# Higgs Physics in Warped Extra Dimensions

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Brussels
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Casagrande, FG, Haisch, Neubert, Pfoh, JHEP 1009(2010)014

# Outline

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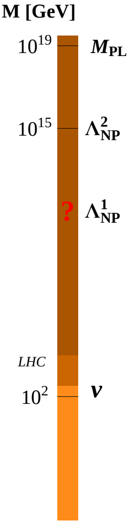
# Motivation: The Gauge Hierarchy Problem




- Higgs mass receives quadratically divergent corrections

$\Rightarrow$ expect $m_h^2 \sim \max[\Lambda^i_{NP}]^2$

- Gauge bosons: gauge symmetry
- Fermions: $SU(2)_L$

} small masses natural

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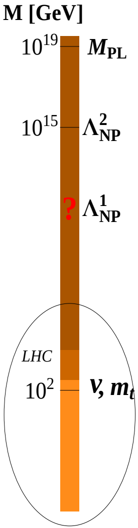


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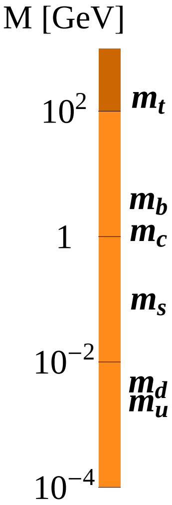
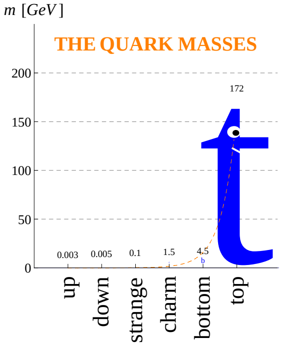



$$m_u/m_t \sim 10^{-5}$$



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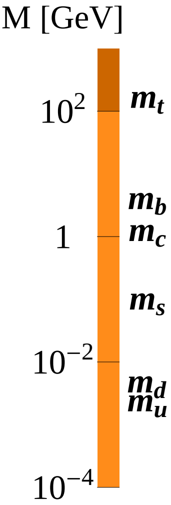


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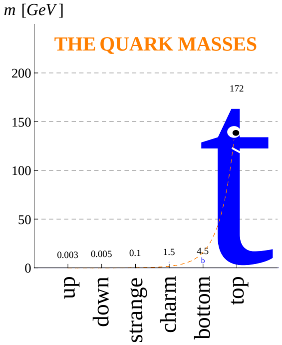


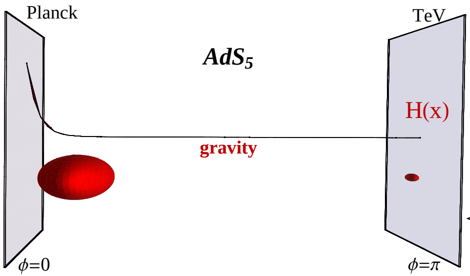

$$\mathbf{V}_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

$$\lambda \sim 0.2$$

# The Randall-Sundrum (RS) Model hep-ph/9905221

- Solution to the gauge hierarchy problem in 5D spacetime
- Hierarchy between the electroweak- and Planck scale generated through non-factorizable metric

$$ds^2 = e^{-2L|\phi|/\pi}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$




$\Leftarrow$ $m = e^{-L} m_0$

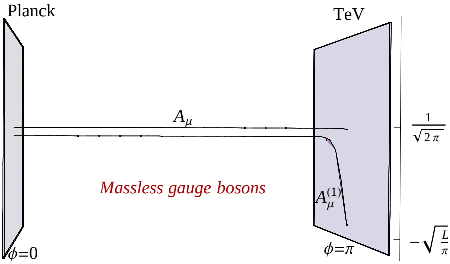
$L = kr\pi \approx 37 \gg 1$

many observables enhanced by L

- All fundamental mass parameters of $\mathcal{O}(M_{PL})$

# The Standard Model in $AdS_5$

- Just the Higgs boson has to be localized at (close to) the TeV brane in order to solve the hierarchy problem $\Rightarrow$ *Bulk-SM*




$m_1 \approx 2.5\, M_{\rm KK}$,
$M_{\rm KK} = ke^{-L} \sim$TeV

Davoudiasl, Hewett, Rizzo, hep-ph/9911262

$$A_\mu(x,\phi) = \frac{1}{\sqrt{r}} \sum_n A_\mu^{(n)}(x)\, \chi_n^A(\phi)$$

$$-\frac{1}{r^2}\, \partial_\phi\, e^{-2\sigma(\phi)}\, \partial_\phi\, \chi_n^A(\phi) = (m_n^A)^2\, \chi_n^A(\phi)$$

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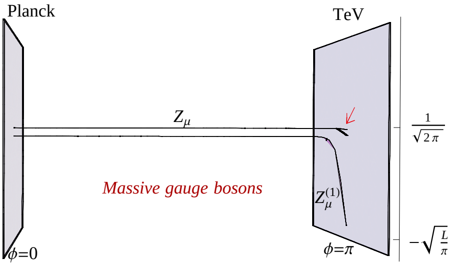


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$$M_{\rm KK} = k e^{-L} \sim \text{TeV}$$

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$$Z_\mu(x,\phi) = \frac{1}{\sqrt{r}} \sum_n Z_\mu^{(n)}(x)\, \chi_n^Z(\phi)$$ KK decomposition in mass basis, treat EWSB exactly

$$-\frac{1}{r^2}\,\partial_\phi\, e^{-2\sigma(\phi)}\,\partial_\phi\, \chi_n^Z(\phi) = (m_n^Z)^2\, \chi_n^Z(\phi) - \frac{\delta(|\phi|-\pi)}{r}\, M_Z^2\, \chi_n^Z(\phi)$$

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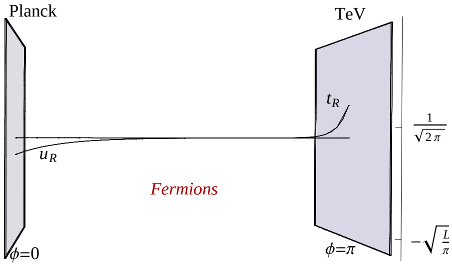


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Grossman, Neubert, hep-ph/9912408

Gherghetta, Pomarol, hep-ph/0003129

$$u_L(x,\phi) = \frac{e^{2\sigma(\phi)}}{\sqrt{r}} \sum_n \mathbf{C}_n^{(Q)}(\phi)\, a_n^{(U)}\, u_L^{(n)}(x)\,, \quad u_L^c(x,\phi) = \frac{e^{2\sigma(\phi)}}{\sqrt{r}} \sum_n \mathbf{S}_n^{(u)}(\phi)\, b_n^{(u)}\, u_L^{(n)}(x)$$

$$\left(\tfrac{1}{r}\partial_\phi + \mathbf{M}_Q\,\mathrm{sgn}(\phi)\right)\mathbf{S}_n^{(Q)}(\phi)a_n^{(U)} = m_n e^{\sigma(\phi)}\mathbf{C}_n^{(Q)}(\phi)a_n^{(U)} - \delta(|\phi|-\pi)e^{\sigma(\phi)}\frac{\sqrt{2}\,v}{kr}\mathbf{Y}_u\mathbf{C}_n^{(u)}(\phi)a_n^{(u)}$$

$\ldots$

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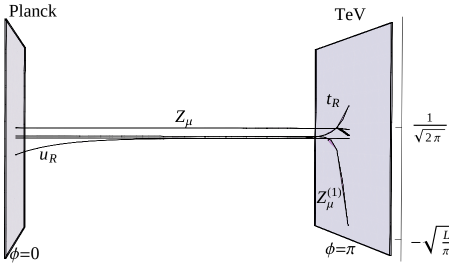


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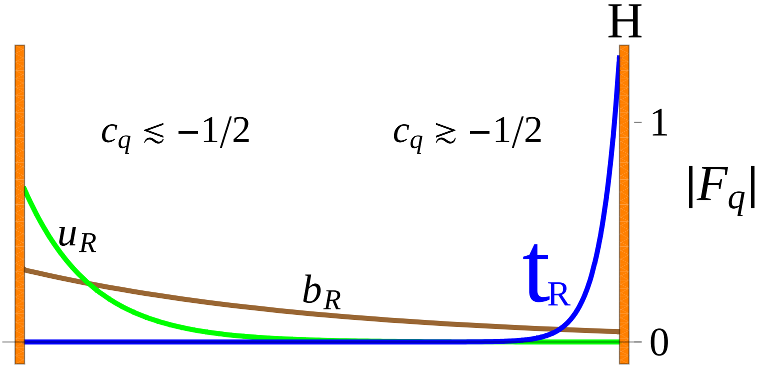
**Couplings $\sim$ flavor dependent overlaps, doublet-singlet mixing**

$\Rightarrow$ Fields with same QN under unbroken symmetry have different couplings to gauge bosons of broken symmetry $\Rightarrow$ tree FCNCs

# RS as a Solution to the Flavor Puzzle

- RS offers explanation for fermion mass hierarchies and small CKM mixing angles Huber, hep-ph/0303183; Agashe, Perez, Soni, hep-ph/0408134




$c_{Q,q} = \pm M_{Q,q}/k$ : $\mathcal{O}(1)$ dimensionless 5D-mass parameters

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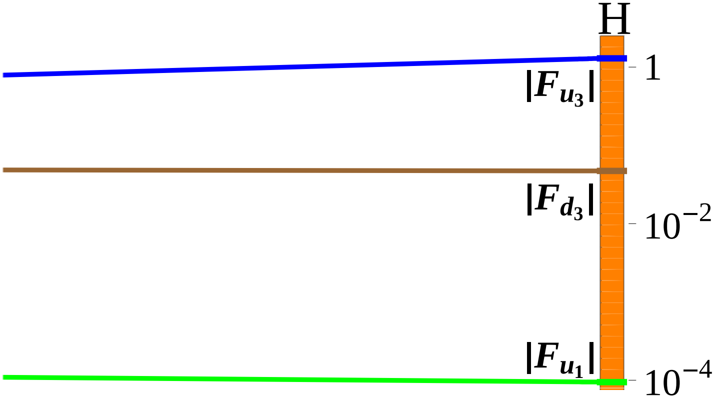

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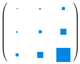
- Zero Mode Approximation:

$$\left(Y_u^{\text{eff}}\right)_{ij} \equiv F(c_{Q_i})\,(Y_u)_{ij}\,F(c_{u_j}) = \frac{\sqrt{2}}{v}\mathbf{U}_q\,\mathrm{diag}[m_{q_i}]\,\mathbf{W}_q^\dagger$$



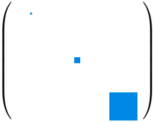
$(Y_u)_{ij} \sim \mathcal{O}(1)$

- One-to-one correspondence to Froggatt-Nielsen mechanism: charge under $U(1)_F \Leftrightarrow$ localization $c_{Q,q} = \pm M_{Q,q}/k \sim \mathcal{O}(1)$

Froggatt, Nielsen, Nucl. Phys. B 147, 277 (1979)
Casagrande, FG, Haisch, Neubert, Pfoh, 0807.4937
Blanke, Buras, Duling, Gori, Weiler, 0809.1073

# RS as a Solution to the Flavor Puzzle

$$m_{q_i} = \mathcal{O}(1) \times \frac{v}{\sqrt{2}} \left| F(c_{Q_i}) F(c_{q_i}) \right|$$



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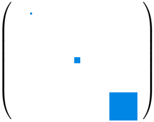

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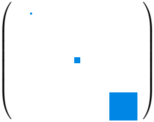

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$$\bar{\rho}, \bar{\eta} \sim \mathcal{O}(1)$$

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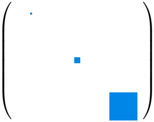

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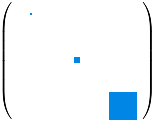

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$$\frac{|F(c_{Q_1})|}{|F(c_{Q_2})|} \sim \lambda \,, \qquad \frac{|F(c_{Q_2})|}{|F(c_{Q_3})|} \sim \lambda^2 \,, \qquad \frac{|F(c_{Q_1})|}{|F(c_{Q_3})|} \sim \lambda^3$$

$$\Rightarrow \mathbf{V}_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

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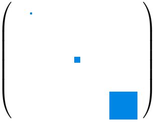

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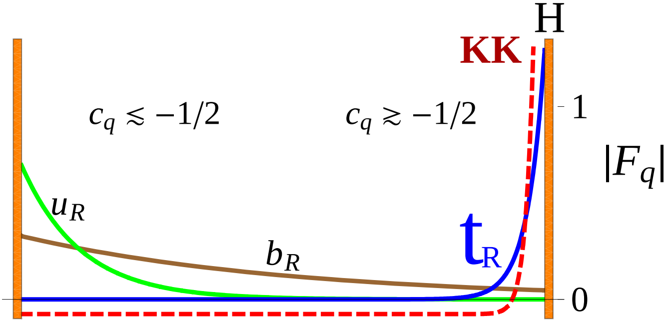



Expect sizable effects in 3rd generation and Higgs physics

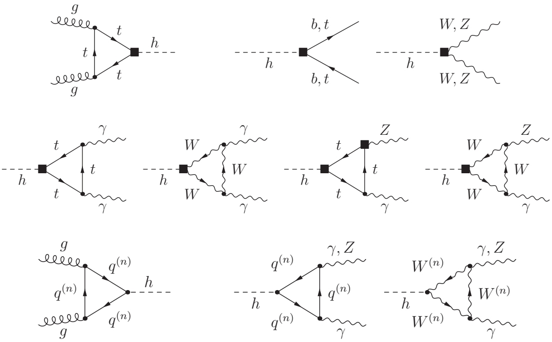
# Outline

# Higgs Production and Decay

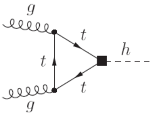
## First complete one-loop calculation in RS

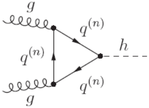
Casagrande, FG, Haisch, Neubert, Pfoh, 1005.4315 (custodial model)

Bouchart, Moreau, 0909.4812; Azatov, Toharia, Zhu, 1006.5939



# Higgs Production




$$\sigma(gg \to h)_{\rm RS} = |\kappa_g|^2\, \sigma(gg \to h)_{\rm SM}$$

$$\kappa_g = \frac{\sum_{i=t,b} \kappa_i A_q^h(\tau_i) + \sum_{j=u,d,\lambda} \nu_j}{\sum_{i=t,b} A_q^h(\tau_i)}$$

- $\tau_i \equiv 4\, m_i^2 / m_h^2$
- Form factor $A_q^h(\tau_i)$ approaches 1 for $\tau_i \to \infty$ and vanishes proportional to $\tau_i$ for $\tau_i \to 0$
- $\kappa_t = 1 - \frac{v}{m_t} (\Delta g_h^u)_{33}\,, \qquad \kappa_b = 1 - \frac{v}{m_b} (\Delta g_h^d)_{33}$
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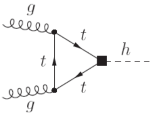


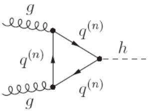


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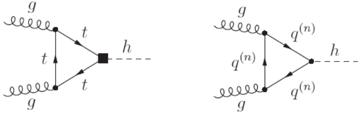


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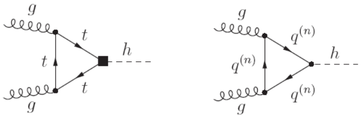


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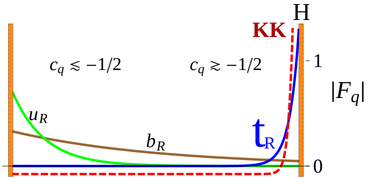
# Higgs Production

Misalignment between the SM fermion masses and Yukawa couplings

$$(\Delta g_h^q)_{ii} = |\cdots|^2 + \mathcal{O}(\frac{m_c}{m_t}) > 0$$

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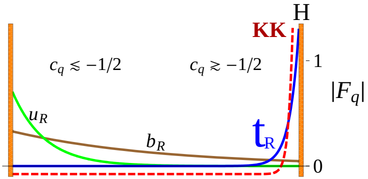


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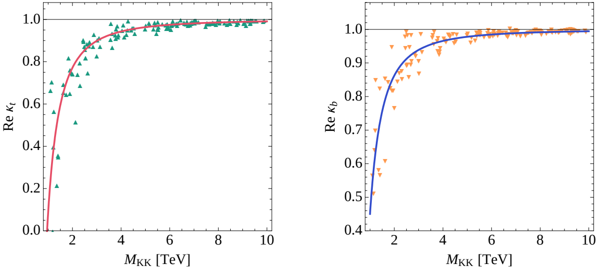

# Higgs Production

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- Sum is naively divergent (without cancellations)
- But: Low energy theorems relate Wilson coefficient of operator $h/v\, G_{\mu\nu}^a G^{a\,\mu\nu}$ to QCD $\beta$-function Low, Rattazzi, Vichi, 0907.5413 + refs therein,

  Logarithmic running of $\alpha_s$ in RS Randall, Schwartz, hep-th/0108114, ...

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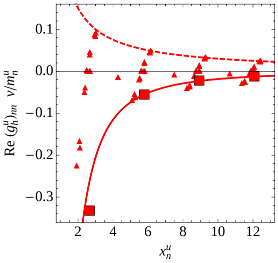
In practice:



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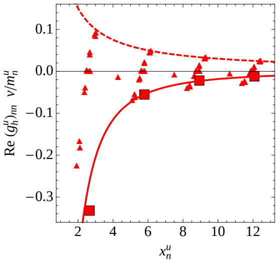
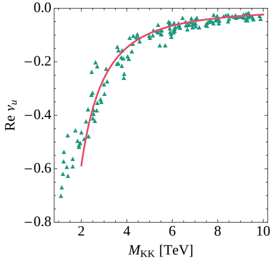
- Sum is naively divergent (without cancellations)
- But: Low energy theorems relate Wilson coefficient of operator $h/v\, G^a_{\mu\nu} G^{a\,\mu\nu}$ to QCD $\beta$-function Low, Rattazzi, Vichi, 0907.5413 + refs therein,
  Logarithmic running of $\alpha_s$ in RS Randall, Schwartz, hep-th/0108114, ...
  $\Rightarrow$ convergence of sum above

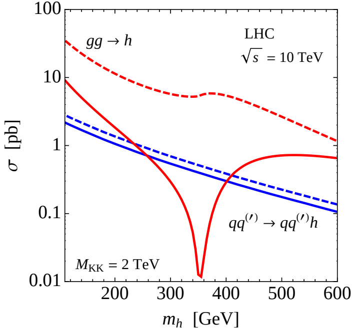
In practice:

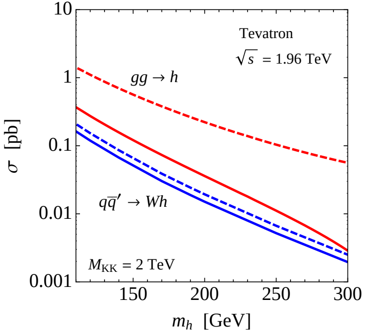



$\Rightarrow$



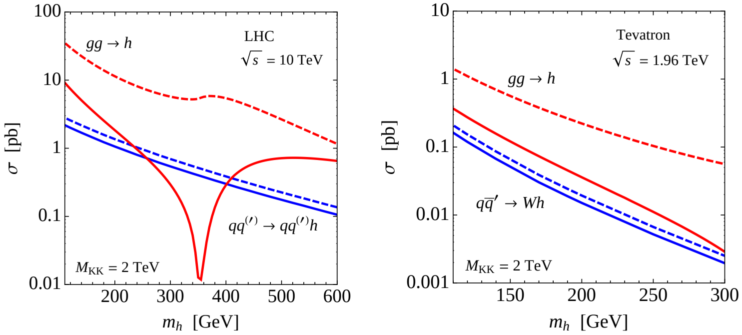
# Higgs Production




solid: custodial RS, dashed: SM

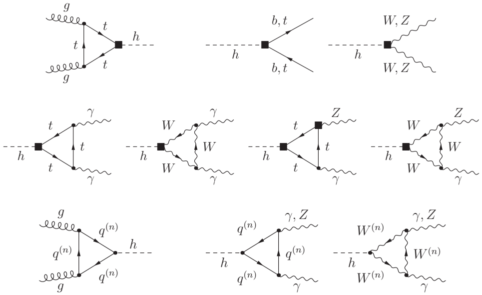
# Higgs Production




solid: custodial RS, dashed: SM

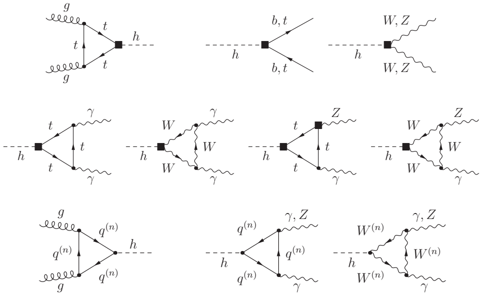
- Higgs mass bounds could be altered
- Only mild dependence on RS parameters besides $M_{\mathrm{KK}}$
- At $M_{\mathrm{KK}} = 5$ TeV still suppressions up to 40 % $\rightarrow$ sensitivity to high scales!

# Higgs Decay




$$\Gamma(h \to f)_{\mathrm{RS}} = |\kappa_f|^2 \, \Gamma(h \to f)_{\mathrm{SM}}$$

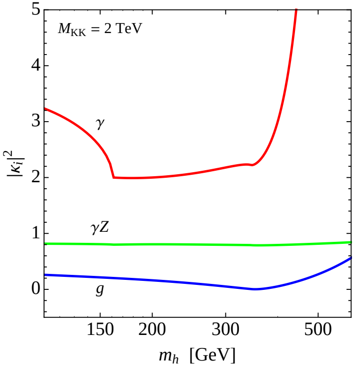
# Higgs Decay

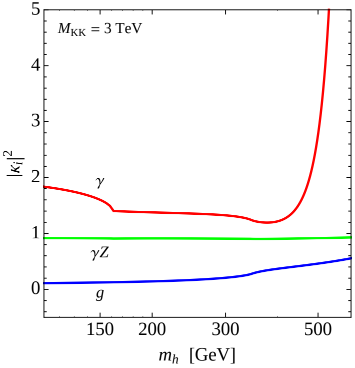



$$\Gamma(h \to f)_{\mathrm{RS}} = |\kappa_f|^2 \; \Gamma(h \to f)_{\mathrm{SM}}$$

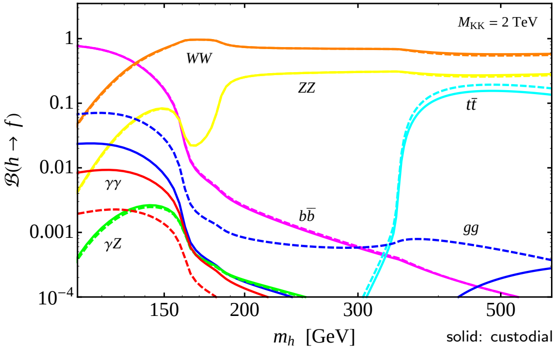
- *WWh* and *ZZh* receive mild suppressions of order $-10\%$ ($-5\%$) in custodial (minimal) model for $M_{\mathrm{KK}} = 2$ TeV
- Sum up fermions and $W$-bosons in loop

# Higgs Decay


$M_{KK}$ = 2 TeV
γ
γZ
g
$|\kappa_i|^2$
5
4
3
2
1
0
150
200
300
500
$m_h$ [GeV]


$M_{KK}$ = 3 TeV
γ
γZ
g
$|\kappa_i|^2$
5
4
3
2
1
0
150
200
300
500
$m_h$ [GeV]

# Higgs Decay




solid: custodial RS, dashed: SM

- Above *WW* threshold: Higgs discovery via golden channel $gg \to h \to Z^{(*)}Z^{(*)} \to l^+l^-l^+l^-$ more difficult
- Below *WW* threshold: slightly better potential to discover the Higgs via $gg \to h \to \gamma\gamma$ for $M_{\mathrm{KK}} = 2$ TeV

# Summary

- RS models offer interesting possibility to address unexplained hierarchies
- Couplings involving third generation quarks or the Higgs boson can receive significant corrections
- Sensitivity to KK masses well above 10 TeV in Higgs Physics

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Thank you for your attention!

# Backup: Higgs Couplings

$$\mathcal{L}_{4\mathrm{D}} \ni - \sum_{q,m,n} (g_h^q)_{mn}\, h\, \bar{q}_L^m\, q_R^n + \mathrm{h.c.}\,,$$

$$(g_h^q)_{mn} \equiv \delta_{mn}\, \frac{m_m^q}{v} - (\Delta g_h^q)_{mn}\,,$$

$$(\Delta g_h^q)_{mn} = \frac{m_m^q}{v}\, (\Phi_q)_{mn} + (\Phi_Q)_{mn}\, \frac{m_n^q}{v} + (\Delta \tilde{g}_h^q)_{mn}\,,$$

$$(\Phi_q)_{mn} = \frac{2\pi}{L\epsilon} \int_\epsilon^1 dt\, \vec{a}_m^{Q\dagger}\, \mathbf{S}_m^Q(t)\, \mathbf{S}_n^Q(t)\, \vec{a}_n^Q\,, \qquad (\Phi_Q)_{mn} = \frac{2\pi}{L\epsilon} \int_\epsilon^1 dt\, \vec{a}_m^{q\dagger}\, \mathbf{S}_m^q(t)\, \mathbf{S}_n^q(t)\, \vec{a}_n^q\,,$$

$$(\Delta \tilde{g}_h^q)_{mn} = \frac{1}{\sqrt{2}}\, \frac{2\pi}{L\epsilon}\, \frac{v^2}{3M_{\mathrm{KK}}^2}\, \vec{a}_m^{Q\,\dagger}\, \mathbf{C}_m^Q(1^-)\, \tilde{\mathbf{Y}}_{\vec{q}}\, \bar{\mathbf{Y}}_{\vec{q}}^\dagger\, \tilde{\mathbf{Y}}_{\vec{q}}\, \mathbf{C}_n^q(1^-)\, \vec{a}_n^q$$