THE INTERPLAY BETWEEN HIGGS & FLAVOR PHYSICS

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INTRODUCTION

- In the standard model (SM), flavor physics is linked to electroweak symmetry breaking (EWSB) & hence the Higgs via the Yukawa interactions

- In TeV extensions of the SM with new & generic flavor-breaking terms, "Higgs-flavor connection" would be lost, but such theories are experimentally ruled out by now

- In new-physics scenarios with close to minimal flavor structure, correlations between Higgs & flavor physics may remain. Of course, only experiment can tell

HIGGS FCNCS: MOTIVATIONS

- Renewed interest in SM extensions with intricate Higgs sectors. Most of the proposed setups feature more than one Higgs doublet with potentially sizable flavor-changing neutral-current (FCNC) couplings

- FCNC scalar amplitudes offer an unique tool to distinguish between different types of flavor-symmetry breaking:
  - easy to mimic the SM in the case of left-handed (LL) operators
  - more difficult to model the SM double suppression (down-type Yukawas & mixing angles) of left-right-chirality (LR) operators

- An interesting possibility to address "tensions" in $\Delta F = 2$ observables (i.e. mixing amplitudes) without spoiling the good overall agreement (at level of 20%) of the Cabibbo-Kobayashi-Maskawa (CKM) picture

PROTECTION OF HIGGS FCNCS

- The main problem in extending the Higgs sector are excessive FCNCs. Generic Yukawa Lagrangian with 2 Higgs doublets (2HDM) reads:

$$\mathcal{L}_{\text{Yukawa}} = \bar{Q}_L^i \, (X_{d1})_{ij} \, d_R^j \phi_d + \bar{Q}_L^i \, (X_{u2})_{ij} \, u_R^j \phi_u + \bar{Q}_L^i \, (X_{d2})_{ij} \, d_R^j \tilde{\phi}_u + \bar{Q}_L^i \, (X_{u1})_{ij} \, u_R^j \tilde{\phi}_d + \text{h.c.}$$

couplings to the "wrong" Higgs doublet will generically induce tree-level FCNCs

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$$+ \bar{Q}_L^i \, \cancel{(X_{d2})_{ij}} \, d_R^j \tilde{\phi}_u + \bar{Q}_L^i \, \cancel{(X_{u1})_{ij}} \, u_R^j \tilde{\phi}_d + \text{h.c.}$$

- There are two main strategies to get rid of this harmful effects

  i) By flavor-blind symmetries ("natural flavor conservation"): in case of 2HDM-II one uses Z_2 subgroup of $U(1)_{PQ}$ such that $X_{d2} = X_{u1} = 0$,

$$\phi_d \to -\phi_d \qquad d_R \to -d_R$$

remaining fields even under Z_2

[Glashow & Weinberg, Phys. Rev. D15, 1958 (1977); Paschos, Phys. Rev. D15, 1966 (1977)]

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- There are two main strategies to get rid of this harmful effects

  ii) By flavor symmetries (& symmetry breaking): for example one can use minimal-flavor violation (MFV), which at lowest order leads to

$$X_{d1} \propto X_{d2} \propto Y_d \qquad X_{u1} \propto X_{u2} \propto Y_u$$

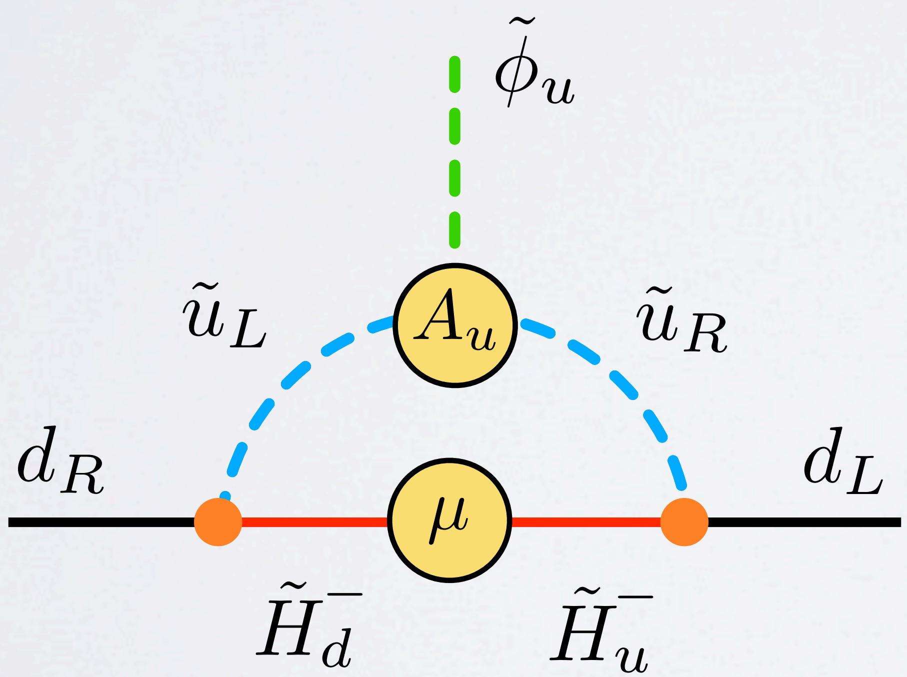
[see for example Babu & Nandi, hep-ph/9907213; Giudice & Lebedev, arXiv:0804.1753; Buras *et al.*, arXiv:1005.5310]

PROTECTION OF HIGGS FCNCS

- But both mechanism are not radiatively stable (problem is particularly severe if the theory contains additional states at the TeV scale):

  i) To avoid massless pseudo scalar, $U(1)_{PQ}$ Peccei-Quinn symmetry must be necessarily broken explicitly (in Higgs potential, ...)

MSSM diagram



Tree level:

$$X_{d2} = 0 \qquad X_{d1} = Y_d$$

One loop:

$$X_{d2} = \epsilon \Delta_d \qquad X_{d1} = Y_d + \dots$$

even if $\varepsilon \approx 10^{-2}$ (typical loop suppression), FCNCs are too large unless Δ_d is very small or aligned with down-type Yukawas

[see for example Hall, Rattazzi & Sadrid, hep-ph/9306309]

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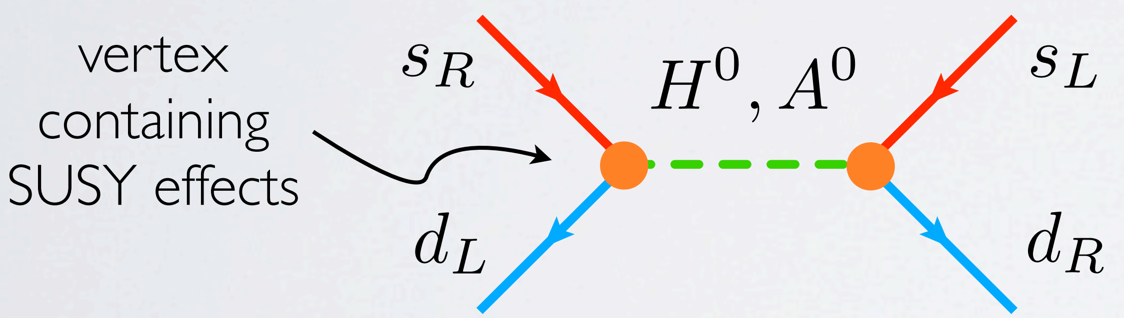
strongest constraint arises from CP violation in neutral kaon system (ε_K)



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implies $(\Delta_d)_{ij} \ll O(10^{-4})$

chiral & RGE enchancements lead to factor of O(100) between LR & LL contribution

$$|\epsilon| \, |\mathrm{Im}\,[(\Delta_d^*)_{21}(\Delta_d)_{12}]|^{1/2} \lesssim 3 \cdot 10^{-7} \, \frac{M_A}{100\,\mathrm{GeV}} \, \cos\beta$$

PROTECTION OF HIGGS FCNCS

- But both mechanism are not radiatively stable (problem is particularly severe if the theory contains additional states at the TeV scale):

  ii) Even if exact (discrete case), symmetries do not protect FCNCs when higher-dimensional operators are taken into account

$$\Delta\mathcal{L}_{\text{Yukawa}} = \frac{c_D}{\Lambda^2}\,\bar{Q}_L i \not{D} Q_L (\phi^\dagger \phi) + \frac{c_\phi}{\Lambda^2}\,\bar{Q}_L \phi d_R (\phi^\dagger \phi) + \ldots$$

if Higgs is a pseudo-Goldstone-boson, operator aligned with SM Yukawa coupling (due to shift symmetry) & gives no FCNCs

[Giudice & Lebedev, arXiv:0804.1753; Agashe & Contino, arXiv:0906.1542; Azatov, Toharia & Zhu, arXiv:0906.1990]

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EWSB: $\phi = v + h$

chirally suppressed — unsuppressed

$$\Delta M_d = -v\,(c_D Y_d + c_\phi)\,\frac{v^2}{\Lambda^2} + \ldots$$

$$\Delta\mathcal{L}_h = -3\,(c_D Y_d + c_\phi)\,\frac{v^2}{\Lambda^2}\,h\bar{d}_L d_R + \ldots$$

[Giudice & Lebedev, arXiv:0804.1753; Agashe & Contino, arXiv:0906.1542; Azatov, Toharia & Zhu, arXiv:0906.1990]

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⇒ mismatch leads to Higgs FCNCs (already for a single Higgs doublet)

[Giudice & Lebedev, arXiv:0804.1753; Agashe & Contino, arXiv:0906.1542; Azatov, Toharia & Zhu, arXiv:0906.1990]

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  ii) Even if exact (discrete case), symmetries do not protect FCNCs when higher-dimensional operators are taken into account

⬇

To reach a sufficient protection of Higgs FCNCs one needs to protect the flavor-symmetry breaking. Possible ways to achieve such a protection is provided by MFV, warped extra dimensions (WEDs) or partial compositeness (hierarchical fermion profiles), ...

HIGGS FCNCS WITH MFV

- Structure of Higgs FCNC couplings (in limit $\tan\beta = v_u/v_d \gg 1$):

$$\mathcal{L}_{\rm FCNC}^{\rm MFV} \propto \bar{d}_L^i V_{3i}^* \left[a_0 + a_1 \delta_{3i} + a_2 \delta_{3k}\right] V_{3k}\, y_k^d\, d_R^k H$$

$$Y_u Y_u^\dagger Y_d$$

$$Y_d Y_d^\dagger Y_u Y_u^\dagger Y_d$$

$$Y_u Y_u^\dagger Y_d Y_d^\dagger Y_d$$

  - double suppression by CKM (V_{3i}) & down-type Yukawas (y_k^d)
  - a_i are O(1) parameters (encoding dependence from 3rd generation Yukawas), complex if one allows for flavor-blind CP-violating phases
  - since in the MSSM the Yukawa insertions of power 5 are very small, one needs non-trivial models to get interesting CP-violating effects

[D'Ambrosia *et al.*, hep-ph/0207036; Buras *et al.*, arXiv:1005.5310]

HIGGS FCNCS WITH MFV

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integrating out heavy Higgs fields H

$$\mathcal{L}^{\rm MFV}_{\Delta F=2} \propto y^d_i\, y^d_k \left(V^*_{3i} V_{3k}\right)^2 (\bar{d}^i_R d^k_L)(\bar{d}^i_L d^k_R) \begin{cases} |a_0|^2, & ik = 21 \\ (a^*_0 + a^*_1)(a_0 + a_2), & ik = 31, 32 \end{cases}$$

effects scale (almost) as $\left\{ \begin{array}{c} m_b m_s \\ m_b m_d \\ m_s m_d \end{array} \right\}$ relative to SM ⇒ $\left\{ \begin{array}{l} \text{large effects in } B_s \text{ mixing} \\ \text{small effects in } B_d \text{ mixing} \\ \text{tiny effects in kaon mixing} \end{array} \right\}$

[Buras *et al.*, arXiv:1005.5310]

HIGGS FCNCS IN WEDS

- SM quark fields couple to the new-physics sector via hierarchical wave functions F^i_Q, F^i_u & F^i_d such that

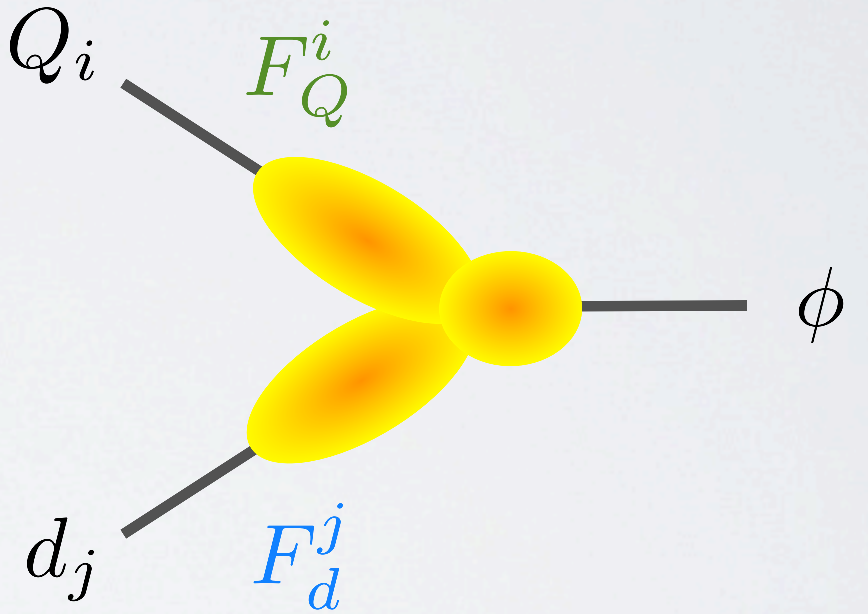
$$(Y_d)_{ij} = F^j_Q \, Y^{5D}_d \, F^i_d \sim F^j_Q \, F^i_d \qquad (Y_u)_{ij} = F^i_Q \, Y^{5D}_u \, F^j_u \sim F^i_Q \, F^j_u$$

$$F^3_Q \gg F^2_Q \gg F^1_Q$$

$$F^3_d \gg F^2_d \gg F^1_d$$

$$F^3_u \gg F^2_u \gg F^1_u$$

$$Y^{5D}_{d,u} = \text{anarchic}, \quad \mathcal{O}(1) \text{ complex}$$



[see for example Huber, hep-ph/0303183]

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  - quark masses & CKM elements simply given in terms of profiles:

$$m^i_u \sim v \, F^i_Q \, F^i_u \qquad V_{ij} \sim \begin{cases} \dfrac{F^i_Q}{F^j_Q}, & i \leq j \\ \dfrac{F^j_Q}{F^i_Q}, & i > j \end{cases}$$

$$m^i_d \sim v \, F^i_Q \, F^i_d$$

[see for example Huber, hep-ph/0303183]

HIGGS FCNCS IN WEDS

- Lagrangian inducing Higgs FCNCs takes the form:

$$\mathcal{L}_{\rm FCNC}^{\rm WED} \sim \left(\frac{v Y_d^{\rm 5D}}{M_{\rm KK}}\right)^2 \bar{d}_L^i \left[y_i^d F_Q^i F_Q^k + y_k^d F_d^i F_d^k + Y_d^{\rm 5D} F_Q^i F_d^k \right] d_R^k h$$

Kaluza-Klein (KK) of O(few TeV)

from "right" Yukawa couplings $\bar{Q}_L d_R$ (or derivative operators)

from "wrong" Yukawa couplings $\bar{d}_L Q_R$ after regularizing Higgs profile & summing whole KK tower (or non-derivative operators)

- suppression by exponentially small wave functions F_Q^i & F_d^i
- if present, term involving 3 powers of the 5D Yukawas gives dominant contribution to Higgs FCNCs involving light quarks

[Agashe & Contino, arXiv:0906.1542; Azatov, Toharia & Zhu, arXiv:0906.1990; Casagrande *et al.*, arXiv:1005.4315]

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Higgs exchange at tree level

$$\mathcal{L}_{\Delta F=2}^{\rm WED} \sim \left(\frac{vY_d^{\rm 5D}}{M_{\rm KK}}\right)^2 y_i^d y_k^d (\bar{d}_R^i d_L^k)(\bar{d}_L^i d_R^k)$$

corrections scale as $\begin{Bmatrix} m_b m_s \\ m_b m_d \\ m_s m_d \end{Bmatrix}$ in absolute terms ⇒ $\begin{Bmatrix} \text{small effects in } B_s \text{ mixing} \\ \text{small effects in } B_d \text{ mixing} \\ \text{large effects in kaon mixing} \end{Bmatrix}$

[Agashe & Contino, arXiv:0906.1542; Azatov, Toharia & Zhu, arXiv:0906.1990; Casagrande *et al.*, arXiv:1005.4315]

HIGGS FCNCS: SCORECARDS

- FCNCs associated to virtual tree-level exchange of Higgs bosons can show notably different patters of enhancements. For example

MFV: double suppression by CKM & down-type Yukawas

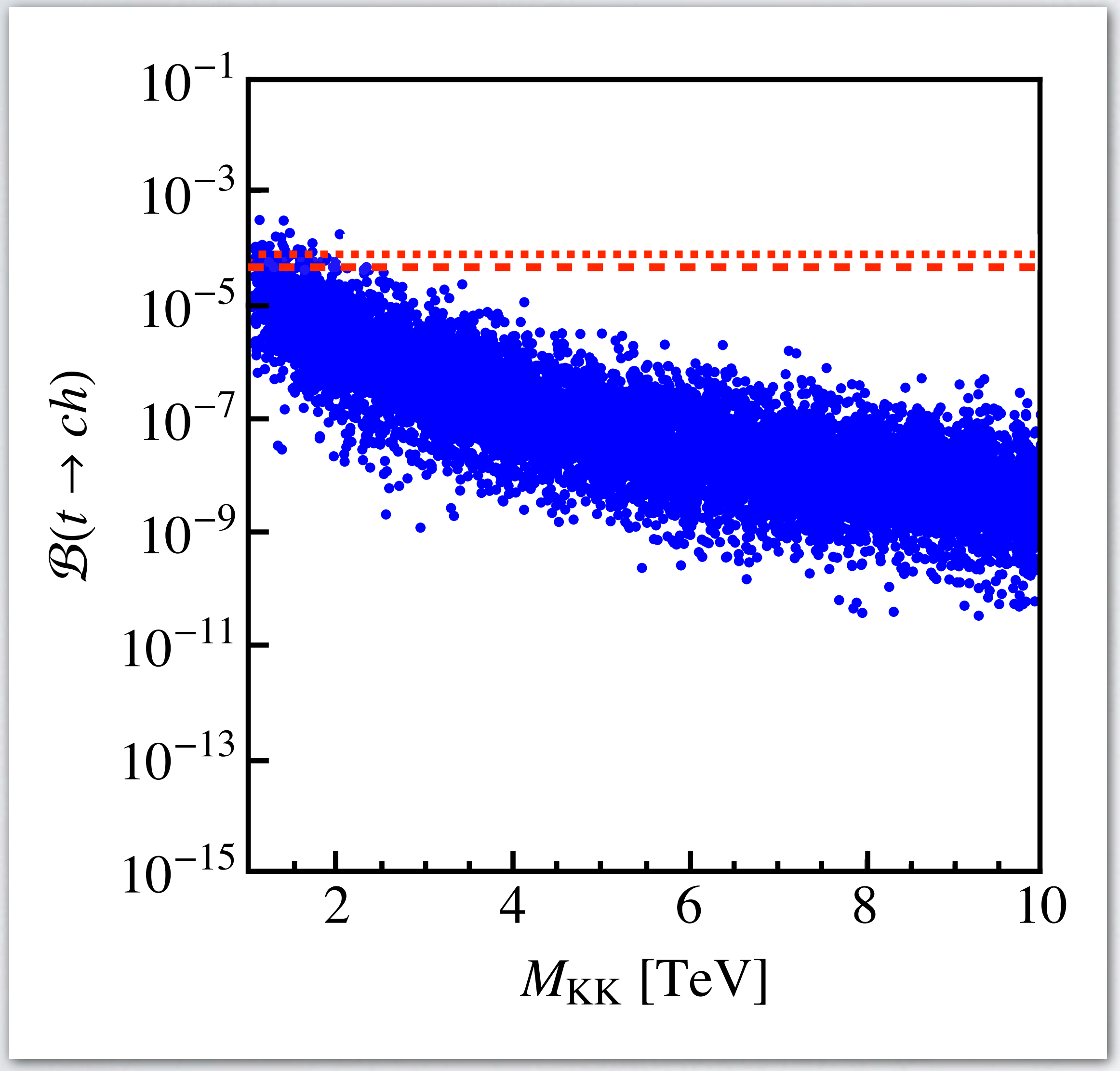
$$\left\{ \begin{array}{l} \text{large effects in } B_s \text{ mixing} \\ \text{small effects in } B_d \text{ mixing} \\ \text{tiny effects in kaon mixing} \end{array} \right\} + \left\{ \begin{array}{c} \text{unobservable effects in} \\ \text{rare top decay } t \to c(u)h \end{array} \right\}$$

WEDs: suppression by down-type Yukawas only

$$\left\{ \begin{array}{l} \text{small effects in } B_s \text{ mixing} \\ \text{small effects in } B_d \text{ mixing} \\ \text{large effects in kaon mixing} \end{array} \right\} + \left\{ \begin{array}{c} \text{promising corrections to} \\ \text{rare top decay } t \to c(u)h \end{array} \right\}$$

RARE TOP DECAYS IN WEDS

- Due to compositeness of top, huge enhancements relative to SM possible in t → ch for low KK scales. Still challenging at LHC



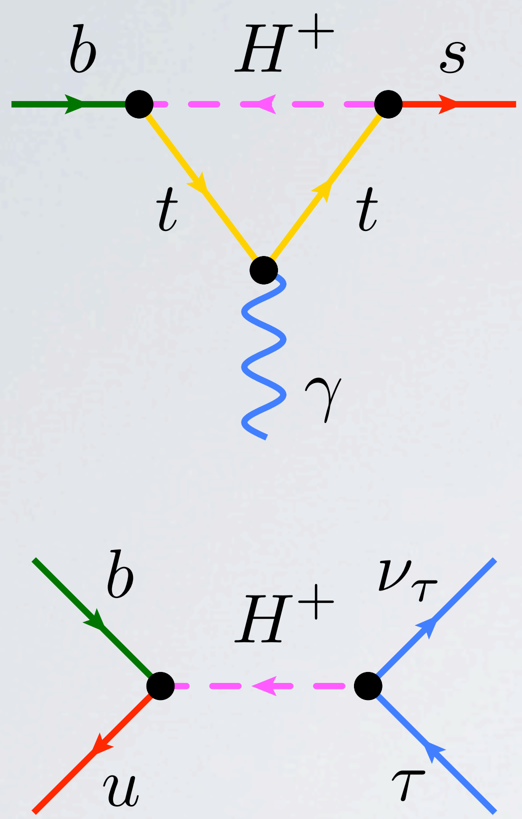
minimum of $6.5 \cdot 10^{-5}$ for 3σ discovery by LHC, 100 fb^{-1}

95% CL limit of $4.5 \cdot 10^{-5}$ from LHC, 100 fb^{-1}

consistent with all flavor constraints

[Agashe *et al.*, hep-ph/0606293; Casagrande *et al.*, arXiv:0807.4537, arXiv:1005.4315]

FCNC CONSTRAINTS ON 2HDM-II

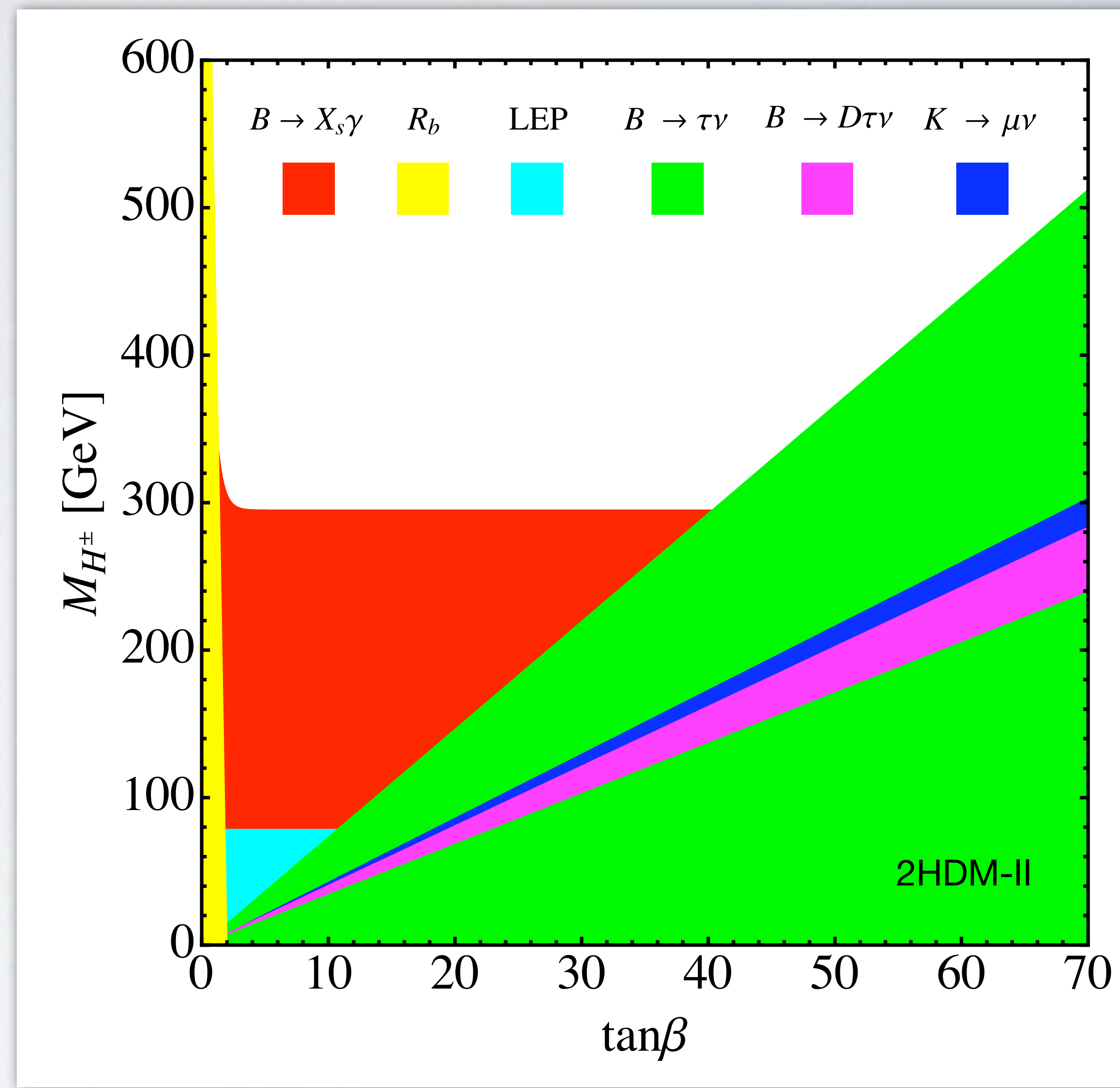


2HDM-II diagrams

$$\frac{m_t^2}{M_{H^\pm}^2} \ln \frac{m_t^2}{M_{H^\pm}^2}$$

$$\tan^2\beta \, \frac{m_B^2}{M_{H^\pm}^2}$$

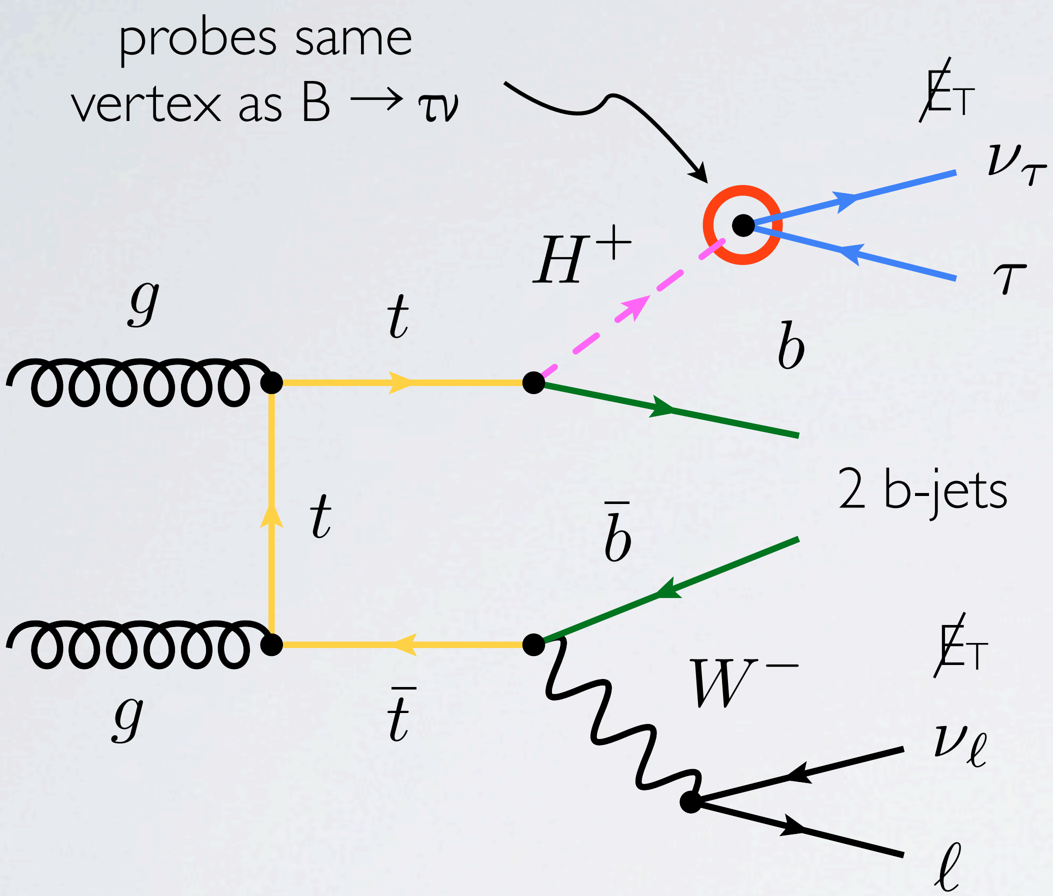
$M_{H^\pm}$ dependence of amplitude

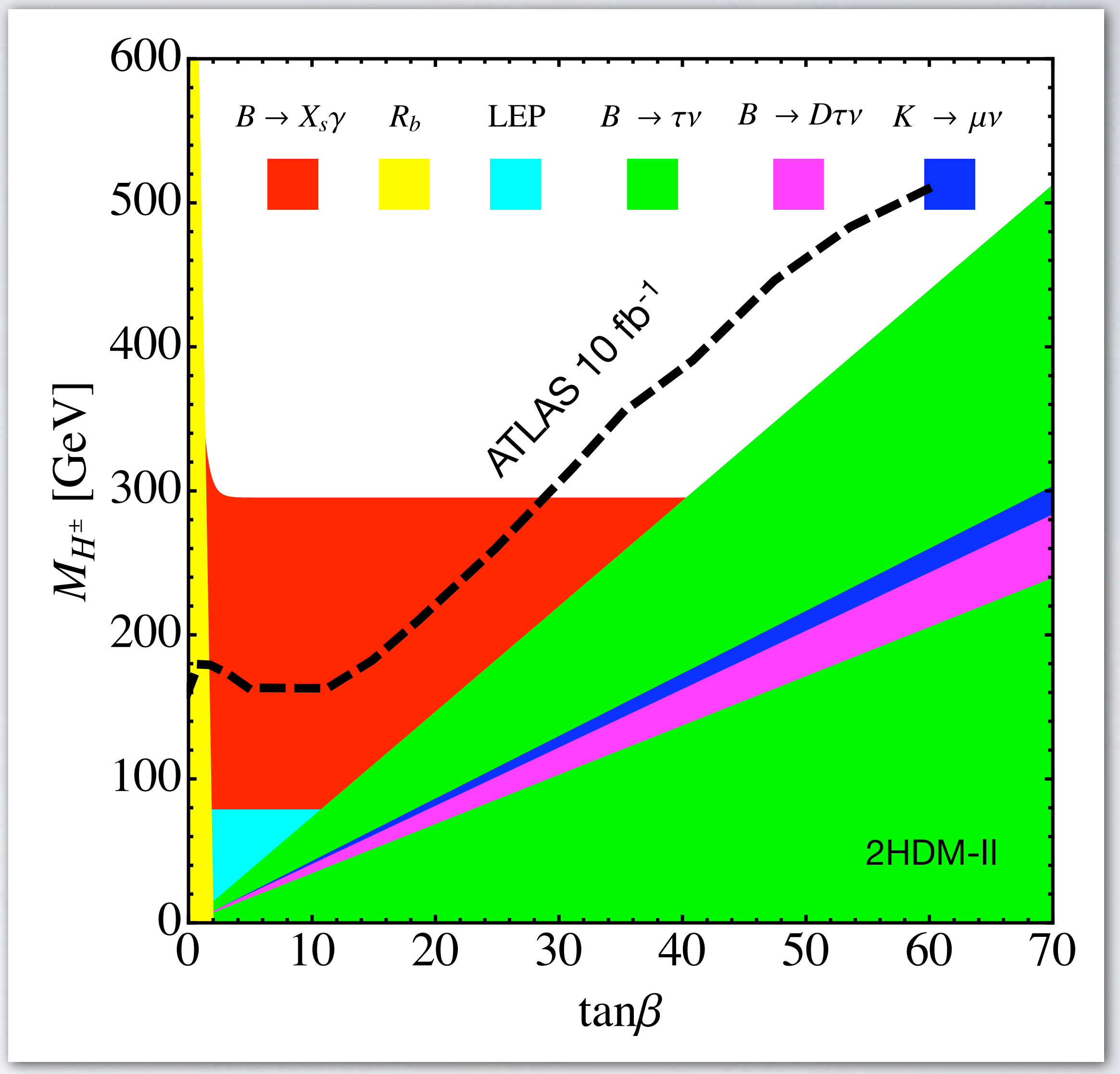


- Including the available flavor data ($B \to X_s\gamma$, $B \to \tau\nu$, $B \to D\tau\nu$ & $K \to \mu\nu$) disfavors a large portion of the parameter space in $\tan\beta - M_{H^\pm}$ plane of the 2HDM model of type II (2HDM-II)

[Misiak *et al.*, hep-ph/0609232; UH, arXiv:0805.2141]

HEAVY HIGGSES: FLAVOR & LHC INTERPLAY





- The current constraints on the 2HDM-II parameters that follow from flavor physics are comparable & thus complementary to the expected 95% CL exclusion limits of the LHC from $gg/gb \to t(b)H^+$, $H^+ \to \tau\nu/tb$

[Robertson, talk SuperB Physics Workshop, Warwick; ATLAS Collaboration, arXiv:0901.0512]

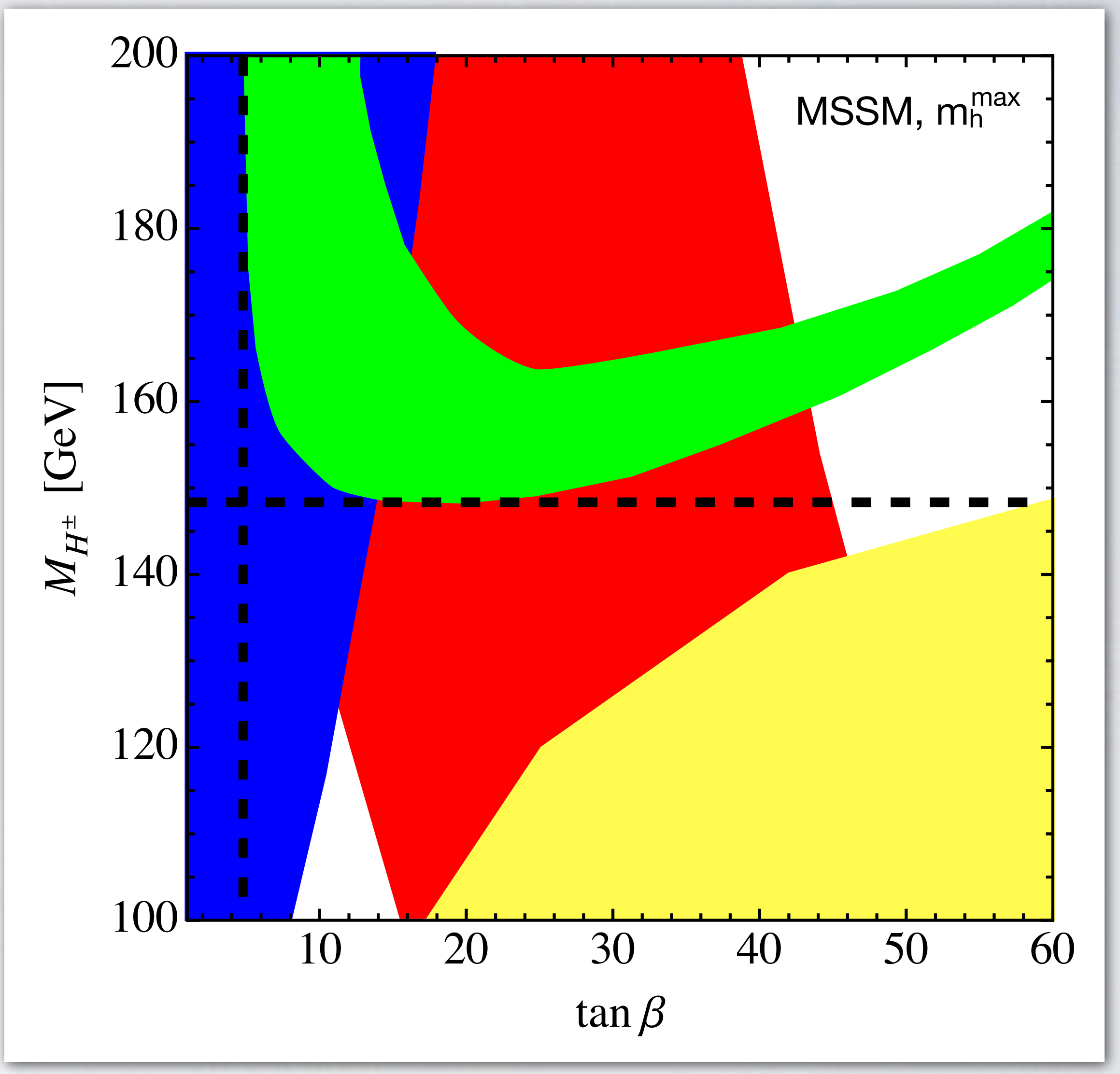
HEAVY HIGGSES: 2011 LHC DATA

$m_h^{\max}$ scenario:

$$M_{\text{SUSY}} = X_t/\sqrt{6} = 1\,\text{TeV}$$
$$2M_1 = M_2 = -\mu = 200\,\text{GeV}$$
$$m_{\tilde{g}} = 800\,\text{GeV}$$

$B_s \to \mu^+\mu^-$ | $B \to X_s\gamma$

$m_h \in [120, 130]$ GeV | CMS, 1 fb^{-1}



- Assuming a Higgs signal (& invoking flavor constraints) allows to derive lower bounds tan$\beta \gtrsim 3$ & $M_{H^\pm} \gtrsim 150$ GeV. These limits are only weakly dependent on M_{SUSY} & stronger than direct exclusions from LHC

[CMS-HIG-11-008; Heinemeyer, Stal & Weiglein, arXiv:1112.3026]

MSSM: FLAVOR & HIGGS INTERPLAY

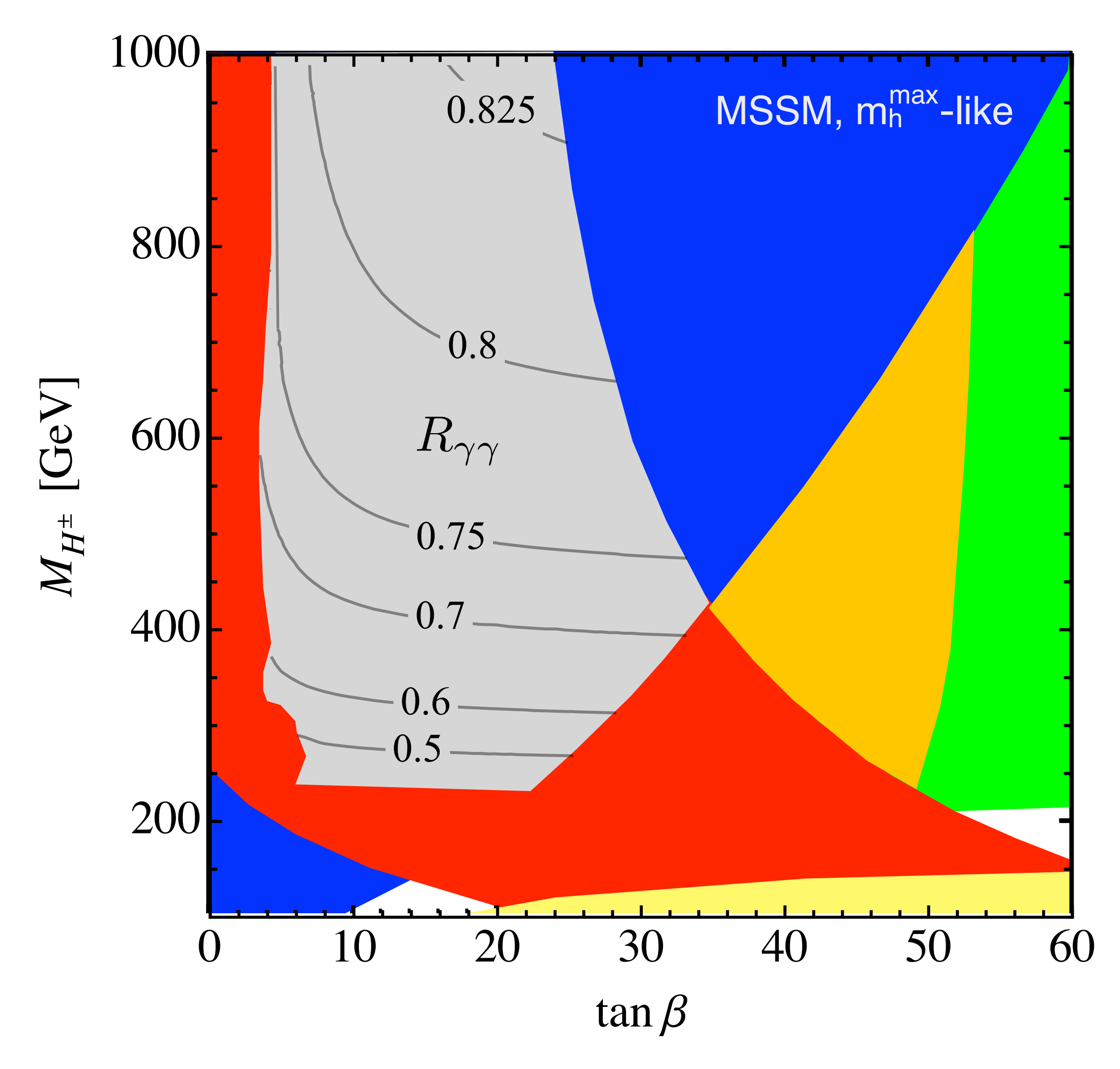
$\underline{m_h^{\text{max}}\text{–like scenario:}}$

$$M_{\text{SUSY}} = X_t/1.8 = 1\,\text{TeV}$$
$$2M_1 = M_2 = -\mu = 200\,\text{GeV}$$
$$m_{\tilde{g}} = 800\,\text{GeV}$$

■ $B_s \to \mu^+\mu^-$ ■ $B \to X_s\gamma$ ■ a_μ

■ $m_h \in [120, 130]\,\text{GeV}$ ■ $\text{CMS}, 1\,\text{fb}^{-1}$

$$R_{\gamma\gamma} = \frac{[\sigma(pp \to h)\text{Br}(h \to \gamma\gamma)]_{\text{MSSM}}}{[\sigma(pp \to h)\text{Br}(h \to \gamma\gamma)]_{\text{SM}}}$$

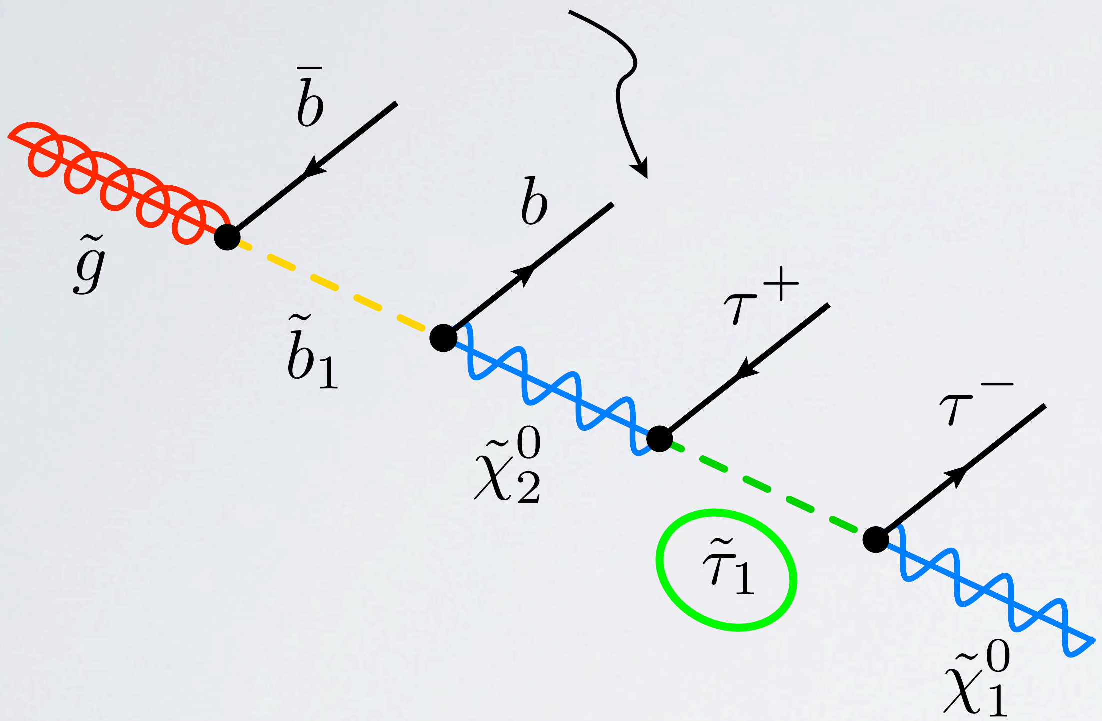


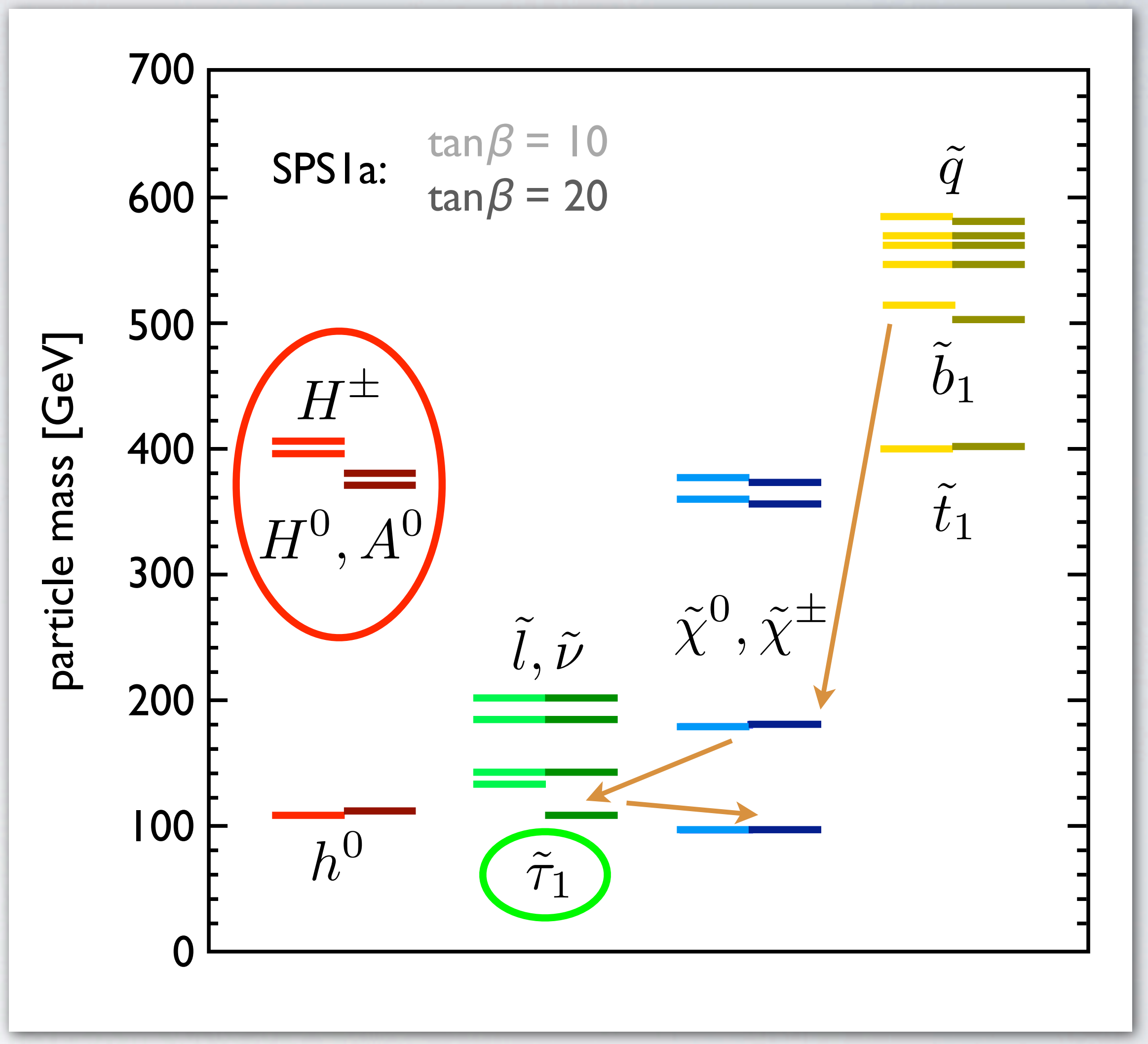
- In wide ranges of MSSM parameter space Higgs to di-photon signal depleted. Combination of Higgs measurements & indirect constraints provide powerful tool to tighten the MSSM parameter space

[see recently for example Hall, Pinner & Ruderman, arXiv:1112.2703; Carena *et al.*, arXiv:1112.3336]

MSUGRA: FLAVOR & LHC INTERPLAY

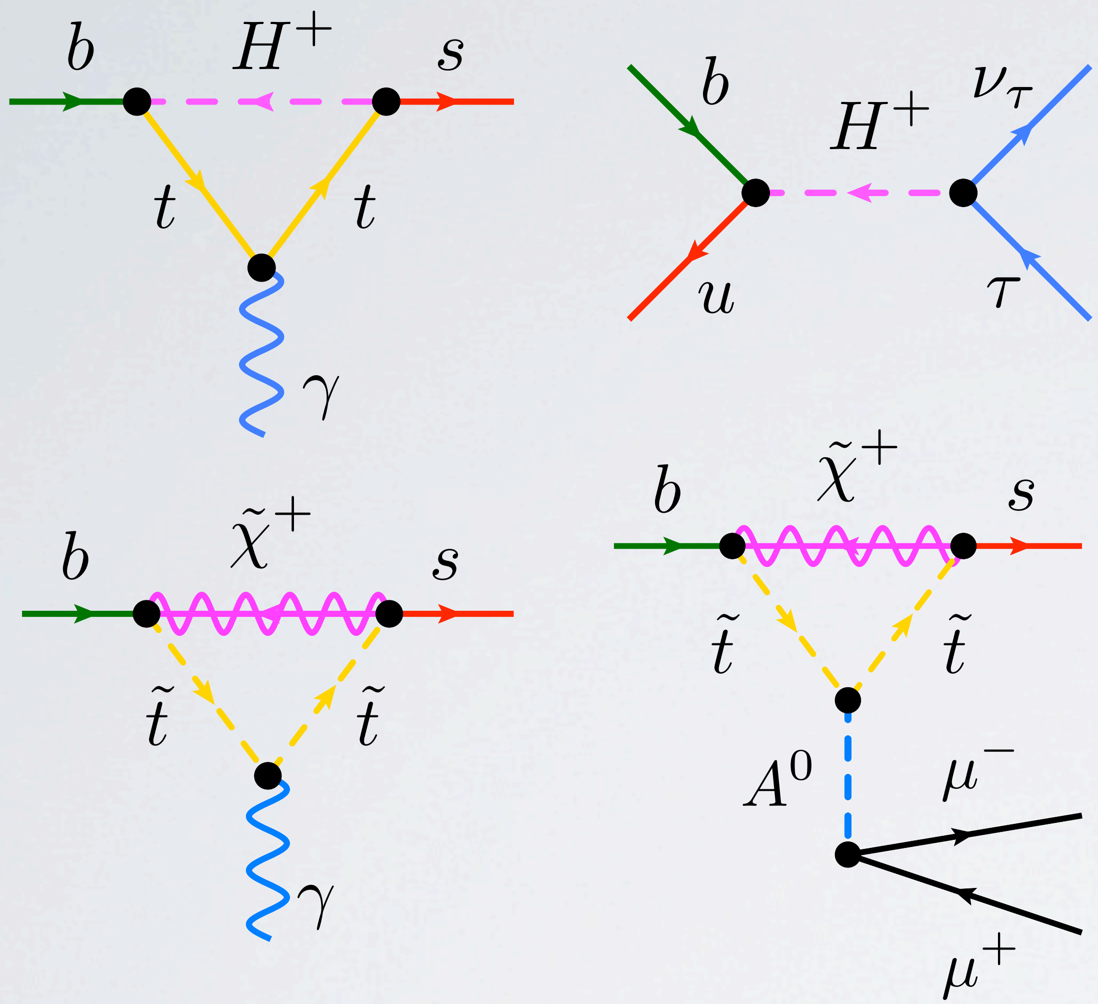
a gluino cascade-decay chain that can be used to reconstruct the mass of the lightest stau at the LHC



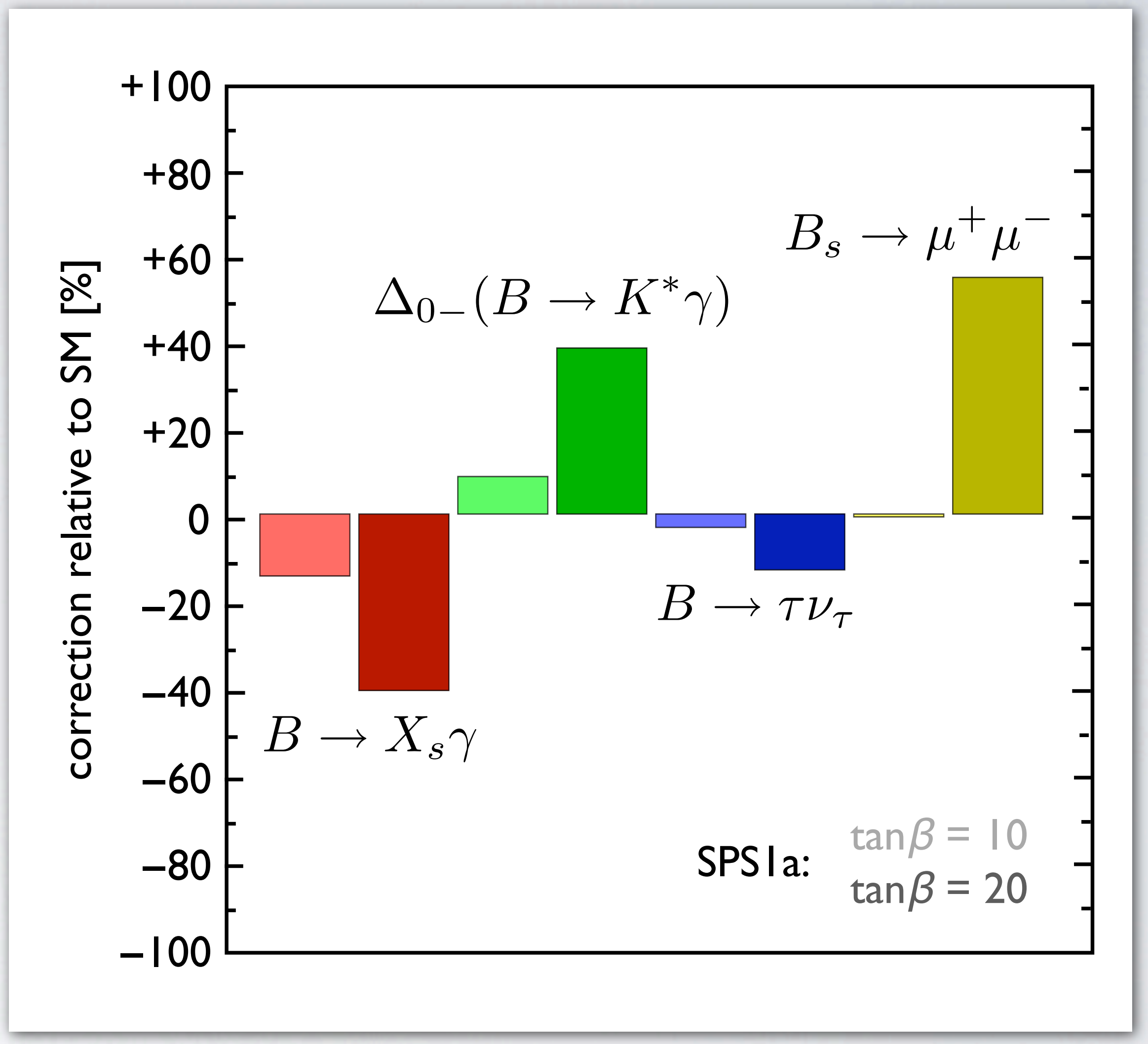


- In typical mSUGRA spectrum only masses of heavy Higgses & lightest stau show dependence on tanβ. SM decay modes of Higgses hard to detect at LHC & stau mass can be measured with precision of 20% at best. As a result, LHC sensitivity to tanβ rather restricted

MSUGRA: FLAVOR & LHC INTERPLAY



mSUGRA diagrams



- B physics is quite sensitive to tanβ (both branching fractions & isospin asymmetries). By measuring correlated shifts in observables one can determine tanβ with 10% accuracy. This exceeds LHC sensitivity based on discovery of stop, A^0 & lightest Higgs

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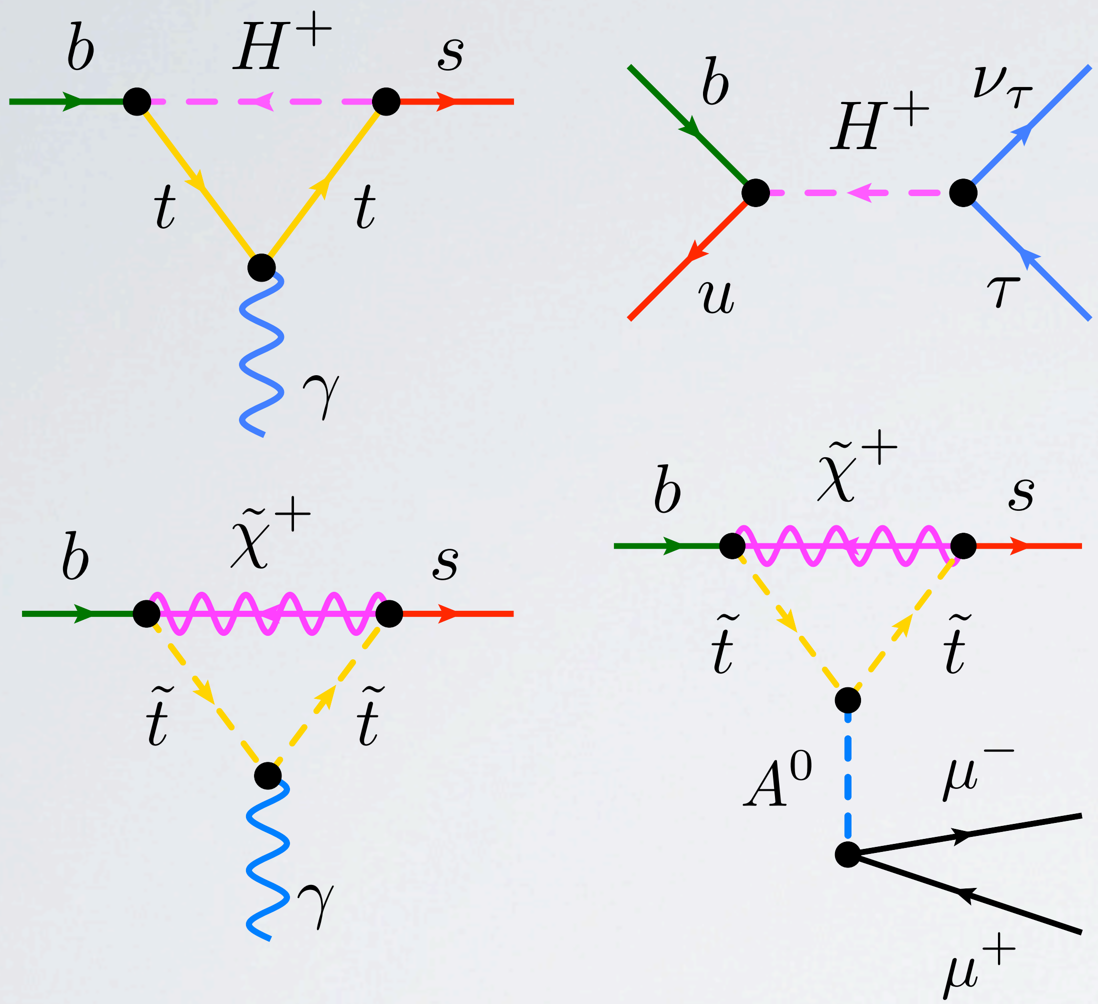

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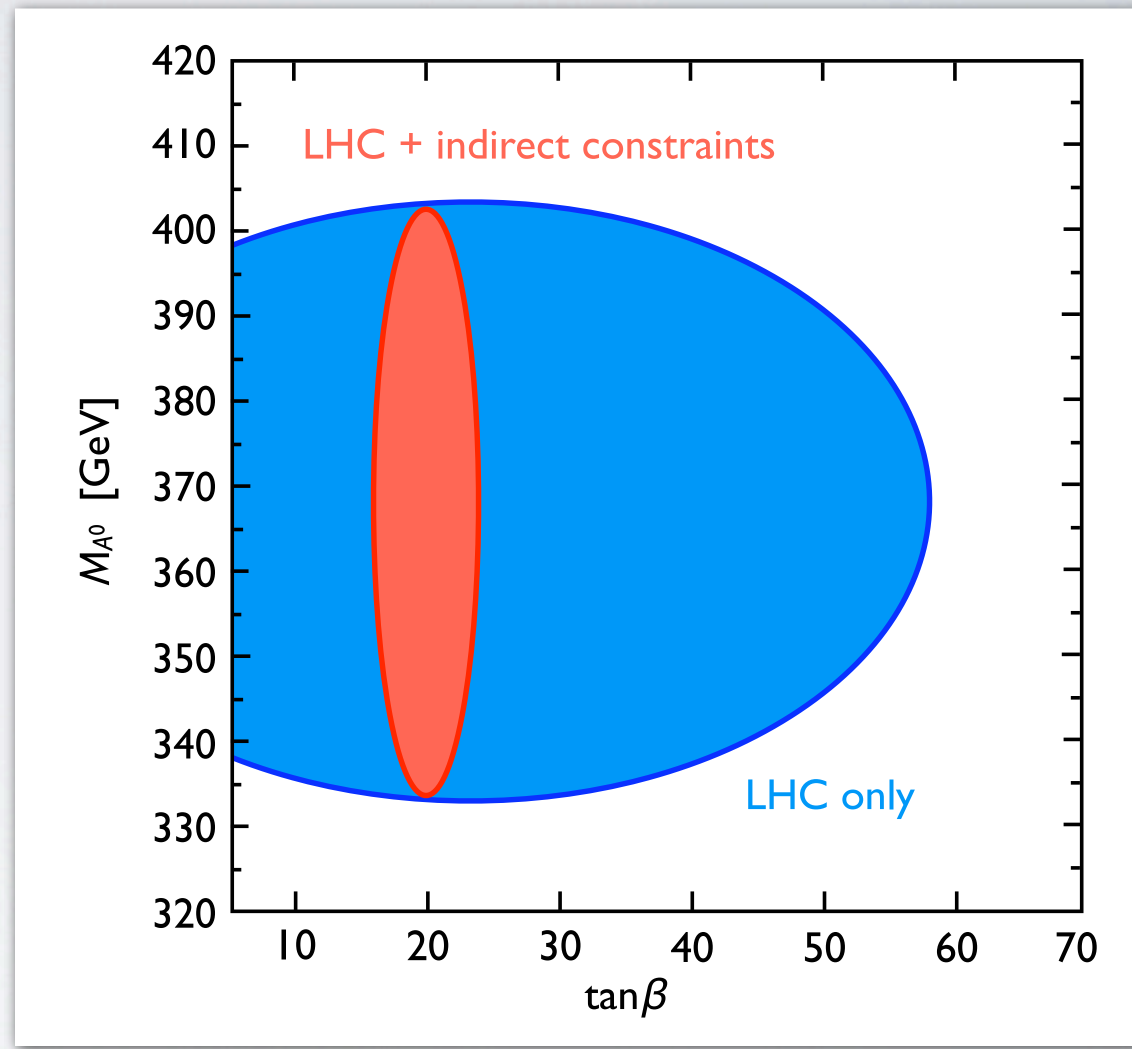

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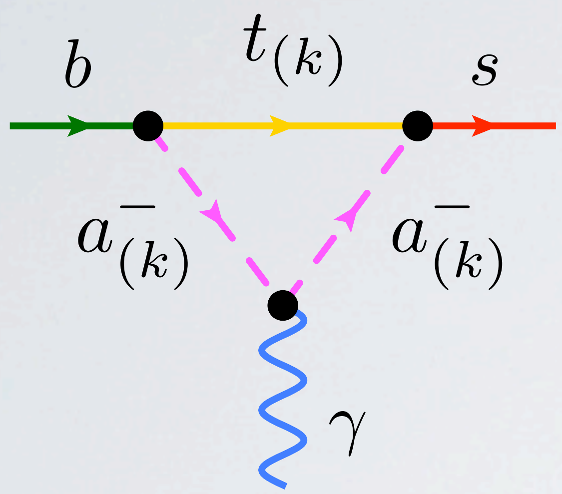
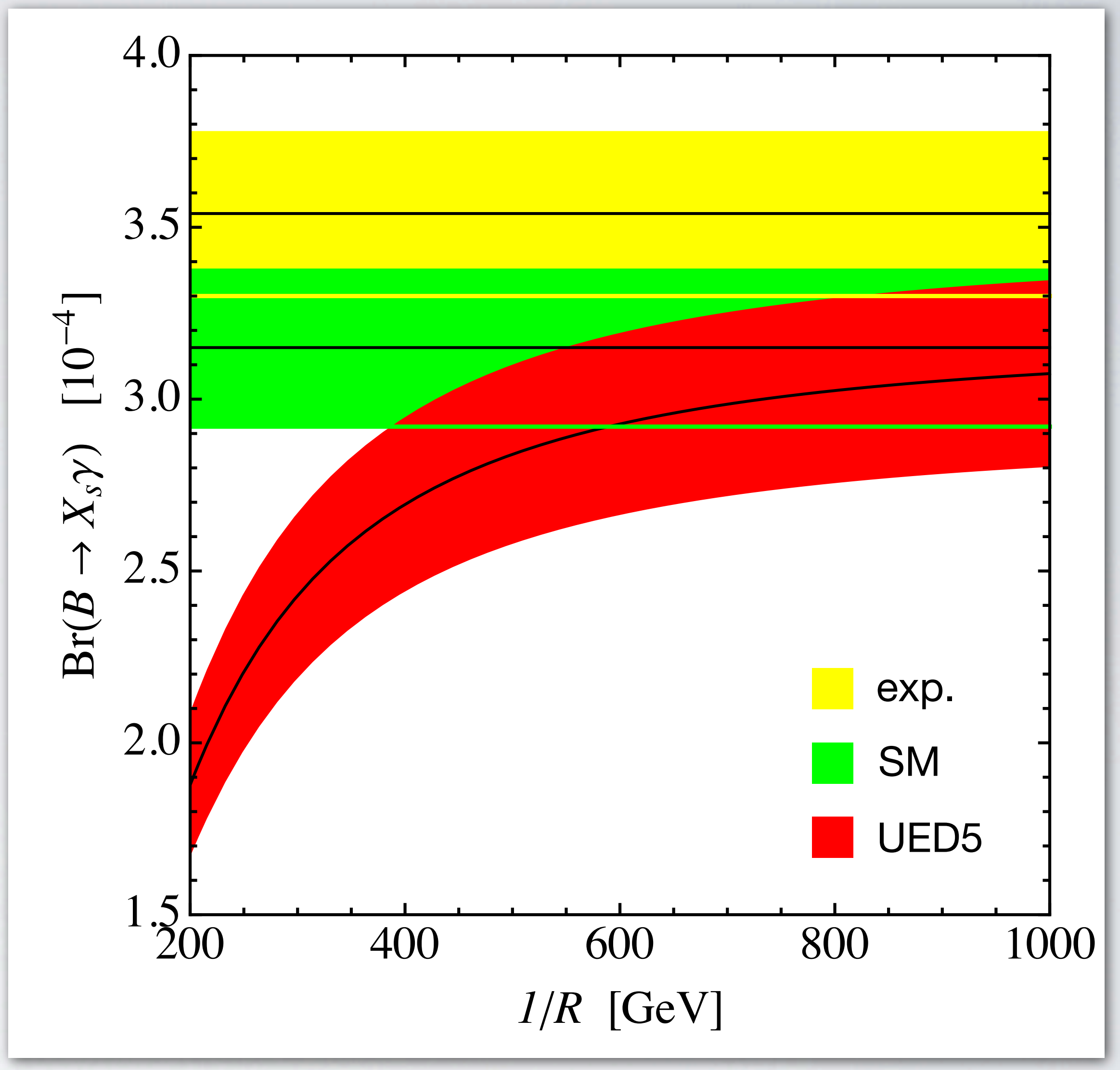
UED: FLAVOR & HIGGS INTERPLAY



UED5 photon
pinguin diagram

$$-\mathrm{sgn}(\mathrm{SM})\,\frac{m_t^2}{R^2}$$

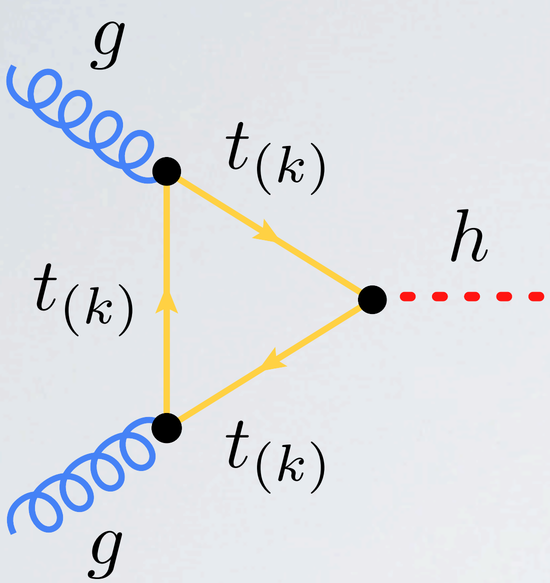
dependence of UED5
amplitude on KK scale



- In universal extra dimension (UED) models, the KK contributions always reduce $B \to X_s\gamma$ rate relative to SM. This feature implies stringent limits on KK scale of 1/R > 550, 650 GeV in 5D, 6D UED

[Buras *et al.*, hep-ph/0306158; UH & Weiler, hep-ph/0703064; Freitas & UH, arXiv:0801.4346]

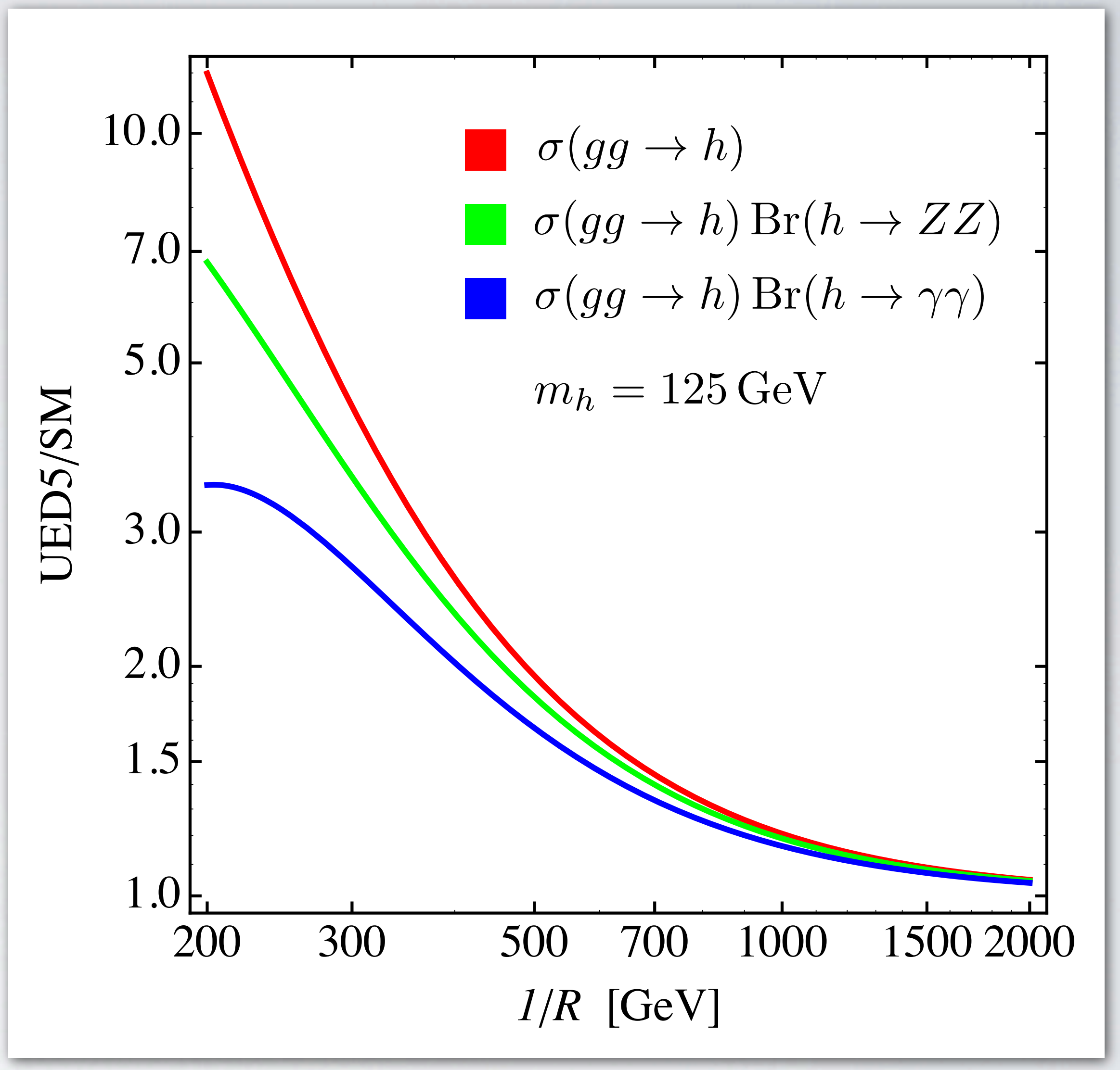
UED: FLAVOR & HIGGS INTERPLAY



UED5 gluon-gluon-fusion diagram

$$\mathrm{sgn(SM)}\,\frac{m_t^2}{R^2}$$

dependence of UED5 amplitude on KK scale



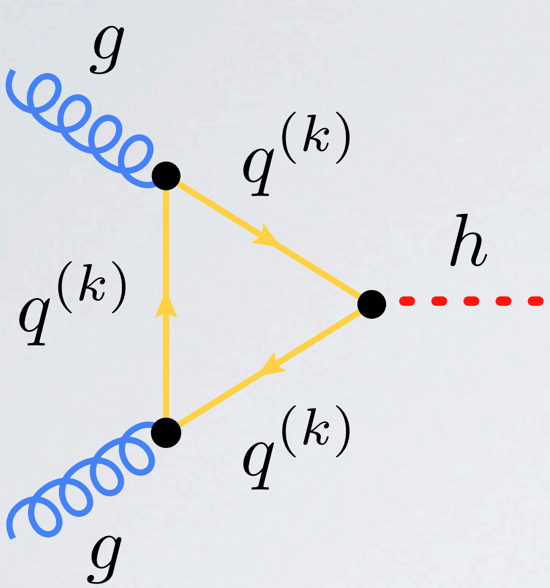
- Virtual effects in UED associated to top partners also alter notably the Higgs properties & enhance channels with respect to SM. Higgs physics has better potential to find evidence/constrain UED than flavor physics

[see for example Petriello, hep-ph/0204067]

CONCLUSIONS

- Like flavor physics, precision studies of Higgs properties allow to probe indirectly for beyond TeV mass scales, complementing the direct LHC searches for new physics
- It is possible to build viable SM extensions with minimal or next-to-minimal flavor structure that feature testable correlations between Higgs & flavor physics observables
- Higgs-mediated FCNCs would provide (if observed) a very interesting window on both the Higgs sector & on the structure of flavor-symmetry breaking

HIGGS PRODUCTION & DECAY IN WEDS



modification of top Yukawa

contribution from quark KK towers, proportional to multiplicity of states

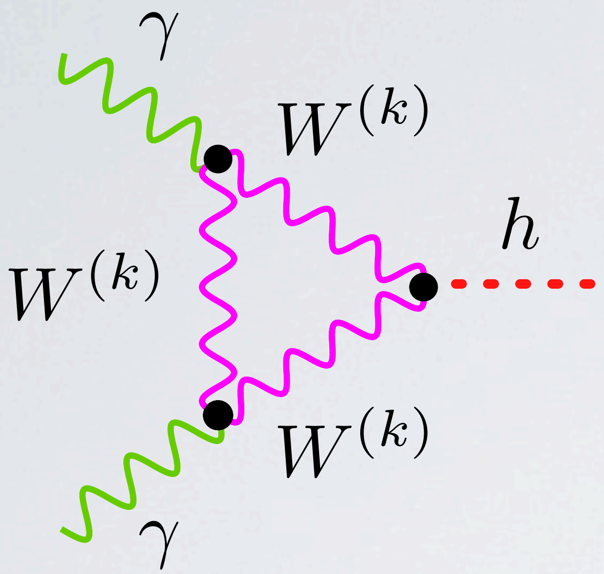
$$\kappa_g \approx \mathrm{Re}\,\kappa_t - \frac{v^2}{2M_{\mathrm{KK}}^2} \sum_q \mathrm{Tr}\left(Y_q^{5\mathrm{D}} Y_q^{5\mathrm{D}\dagger}\right)$$

$$\kappa_q \approx 1 - \frac{v^2}{M_{\mathrm{KK}}^2} \left\{ \frac{(Y_q^{5\mathrm{D}} Y_q^{5\mathrm{D}\dagger} Y_q^{5\mathrm{D}})_{33}}{3\,(Y_q^{5\mathrm{D}})_{33}} + \delta_{tq}\,|Y_q^{5\mathrm{D}}|^2 \left[(F_Q^3)^2 + (F_q^3)^2\right] \right\}$$

- In WEDs addressing hierarchy problem (which must be considered as effective theories with ultra-violet cutoff) ggh coupling suppressed. Dominant effect due to KK-quark loops which contribute universal

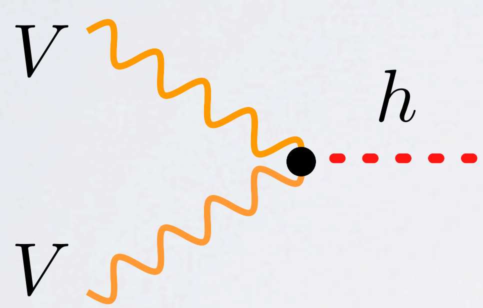
[Casagrande *et al.*, arXiv:1005.4315; Goertz, UH & Neubert, arXiv:1112.5099]

HIGGS PRODUCTION & DECAY IN WEDS



contribution from W boson & its KK tower

$$\approx -\frac{21}{8}(\kappa_W - 1)$$



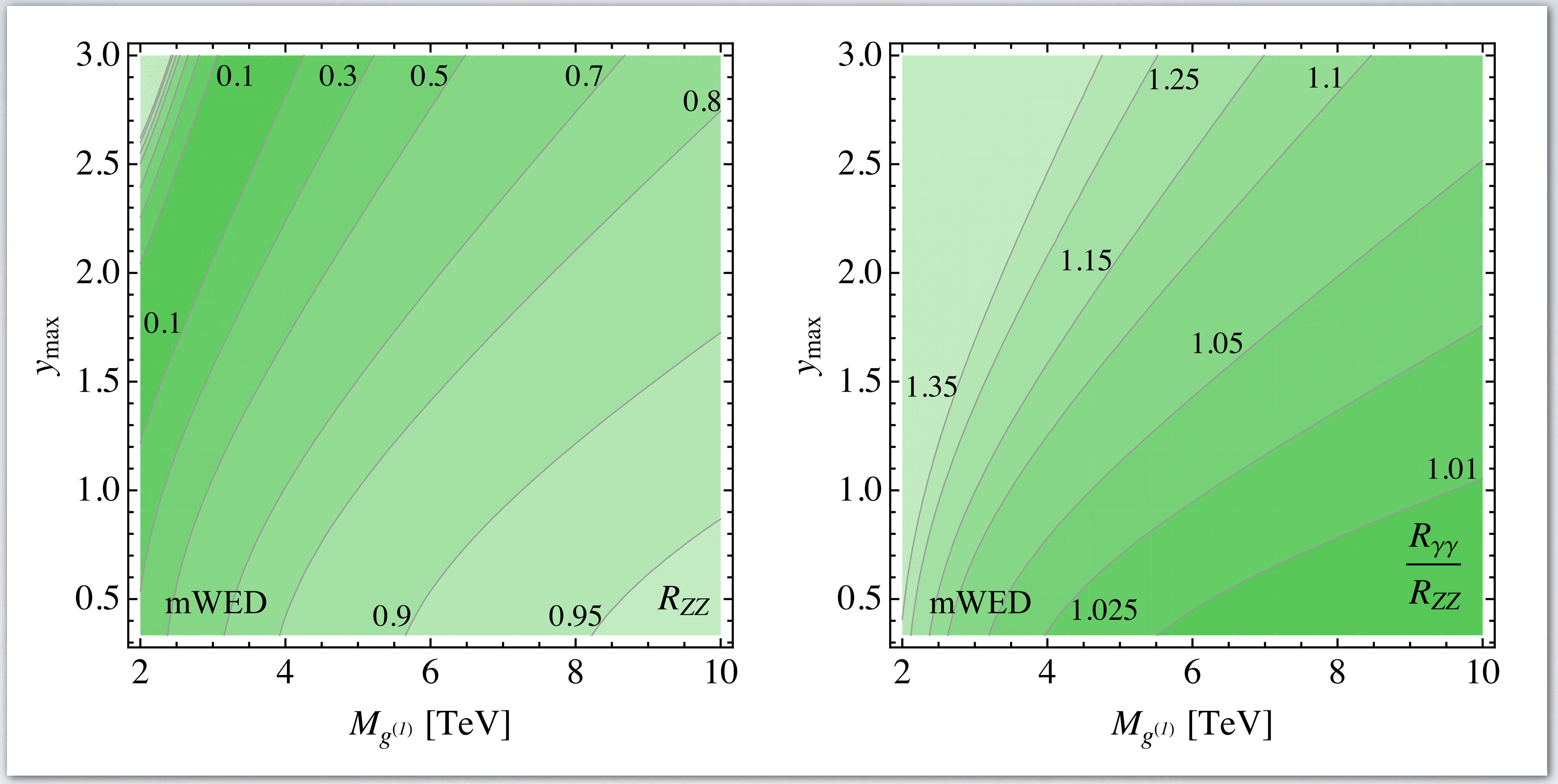
"volume" of extra dimension $\ln(M_P/M_W) \approx 37$

$$\kappa_V \approx 1 - \frac{v^2}{M_{\mathrm{KK}}^2}(L-1), \quad V = W, Z$$

- The contribution of W boson & its KK modes to effective $\gamma\gamma h$ vertex interfere destructively with SM. Gauge-boson-Higgs couplings reduced. Both types of corrections enhanced by extra-dimensional volume L

[Casagrande *et al.*, arXiv:1005.4315; Goertz, UH & Neubert, arXiv:1112.5099]

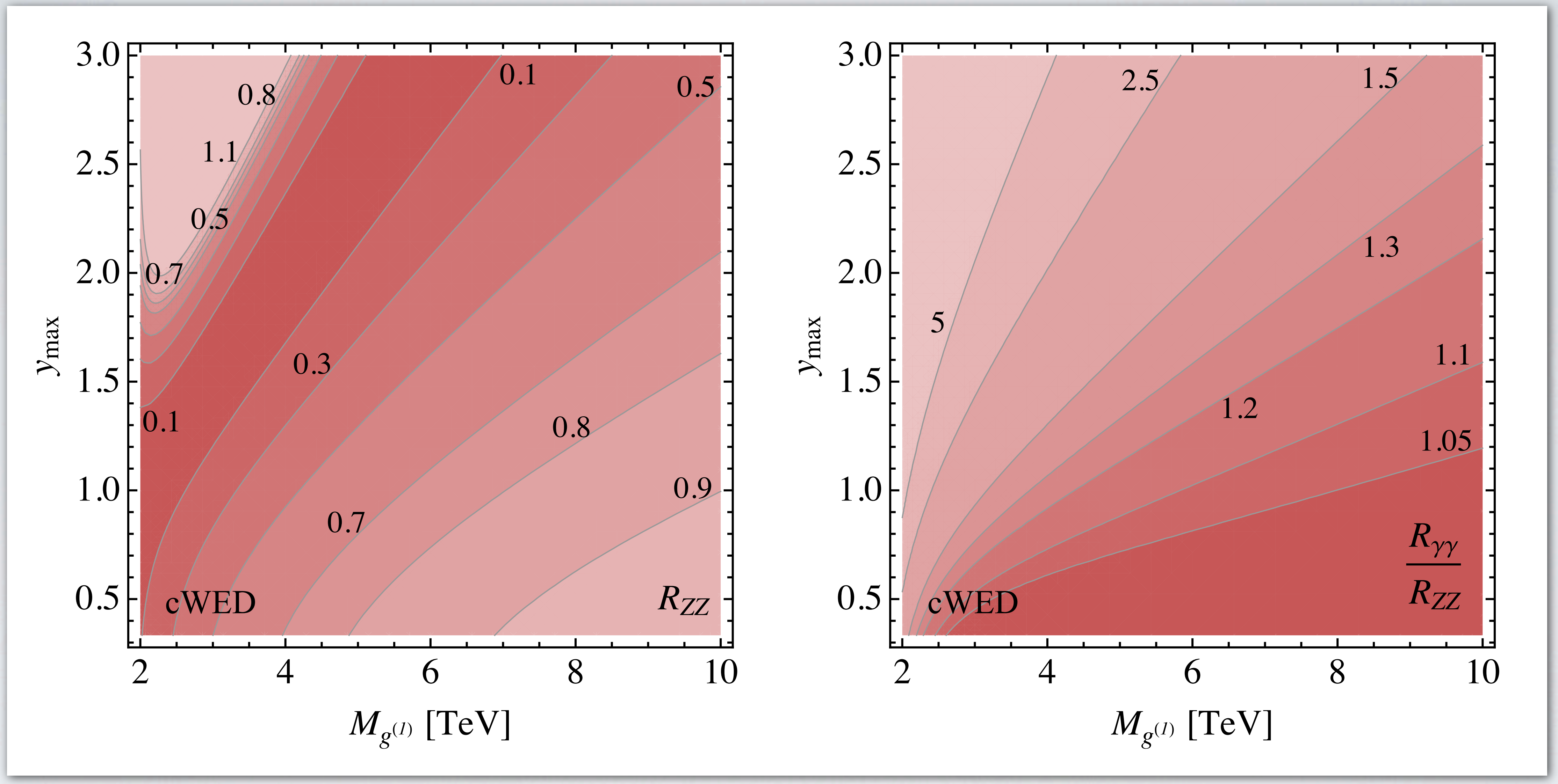
HIGGS PRODUCTION & DECAY IN WEDS



- Notable relative suppressions in minimal WED (mWED) model of products (R_{ff}) of total cross section & braching ratios $h \to ff$. Effects particularly large for $|Y_q^{5D}| = y_{max}$ close to perturbative bound $y_{max} = 3$

[Casagrande *et al.*, arXiv:1005.4315; Goertz, UH & Neubert, arXiv:1112.5099]

HIGGS PRODUCTION & DECAY IN WEDS



- Due to higher multiplicity of fermionic states in custodial WED model (cWED) shifts in R_{ff} even more pronounced. Measurements of Higgs properties can probe KK masses far beyond direct LHC reach of 3 TeV

[Casagrande *et al.*, arXiv:1005.4315; Goertz, UH & Neubert, arXiv:1112.5099]