Higgs Physics beyond the Standard Model

Footprints of a Warped Extra Dimension ?

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PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

erc
ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Higgs and flavor physics as indirect BSM probes

The **hierarchy problem** and the **origin of flavor** are two major, unsolved mysteries of fundamental physics

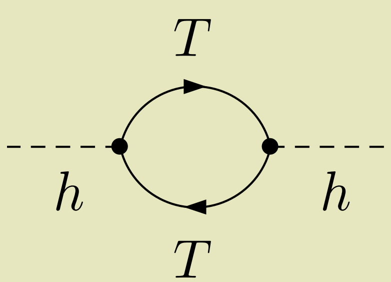
- connected to deep questions such as the **origin of mass**, the **stability of the electroweak scale**, the **matter-antimatter asymmetry**, the **origin of fermion generations**, and the reason for the **hierarchies** observed in the fermion sector
- we **do not understand the SM** until we understand these puzzles (both rooted in Higgs Yukawa interactions)

Higgs and flavor physics provide unique opportunities to probe the **structure of electroweak interactions at the quantum level**, thereby offering sensitive probes of physics beyond the SM

Higgs and flavor physics as indirect BSM probes

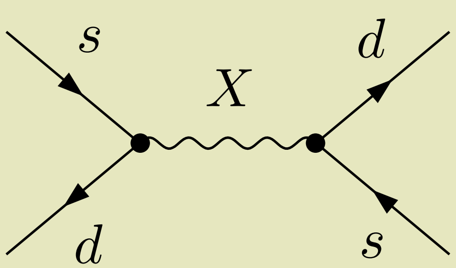
$$\mathcal{L}_{\rm EFT} = \Lambda_{\rm UV}^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2} + \dots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass



$$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\rm UV}^2$$

$\Downarrow$



$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$ assuming generic flavor structure

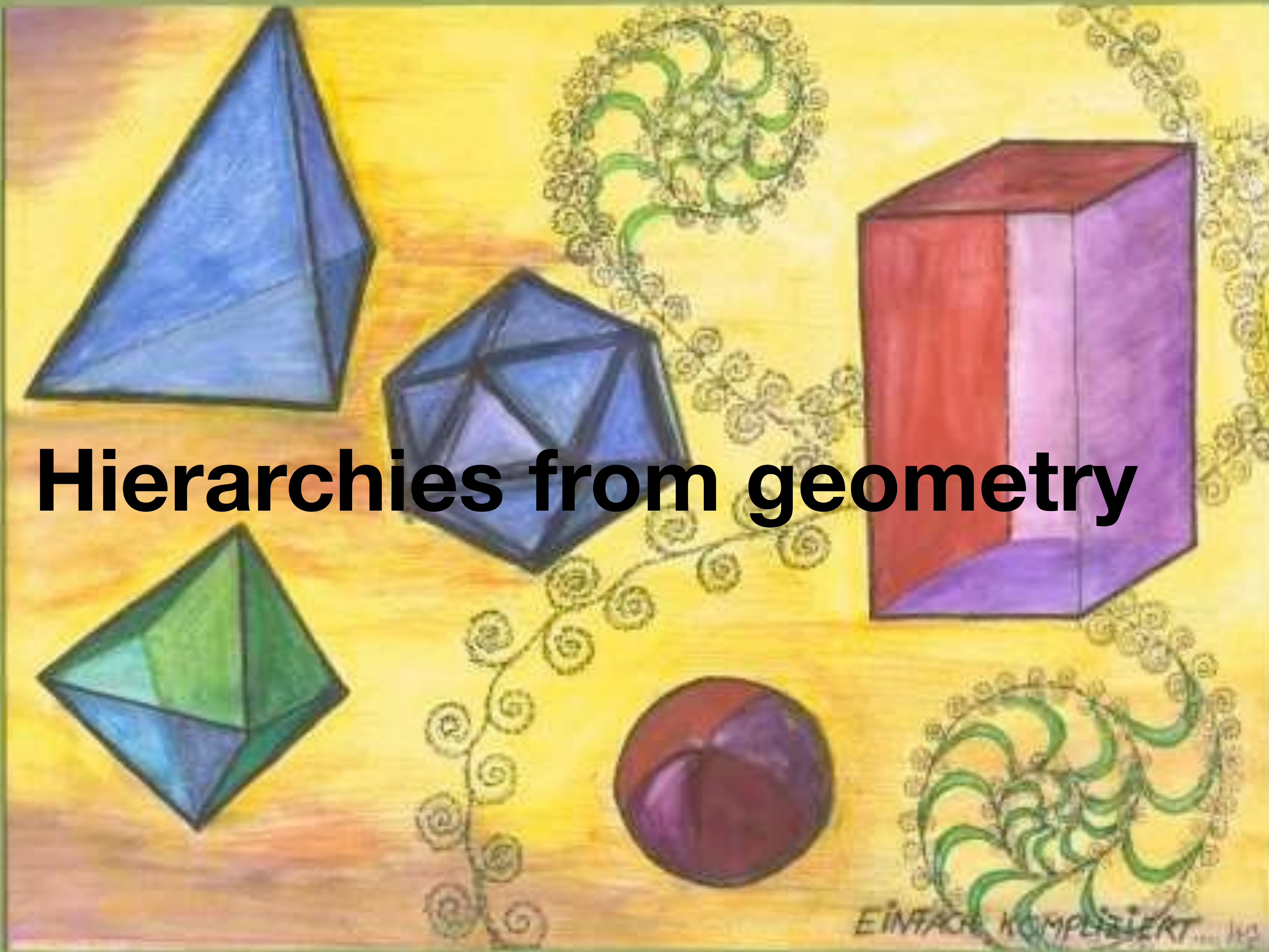
$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

Possible solutions to flavor problem explaining $\Lambda_{\rm Higgs} \ll \Lambda_{\rm flavor}$:

(i) $\Lambda_{\rm UV} \gg 1$ TeV: **Higgs fine tuned**, new particles too heavy for LHC

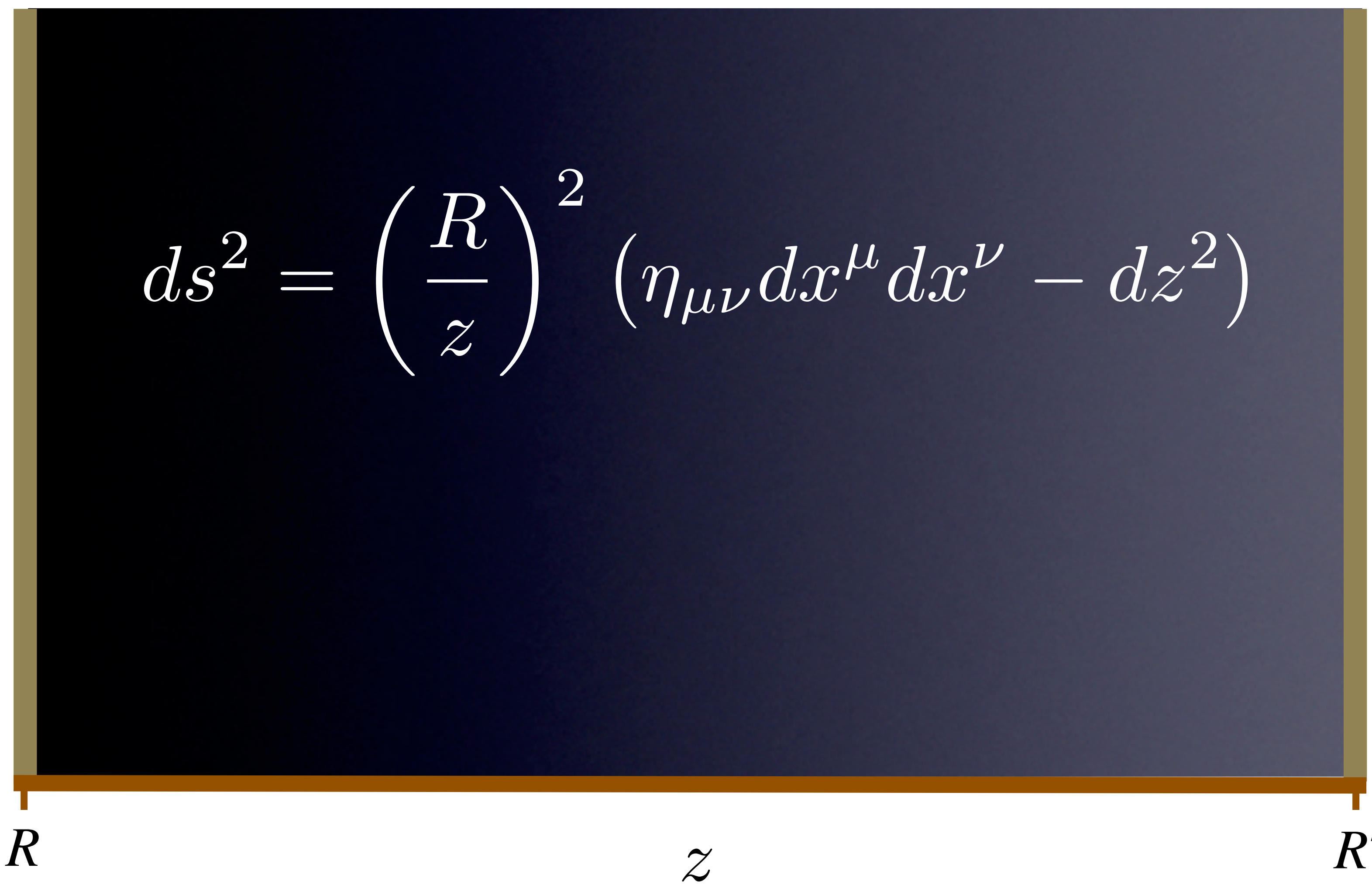
(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a **flavor symmetry**

Hierarchies from geometry



Flavor structure in RS models

ultraviolet (UV) brane

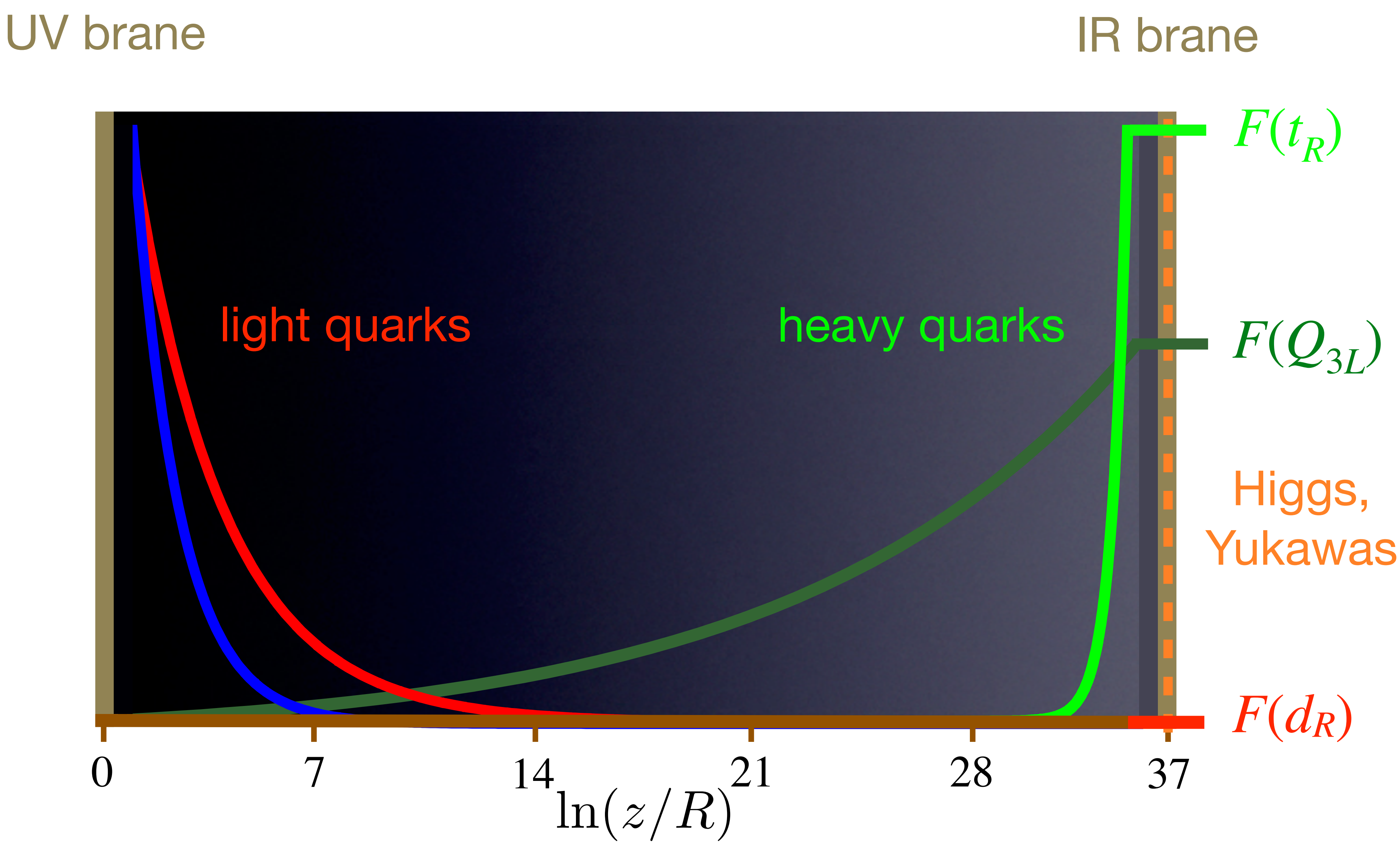


infrared (IR) brane

Randall-Sundrum (RS) models with a warped extra dimension address, at the same time, the **hierarchy problem** and the **flavor puzzle** (hierarchies seen in the spectrum of quark masses and mixing angles)

Randall, Sundrum (1999)

Flavor structure in RS models



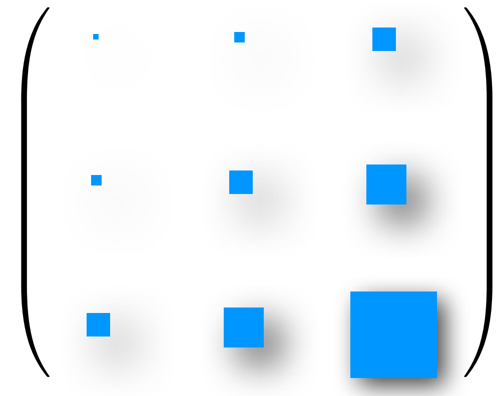
Localization of fermions in extra dimension depends exponentially on O(1) parameters related to the **5D bulk masses.** Overlap integrals $F(Q_L)$, $F(q_R)$ with Higgs profile are **exponentially small** for light quarks, while O(1) for top quark

Grossman, Neubert (1999); Ghergetta, Pomarol (2000)

Flavor structure in RS models

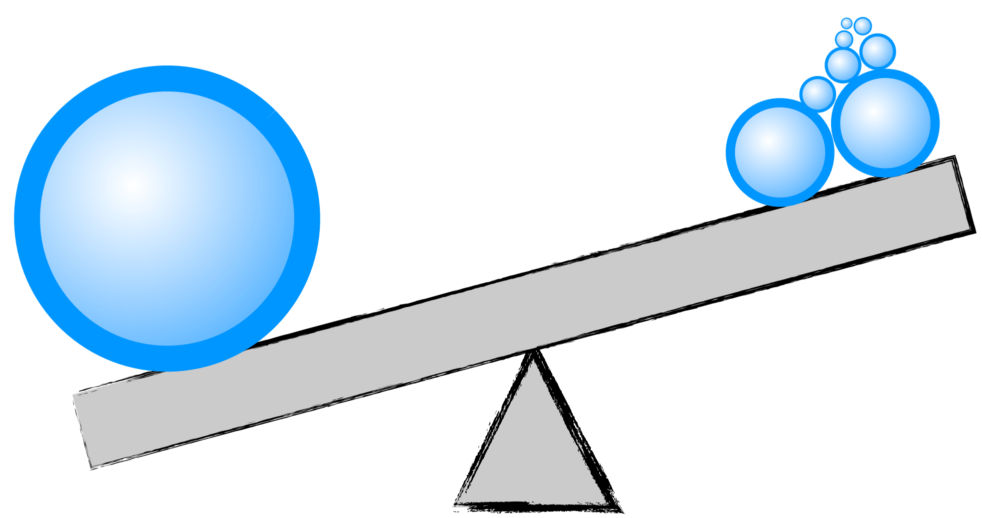
SM mass matrices can be written as: Huber (2003)

$$\boldsymbol{m}_q^{\mathrm{SM}} = \frac{v}{\sqrt{2}}\,\mathrm{diag}\left[F(Q_i)\right]\boldsymbol{Y}_q\,\mathrm{diag}\left[F(q_i)\right] =$$



where $\boldsymbol{Y}_q$ with $q = u,d$ are structureless, complex Yukawa matrices with O(1) entries, and $F(Q_i) \ll F(Q_j)$, $F(q_i) \ll F(q_j)$ for $i < j$

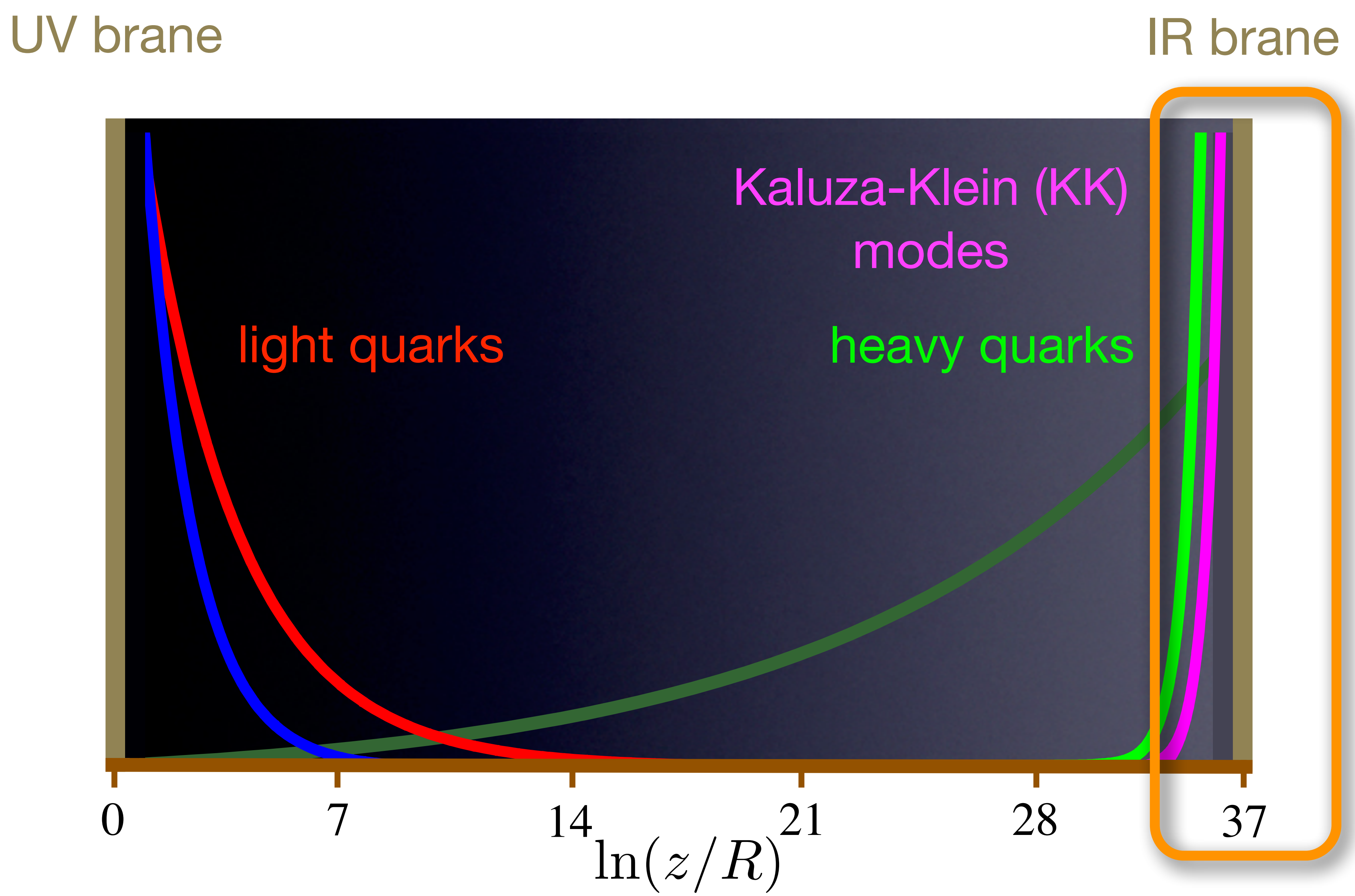
- in analogy to seesaw mechanism, matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices
- hierarchies can be adjusted by O(1) variations of bulk mass parameters
- yet the CKM phase is predicted to be O(1)



Warped-space Froggatt-Nielsen mechanism!

Casagrande et al. (2008); Blanke et al. (2008)

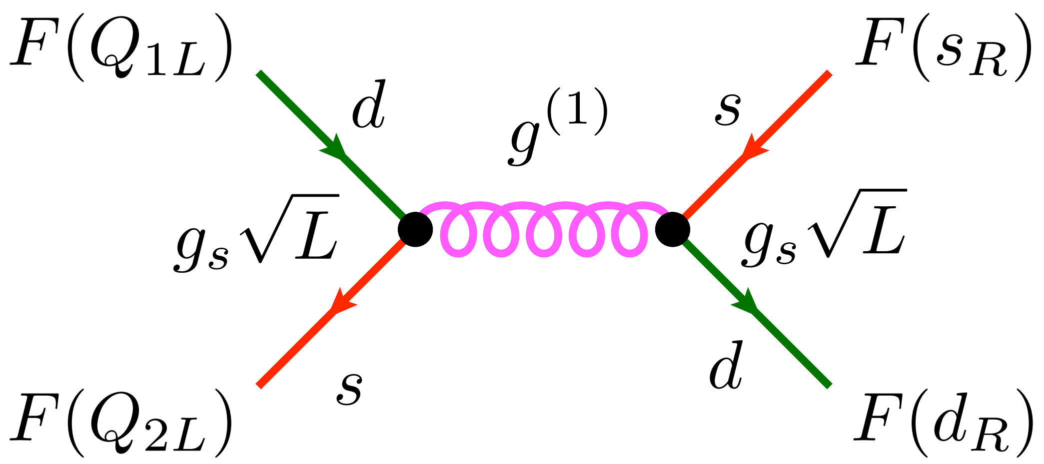
Flavor structure in RS models



Kaluza-Klein (KK) excitations of SM particles live close to the IR brane

Davoudiasl, Hewett, Rizzo (1999); Pomarol (1999)

RS-GIM protection of FCNCs



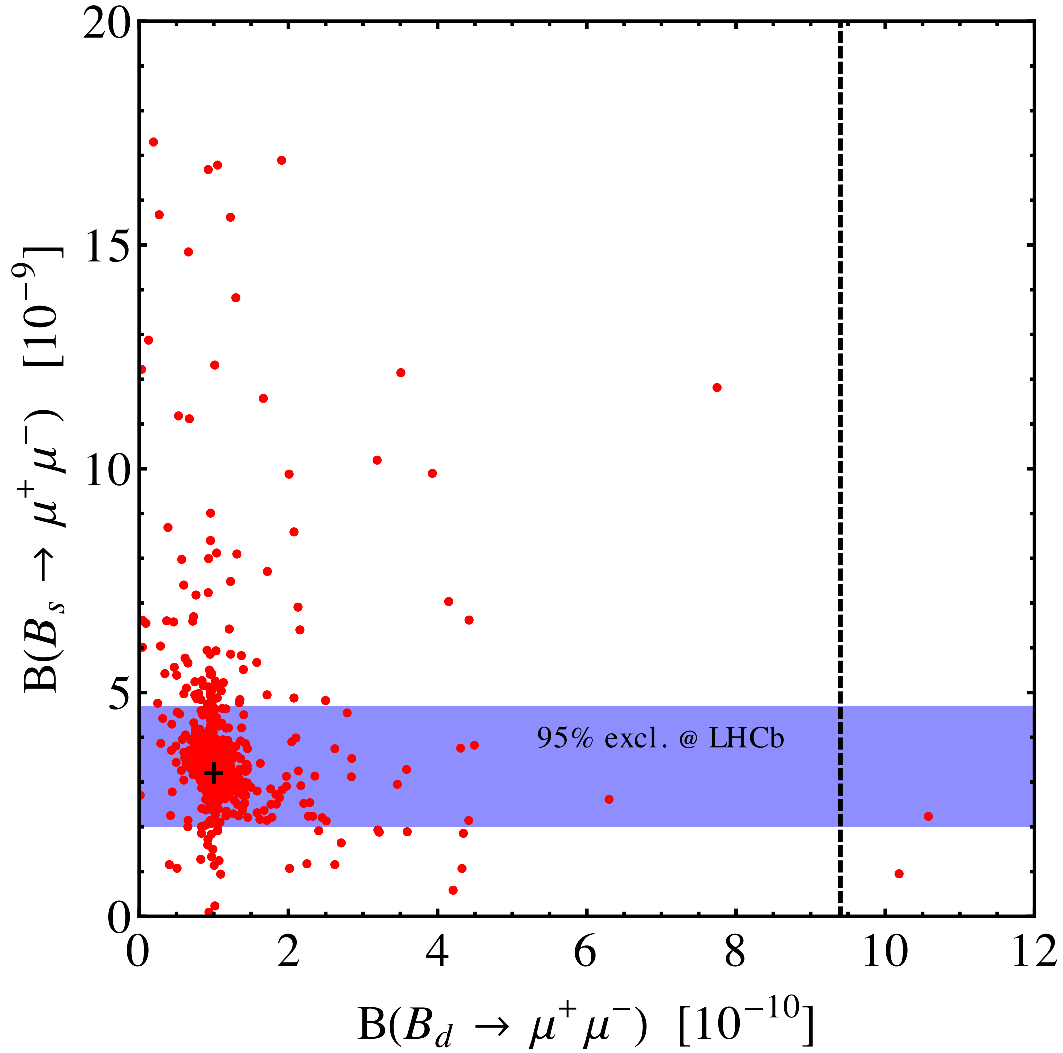
$$\sim \frac{g_s^2}{M_{\rm KK}^2}\, L\, F(Q_{1L})F(d_R)\, F(Q_{2L})F(s_R)$$

- Tree-level quark FCNCs induced by **virtual exchange of Kaluza-Klein (KK) gauge bosons** (including gluons!) Huber (2003); Burdman (2003); Agashe et al. (2004); Casagrande et al. (2008)
- Resulting FCNC couplings depend on same exponentially small overlap integrals $F(Q_L)$, $F(q_R)$ that generate fermion masses
- FCNCs involving light quarks are strongly suppressed: **RS-GIM mechanism** Agashe et al. (2004)

This mechanism suffices to suppress most of the dangerous FCNC couplings!

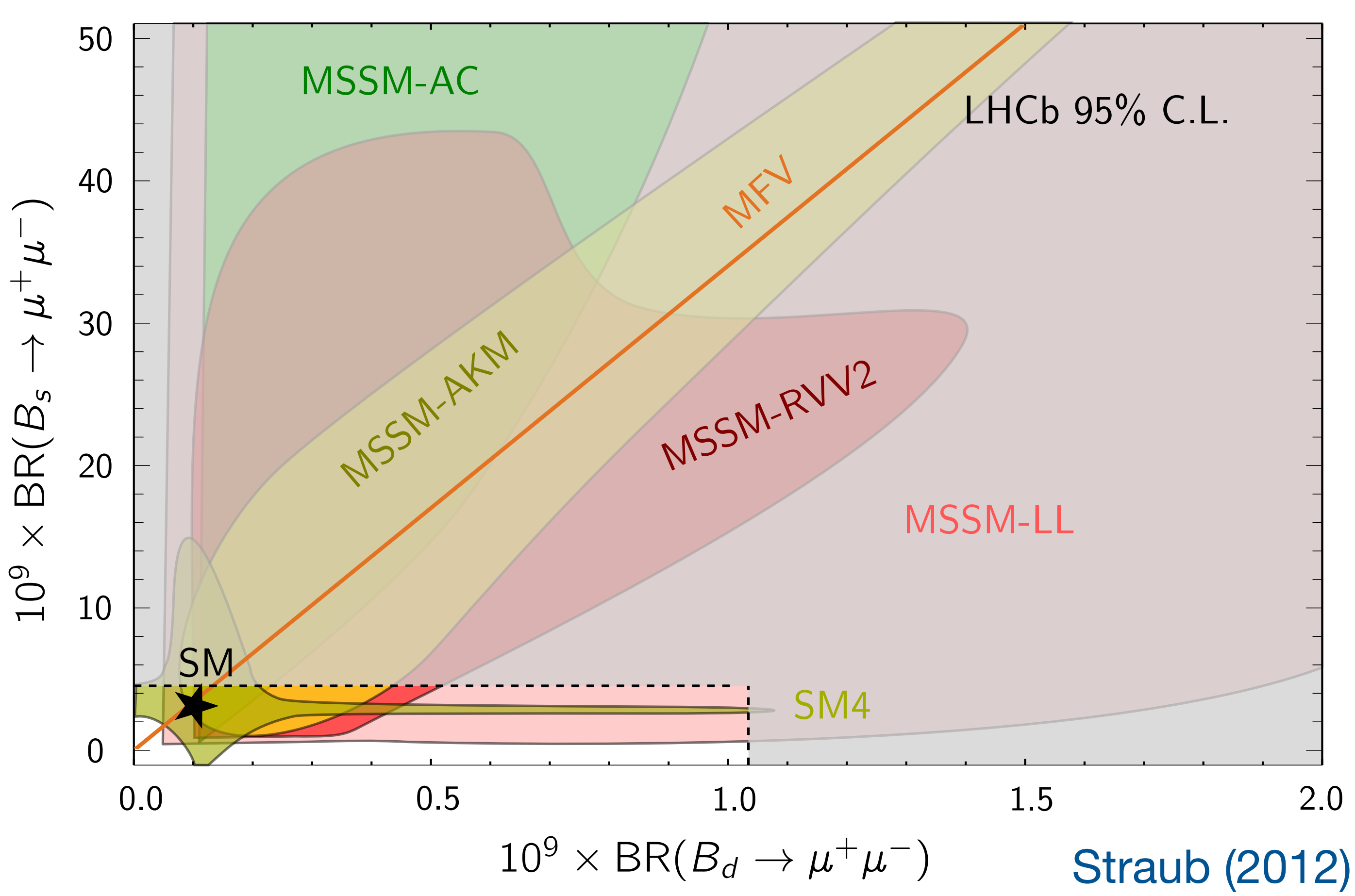
Example: Rare leptonic $B_{s/d} \to \mu^+\mu^-$ decays

Rare decays $B_{d,s} \to \mu^+\mu^-$ could be significantly affected, but RS-GIM protection is sufficient to prevent too large deviations from SM:



Bauer, Casagrande, Haisch, MN (2009)
see also: Blanke et al. (2008)

SUSY models for comparison



Straub (2012)

Recent LHC(b) results on $B_s \to \mu^+\mu^-$ begin cutting into the interesting parameter space!

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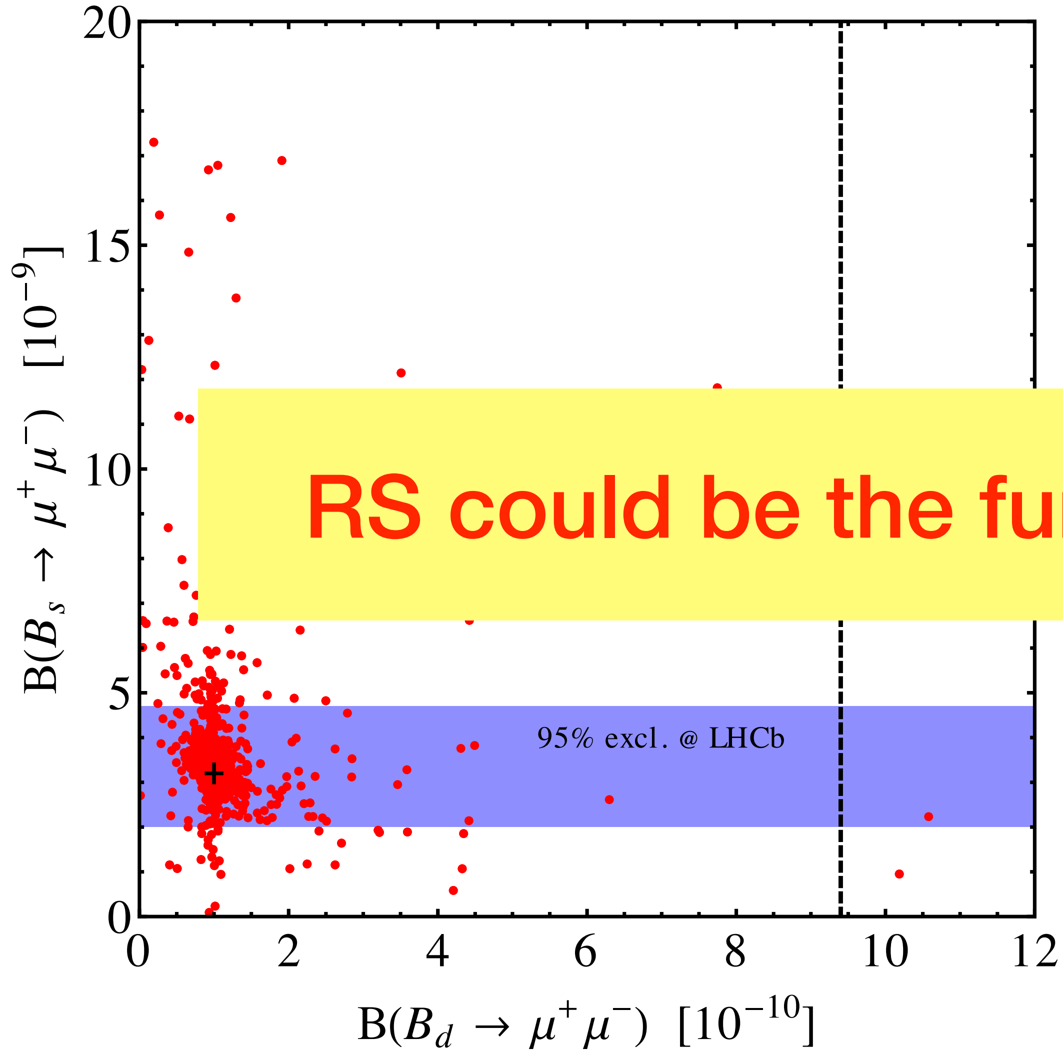

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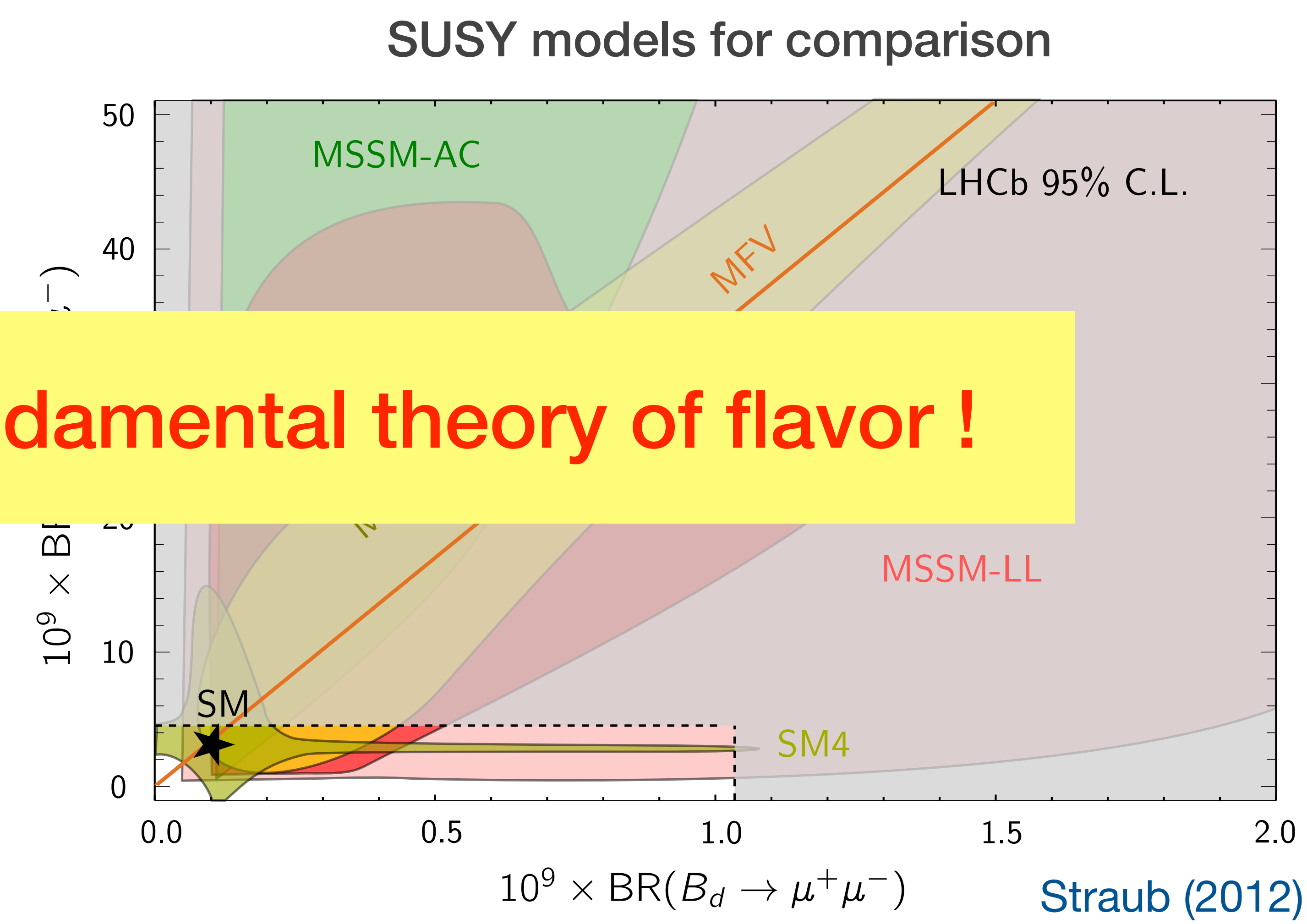

Straub (2012)

RS could be the fundamental theory of flavor !

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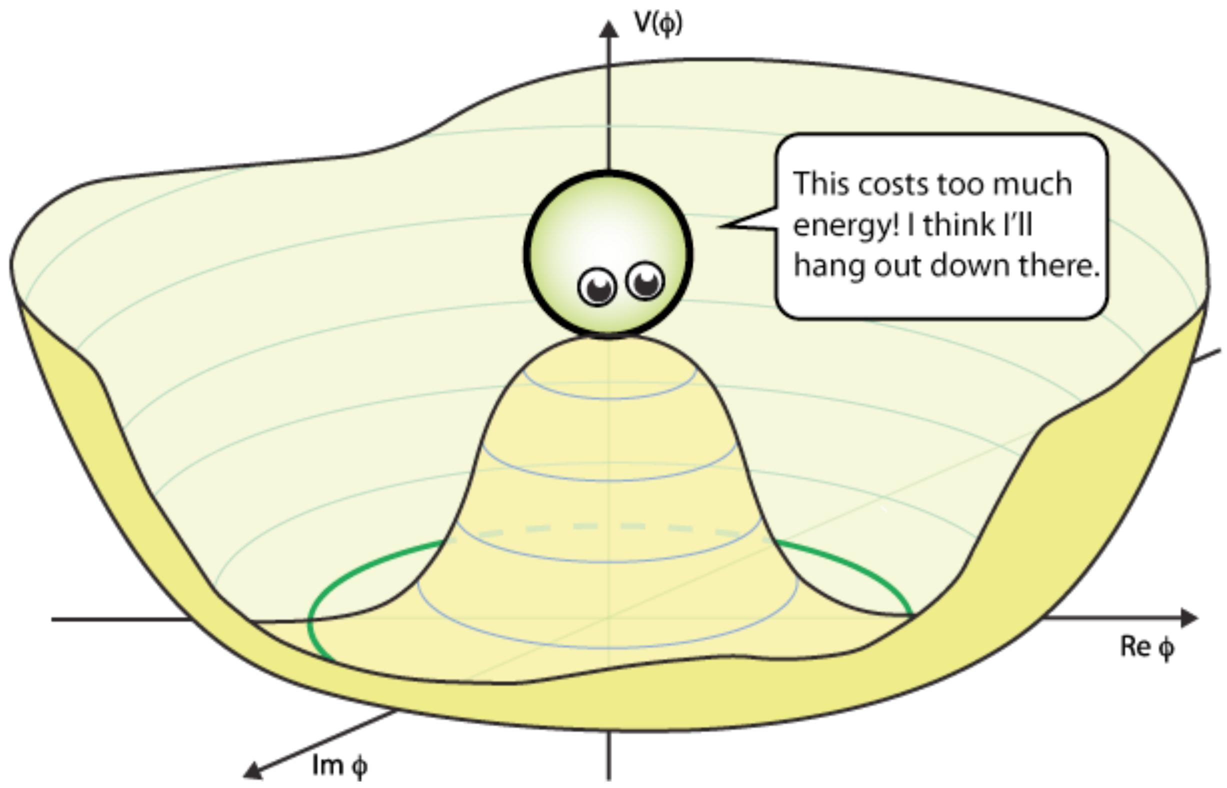
Higgs Properties as an Indirect Probe for New Physics



Goertz, Haisch, MN: arXiv:1112.5099 (PLB)

Carena, Casagrande, Goertz, Haisch, MN: arXiv:1204.0008 (JHEP)

Malm, MN, Novotny, Schmell: arXiv:1303.5702 (JHEP)

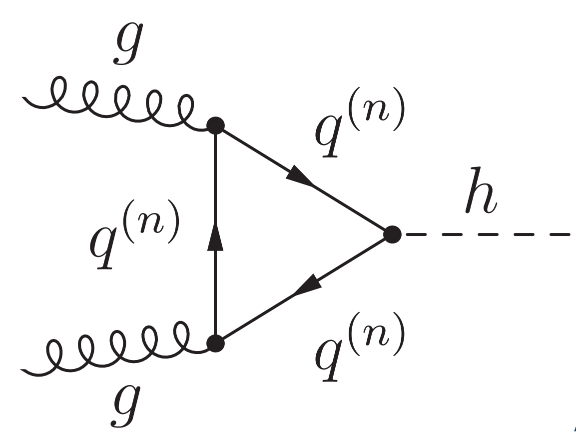
Hahn, Hörner, Malm, MN, Novotny, Schmell: arXiv:1312.5731

Higgs physics as an indirect BSM probe

Higgs discovery marks the birth of the **hierarchy problem**:

- one of the main motivations for physics beyond the SM
- detailed study of **Higgs properties** (mass, width, cross section, branching fractions) will help to probe whether the Higgs sector is as simple as predicted by the SM
- **Higgs couplings to photons and gluons** are loop-suppressed in the SM and hence are **particularly sensitive** to the presence of new particles

In RS models, **large number of bulk fermionic fields** in 5D theory gives rise to large loop effects, which change the effective hgg and hγγ couplings



Casagrande, Goertz, Haisch, MN, Pfoh (2010); Azatov, Toharia, Zhu (2010)

- KK towers of light quarks contribute as much as those of heavy quarks
- effect even more pronounced in models with custodial protection

Much like flavor physics, precision Higgs physics probes quantum effects of new particles!

Higgs physics as an indirect BSM probe

RS model is an effective theory defined with a **physical, 5D position-dependent cutoff** - the warped Planck scale:

$$\Lambda_{\rm UV}(z) \sim M_{\rm Pl}\,\frac{R}{z} = \Lambda_{\rm TeV}\,\frac{R'}{z}$$

- for loop graphs including a Higgs boson as an external particle, the warped Planck scale is in the **several TeV range** (since z≈R')
- two **physically different** variants of the RS model can be defined, depending on whether the structure of the Higgs boson as a 5D bulk field can be resolved by the high-momentum modes of the theory, i.e., whether the **inverse 5D Higgs width** v/η (with $\eta \ll 1$) is larger or smaller than the cutoff scale:

$$\frac{v}{\eta} \gg \Lambda_{\rm TeV} \quad \text{(brane-localized Higgs)}$$

$$M_{\rm KK} \ll \frac{v}{\eta} \ll \Lambda_{\rm TeV} \quad \text{(narrow bulk Higgs)}$$

Carena, Casagrande, Goertz, Haisch, MN (2012)
Delaunay, Kamenik, Perez, Randall (2012)
Malm, MN, Novotny, Schmell: arXiv:1303.5702

New physics in Higgs decays: 3 portals

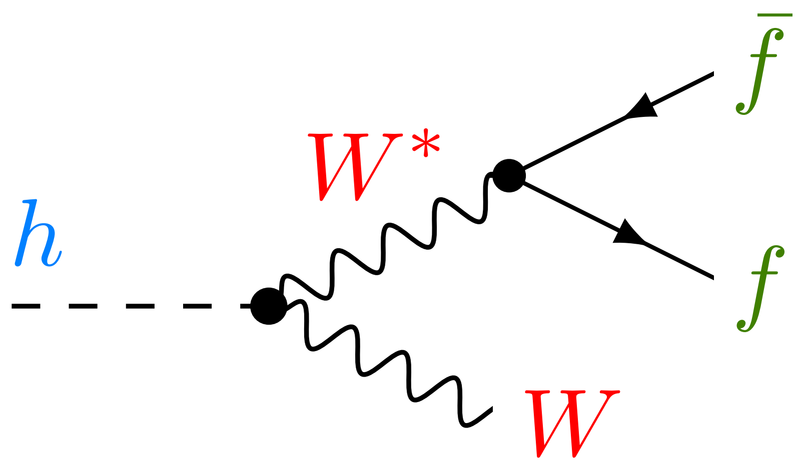
In any extension of the Standard Model, new-physics contributions can affect the measured rates for Higgs production and decay in three ways:

$$(\sigma \cdot \mathrm{BR})(pp \to h \to VV) = \sigma(pp \to h)\,\frac{\Gamma(H \to VV)}{\Gamma(h \to \text{anything})}$$

- Higgs **production cross section** (~90% gluon fusion, <10% vector-boson fusion, ~few % VH prod.)
- Higgs **decay rate** to the observed final state (here VV)
- **total Higgs width** (sensitive to h→b$\bar{\text{b}}$, h→WW, also h→invisible)

Higgs decay rates to WW* and ZZ*

Four different sources of effects from new physics:



- modification of Higgs vev: κ_v
- modification of Higgs coupling to gauge-boson pairs: κ_W
- modification of W- and Z-boson couplings to fermions: κ_Γ
- contribution of heavy KK bosons

Expression for the decay rate:

$$\Gamma(h \to WW^*) = \frac{m_H^3}{16\pi\kappa_v^2 v_{\rm SM}^2}\,\frac{\kappa_\Gamma \Gamma_W}{\pi m_W}\left\{\kappa_W\, g\!\left(\frac{m_W^2}{m_H^2}\right) - \frac{m_H^2}{2M_{\rm KK}^2}\left(1-\frac{1}{L}\right) h\!\left(\frac{m_W^2}{m_H^2}\right)\right\}$$

Malm, MN, Schmell: in preparation

Higgs decay rates to WW* and ZZ*

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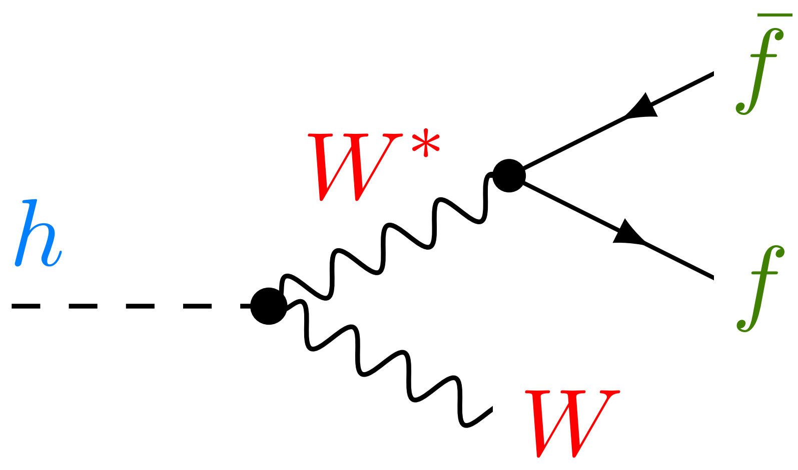

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Malm, MN, Schmell: in preparation

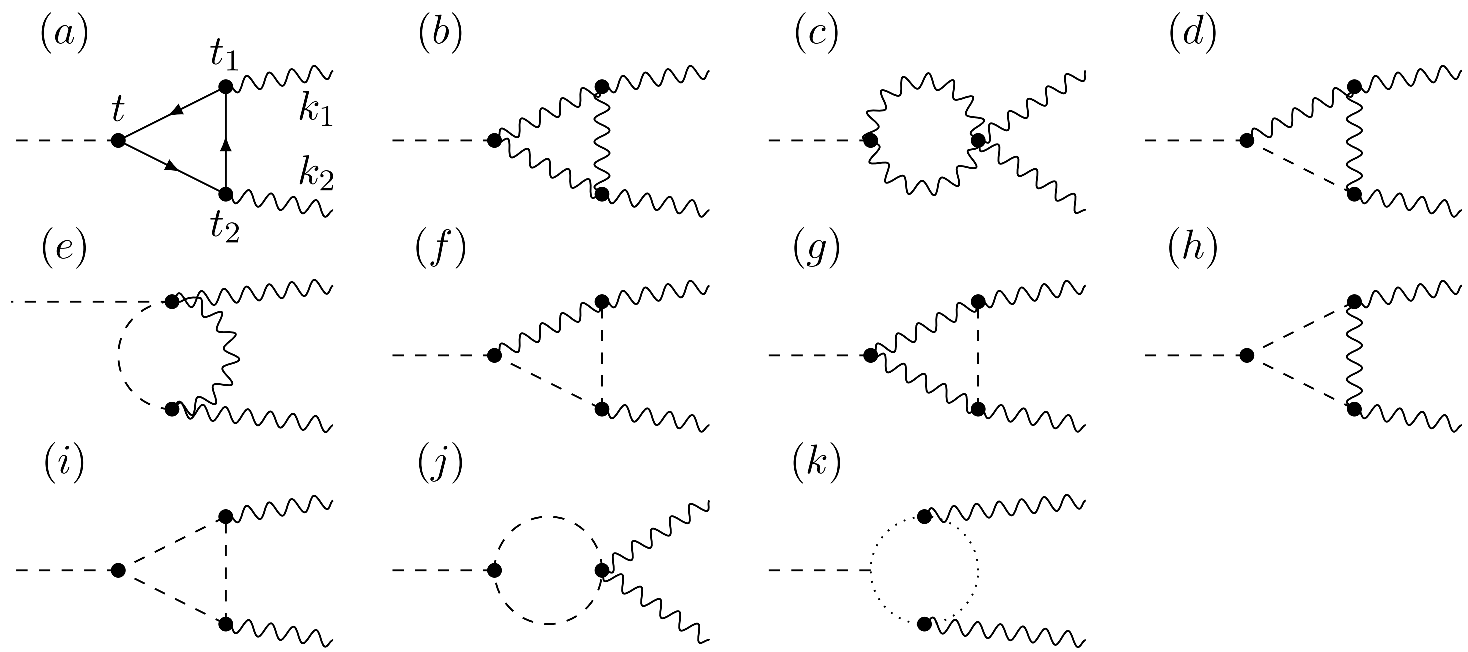
Correction factors:

$$\kappa_v = 1 + \frac{L m_W^2}{4M_{\rm KK}^2}\,, \qquad \kappa_\Gamma = 1 - \frac{m_W^2}{4L M_{\rm KK}^2}\,, \qquad \kappa_W = 1 - \frac{m_W^2}{2M_{\rm KK}^2}\left(L - 1 + \frac{1}{2L}\right)$$

$$\left(\text{with:} \quad L = \ln(M_{\rm Pl}/\Lambda_{\rm TeV}) \approx 34\right)$$

h→γγ decay rate (details of the calculation)

Decay h→γγ mediated by loops of gauge bosons (+ KK modes) and fermions (+ KK modes):



Bosonic contribution expressed in terms of 5D gauge-boson propagators:

$$
\begin{aligned}
i\mathcal{A}(h \to \gamma\gamma) = & -\frac{2\tilde{m}_W^2}{v}\, 2\pi e^2\, \epsilon_\mu^*(k_1)\, \epsilon_\nu^*(k_2)\, \eta^{\alpha\beta} \int \frac{d^d p}{(2\pi)^d} \int_\epsilon^1 dt\, \delta^\eta(t-1)\, \frac{2\pi}{L} \int_\epsilon^1 \frac{dt_1}{t_1} \\
& \times \Bigg[\frac{2\pi}{L} \int_\epsilon^1 \frac{dt_2}{t_2}\, 2V^{\gamma\mu\lambda\rho\nu\delta}\, D_{W,\alpha\gamma}^{\xi\to\infty}(t, t_1, p+k_1)\, D_{W,\lambda\rho}^{\xi\to\infty}(t_1, t_2, p)\, D_{W,\delta\beta}^{\xi\to\infty}(t_2, t, p-k_2) \\
& + \left(2\eta^{\gamma\delta}\eta^{\mu\nu} - \eta^{\delta\nu}\eta^{\gamma\mu} - \eta^{\nu\gamma}\eta^{\mu\delta}\right) D_{W,\alpha\gamma}^{\xi\to\infty}(t, t_1, p+k_1)\, D_{W,\beta\delta}^{\xi\to\infty}(t_1, t, p-k_2) \Bigg]
\end{aligned}
$$

h→γγ decay rate (details of the calculation)

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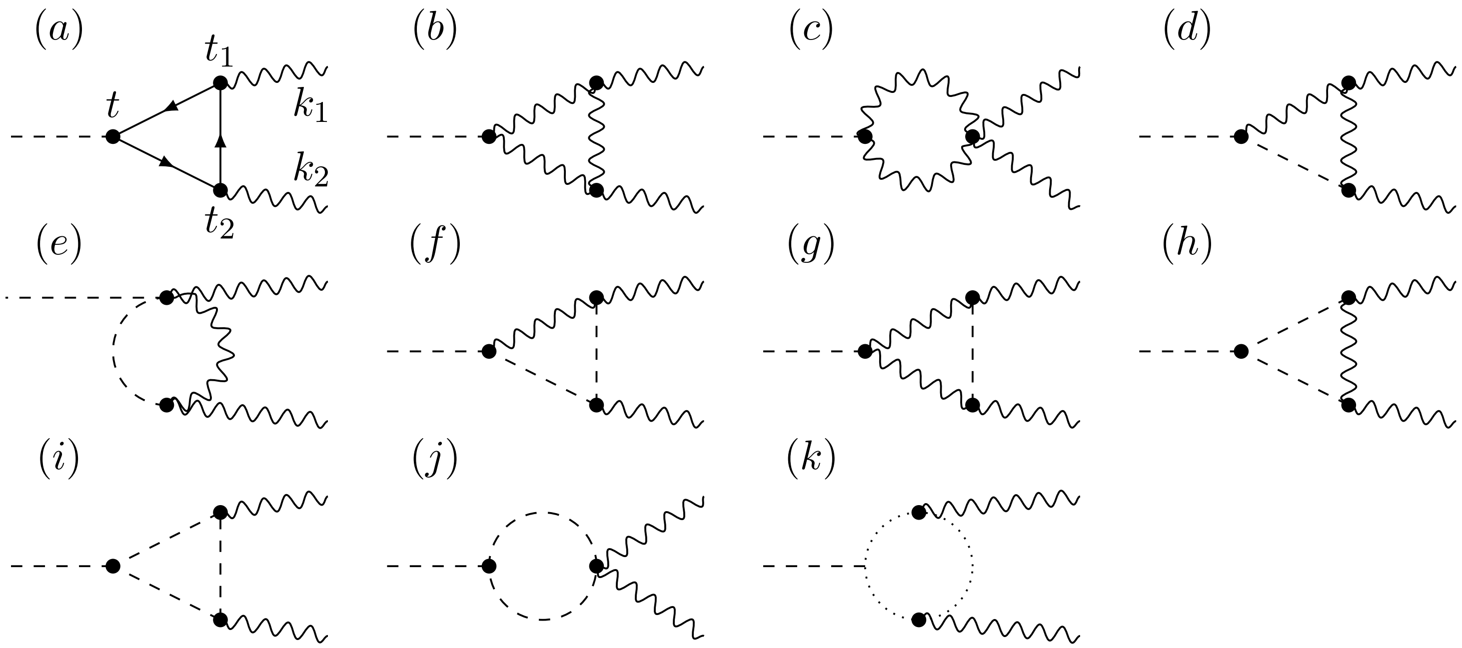


Parameterization of the decay amplitude:

$$\mathcal{A}(h \to \gamma\gamma) = C_{1\gamma}\,\frac{\alpha_e}{6\pi v}\langle\gamma\gamma|F_{\mu\nu}F^{\mu\nu}|0\rangle - C_{5\gamma}\,\frac{\alpha_e}{4\pi v}\langle\gamma\gamma|F_{\mu\nu}\tilde{F}^{\mu\nu}|0\rangle$$

h→γγ decay rate (details of the calculation)

Exact result for $C_{1\gamma}^{W}$ expressed in terms of a **single 5D propagator**:

$$C_{1\gamma}^{W} = -3\pi\tilde{m}_W^2 \left[T_W(0) + 6\int_0^1 dx \int_0^{1-x} dy\,(1-2xy)\,T_W(-xym_h^2) \right]$$

Hahn, Hörner, Malm, MN, Novotny, Schmell: arXiv:1312.5731

with:

$$T_W(-p^2) = \int_\epsilon^1 dt\,\delta^\eta(t-1)\,B_W(t,t;-p^2-i0) = B_W(1,1;-p^2-i0) + \mathcal{O}(\eta)$$

$$D_{W,\mu\nu}^{\xi}(t,t';p) = B_W(t,t';-p^2-i0)\left(\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) + B_W(t,t';-p^2/\xi - i0)\,\frac{p_\mu p_\nu}{p^2}$$

Results for bosonic contributions:

$$C_{1\gamma}^{W} = -\frac{21}{4}\left[\kappa_W A_W(\tau_W) + \nu_W\right] + \mathcal{O}\left(\frac{v^4}{M_{\rm KK}^4}\right), \qquad C_{5\gamma}^{W} = 0$$

$$\kappa_W = 1 - \frac{m_W^2}{2M_{\rm KK}^2}\left(L - 1 + \frac{1}{2L}\right), \qquad \nu_W = \frac{m_W^2}{2M_{\rm KK}^2}\left(L - 1 + \frac{1}{2L}\right)$$

Higgs production in gluon fusion

Results for fermionic contributions (quarks and charged leptons):

$$C_{1\gamma}^q \approx \left[1 - \frac{v^2}{3M_{\rm KK}^2}\,{\rm Re}\,\frac{(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u)_{33}}{(\boldsymbol{Y}_u)_{33}}\right] N_c\, Q_u^2\, A_q(\tau_t) + N_c\, Q_d^2\, A_q(\tau_b) + \sum_{q=u,d} N_c\, Q_q^2\, {\rm Re\,Tr}\, g(\boldsymbol{X}_q)$$

$$C_{5\gamma}^q \approx -\frac{v^2}{3M_{\rm KK}^2}\,{\rm Im}\left[\frac{(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u)_{33}}{(\boldsymbol{Y}_u)_{33}}\right] N_c\, Q_u^2\, B_q(\tau_t) + \sum_{q=u,d} N_c\, Q_q^2\, {\rm Im\,Tr}\, g(\boldsymbol{X}_q)$$

$$\boldsymbol{X}_q = \frac{v}{\sqrt{2}M_{\rm KK}}\sqrt{\boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger}$$

$$0 \le |(\boldsymbol{Y}_f)_{ij}| \le y_\star$$

$$C_{1\gamma}^l + i C_{5\gamma}^l \approx Q_e^2\, {\rm Tr}\, g(\boldsymbol{X}_e)$$

Hahn, Hörner, Malm, MN, Novotny, Schmell: arXiv:1312.5731

with:

$$g(\boldsymbol{X}_q)\big|_{\rm brane\ Higgs} = \boldsymbol{X}_q \tanh \boldsymbol{X}_q - \boldsymbol{X}_q \tanh 2\boldsymbol{X}_q$$

$$g(\boldsymbol{X}_q)\big|_{\rm narrow\ bulk\ Higgs} = \boldsymbol{X}_q \tanh \boldsymbol{X}_q$$

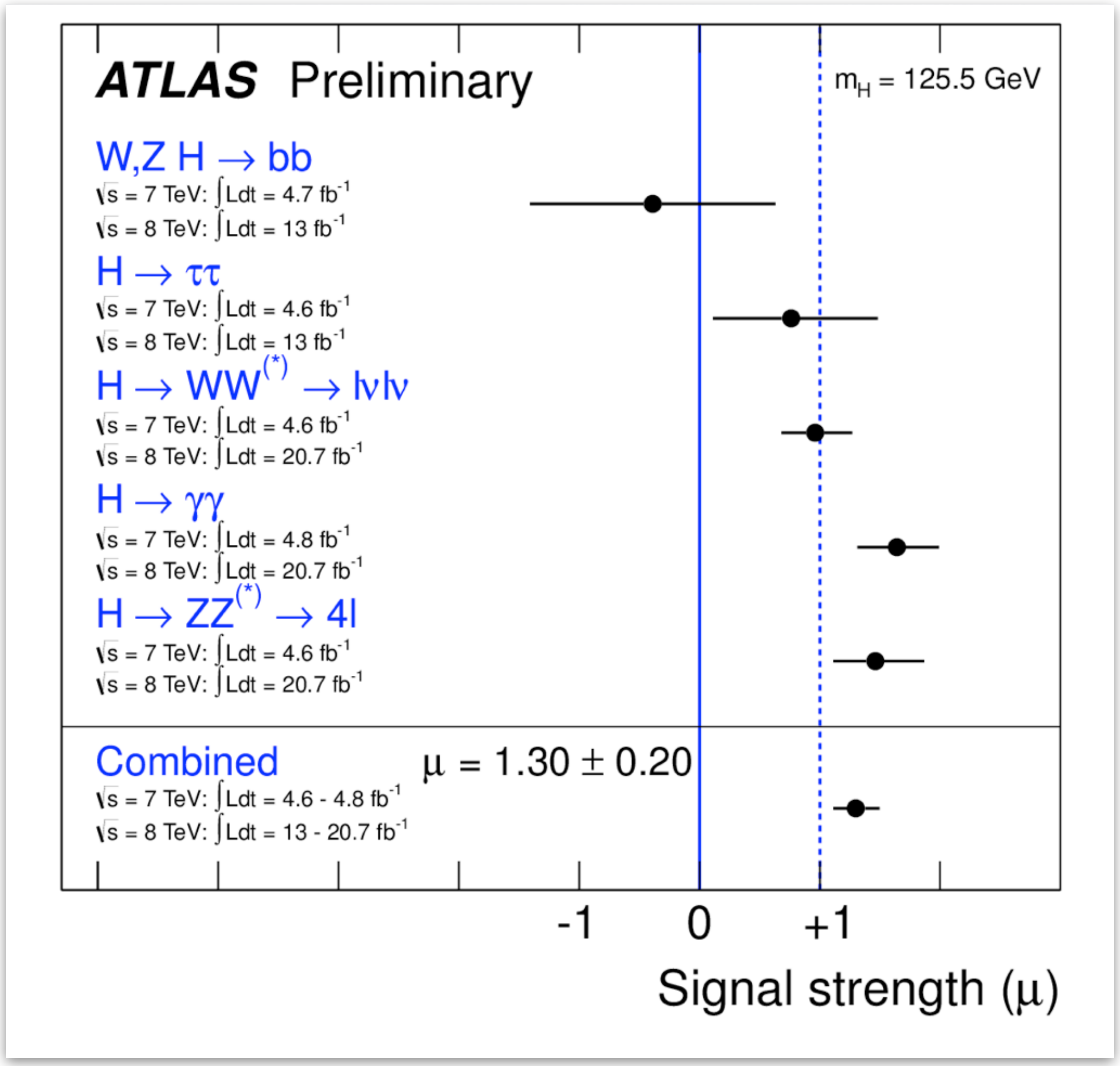
difference due to “resonant” contribution from high-mass KK modes (~1/η) near the cutoff

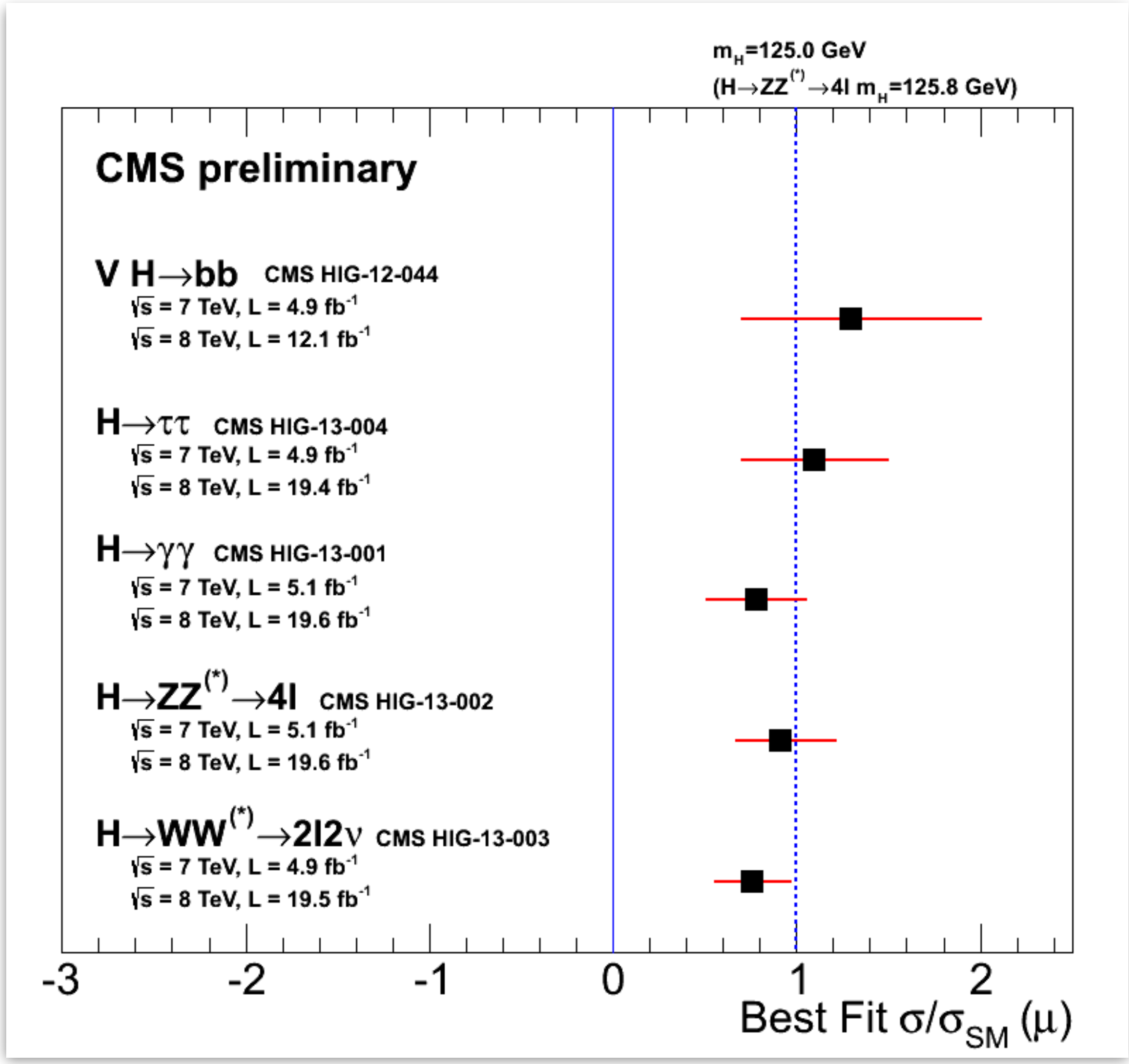
Results depend on very few parameters only:

$$M_{\rm KK}\,, \qquad L\,, \qquad \left\langle {\rm Tr}\, \boldsymbol{Y}_f \boldsymbol{Y}_f^\dagger \right\rangle = N_g^2\, \frac{y_\star^2}{2}\,, \qquad \left\langle \frac{(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u)_{33}}{(\boldsymbol{Y}_u)_{33}} \right\rangle = (2N_g - 1)\, \frac{y_\star^2}{2}$$

Phenomenological predictions and LHC data

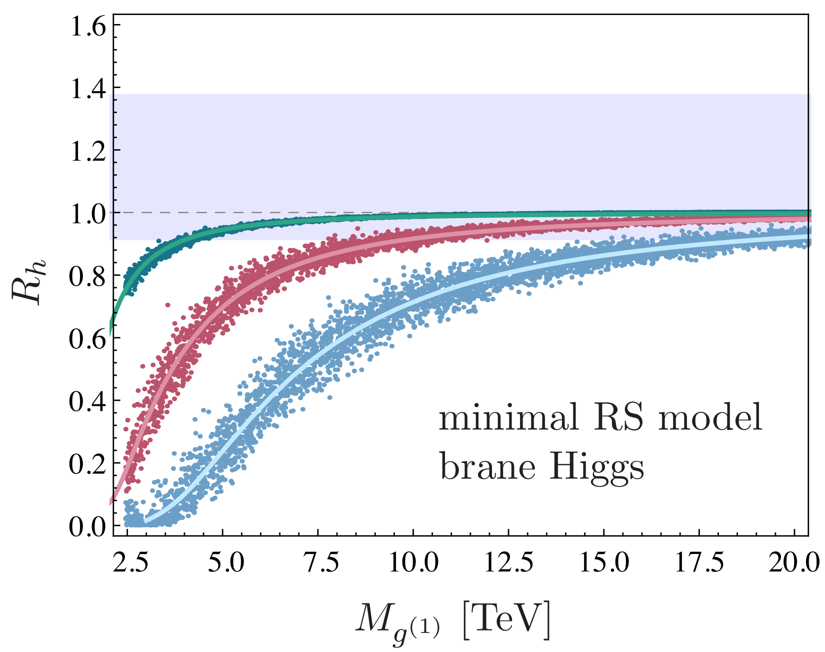
Use Run-I date sets from ATLAS and CMS:

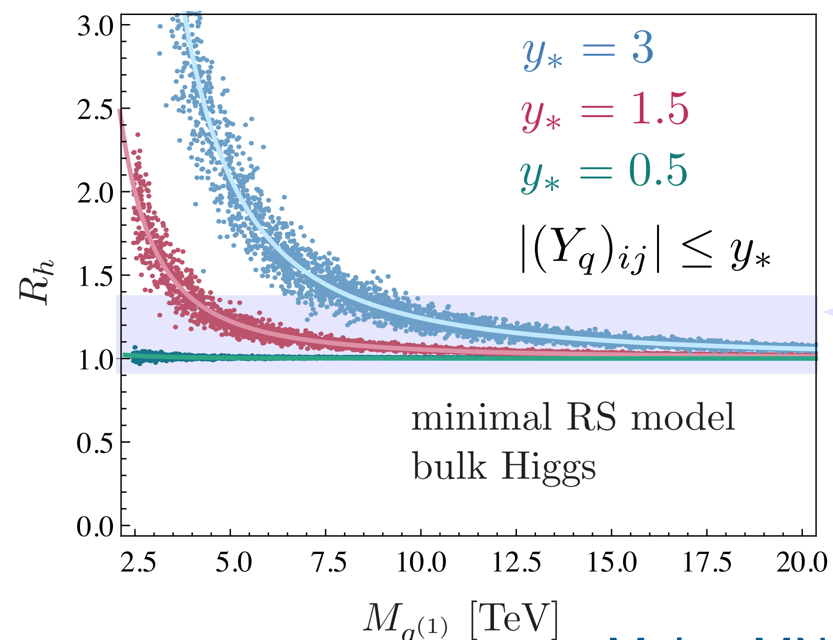




Phenomenological predictions and LHC data

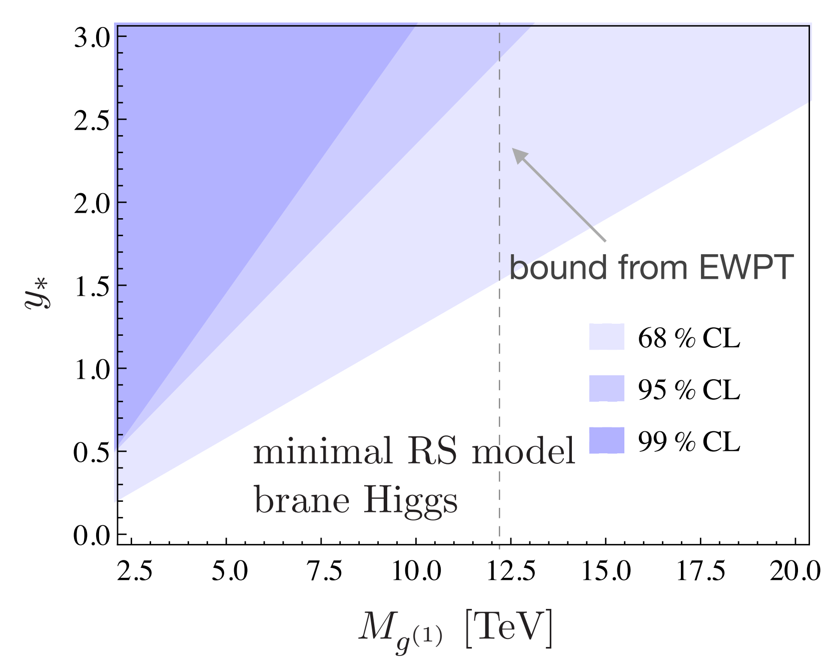
Ratio $R_h = \dfrac{\sigma(gg \to h)_{\rm RS}}{\sigma(gg \to h)_{\rm SM}}$ compared with data from ATLAS and CMS:

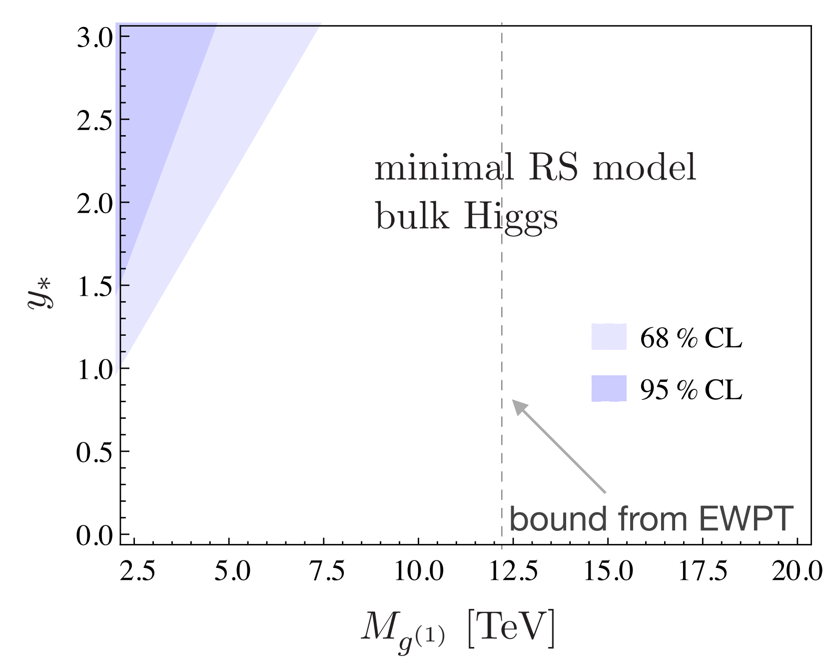




experimental data extracted from
$pp \to h \to ZZ^{(*)} \to 4\ell$

Malm, MN, Novotny, Schmell: arXiv:1303.5702





Phenomenological predictions and LHC data

Extended RS model with **custodial symmetry** protecting the T parameter, the left-handed $Zb\bar{b}$ couplings and flavor-violating Z-boson couplings

Bulk symmetry group: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$

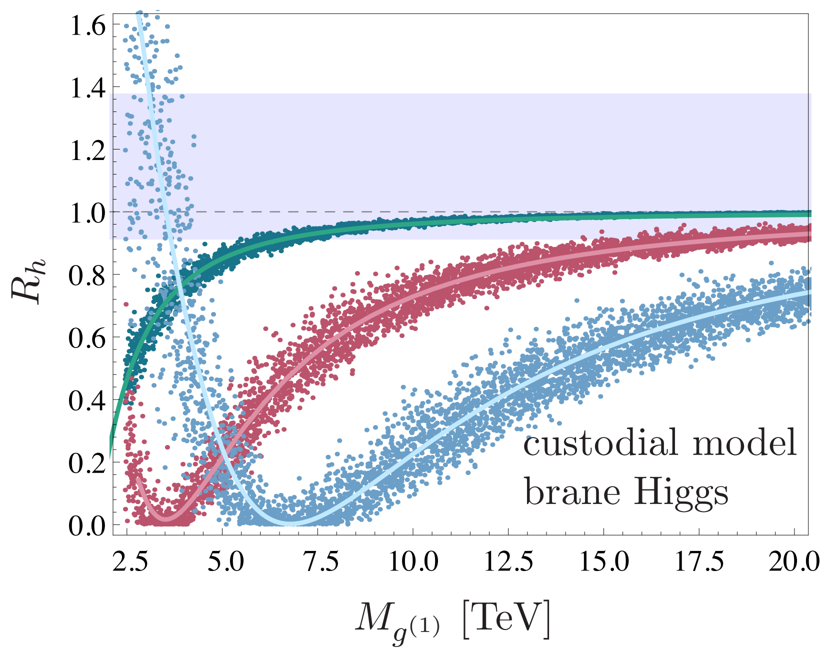
Representations of quark multiplets:

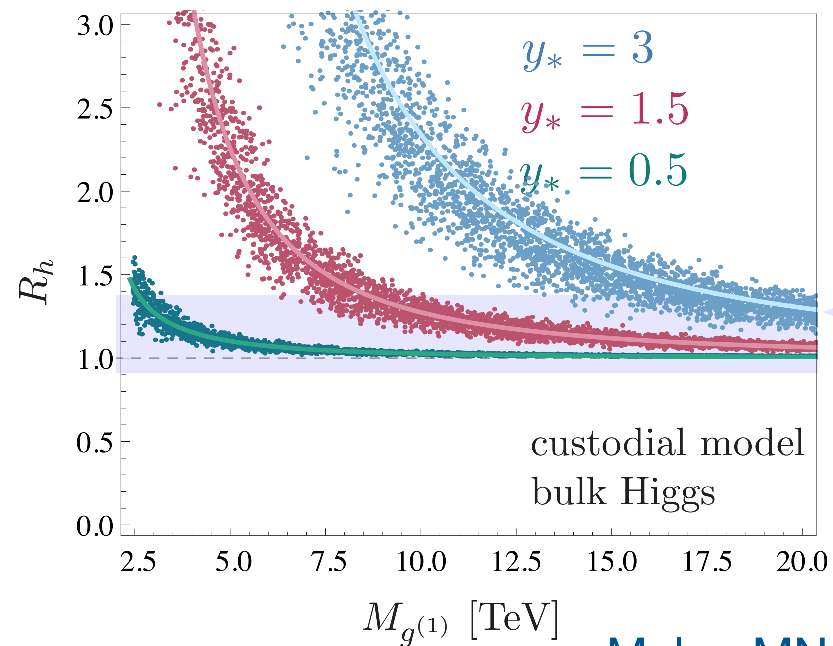
$$Q_L = \begin{pmatrix} u_L^{(+)}{}_{\frac{2}{3}} & \lambda_L^{(-)}{}_{\frac{5}{3}} \\ d_L^{(+)}{}_{-\frac{1}{3}} & u_L'^{(-)}{}_{\frac{2}{3}} \end{pmatrix}_{\frac{2}{3}}, \qquad u_R^c = \left(u_R^{c\,(+)}{}_{\frac{2}{3}} \right)_{\frac{2}{3}}$$

$$\mathcal{T}_R = \mathcal{T}_{1R} \oplus \mathcal{T}_{2R} = \begin{pmatrix} \Lambda_R'^{(-)}{}_{\frac{5}{3}} \\ U_R'^{(-)}{}_{\frac{2}{3}} \\ D_R'^{(-)}{}_{-\frac{1}{3}} \end{pmatrix}_{\frac{2}{3}} \oplus \left(D_R^{(+)}{}_{-\frac{1}{3}} \quad U_R^{(-)}{}_{\frac{2}{3}} \quad \Lambda_R^{(-)}{}_{\frac{5}{3}} \right)_{\frac{2}{3}}$$

Phenomenological predictions and LHC data

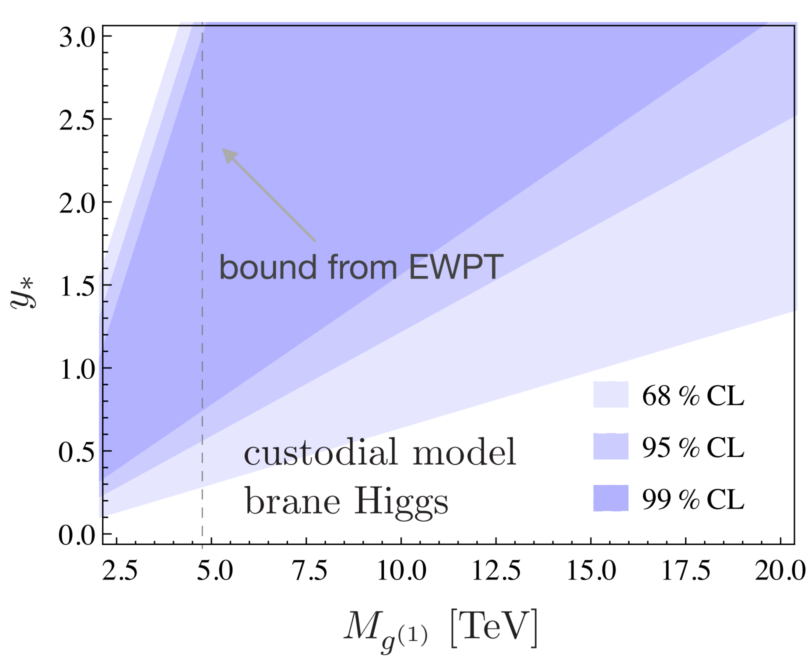
Ratio $R_h = \dfrac{\sigma(gg \to h)_{\rm RS}}{\sigma(gg \to h)_{\rm SM}}$ in RS model with **custodial symmetry**:

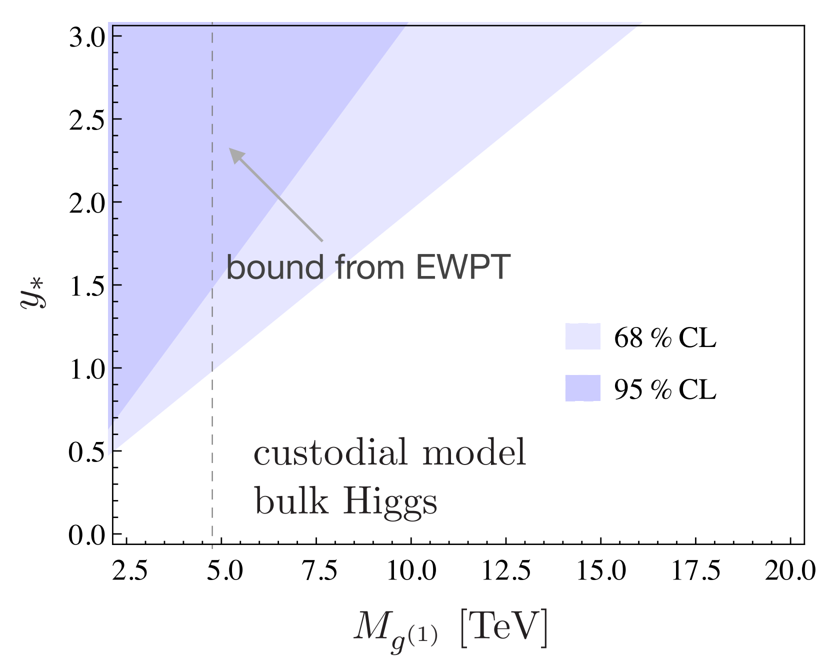




experimental data extracted from $pp \to h \to ZZ^{(*)} \to 4\ell$

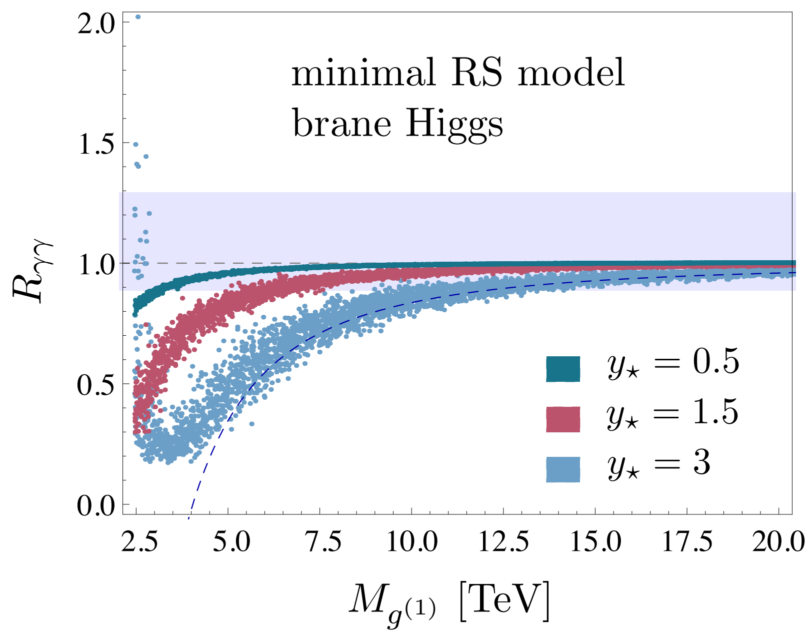
Malm, MN, Novotny, Schmell: arXiv:1303.5702

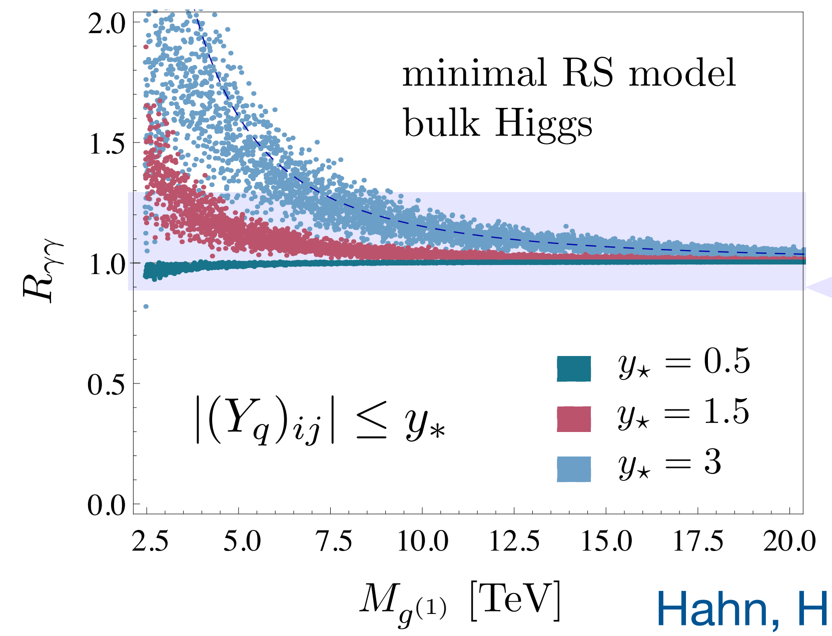




Phenomenological predictions and LHC data

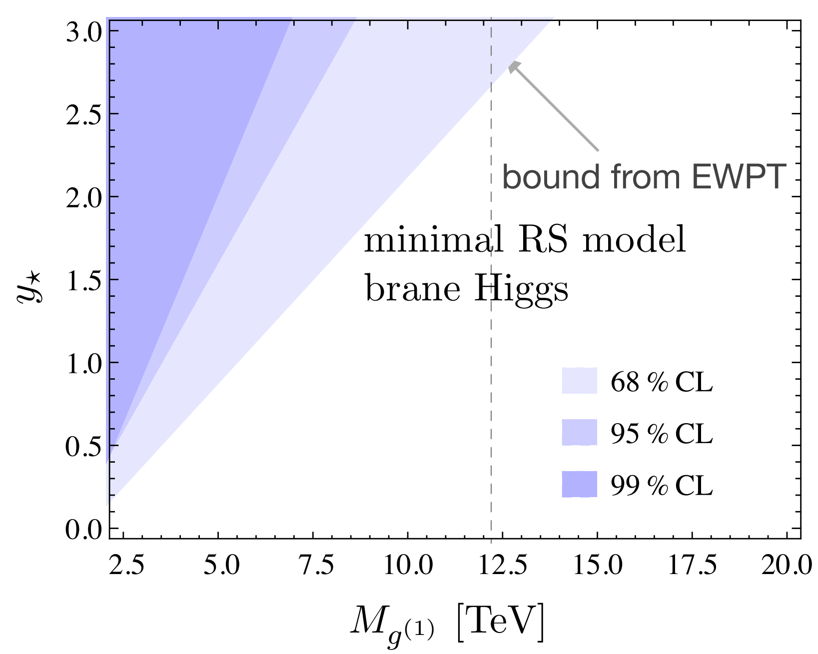
Ratio $R_{\gamma\gamma} \equiv \dfrac{(\sigma \cdot \mathrm{BR})(pp \to h \to \gamma\gamma)_{\mathrm{RS}}}{(\sigma \cdot \mathrm{BR})(pp \to h \to \gamma\gamma)_{\mathrm{SM}}}$ compared with data from ATLAS and CMS:

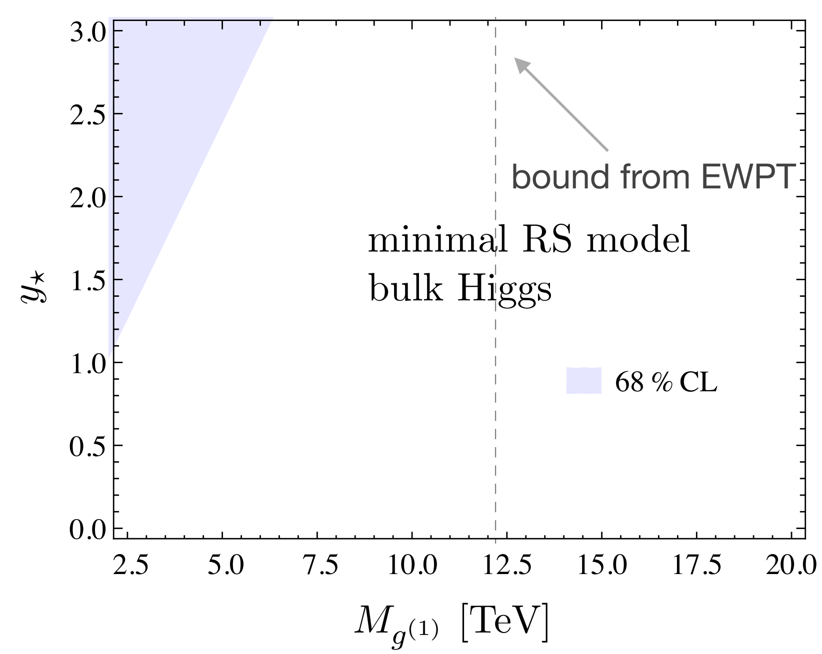




experimental data from ATLAS/CMS (combined)

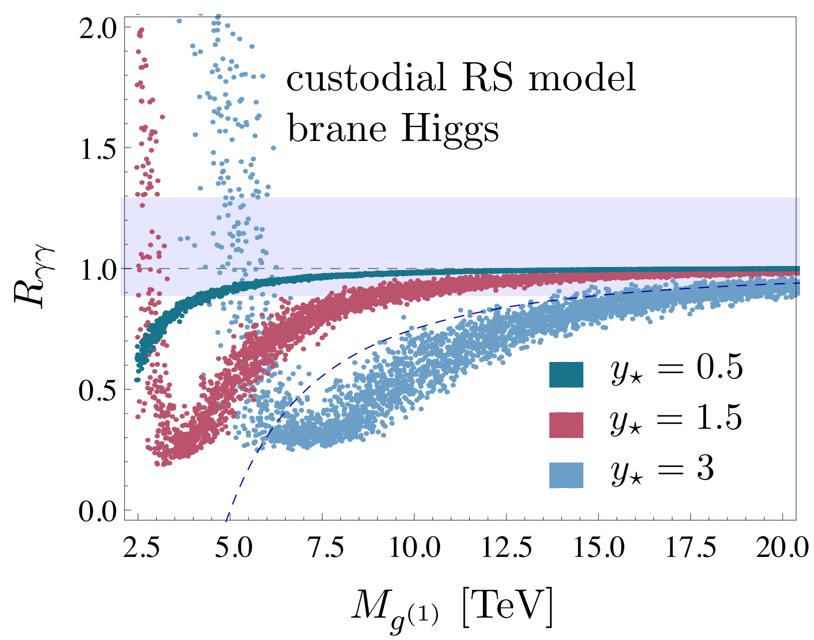
Hahn, Hörner, Malm, MN, Novotny, Schmell: arXiv:1312.5731

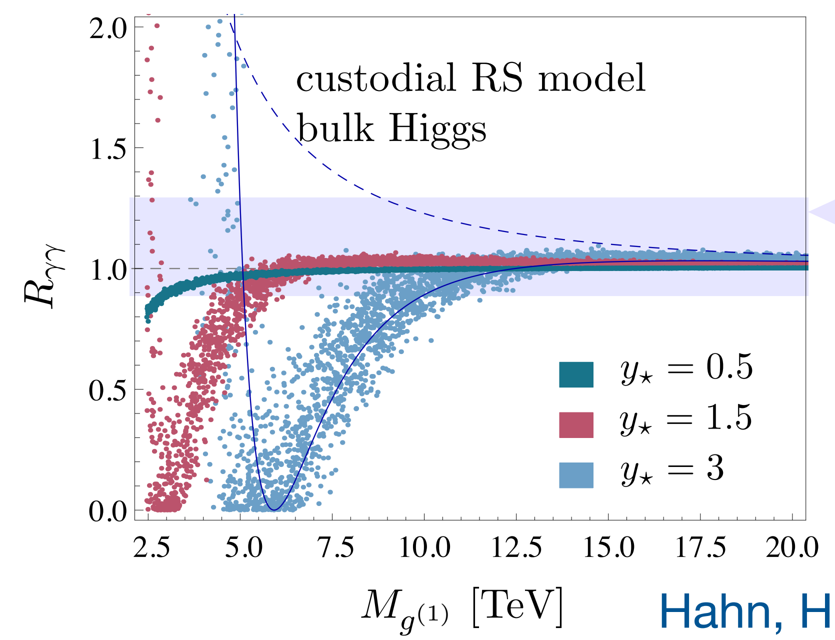




Phenomenological predictions and LHC data

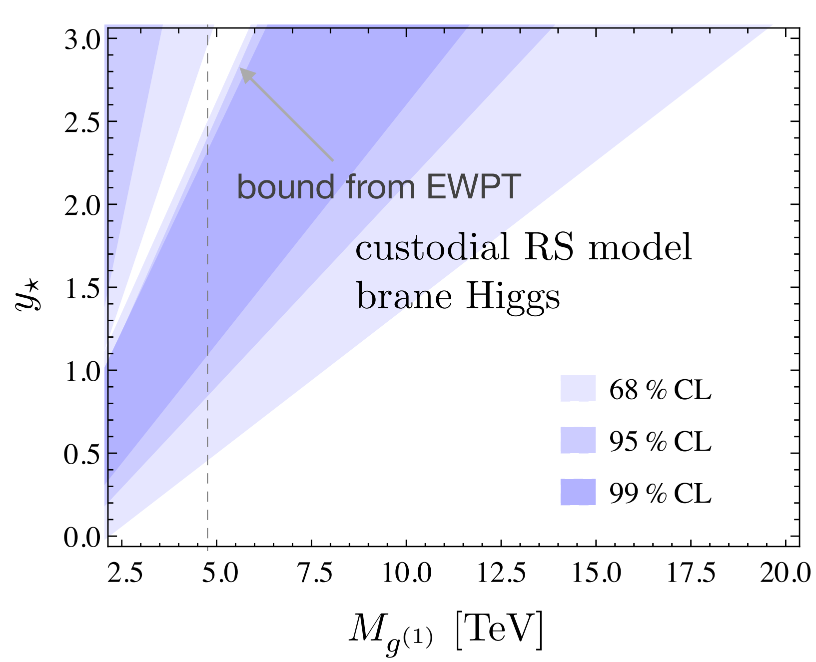
Ratio $R_{\gamma\gamma} \equiv \dfrac{(\sigma \cdot \mathrm{BR})(pp \to h \to \gamma\gamma)_{\mathrm{RS}}}{(\sigma \cdot \mathrm{BR})(pp \to h \to \gamma\gamma)_{\mathrm{SM}}}$ in RS model with **custodial symmetry**:

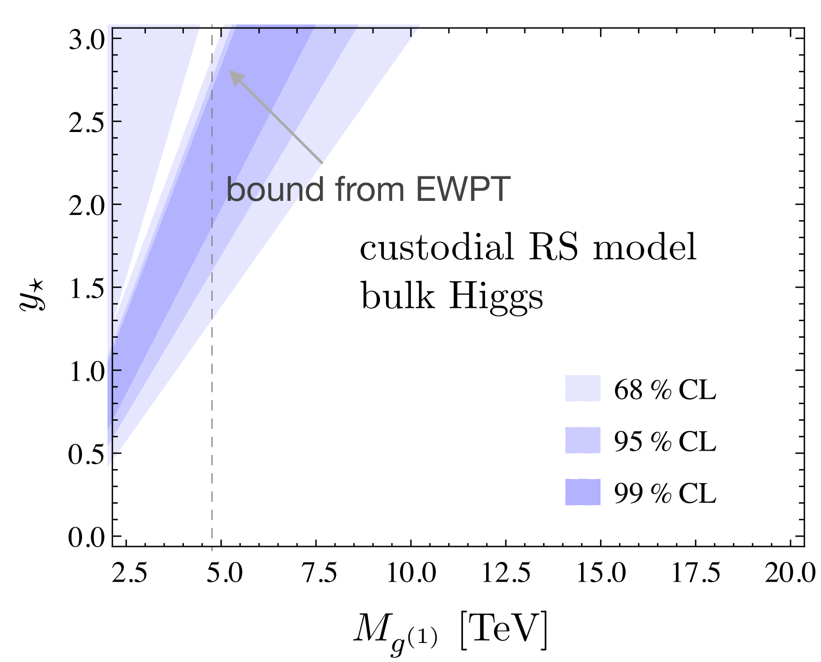




experimental data from ATLAS/CMS (combined)

Hahn, Hörner, Malm, MN, Novotny, Schmell: arXiv:1312.5731



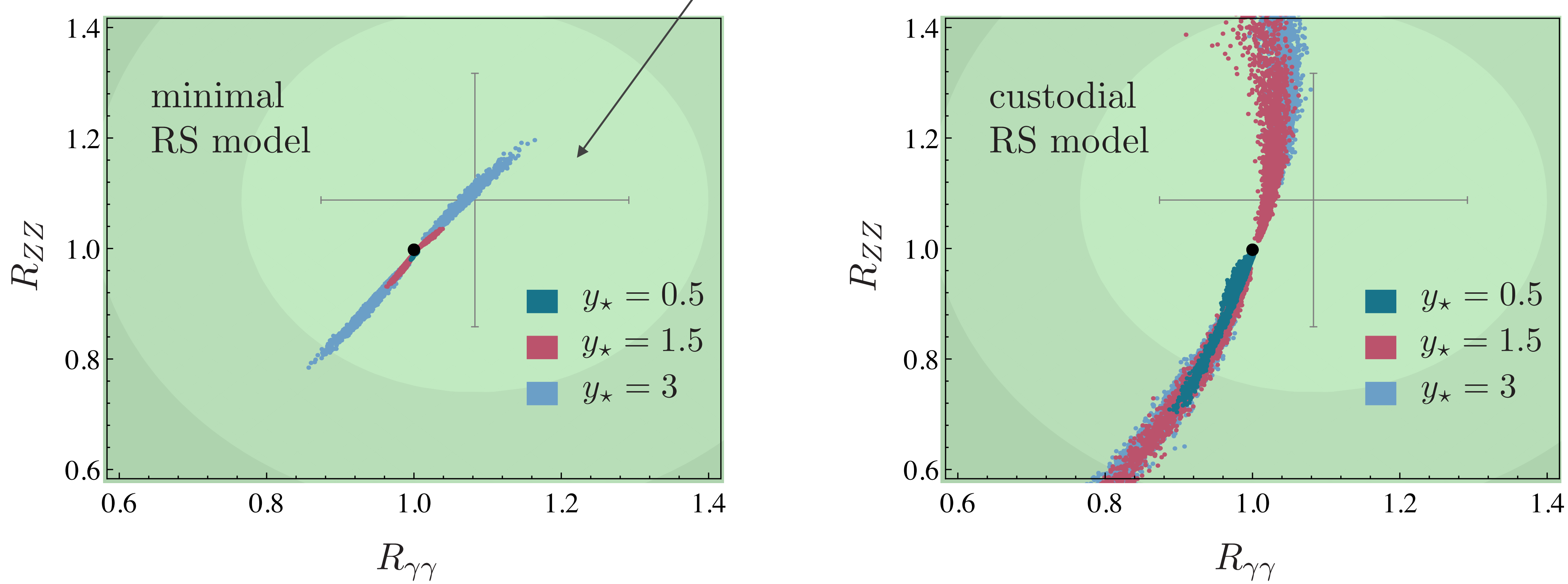


Strong correlation between $R_{\gamma\gamma}$ and R_{ZZ}

Strong correlation of the predictions for $R_{\gamma\gamma}$ and R_{ZZ} is observed!

Parameter scan of model points satisfying the bounds from electroweak precision tests:

experimental data from ATLAS/CMS (combined)



Malm, MN, Schmell: in preparation

More precise measurements at LHC and ILC will allow one to differentiate between different variants of RS models

Conclusions

- **Higgs phenomenology** provides a **superb laboratory for probing new physics** in the EWSB sector at the quantum level
- Much like rare FCNC processes, Higgs production in gluon fusion and Higgs decays into two photons are **loop-suppressed processes**, which are sensitive to new heavy particles
- **Warped extra-dimension models** provide an appealing framework for addressing the **hierarchy problem** and the **flavor puzzle** within the same geometrical approach
- Find that the contribution of the Kaluza-Klein towers of SM quarks and gauge bosons are universal and given entirely in terms of fundamental **5D Yukawa matrices** and **KK mass scale**
- Effects are enhanced by the **large multiplicity** of 5D fermion states and probe regions of parameter space **not accessible to direct searches**


LEKI

BACKUP SLIDES

Representations of lepton multiplets

Extended RS model with **custodial symmetry** protecting the *T* parameter, the left-handed $Zb\bar{b}$ couplings and flavor-violating *Z*-boson couplings

Bulk symmetry group: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$

Representations of lepton multiplets: **minimal model**

$$L_L = \begin{pmatrix} \nu_L^{(+)}{}_0 \\ e_L^{(+)}{}_{-1} \end{pmatrix}_{-\frac{1}{2}} , \qquad L_R^c = \begin{pmatrix} e_R^{c(+)}{}_{-1} \\ N_R^{(-)}{}_0 \end{pmatrix}_{-\frac{1}{2}}$$

→ used as default

Representations of lepton multiplets

Extended RS model with **custodial symmetry** protecting the T parameter, the left-handed $Zb\bar{b}$ couplings and flavor-violating Z-boson couplings

Bulk symmetry group: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$

Representations of lepton multiplets: **extended model**

$$\xi_{1L} = \begin{pmatrix} \nu_L^{(+)}{}_0 & \psi_L^{(-)}{}_1 \\ e_L^{(+)}{}_{-1} & \nu_L'^{(-)}{}_0 \end{pmatrix}_0 , \qquad \xi_{2R} = \left(\nu_R^{c\,(+)}{}_0\right)_0$$

$$\xi_{3R} = \mathcal{T}_{3R} \oplus \mathcal{T}_{4R} = \begin{pmatrix} \Psi_R'^{(-)}{}_1 \\ N_R'^{(-)}{}_0 \\ E_R'^{(-)}{}_{-1} \end{pmatrix}_0 \oplus \left(E_R^{(+)}{}_{-1} \quad N_R^{(-)}{}_0 \quad \Psi_R^{(-)}{}_1 \right)_0$$

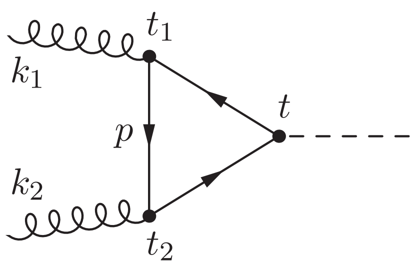
$$L_L = \begin{pmatrix} \nu_L^{(+)}{}_0 \\ e_L^{(+)}{}_{-1} \end{pmatrix}_{-\frac{1}{2}} , \qquad L_R^c = \begin{pmatrix} e_R^{c(+)}{}_{-1} \\ N_R^{(-)}{}_0 \end{pmatrix}_{-\frac{1}{2}}$$

gg→h production (details of the calculation)

Definition of the gg→h amplitude:

$$\mathcal{A}(gg \to h) = C_1 \frac{\alpha_s}{12\pi v} \langle 0 | G^a_{\mu\nu} G^{\mu\nu,a} | gg \rangle - C_5 \frac{\alpha_s}{8\pi v} \langle 0 | G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} | gg \rangle$$

Expression in terms of 5D propagators:



$$\mathcal{A}(gg \to h) = i g_s^2 \, \delta^{ab} \sum_{q=u,d} \int \frac{d^d p}{(2\pi)^d} \int_\epsilon^1 dt_1 \int_\epsilon^1 dt_2 \int_\epsilon^1 dt \, \delta_h^\eta(t-1)$$

$$\times \, \mathrm{Tr} \left[\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \boldsymbol{Y}_q \\ \boldsymbol{Y}_q^\dagger & 0 \end{pmatrix} \boldsymbol{S}^q(t, t_2; p - k_2) \, \not{\epsilon}(k_2) \, \boldsymbol{S}^q(t_2, t_1; p) \, \not{\epsilon}(k_1) \, \boldsymbol{S}^q(t_1, t; p + k_1) \right]$$

with:

$$i\boldsymbol{S}^q(t, t'; p) = \int d^4x \, e^{ip\cdot x} \langle 0 | \, T\big(\mathcal{Q}_L(t,x) + \mathcal{Q}_R(t,x)\big)\big(\bar{\mathcal{Q}}_L(t',0) + \bar{\mathcal{Q}}_R(t',0)\big) | 0 \rangle$$

$$= \left[\boldsymbol{\Delta}^q_{LL}(t, t'; -p^2) \, \not{p} + \boldsymbol{\Delta}^q_{RL}(t, t'; -p^2) \right] P_R + (L \leftrightarrow R)$$

Malm, MN, Novotny, Schmell: arXiv:1303.5702

gg→h production (details of the calculation)

Exact analytic results for Wilson coefficients in terms of an integral over a single 5D propagator function:

$$C_{1\gamma}^q = 3N_c \sum_{f=u,d} Q_q^2 \int_0^1 dx \int_0^{1-x} dy\,(1-4xy)\left[T_+^q(-xym_h^2) - T_+^q(\Lambda_{\rm TeV}^2)\right]$$

$$C_{5\gamma}^q = 2N_c \sum_{f=u,d} Q_q^2 \int_0^1 dx \int_0^{1-x} dy\left[T_-^q(-xym_h^2) - T_-^q(\Lambda_{\rm TeV}^2)\right]$$

where:

$$T_+(p_E^2) = -\sum_{q=u,d} \frac{v}{\sqrt{2}} \int_\epsilon^1 dt\, \delta_h^\eta(t-1)\,\mathrm{Tr}\left[\begin{pmatrix} 0 & \boldsymbol{Y}_q \\ \boldsymbol{Y}_q^\dagger & 0 \end{pmatrix} \frac{\boldsymbol{\Delta}_{RL}^q(t,t;p_E^2) + \boldsymbol{\Delta}_{LR}^q(t,t;p_E^2)}{2}\right]$$

$$T_-(p_E^2) = -\sum_{q=u,d} \frac{v}{\sqrt{2}} \int_\epsilon^1 dt\, \delta_h^\eta(t-1)\,\mathrm{Tr}\left[\begin{pmatrix} 0 & \boldsymbol{Y}_q \\ \boldsymbol{Y}_q^\dagger & 0 \end{pmatrix} \frac{\boldsymbol{\Delta}_{RL}^q(t,t;p_E^2) - \boldsymbol{\Delta}_{LR}^q(t,t;p_E^2)}{2i}\right]$$

Contributions at large momenta (near cutoff) vanish if the Higgs is a bulk field, but not if it lives on the IR brane!

Impact of higher-dimensional hgg operators

Consider a dimension-6 operator localized on the IR brane, which can mediate gg→h at tree level with effective strength $c_{\rm eff}$ (could be O(1) for strong coupling):

$$S_{\rm eff} = \int d^4x \int_{-r\pi}^{r\pi} dx_5\, c_{\rm eff}\, \delta(|x_5| - r\pi)\, \frac{\Phi^\dagger \Phi}{\Lambda_{\rm TeV}^2}\, \frac{g_{s,5}^2}{4}\, \mathcal{G}_{\mu\nu}^a\, \mathcal{G}^{\mu\nu,a} + \dots$$

Resulting effective Lagrangian:

$$\mathcal{L}_{\rm eff} = \frac{c_{\rm eff}}{\Lambda_{\rm TeV}^2}\, \mathcal{O}_{\rm eff} \qquad \text{with} \qquad \mathcal{O}_{\rm eff} = \Phi^\dagger \Phi\, \frac{g_s^2}{4}\, G_{\mu\nu}^a\, G^{\mu\nu,a} \ni \frac{g_s^2 v^2}{8} \left(1 + \frac{h(x)}{v}\right)^2 G_{\mu\nu}^a\, G^{\mu\nu,a}$$

Resulting contribution to Wilson coefficient C_1:

$$\Delta C_1 = \frac{3 c_{\rm eff}}{4} \left(\frac{4\pi v}{\Lambda_{\rm TeV}}\right)^2 \approx c_{\rm eff} \left(\frac{2.7\,\text{TeV}}{\Lambda_{\rm TeV}}\right)^2$$

for $\Lambda_{\rm TeV}$~20-50 TeV, as is appropriate for KK masses in 5-15 TeV range, this effect is very small !