On the Interplay Between Higgs & Flavor Physics

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Introduction

- In standard model (SM), flavor physics is linked to electroweak symmetry breaking & hence Higgs via Yukawa interactions
- Since both flavor-changing & Higgs couplings probe quantum structure of underlying theory, interesting to ask whether "Higgs-flavor connection" can survive even in presence of new dynamics
- Goal of this talk is to show that models with vector-like matter as well as minimal supersymmetric SM (MSSM) can feature testable correlations between Higgs & flavor observables

Part I: Vector-Like Quarks

based on Casagrande et al., 1005.4315; Goertz et al., 1112.5099; Carena et al., 1204.0008 & work in progress

Minimal Effective Theory of Flavor

- Effective Lagrangian

$$\mathcal{L} \sim mq\bar{Q} + MQ\bar{Q} + \lambda hQQ + \gamma h\bar{Q}\bar{Q} + \alpha hqQ$$

describing interactions of chiral (q) with vector-like quarks (Q) captures most important flavor-physics aspects of many theories of flavor such as Froggatt-Nielsen models, partial compositeness, warped extra dimensions, ...

[see recently for example Ziegler et al., 1105.3725]

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Will use idea of compositeness to illustrate effective framework ...

[Kaplan, Nucl. Phys. B365 (1991) 259]

Partial Compositeness

- In case of partial compositeness, hqQ coupling absent

$$\mathcal{L} \sim mq\bar{Q} + MQ\bar{Q} + \lambda hQQ + \gamma h\bar{Q}\bar{Q} + \cancel{\alpha hqQ}$$

since q is an elementary field that does not couple to strong sector, which includes (at least†) composite Q & h fields

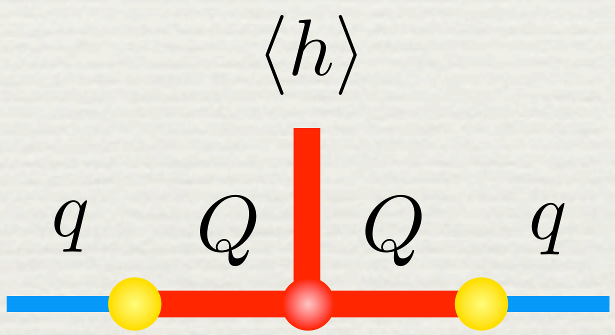
†presence of additional composite states introduces model dependence

Partial Compositeness

- Although hqQ coupling absent

$$\mathcal{L} \sim mq\bar{Q} + MQ\bar{Q} + \lambda hQQ + \gamma h\bar{Q}\bar{Q} + \alpha \cancel{hq}Q$$

mass term for q arises from mixing with strong sector

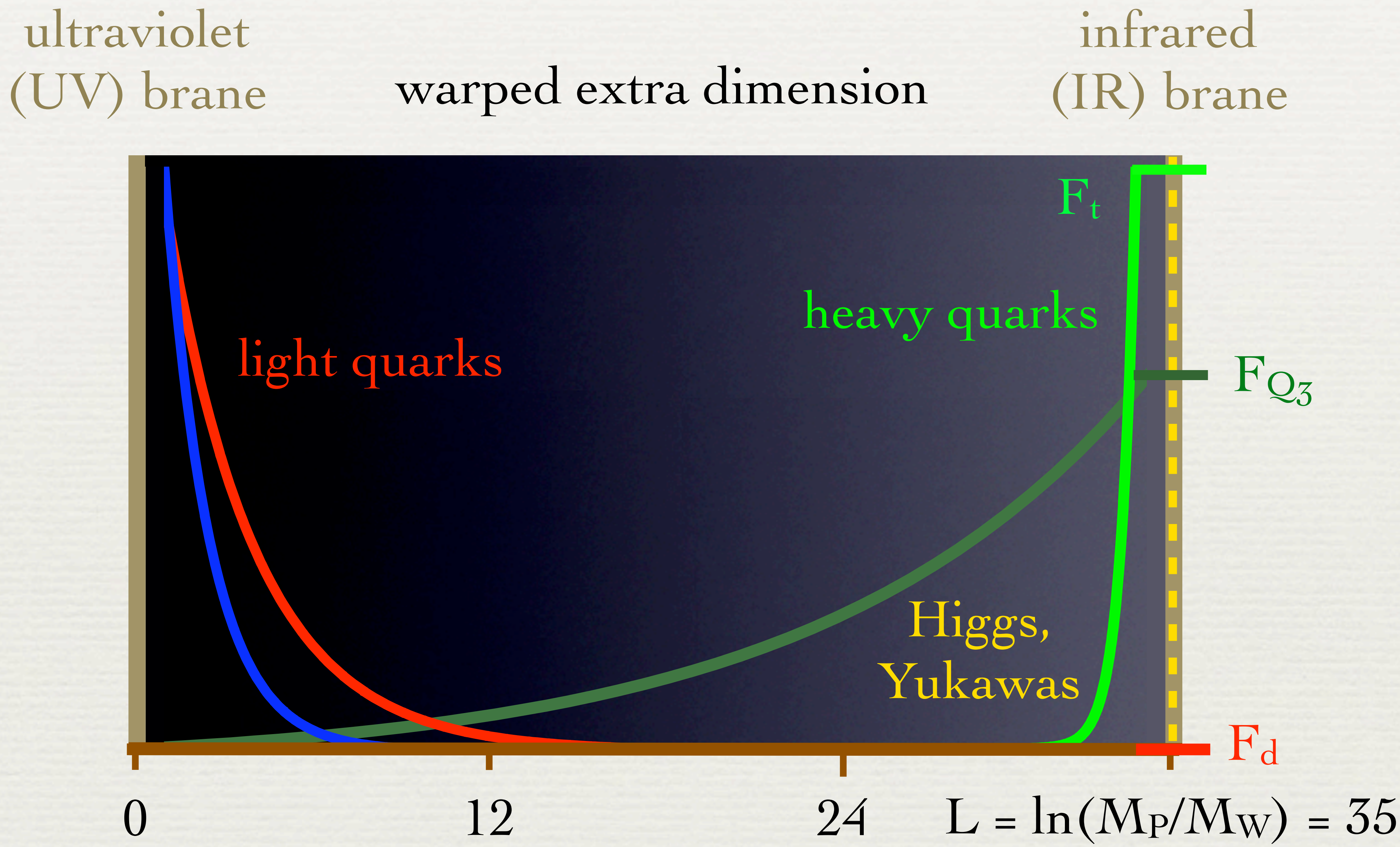


$$m_q \sim v\lambda \frac{m^2}{M^2}$$

Mechanism gives neat explanation of SM flavor puzzle in terms of anarchic Yukawa couplings λ & hierarchy between m & M

$$\lambda = \mathcal{O}(1)\,, \qquad \epsilon = \frac{m}{M} \ll 1$$

Geometrical Sequestering



- In warped scenarios, role of ε is played by overlap F = exp(-Lc) of quark profile with IR brane, where c is bulk mass parameter

Flavor Anarchy

- Full anarchic description of SM quark mass & mixing hierarchies involves 3 generations (i = 1,2,3) of chiral quarks (f = d,u) with a vector-like pair of heavy quarks each (F =D,U)†

$$f_R^i, q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \;, \quad F_R^i, F_L^i, Q_R^i = \begin{pmatrix} U_R^{Qi} \\ D_R^{Qi} \end{pmatrix}, Q_L^i = \begin{pmatrix} U_L^{Qi} \\ D_L^{Qi} \end{pmatrix}$$

& following interaction terms

$$-\mathcal{L} = h\lambda_{ij}^D \bar{Q}_L^i D_R^j + \tilde{h}\gamma_{ij}^D \bar{Q}_R^i D_L^j + M_{ij}^D \bar{D}_L^i D_R^j + M_{ij}^Q \bar{Q}_R^i Q_L^j$$
$$+ m_{ij}^D \bar{D}_L^i d_R^j + m_{ij}^Q \bar{Q}_R^i q_L^j + (D \leftrightarrow U, h \leftrightarrow \tilde{h}) + \text{h.c.}$$

involving both Yukawa couplings of "right" & "wrong" chirality

†protection of T & Z → b$\bar{\text{b}}$ calls for enhanced gauge & fermionic sector

Quark Masses & Mixings

- To leading order, Yukawa couplings of "wrong" chirality irrelevant in generation of quark mass & mixing hierarchies:

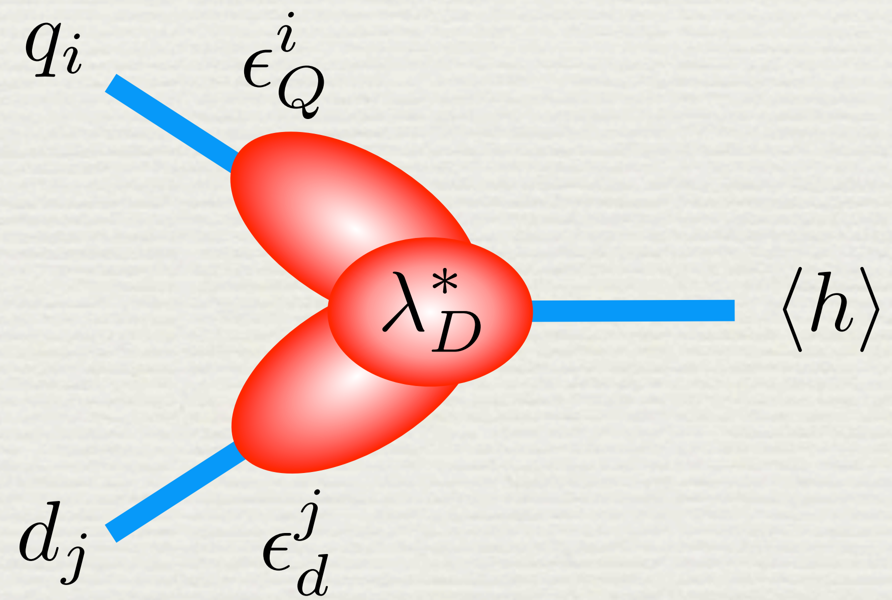
$$(y_d)_{ij} = \epsilon^i_Q \lambda^D_{ij} \epsilon^j_d \sim \lambda^*_D \epsilon^i_Q \epsilon^j_d, \qquad (y_u)_{ij} = \epsilon^i_Q \lambda^U_{ij} \epsilon^j_u \sim \lambda^*_U \epsilon^i_Q \epsilon^j_u$$

with (A = Q,D,U)

$$\epsilon^i_A \approx \frac{m^i_A}{M^i_A}$$

$$\epsilon^3_A \gg \epsilon^2_A \gg \epsilon^1_A$$

$$\lambda^*_{D,U} = \mathcal{O}(1) \text{ complex}$$



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After diagonalization quark masses & mixings are given by†

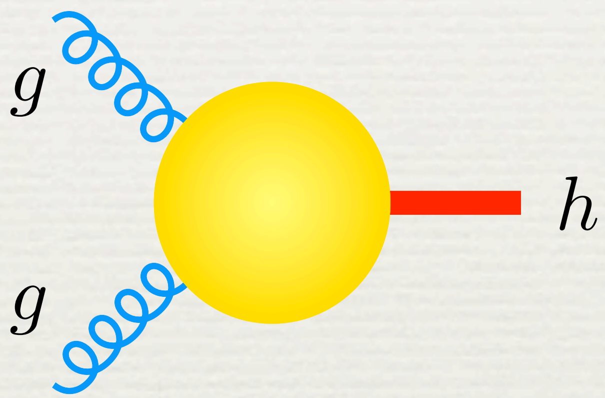
$$m_d^i \sim v\lambda_D^* \epsilon_Q^i \epsilon_d^i$$
$$m_u^i \sim v\lambda_U^* \epsilon_Q^i \epsilon_u^i$$

$$V_{ij} \sim \begin{cases} \dfrac{\epsilon_Q^i}{\epsilon_Q^j}, & i \leq j \\ \dfrac{\epsilon_Q^j}{\epsilon_Q^i}, & i > j \end{cases}$$

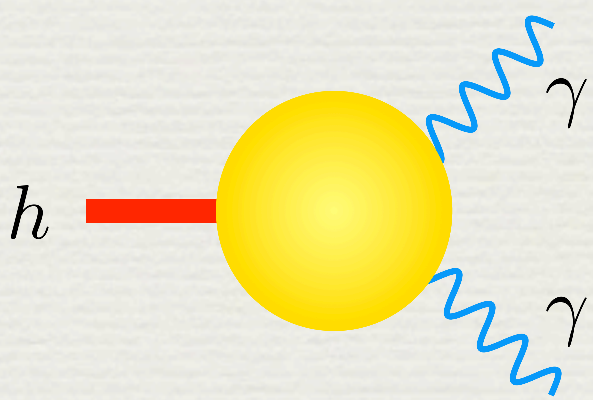
†CP violation of O(1), but exact amount to first order independent of ε

Higgs-Boson Production & Decay

- In view of large multiplicity of colored, fermionic states with O(1) couplings to composite sector, expect changes in both production cross section & branching ratios of Higgs boson relative to SM:



$$R_h = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} = (1 + \kappa_g)^2$$



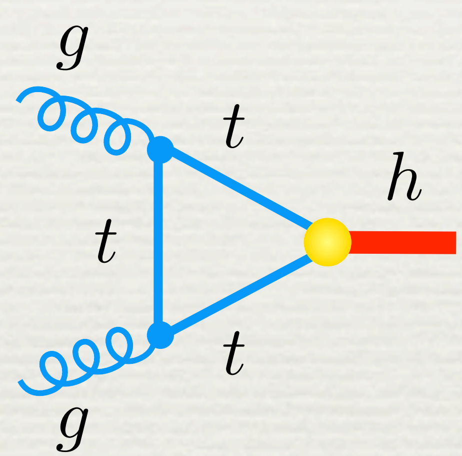
$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1 + \kappa_\gamma)^2$$

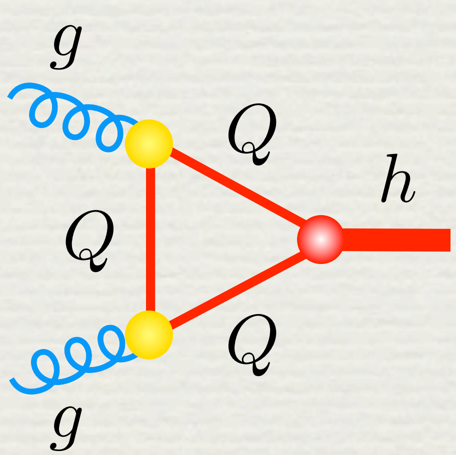
$$R_f = \frac{[\sigma(pp \to h){\rm Br}(h \to f)]}{[\sigma(pp \to h){\rm Br}(h \to f)]_{\rm SM}}\,, \quad f = WW, ZZ, \gamma\gamma$$

Higgs-Boson Production & Decay

- Effective hgg coupling receives correction from modification of top Yukawa & loops involving non-SM quarks. Soft-Higgs theorems relate non-SM loop contributions to logarithmic derivative of mass matrices M_q with respect to vacuum expectation value v:

$$\boxed{\kappa_g} \approx -2\,\frac{v^2}{M_U M_Q}\,\mathrm{Re}\left(\lambda_U^* \gamma_U^*\right)$$





$$+\,\mathrm{Re}\left[\sum_{q=d,u} \frac{1}{2}\left\{ v\,\frac{\partial}{\partial v}\ln\left[\det\left(\mathcal{M}_q^\dagger \mathcal{M}_q\right)\right]\right\}\right]$$

[see for example Spira et al., hep-ph/9504378; Kniehl & Spira, hep-ph/9505225]

Higgs-Boson Production & Decay

- Yukawa couplings of "wrong" chirality play crucial role in gluon fusion Higgs-boson production. In fact, each non-SM quark gives same correction regardless of mass of corresponding SM partner. $gg \to h$ hence highly sensitive to size & structure of quark sector

$$\kappa_g \approx -2\,\frac{v^2}{M_U M_Q}\,\mathrm{Re}\left(\lambda_U^* \gamma_U^*\right)$$

$$-\sum_{A=D,U} \frac{v^2}{M_A M_Q}\,\mathrm{Re}\left[\mathrm{Tr}\left(\lambda_A \gamma_A^\dagger\right)\right]$$

[see also Azatov et al., 1006.5939]

Higgs-Boson Production & Decay

- Result for effective hγγ vertex derives from that of loop-induced hgg coupling after including relevant charge factors. In terms of $A_W = 6.25$, describing W-boson effects for Higgs of 125 GeV, one obtains:

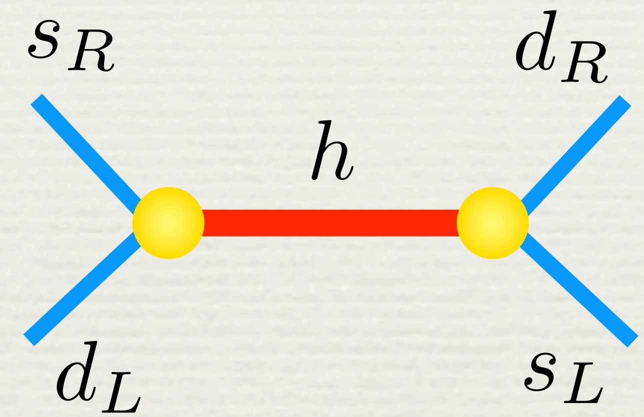
$$\kappa_\gamma \approx \frac{1}{A_W - 4/3} \left[\frac{8}{3} \frac{v^2}{M_U M_Q} \mathrm{Re} \left(\lambda_U^* \gamma_U^* \right) + \frac{1}{3} \frac{v^2}{M_D M_Q} \mathrm{Re} \left[\mathrm{Tr} \left(\lambda_D \gamma_D^\dagger \right) \right] + \frac{4}{3} \frac{v^2}{M_U M_Q} \mathrm{Re} \left[\mathrm{Tr} \left(\lambda_U \gamma_U^\dagger \right) \right] \right]$$

[see also Azatov et al., 1006.5939]

Higgs Flavor-Changing Neutral Currents

- In quark-flavor sector, most stringent bound on new-physics scale arises from CP violation of neutral kaons (ε_K). Corrections to left-right chirality-flipped operator are particularly dangerous due to chiral & renormalization group enhancements:

$$Q_{LR}^{sd} = (\bar{s}_R d_L)(\bar{s}_L d_R)$$



$$\mathrm{Im}\left(C_{LR}^{sd}\right) < 2.7 \cdot 10^{-11}\,\mathrm{TeV}^{-2}$$

[see for example UTfit, 0707.0636; Isidori et al., 1002.0900]

Higgs Flavor-Changing Neutral Currents

- Like contributions to Higgs-boson observables, dominant effects in ε_K also involve "wrong" Yukawas. Vector-like quark masses below TeV typically excluded:

$$C_{LR}^{sd} \sim \frac{4}{m_h^2}\,\frac{v^4}{M_D^2 M_Q^2}\,\epsilon_D^1\epsilon_Q^1\,\epsilon_D^2\epsilon_Q^2\,(\lambda_D^*)^4(\gamma_D^*)^2$$

$$\sim \frac{4}{m_h^2}\,\frac{v^2}{M_D^2 M_Q^2}\,m_d m_s\,(\lambda_D^*)^2(\gamma_D^*)^2$$

$$\Downarrow$$

$$\sqrt{M_D M_Q} > 2.6\,\text{TeV}\sqrt{\lambda_D^*\gamma_D^*} \sim 2.6\,\text{TeV}$$

[see also Agashe & Contino, 0906.1542; Azatov et al., 0906.1990; Ziegler et al., 1105.3725]

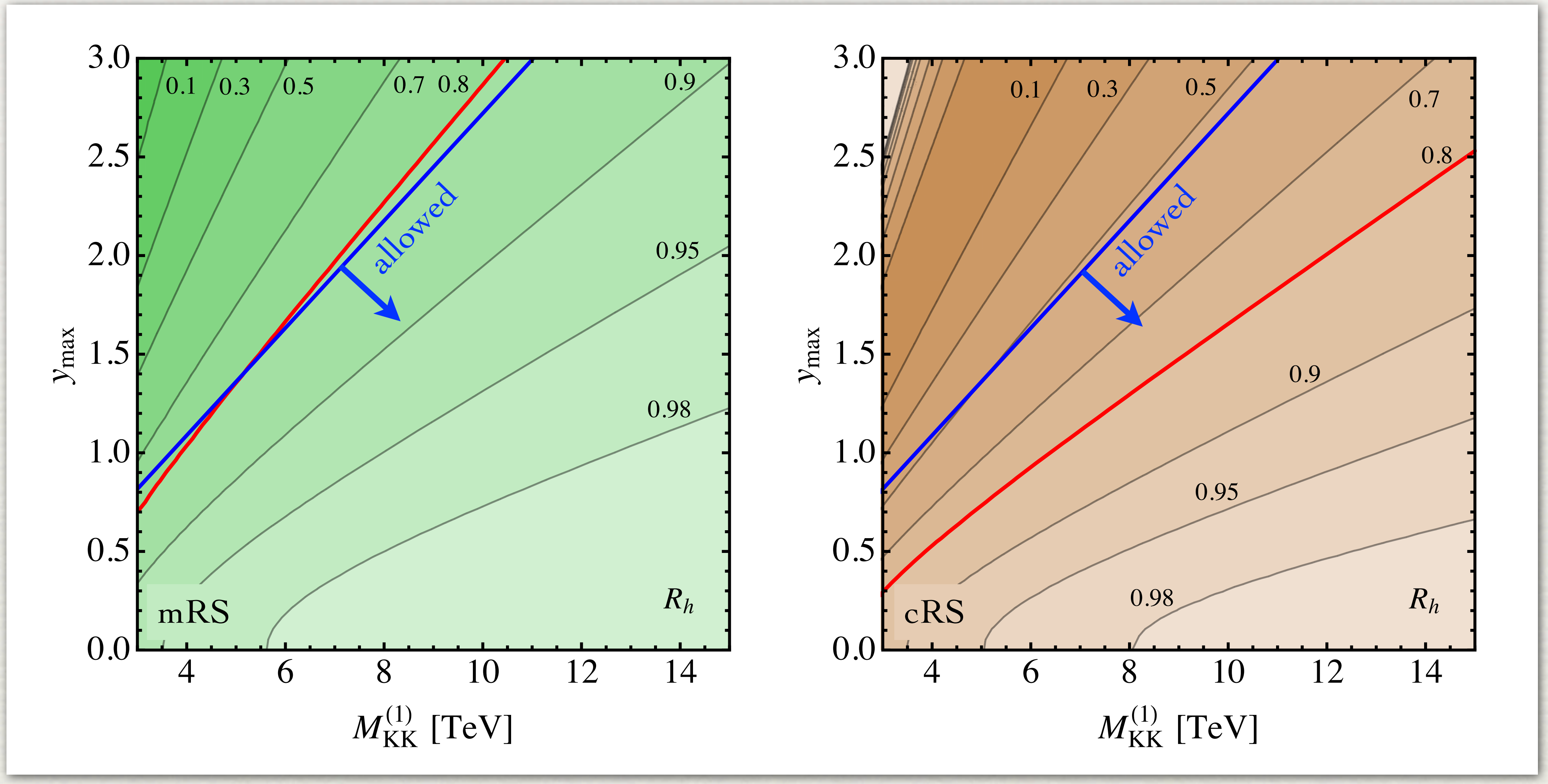
R_h or ε_K, Which Constraint is Stronger?

- In order to compare constraining power of gluon-fusion Higgs production & kaon mixing will make following assumptions:
  - vector-like quarks are of Kaluza-Klein type & arise from Randall-Sundrum (RS) setup with IR-localized Higgs sector
  - Yukawa couplings of "right" & "wrong" chirality are equal, $\lambda_D = \gamma_D$, $\lambda_U = \gamma_U$ & anarchic with elements smaller than y_{max}
  - future measurement of ratio of Higgs production $R_h \approx 0.8$, in line with model-independent analyses of latest LHC data
  - no accidental suppression of contribution to ε_K due to small or vanishing imaginary parts of C_{LR}^{sd}

Will show result for both minimal (mRS) & custodial model (cRS)

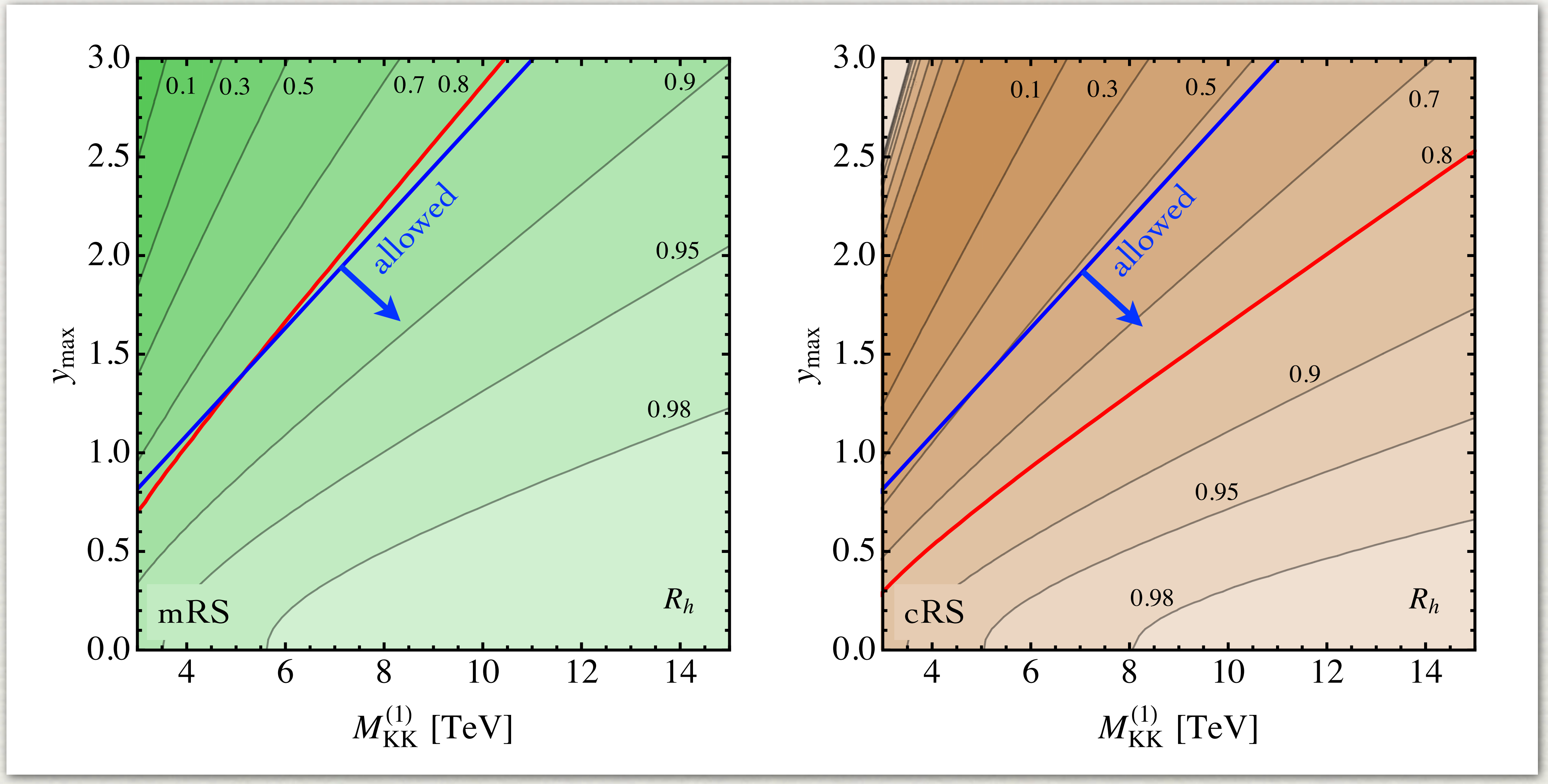
[see for example Carmi et al., 1202.3144; Azatov et al., 1202.3415; Espinosa et al., 1202.3697; ...]

R_h or ε_K, Which Constraint is Stronger?



- Both observables allow to probe scales above direct LHC reach of around 4 TeV. Depending on structure of quark sector either Higgs (red lines) or flavor physics (blue lines) more constraining

R_h or ε_K, Which Constraint is Stronger?



- If vector-like quarks responsible for effects in Higgs physics, should also see modified CP violation in kaon sector, because observables are driven by "wrong" Yukawas & cannot be fully decoupled

Part II: MSSM

based on work in progress with Mahmoudi

Anatomy of Higgs Mass in MSSM

- Tree-level mass of lightest CP-even Higgs maximized in decoupling limit $M_A >> M_Z$ with $\tan\beta = t_\beta >> 1$:

$$m_h^2 \approx M_Z^2\, c_{2\beta}^2 \left(1 - \frac{M_Z^2}{M_A^2}\, s_{2\beta}^2\right) \leq M_Z^2$$

- Large one-loop contributions arise from incomplete cancellation of top-quark & -squark loop

$$(\Delta m_h^2)_{\tilde{t}} \approx \frac{3\sqrt{2}G_F}{2\pi^2}\, m_t^4 \left[-\ln\left(\frac{m_t^2}{m_{\tilde{t}}^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

that can make m_h sufficiently heavy if $m_{\tilde{t}} = \sqrt{m_{\tilde{t}1}\, m_{\tilde{t}2}} >> m_t$ and/or $X_t = A_t - \mu/t_\beta$ close to maximal $|X_t| = \sqrt{6}\, m_{\tilde{t}}$. Two-loop effects break symmetry $X_t \leftrightarrow -X_t$ & allow larger value of m_h for $\mathrm{sgn}(X_t M_3) = +1$

Anatomy of Higgs Mass in MSSM

- For large t_β there are further contributions from sbottom & stau sector that can be relevant ($\tilde{f} = \tilde{b},\tilde{\tau}$):

$$(\Delta m_h^2)_{\tilde{f}} \approx -\frac{N_c^{\tilde{f}}}{\sqrt{2}G_F}\,\frac{y_f^4}{48\pi^2}\,\frac{\mu^4}{m_{\tilde{f}}^4}$$

where $N_c^{\tilde{b},\tilde{\tau}} = 3,1$. Corrections are negative & quartic in Higgsino mass μ. Their impact is minimized for $\mathrm{sgn}(\mu M_{3,2}) = +1$

[see for example Carena et al., hep-ph/9504316, hep-ph/9508343; Haber et al., hep-ph/9609331]

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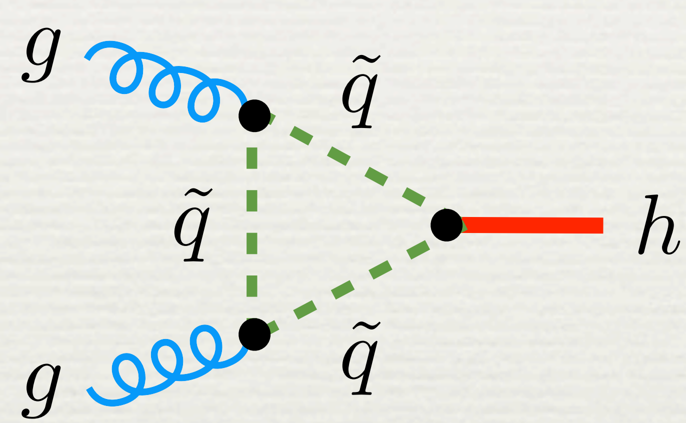
- Needless to say that in view of hints of Higgs at around 125 GeV MSSM is not very natural. Will be agnostic about issue & instead ask following question. Let's assume fine-tuned region of MSSM parameter space realized with $M_A \gg M_Z$ & t_β & trilinear term A_t large. Are there other observable consequences?

Dissecting Higgs Production

- Structure of MSSM corrections to gg → h & h → γγ can be easily understood by again studying soft-Higgs case. In decoupling limit one finds for stop & sbottom contributions to hgg vertex:

$$\kappa_{\tilde{q}} \approx \frac{1}{4}\, m_q^2\, \frac{\partial}{\partial m_q^2}\, \ln\left[\det\left(\mathcal{M}_{\tilde{q}}^2\right)\right]$$



$$\approx \begin{cases} \dfrac{m_t^2}{4}\left(\dfrac{1}{m_{\tilde{t}_1}^2} + \dfrac{1}{m_{\tilde{t}_2}^2} - \dfrac{X_t^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right), & \tilde{q} = \tilde{t} \\[2ex] -\dfrac{m_b^2 X_b^2}{4 m_{\tilde{b}_1}^2\, m_{\tilde{b}_2}^2}, & \tilde{q} = \tilde{b} \end{cases}$$

Dissecting Higgs Production

- Assuming degenerate stops & neglecting sbottom-loop effects, shift in Higgs production cross section hence approximately given by:

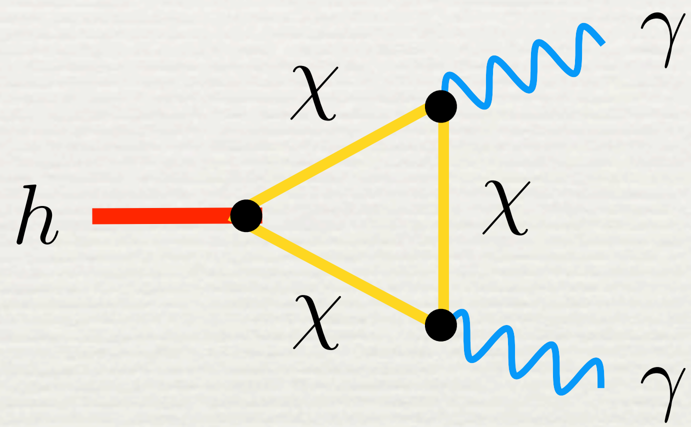
$$R_h \approx (1+\kappa_{\tilde{t}})^2 \approx \begin{cases} 1 + \dfrac{m_t^2}{m_{\tilde{t}}^2}\,, & X_t = 0 \\[2ex] 1 - 2\,\dfrac{m_t^2}{m_{\tilde{t}}^2}\,, & X_t = \sqrt{6}\, m_{\tilde{t}} \end{cases}$$

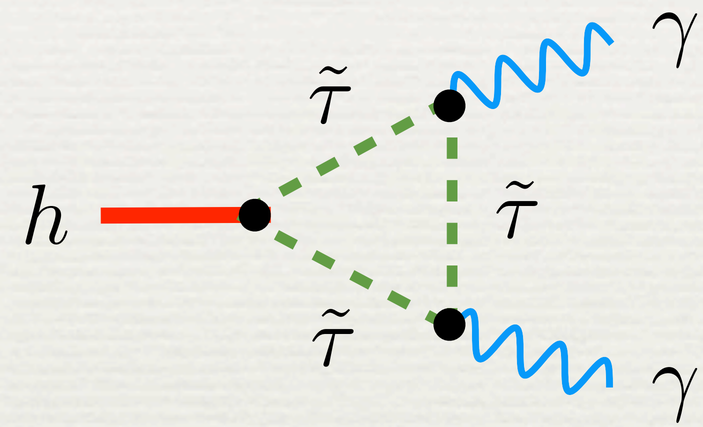
As Higgs-boson mass around 125 GeV calls for close to maximal mixing, natural to expect suppression of gg → h. In fact, this is exactly what happens in wide ranges of MSSM parameter space

[see for example Dermisek & Low, hep-ph/0701235; Cacciapaglia et al., 0901.0927]

Dissecting Higgs Decay to Diphotons

- For $M_A >> M_Z$, charged Higgs effects are strongly suppressed, but chargino & stau loops can have notable impact on diphoton rate:





$$\kappa_\chi \approx \mathrm{sgn}\left[\det\left(\mathcal{M}_\chi\right)\right]\ \frac{2}{t_\beta}\frac{M_W^2}{m_\chi^2}$$

$$\kappa_{\tilde{\tau}} \approx -\frac{m_\tau^2 X_\tau^2}{4m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

[see for example Djouadi et al., hep-ph/9612362; Carena et al., 1112.3336; 1205.5842]

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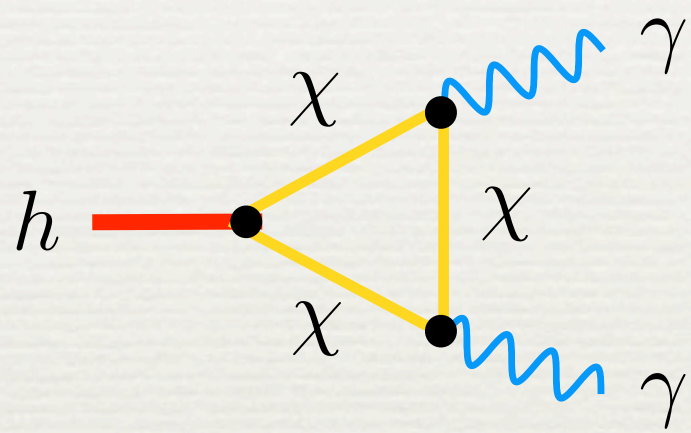
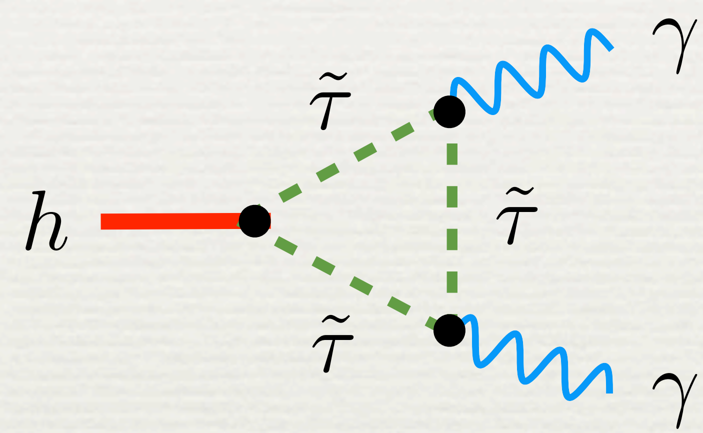




$$\kappa_\chi \approx \mathrm{sgn}\left[\det\left(\mathcal{M}_\chi\right)\right]\ \frac{2}{t_\beta}\frac{M_W^2}{m_\chi^2}$$

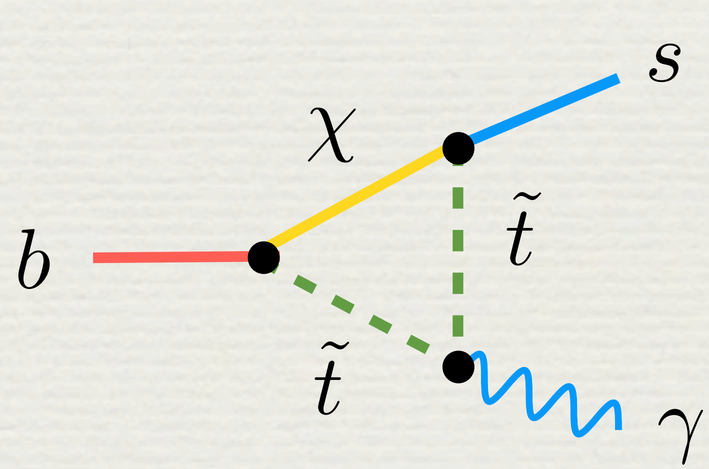
$$\kappa_{\tilde{\tau}} \approx -\frac{m_\tau^2 X_\tau^2}{4 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

Unlike chargino effects, stau loops not t_β suppressed. In fact, $R_\gamma > 1$ needs light stau with large mixing $X_\tau = A_\tau - \mu t_\beta$, which is most easily achieved for $t_\beta >> 1$ & μ significantly above weak scale

Anatomy of B → $X_s\gamma$

- In parameter region of interest, dominant MSSM contributions to inclusive radiative B decay stems from loops with stop & higgsino-like chargino:

$$R_{X_s} = \frac{\mathrm{Br}(B \to X_s\gamma)}{\mathrm{Br}(B \to X_s\gamma)_{\mathrm{SM}}} \approx 1 - 2.55\,\Delta C_7 + 1.57\,(\Delta C_7)^2$$



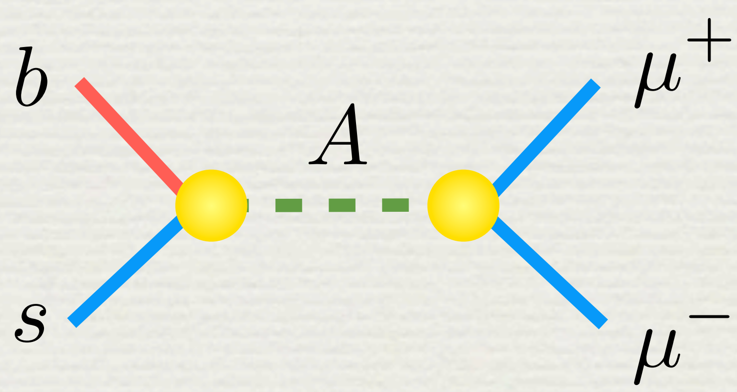
$$\Delta C_7^{\chi} \propto -\mu A_t\, t_\beta\, \frac{m_t^2}{m_{\tilde{t}}^4}$$

For $t_\beta = 50$, $m_{\tilde{t}} = |\mu| = 1$ TeV & $|A_t| = 2$ TeV, MSSM rate enhanced (suppressed) by around 20% relative to SM for $\mathrm{sgn}(\mu A_t) = +1$ (-1)

Anatomy of $B_s \to \mu^+\mu^-$

- In large-t_β regime, rare purely leptonic B_s decay receives dominant corrections from neutral Higgs double penguins:

$$R_{\mu^+\mu^-} = \frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1 - 13.2\, C_P + 43.8 \left(C_S^2 + C_P^2\right)$$



$$\Rightarrow \quad C_S \approx C_P \propto \mu A_t\, t_\beta^3\, \frac{m_t^2}{m_{\tilde{t}}^2}\, \frac{m_b m_\mu}{M_W^2 M_A^2}$$

Term linear in pseudoscalar coefficient C_P due to interference with semileptonic axial-vector SM contribution. Data prefers $C_P > 0$

[see for example Babu & Kolda, hep-ph/9900476]

Anatomy of $B_s \to \mu^+\mu^-$

- In fact, upper bound on branching ratio of $B_s \to \mu^+\mu^-$ translates into two-sided limit on product μA_t. For example, $R_{\mu^+\mu^-} < 1.3$ gives

$$-\frac{0.6}{\mathrm{TeV}^2} \lesssim \frac{\mu A_t}{m_{\tilde{t}}^2 M_A^2} \left(\frac{t_\beta}{50}\right)^3 \lesssim \frac{5.2}{\mathrm{TeV}^2}$$

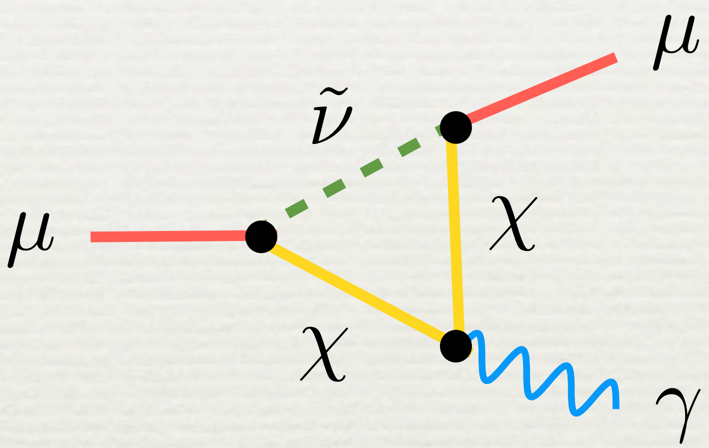
Inequality shows that for $\mathrm{sgn}(\mu A_t) = +1$ constraint from $B_s \to \mu^+\mu^-$ more easily evaded. For $\mu A_t > 0$ rate below SM. Taking

$$\frac{\mu A_t}{m_{\tilde{t}}^2 M_A^2} \left(\frac{t_\beta}{50}\right)^3 \approx \frac{2.3}{\mathrm{TeV}^2}$$

for example implies suppression by about 50%

Anatomy of a_μ

- Throughout parameter space of interest, dominant contribution to muon anomalous magnetic moment arises from chargino-sneutrino diagrams:



$$\Delta a_\mu^\chi \propto \frac{G_F M_W^2}{\sqrt{2}\pi^2}\, \mu M_2\, t_\beta\, \frac{m_\mu^2}{m_{\tilde{\nu}}^4}$$

For $t_\beta = 50$, $m_{\tilde{\nu}} = |\mu| = 1$ TeV & $|M_2| = 0.2$ TeV, one has numerically

$$\Delta a_\mu^\chi \approx \mathrm{sgn}\,(\mu M_2)\, 7.5 \cdot 10^{-10}$$

meaning that for $\mu M_2 > 0$ tension between experimental result & SM prediction is reduced

[see for example Moroi, hep-ph/9512396]

Slice of MSSM Parameter Space

- Above suggests that parameter space with $\mu > 0$ & $A_t > 0$ is least constrained & may lead to interesting effects. Fix relevant MSSM parameters to following weak-scale values

$$t_\beta = 60\,, \quad M_A = 1\,\mathrm{TeV}$$

$$\tilde{m}_{Q_3} = 1.5\,\mathrm{TeV}\,, \quad \tilde{m}_{u_3} = 1.5\,\mathrm{TeV}$$

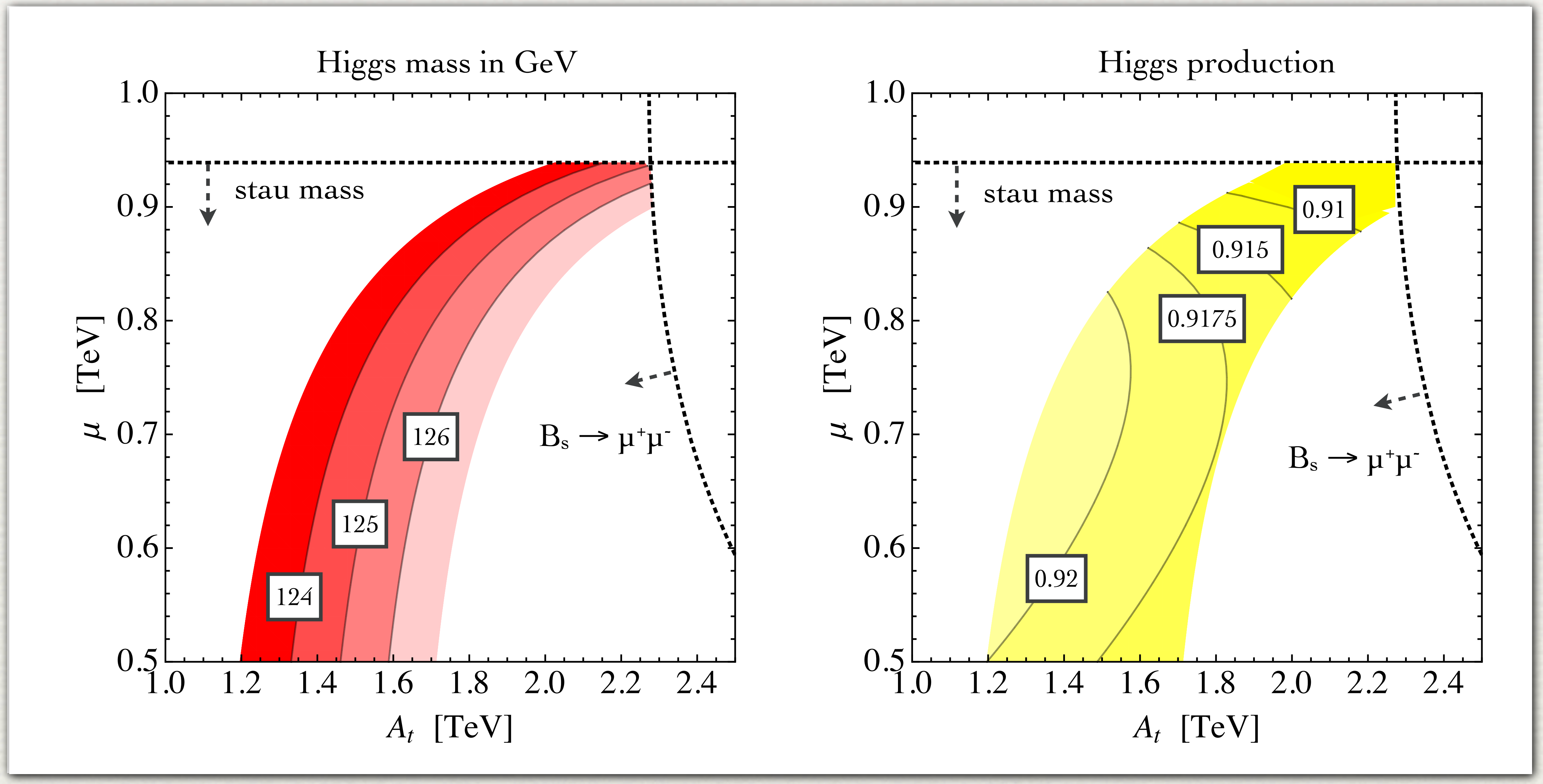
$$\tilde{m}_{L_3} = 325\,\mathrm{GeV}\,, \quad \tilde{m}_{l_3} = 325\,\mathrm{GeV}\,, \quad A_\tau = 500\,\mathrm{GeV}$$

$$M_1 = 100\,\mathrm{GeV}\,, \quad M_2 = 300\,\mathrm{GeV}\,, \quad M_3 = 1.2\,\mathrm{TeV}$$

& vary trilinear term A_t & Higgsino mass parameter μ

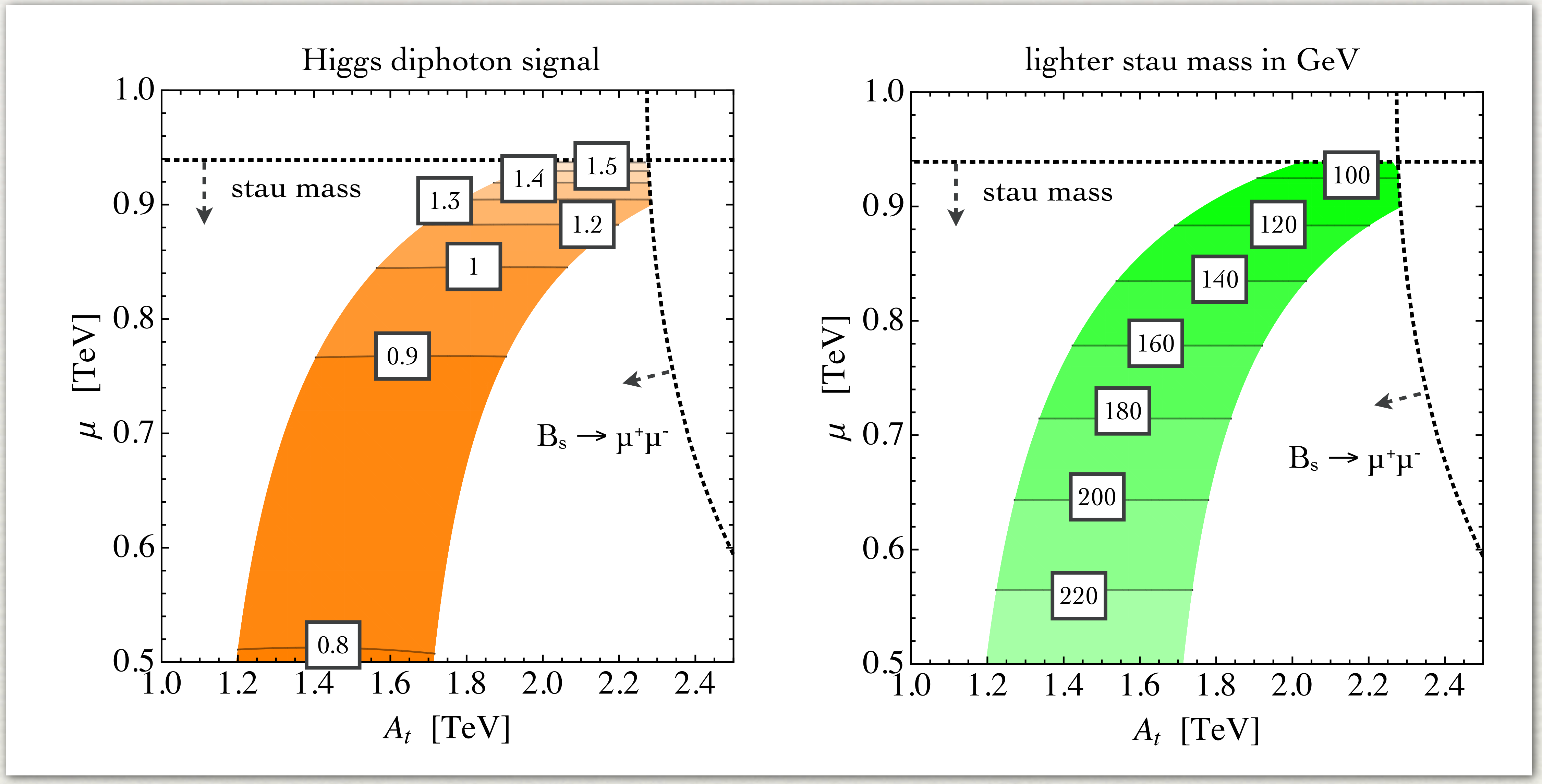
[see also Carena et al., 1112.3336; 1205.5842]

A_t-μ planes: m_h & R_h



- Higgs mass "measurement" & lower limit on stau mass of 92 GeV (LHCb bound on $B_s \to \mu^+\mu^-$) bound μ (A_t) from above. In preferred parameter space, Higgs production smaller than SM by about 10%

A_t-μ planes: $R_{\gamma\gamma}$ & $m_{\tilde{\tau}_1}$



- Enhancement in diphoton rate strongly correlated with mass of lighter stau mass eigenstate & μ parameter. Can find upper bound on $R_{\gamma\gamma}$ as function of $m_{\tilde{\tau}_1}$ & absolute limit of $R_{\gamma\gamma} \lesssim 1.7$

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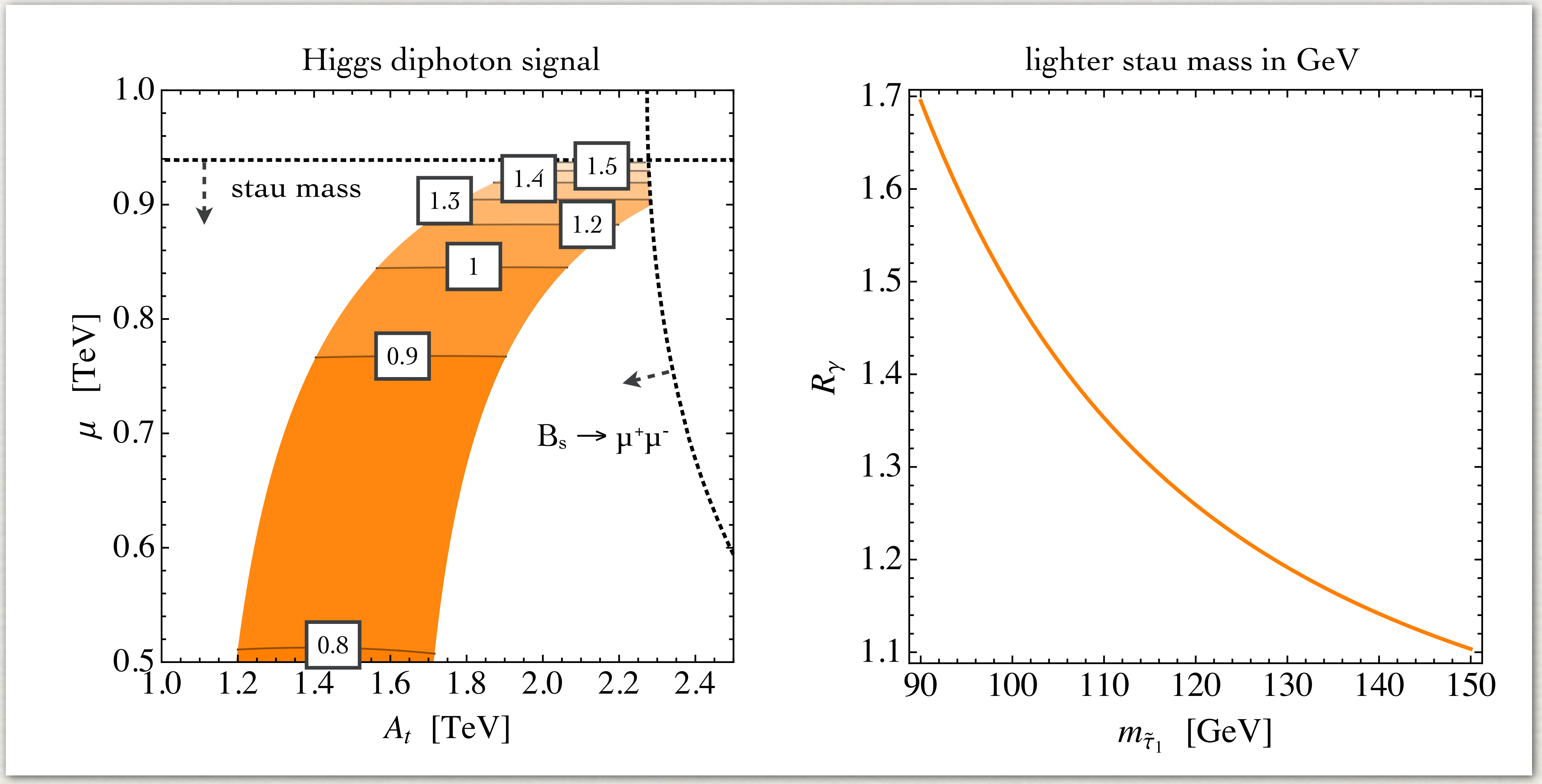

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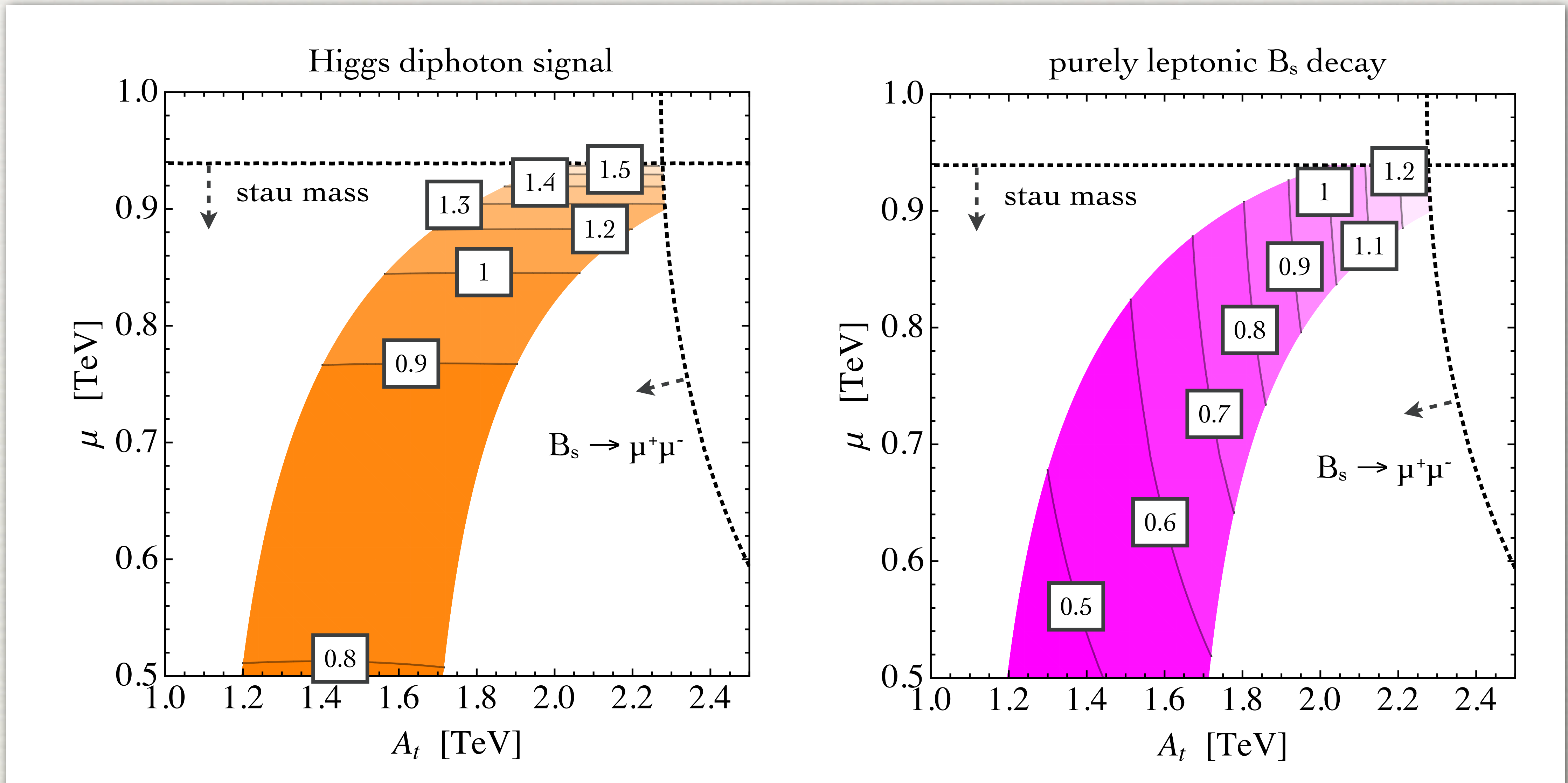
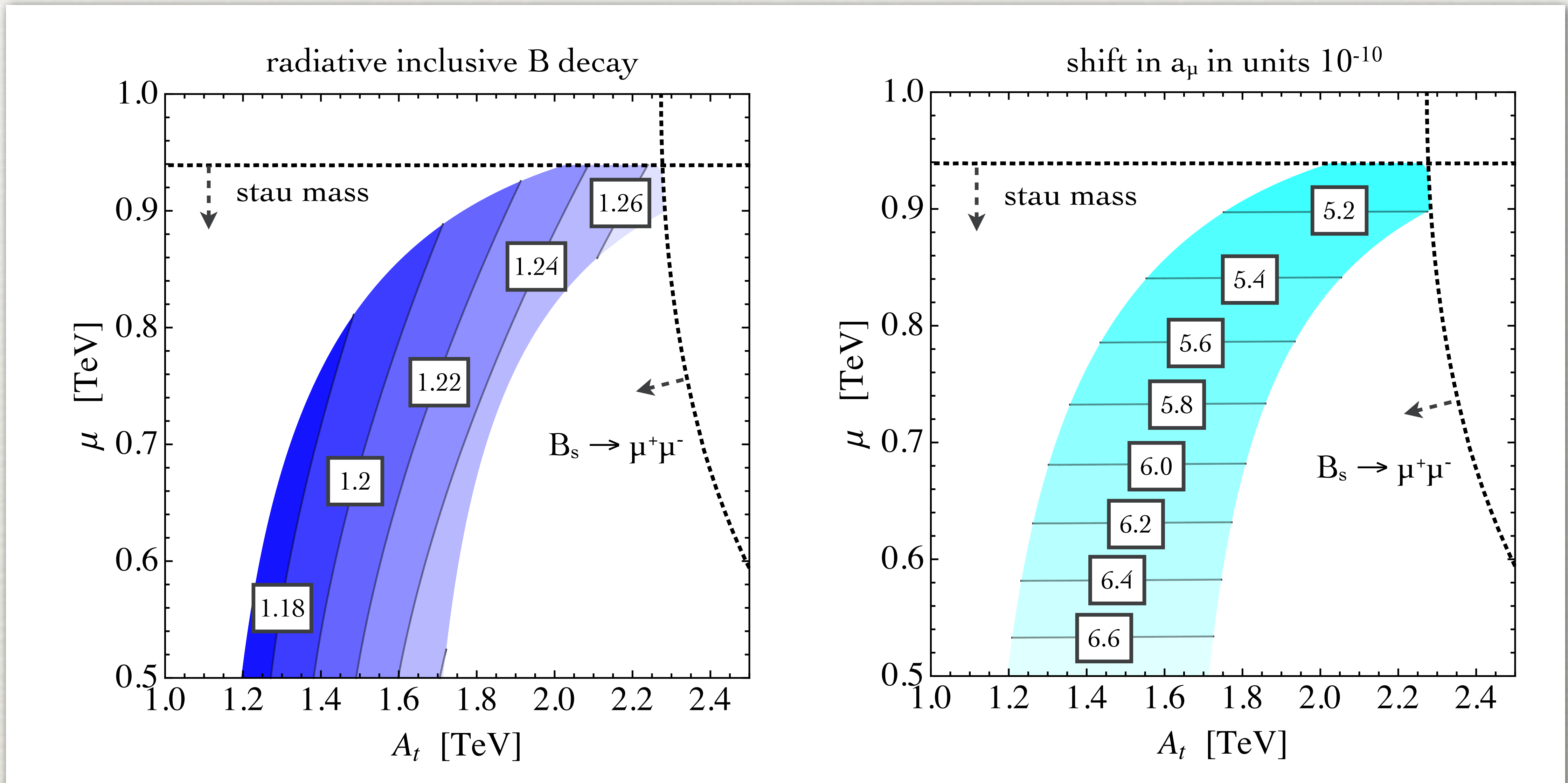
A_t-μ planes: $R_{\gamma\gamma}$ & $R_{\mu^+\mu^-}$



- Increases in & depletions of $R_{\gamma\gamma}$ & $B_s \to \mu^+\mu^-$ branching ration occur simultaneously. Stringent link can be broken by further decoupling heavy Higgses, $M_A >> 1$ TeV

A_t-μ plane: R_{X_s} & Δa_μ



- Branching ratio of $B \to X_s\gamma$ enhanced by (20-30)%, which can be probed with improved theoretical & experimental accuracy. Tension in anomalous magnetic moment of muon reduced

Conclusions

- Much like flavor physics, precision studies of Higgs-boson properties provide powerful way to illuminate dynamics of electroweak symmetry breaking
- Both in models with vector-like quarks & MSSM there can be testable correlations between Higgs-boson measurements & flavor physics observables
- Only synergy between high- & low-p_T observations may give us key to solving puzzles of fundamental physics. LHCb precision measurements of $B_s \to \mu^+\mu^-$, $B \to K^* l^+ l^-$, angle γ, ... crucial in endeavour

Vector Quarks: Z-Boson Constraints

- Left- & right-handed Z-boson couplings are modified:

$$\left(\delta g^d_{L,R}\right)_{ij} \sim \frac{v^2}{2M^2_{D,Q}} \epsilon^i_{Q,D}\epsilon^j_{Q,D} \left(\lambda^*_D\right)^2$$

- From $K_L \to \mu^+\mu^-$ & $K \to \pi\nu\bar{\nu}$:

$$\left|\left(\delta g^d_{L,R}\right)_{12}\right| < 9 \cdot 10^{-6}$$

$$\Downarrow$$

$$M_{D,Q} \gtrsim \{1.0, 0.1\}\ \mathrm{TeV}$$

- From $Z \to b_L\bar{b}_L$:

$$\left|\left(\delta g^d_{L}\right)_{33}\right| < 0.0032$$

$$\Downarrow$$

$$M_{D} \gtrsim 2.2\ \mathrm{TeV}$$

Vector Quarks: W-Boson Constraints

- Right-handed W-boson coupling arises:

$$(\delta g_R)_{33} \sim \frac{v^2}{M_Q^2} \epsilon_D^3 \epsilon_U^3 \lambda_D^* \lambda_U^*$$

- From $B \rightarrow X_s \gamma$:

$$|(\delta g_R)_{33}| < 0.0057$$

$$\Downarrow$$

$$M_Q \gtrsim 0.3\,\mathrm{TeV}$$

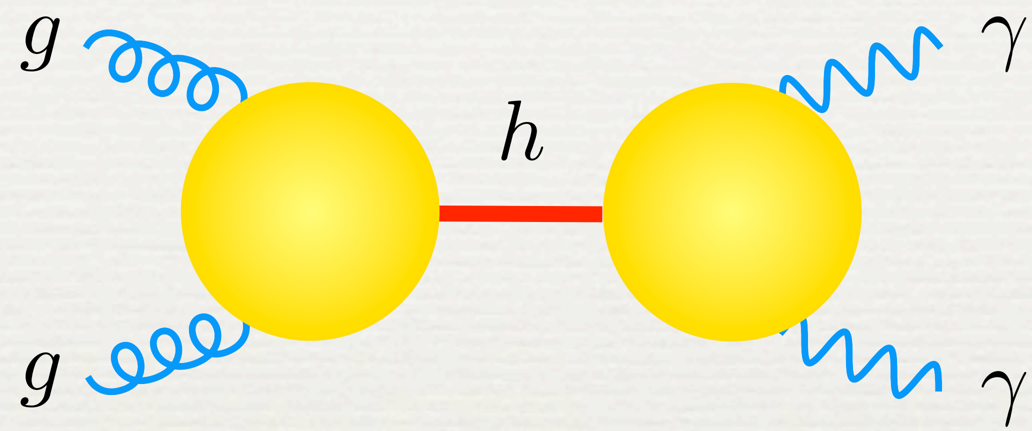
- From oblique corrections:

$$|T| < 0.2$$

$$\Downarrow$$

$$M_U \gtrsim 2.7\,\mathrm{TeV}$$

Master Formula for pp → γγ

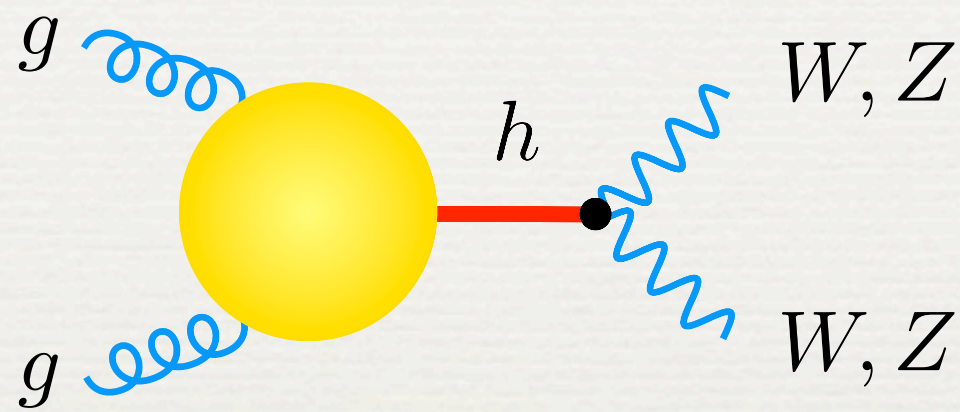


$$R_\gamma \approx 1 + 0.33\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right) - 0.43\,\frac{m_b^2 X_b^2}{m_{\tilde{b}_1}^2\, m_{\tilde{b}_2}^2}$$

$$+\, 0.10\,\frac{m_\tau^2 X_\tau^2}{m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} + 1.63\,\mathrm{sgn}\,(\mu M_2)\;\frac{1}{t_\beta}\;\frac{M_W^2}{m_{\chi_1^\pm}\, m_{\chi_2^\pm}} - 2.46\,\frac{M_Z^2}{M_A^2}$$

- Large non-decoupling corrections arise from fact that for Higgs of around 125 GeV branching fraction of Higgs to $b\bar{b}$ is about 60%

Master Formula for pp → WW,ZZ

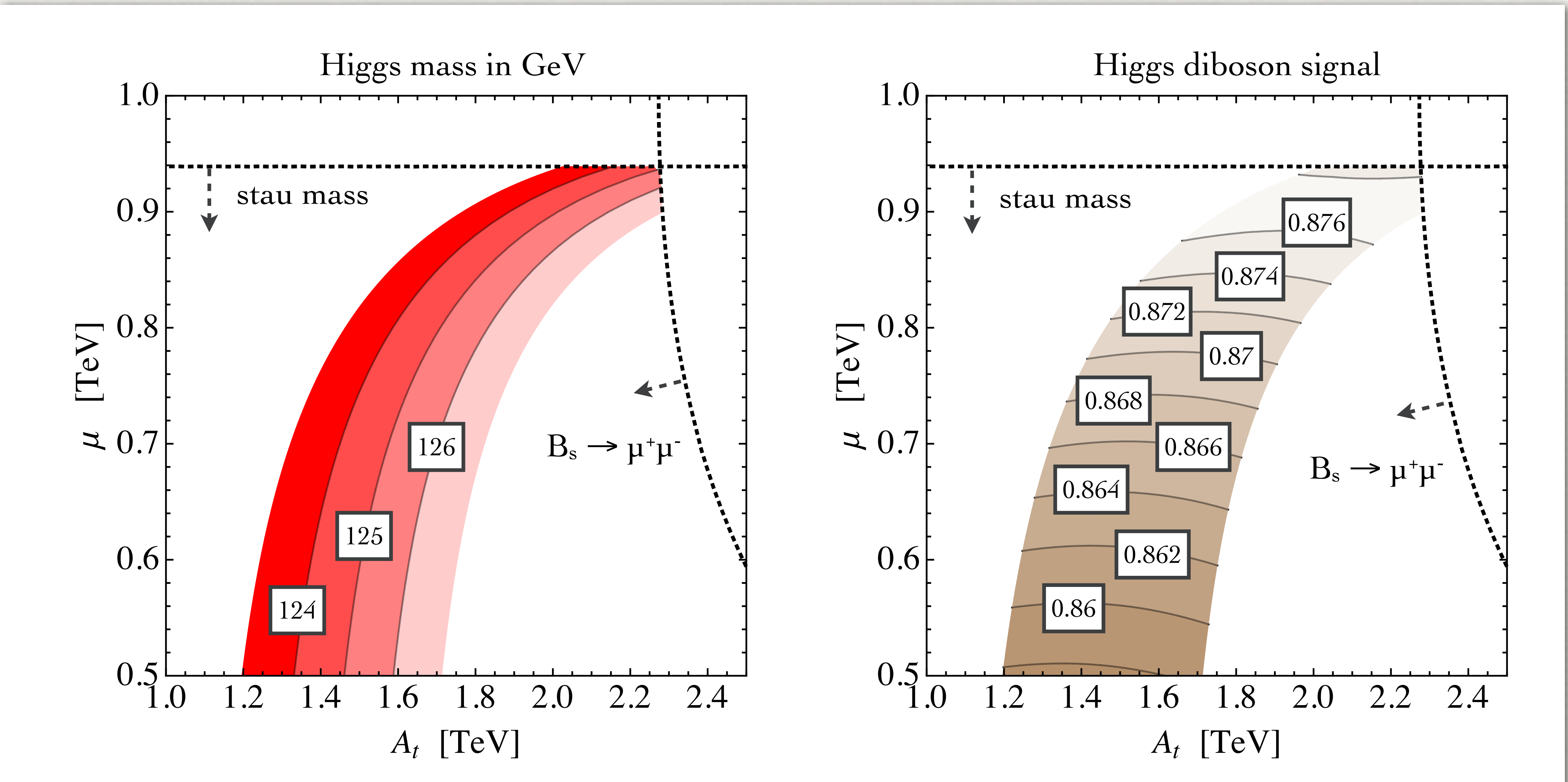


$$R_V \approx 1 + 0.46 \left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} - \frac{m_b^2 X_b^2}{m_{\tilde{b}_1}^2 m_{\tilde{b}_2}^2} \right)$$

$$- 2.46 \frac{M_Z^2}{M_A^2}$$

- Also massive vector-boson channels plagued by non-decoupling corrections associated to Br(h → b$\bar{\text{b}}$) ≈ 60%

A_t-μ planes: m_h & $R_{WW,ZZ}$



- Production of Higgs boson times decay to electroweak dibosons reduced with respect to SM by about (10-15)%