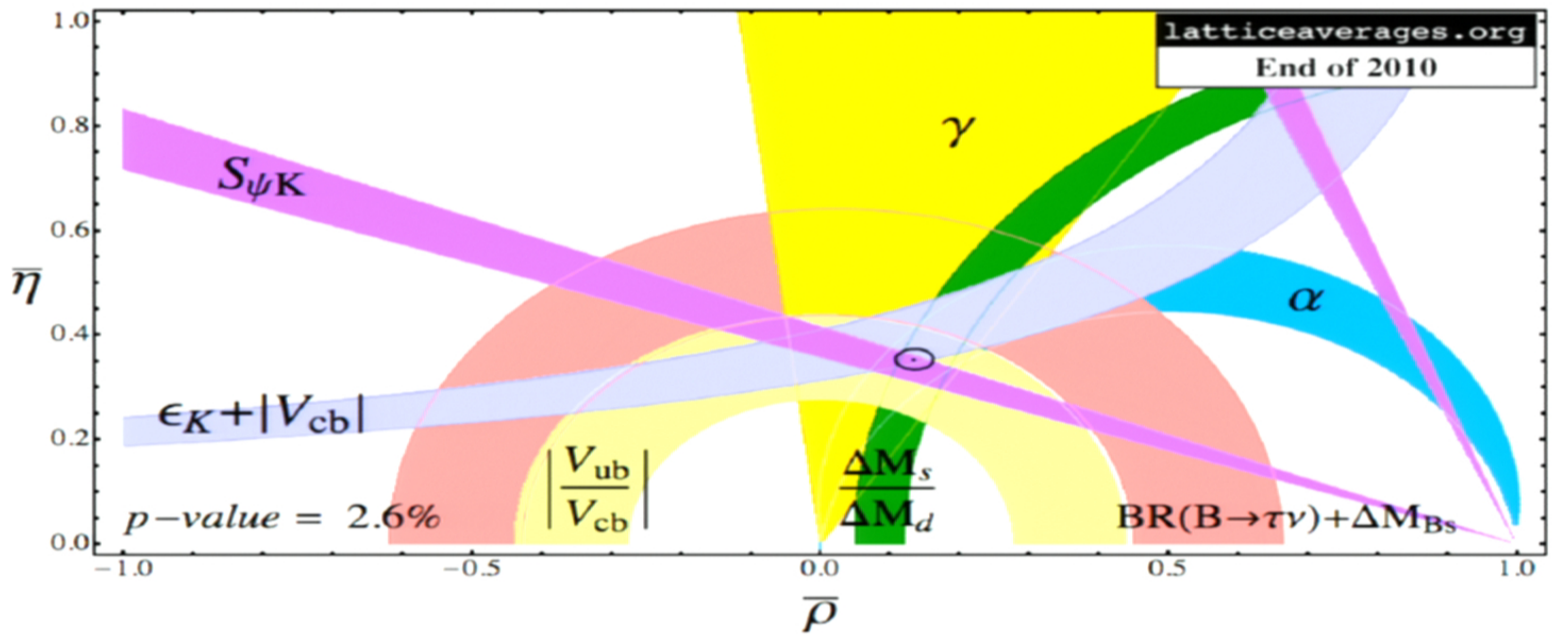
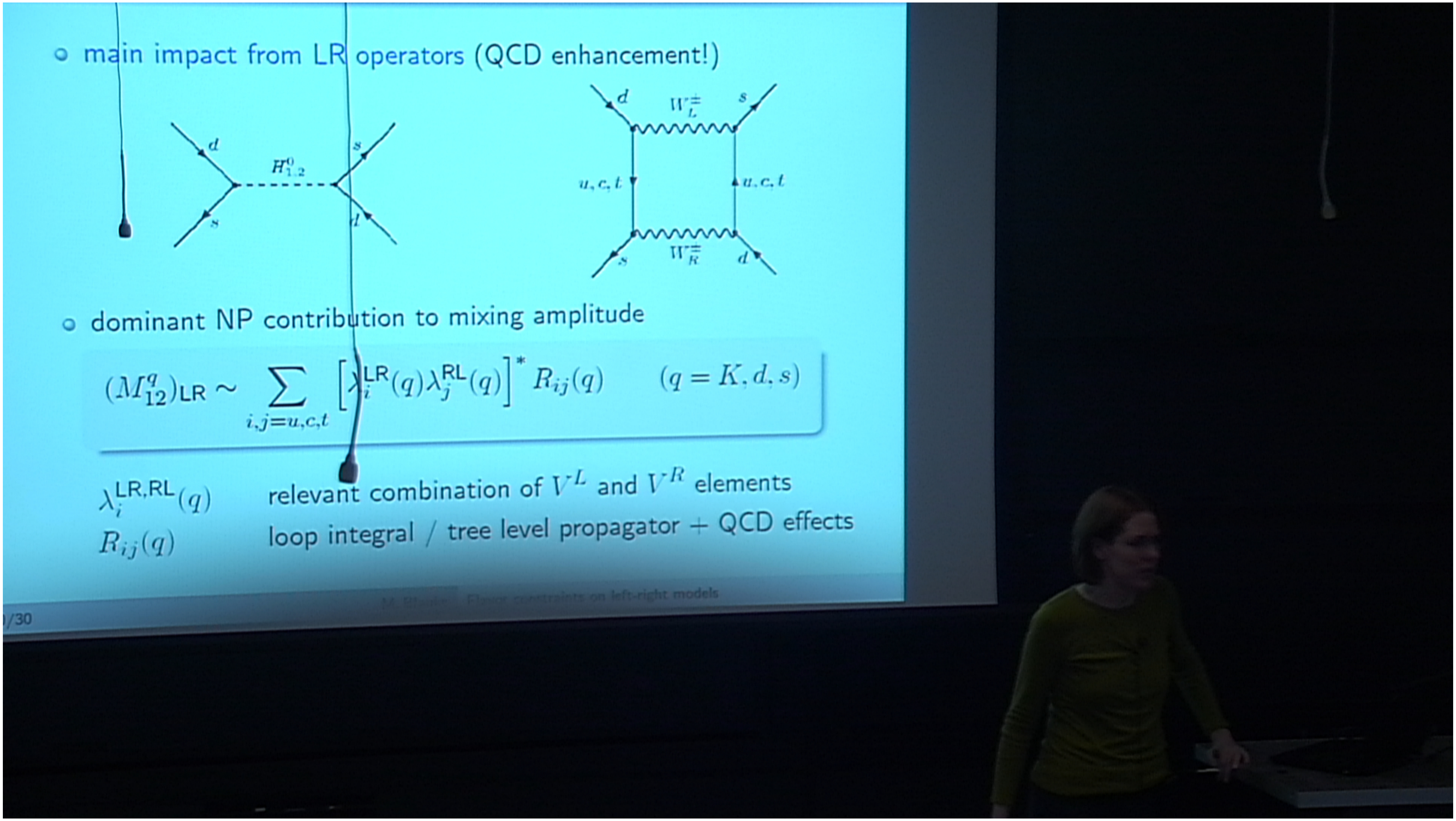
The global fit



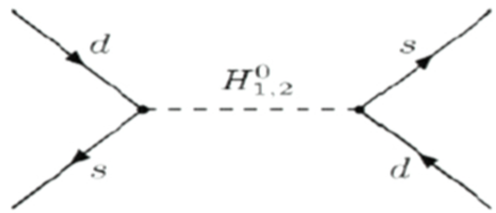
➢ **strong constraints on new physics**

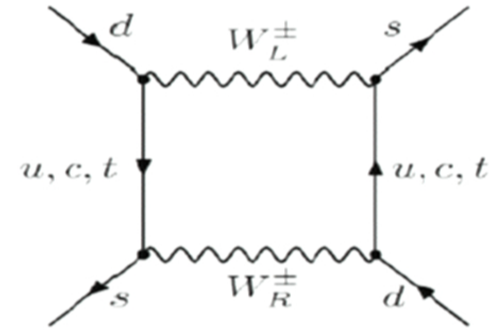
again we impose constraints at the 2σ level (except $S_{\psi\phi}$)


main impact from LR operators (QCD enhancement!)
d $H^0_{1,2}$ s s d
d $W^\pm_L$ s u,c,t u,c,t s $W^\mp_R$ d
dominant NP contribution to mixing amplitude
$(M_{12}^q)_{LR} \sim \sum_{i,j=u,c,t} \left[\lambda_i^{LR}(q)\lambda_j^{RL}(q)\right]^* R_{ij}(q) \qquad (q = K, d, s)$
$\lambda_i^{LR,RL}(q)$ relevant combination of V^L and V^R elements
$R_{ij}(q)$ loop integral / tree level propagator + QCD effects
/30

New LR contributions to $\Delta F = 2$

- main impact from LR operators (QCD enhancement!)





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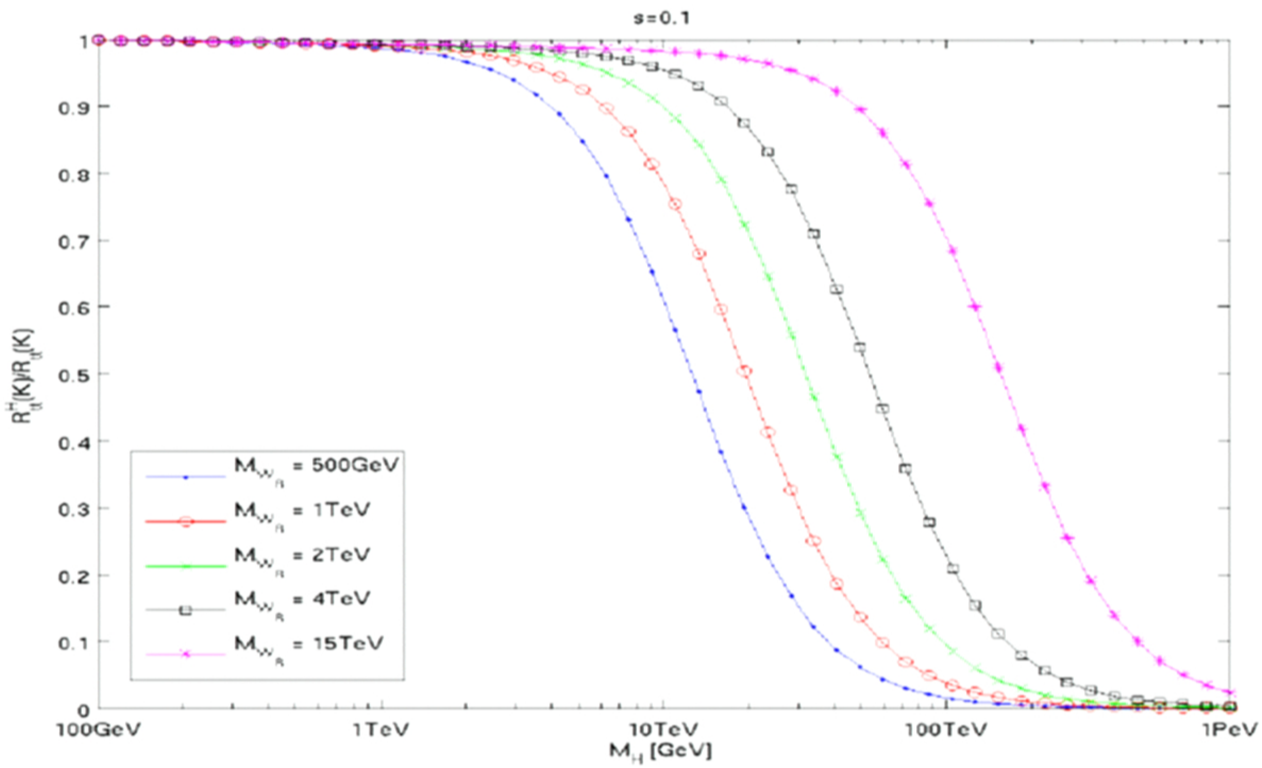
$\lambda_i^{\mathrm{LR,RL}}(q)$	relevant combination of V^L and V^R elements
$R_{ij}(q)$	loop integral / tree level propagator + QCD effects

Relative size of neutral Higgs contribution

▸ $s = 0.5$



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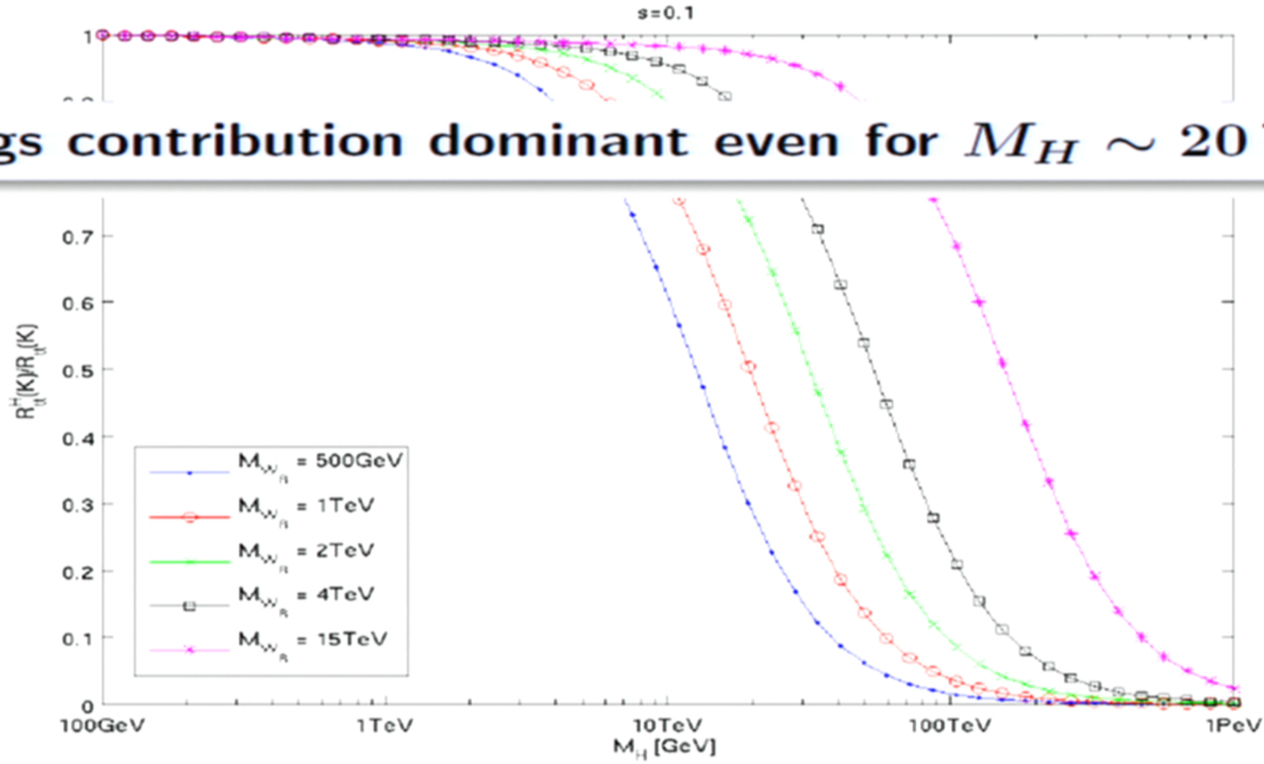
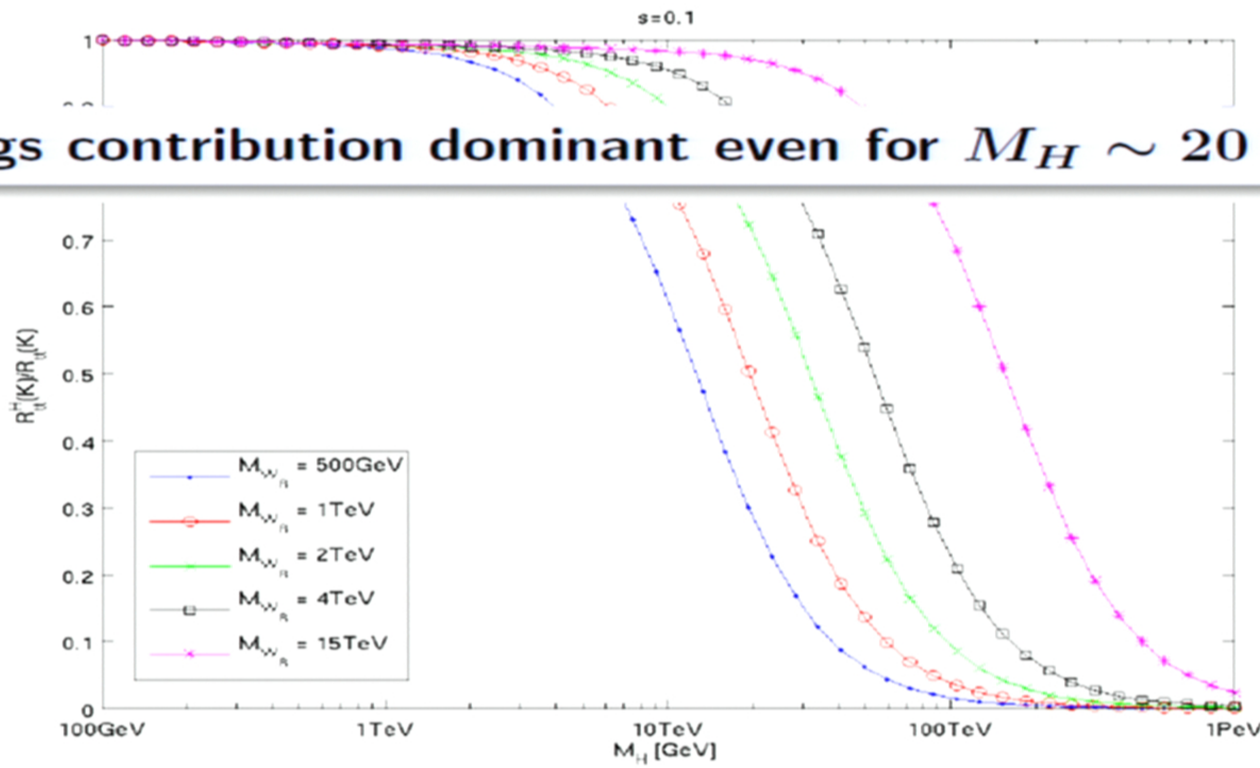


Higgs contribution dominant even for $M_H \sim 20$ TeV!

Relative size of neutral Higgs contribution

▸ $s = 0.5$



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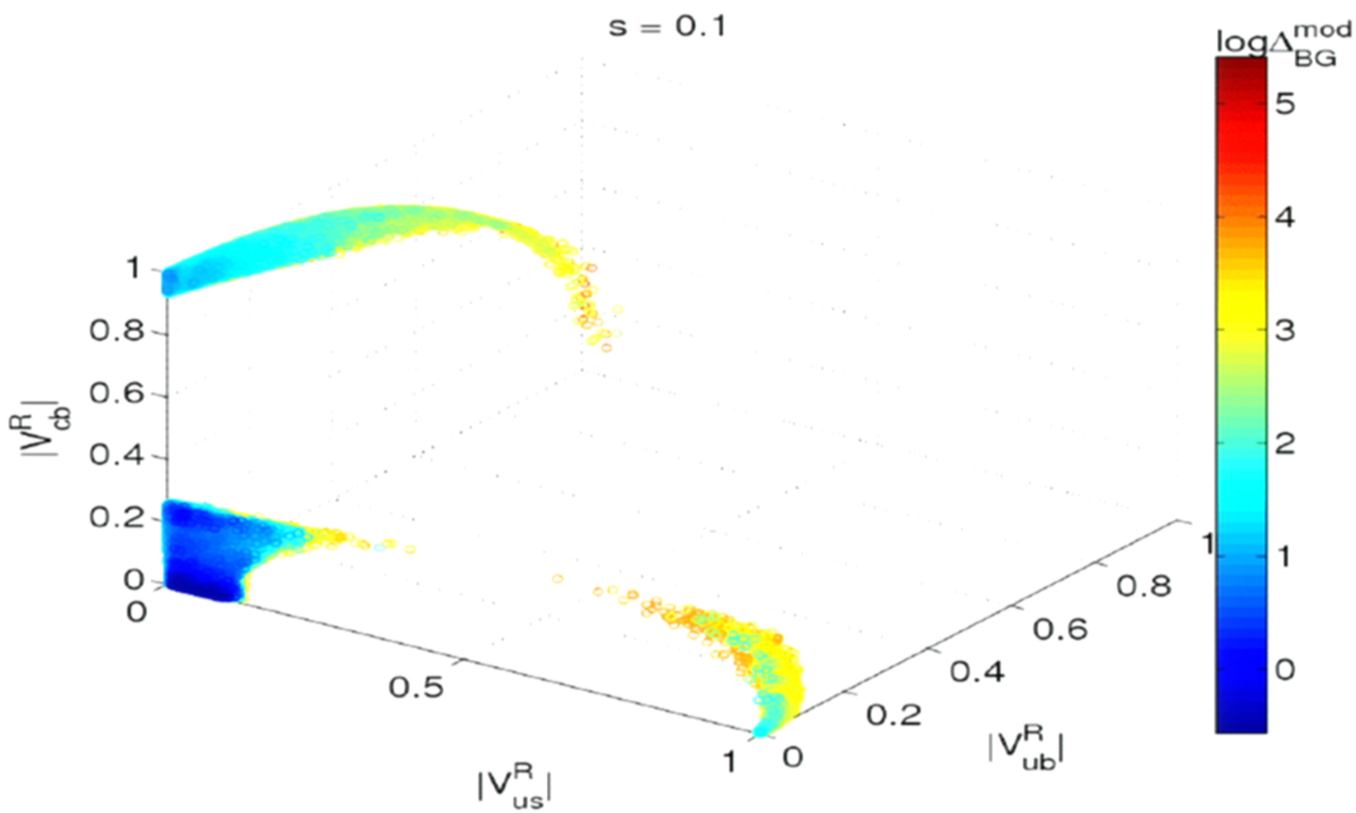
Allowed ranges for V^R

▸ Δ_{BG}^{mod} ▸ no Higgs



Fine tuning measure

▸ back

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

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

measures sensitivity of observable O
to small variations in paramteres p_i

- **modified Barbieri-Giudice measure**

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

Fine tuning measure

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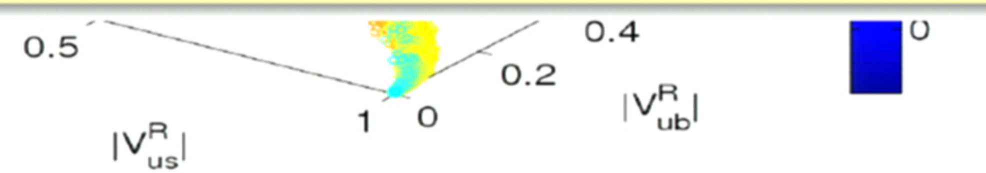
for points with small fine tuning $\Delta_{\text{BG}}^{\text{mod}} < 10$

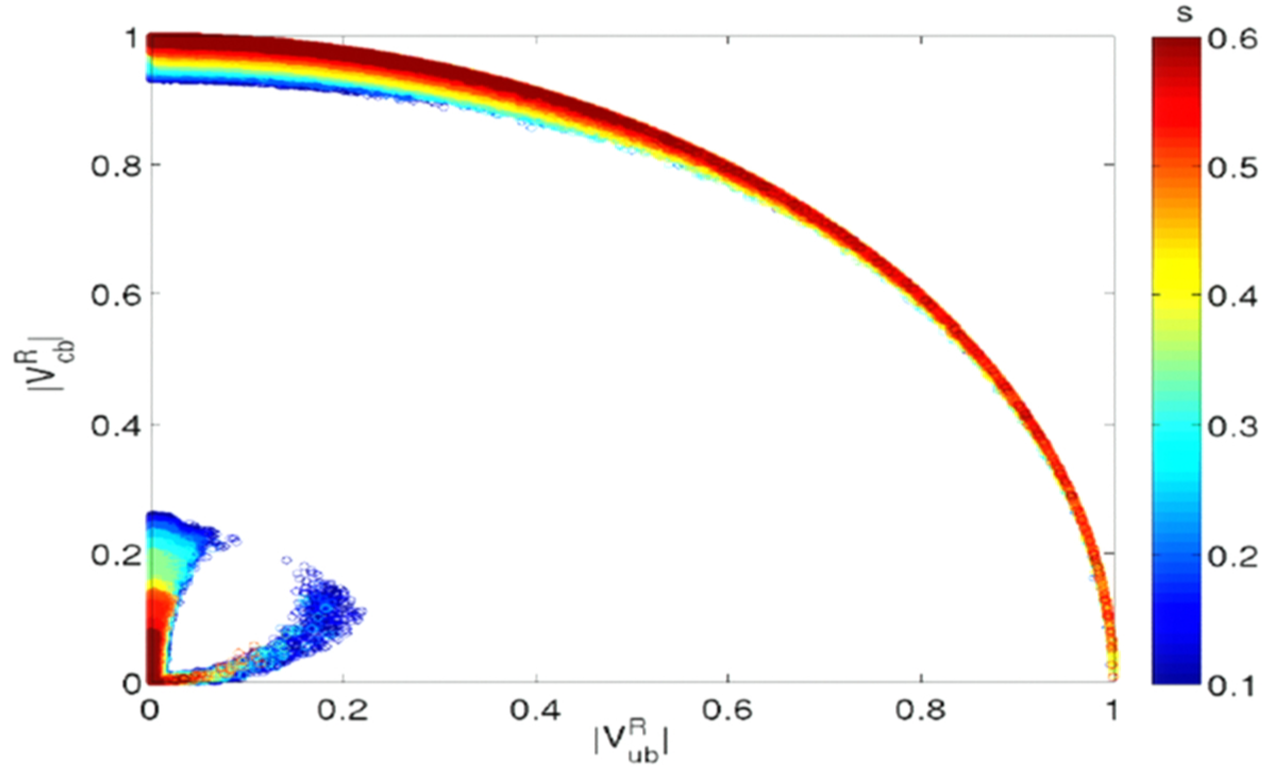
$$|V_{td}^R| < 1.2 \cdot 10^{-2} \qquad \text{and} \qquad |V_{us}^R| < \begin{cases} 0.18 & (s = 0.1) \\ 0.13 & (s = 0.5) \end{cases}$$

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



Allowed ranges for V^R — s dependence

▸ others



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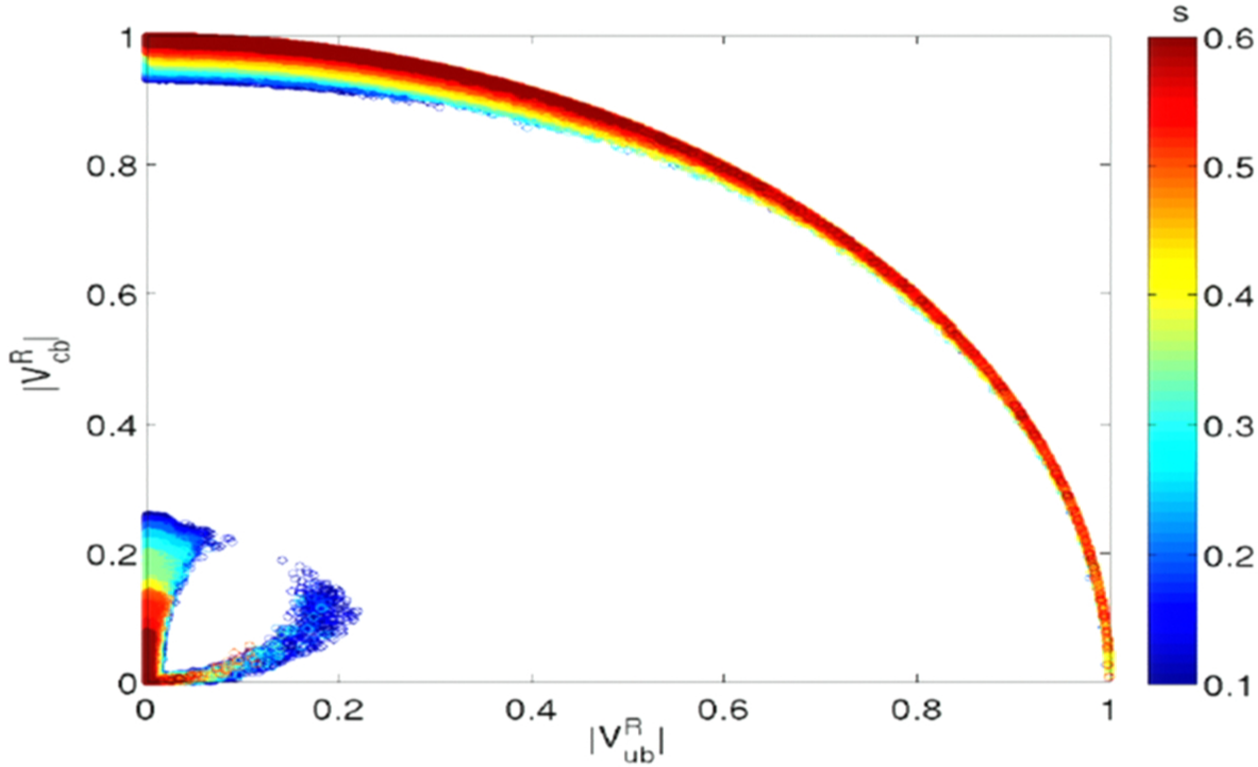
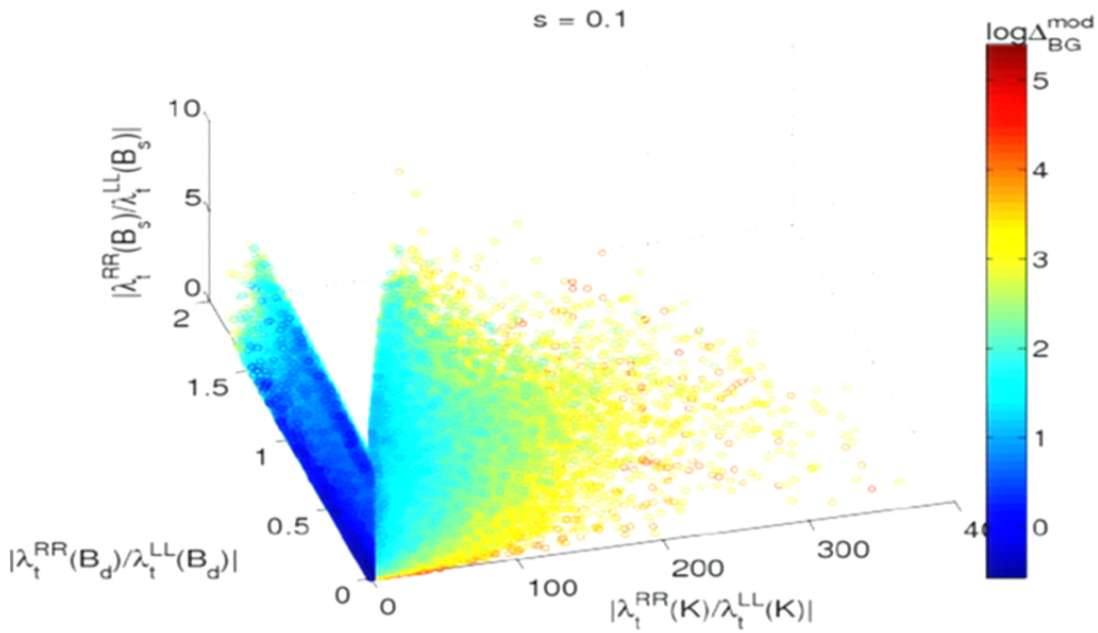
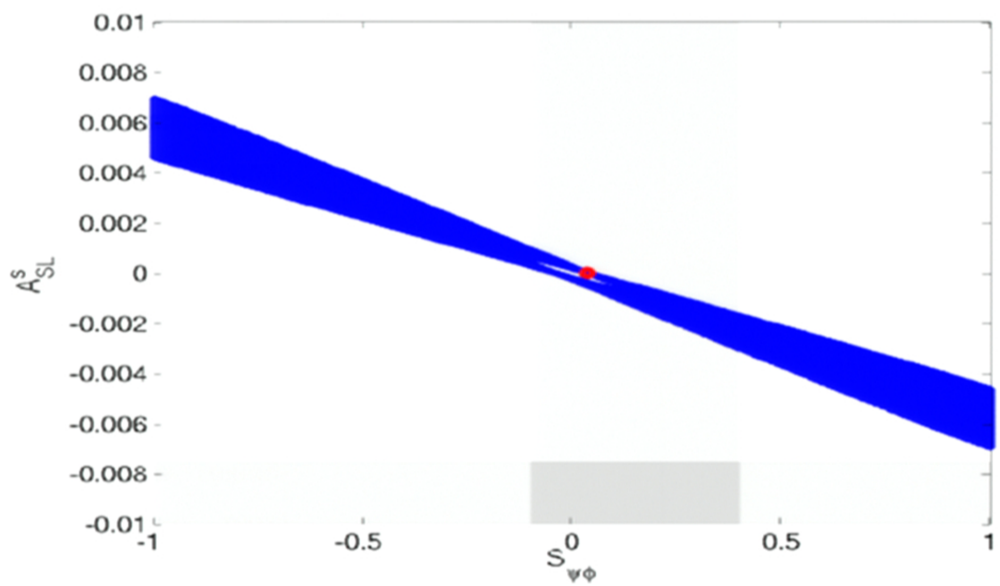


Relative size of effects in K, B_d and B_s systems

- relative size of LR effects in $\Delta F = 2$: $\frac{\lambda_t^{\rm LR}(q)\lambda_t^{\rm RL}(q)}{\lambda_t^{\rm LL}(q)\lambda_t^{\rm LL}(q)} = \frac{\lambda_t^{\rm RR}(q)}{\lambda_t^{\rm LL}(q)}$
- same combination will enter also rare K and B decays



CP violation in $B_s - \bar{B}_s$ mixing



- LR model can accomodate any CP phase in $B_s - \bar{B}_s$ mixing
- D0 data on A^s_{SL} hard to acconmodate due to
  - model-independent correlation with $S_{\psi\phi}$ asymmetry
  - LHCb determination of the latter

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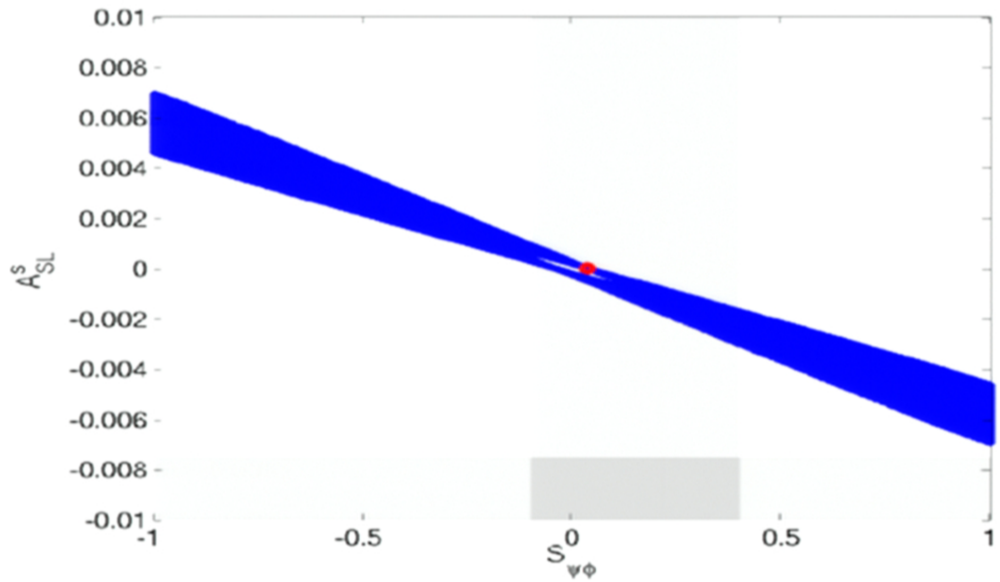

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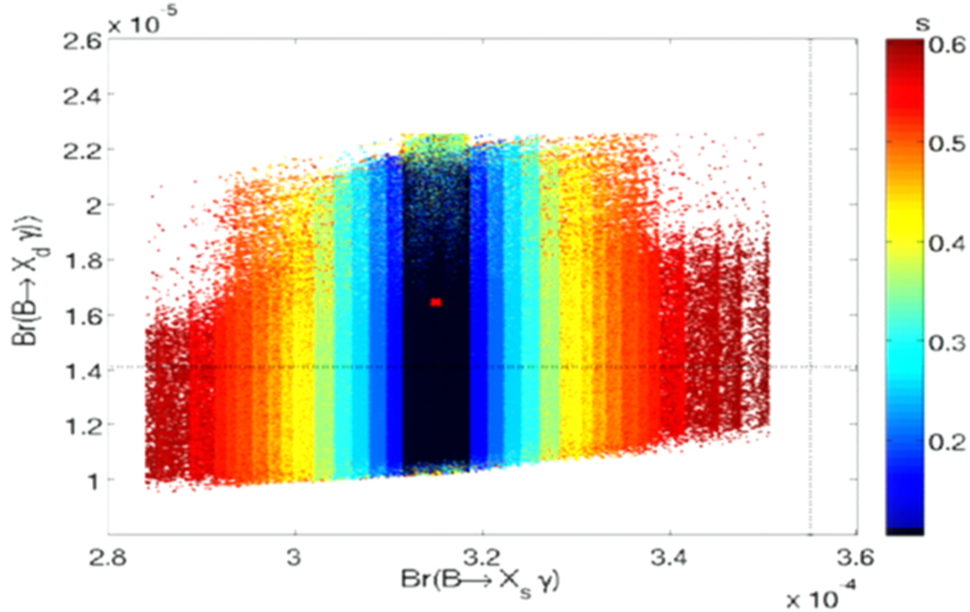
The $B \to X_{s,d}\gamma$ decays

▸ Higgs



$B \to X_{s,d}\gamma$ constraints relevant for $s > 0.5$:

$$\frac{1}{(1-2s^2)^2}$$ enhancement of charged Higgs contribution

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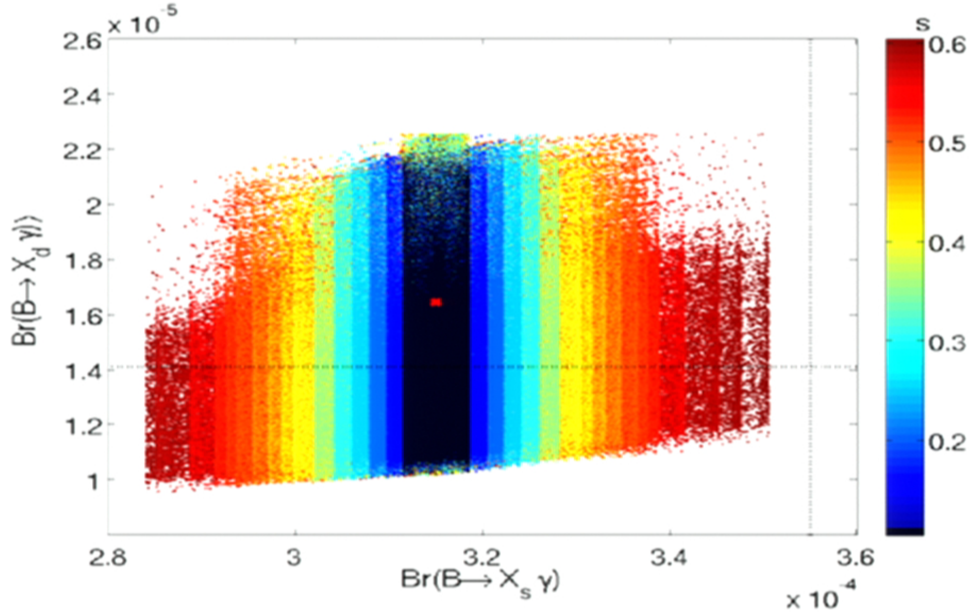

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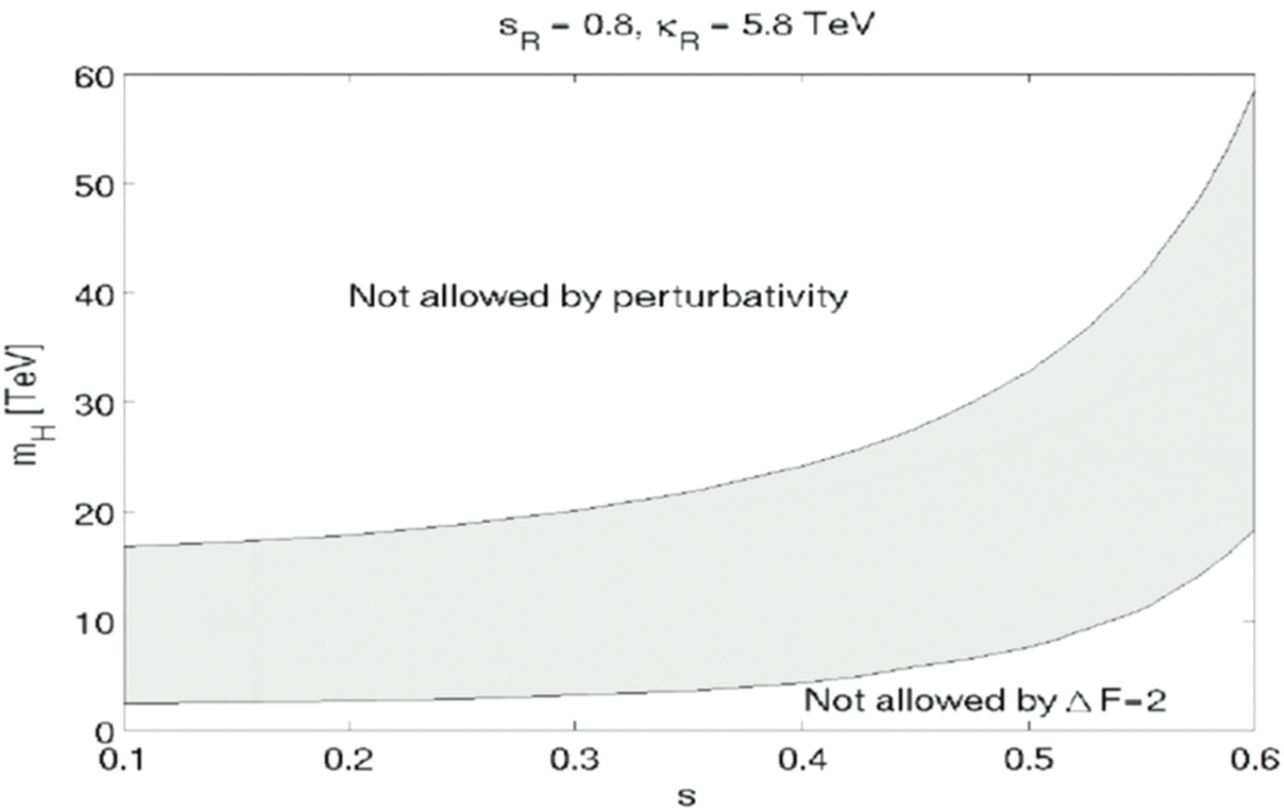

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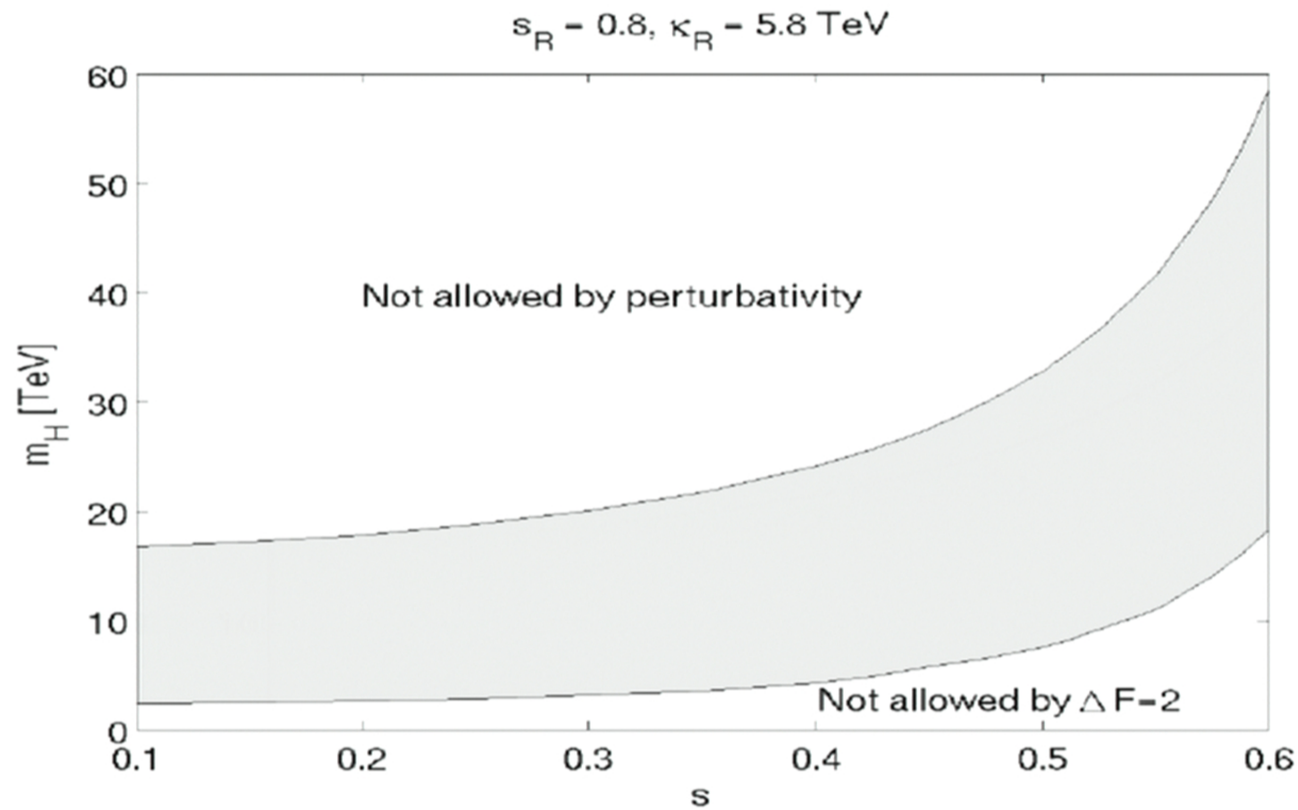
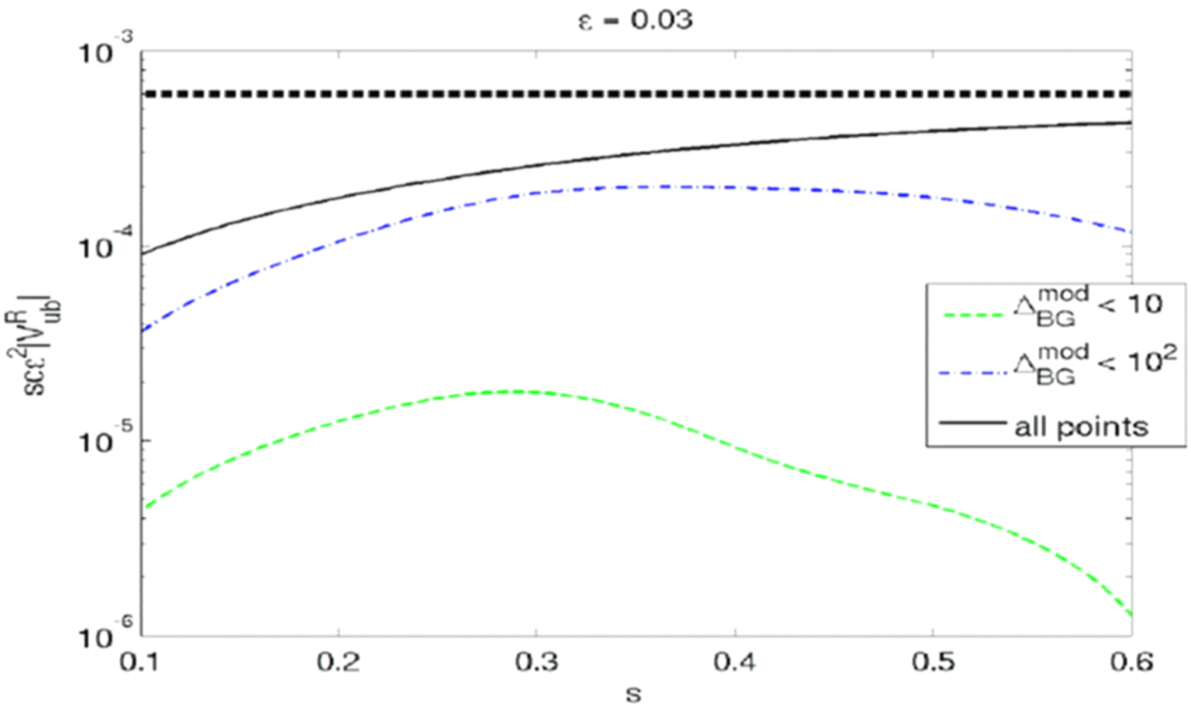


Revisiting the $|V_{ub}|$ problem

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

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



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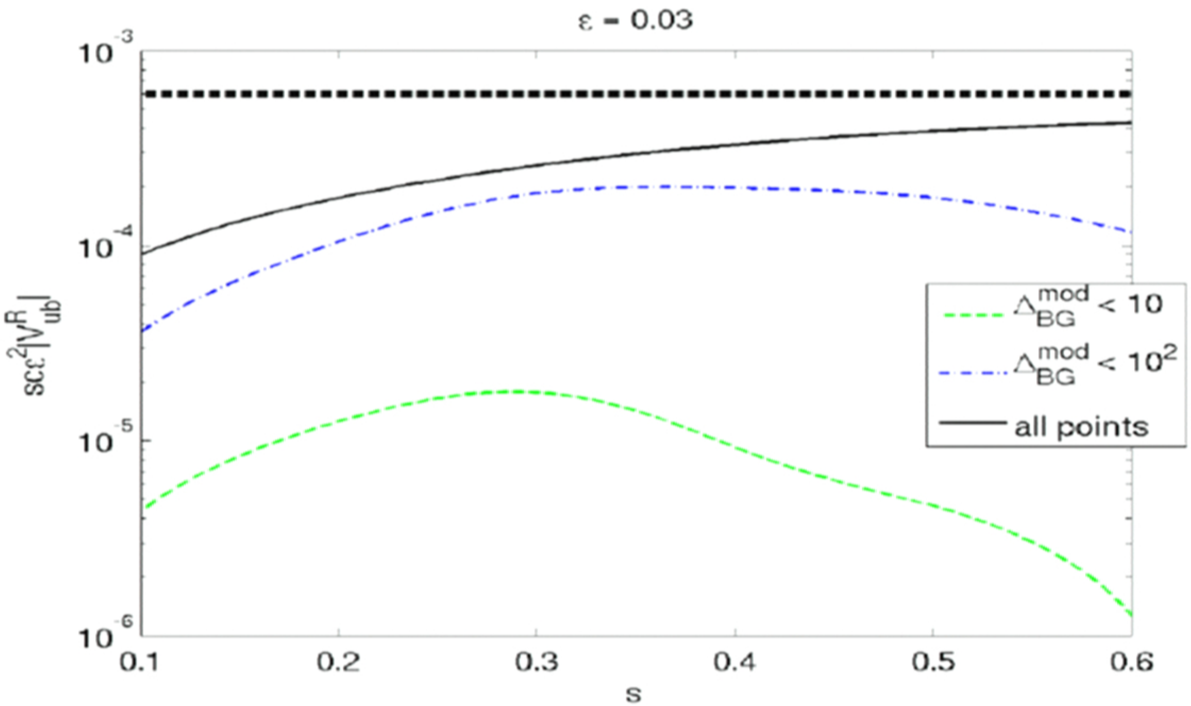

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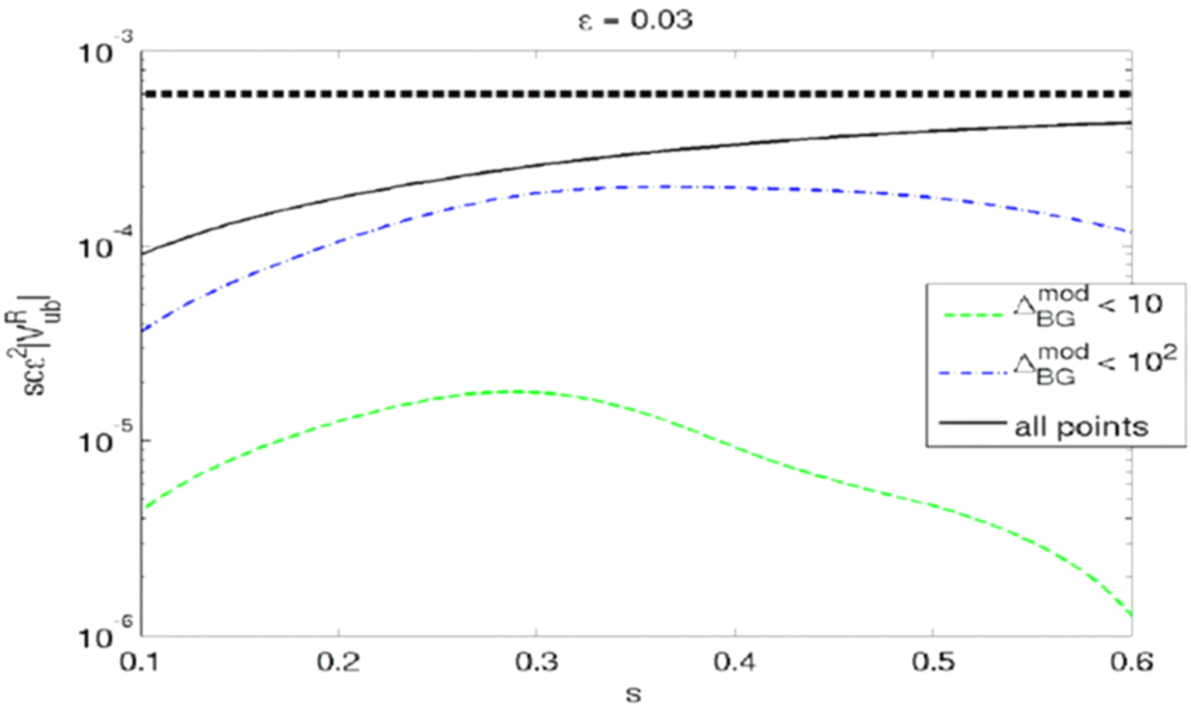

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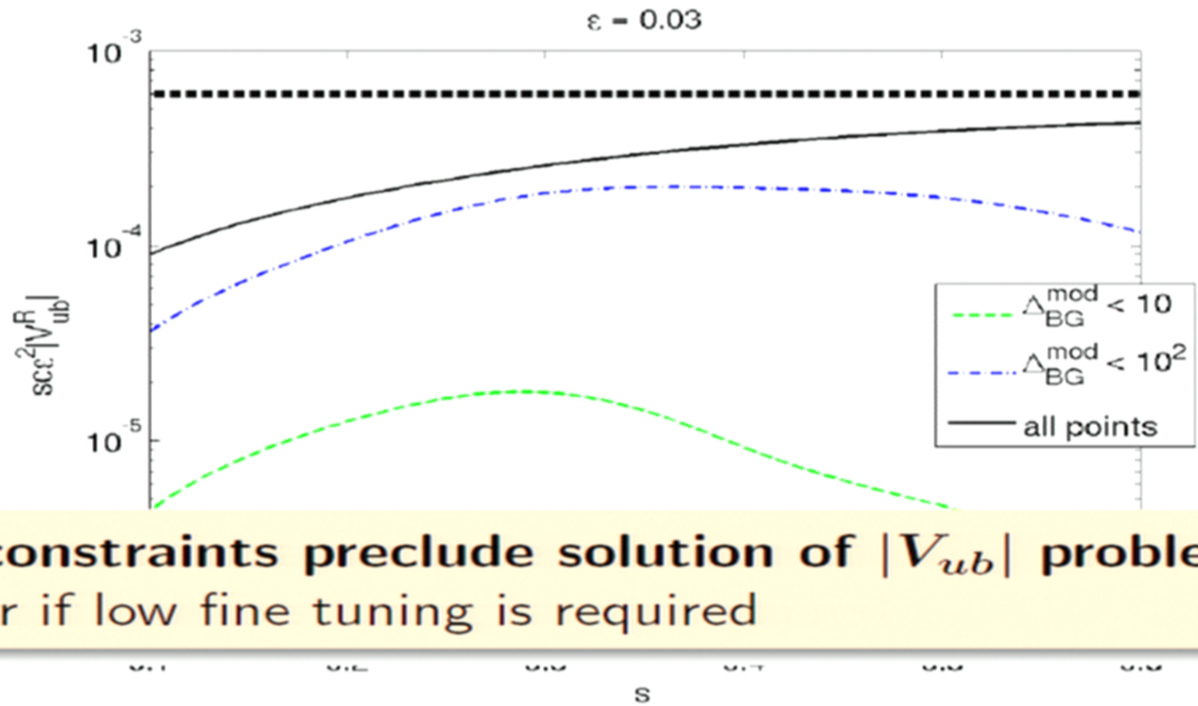

$\Delta F = 2$ constraints preclude solution of $|V_{ub}|$ problem
in particular if low fine tuning is required

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
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