Loop-induced Processes and Higgs Phenomenology in Warped Extra Dimensions

in collaboration with C. Schmell and M. Neubert

based on [hep-ph/1303.5702, hep-ph/1312.5731] and current work

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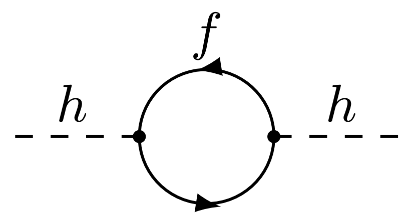
Outline

- Motivation and introduction to the model
- Loop-induced Higgs production and decay
    - $gg \to h$
    - $h \to \gamma\gamma$
- Tree-level Higgs production and decay
- Higgs phenomenology and implications for the RS parameter space

Motivation - hierarchy puzzles of the SM

Gauge Hierarchy Puzzle

- why is the Higgs so light, $m_h^2 \ll M_{\rm Pl}^2$ (roughly 32 orders of magnitude) ?
- Higgs mass operator not protected by any symmetry (radiatively unstable)



$$\Rightarrow \qquad \delta m_h^2 = \frac{\mathcal{O}(1)}{16\pi^2} \times \left(\Lambda_{\rm UV}^2 + m_f^2 \, \log(\Lambda_{\rm UV}/m_f) + \dots\right)$$

Flavour Hierarchy Puzzle

- why do Yukawa matrices have a hierarchical pattern (flavor puzzle) ?

$$|Y_u| \sim \begin{pmatrix} 4.3\,10^{-6} & 4.8\,10^{-4} & 8.6\,10^{-3} \\ 2.8\,10^{-5} & 2.8\,10^{-3} & 6.4\,10^{-2} \\ 2.7\,10^{-4} & 3.3\,10^{-2} & 0.8 \end{pmatrix} \quad \Leftrightarrow \quad y_t \sim 1,\; y_c \sim 10^{-3},\; y_u \sim 10^{-6}$$

- new physics at the TeV scale should explain the suppression of FCNC processes (GIM-like mechanism)

$$\mathcal{L}_{\rm eff} = \sum_i \frac{c_i}{\Lambda^2}\,\mathcal{O}_i \qquad \xleftrightarrow{\; c_i \sim \mathcal{O}(1) \;}$$

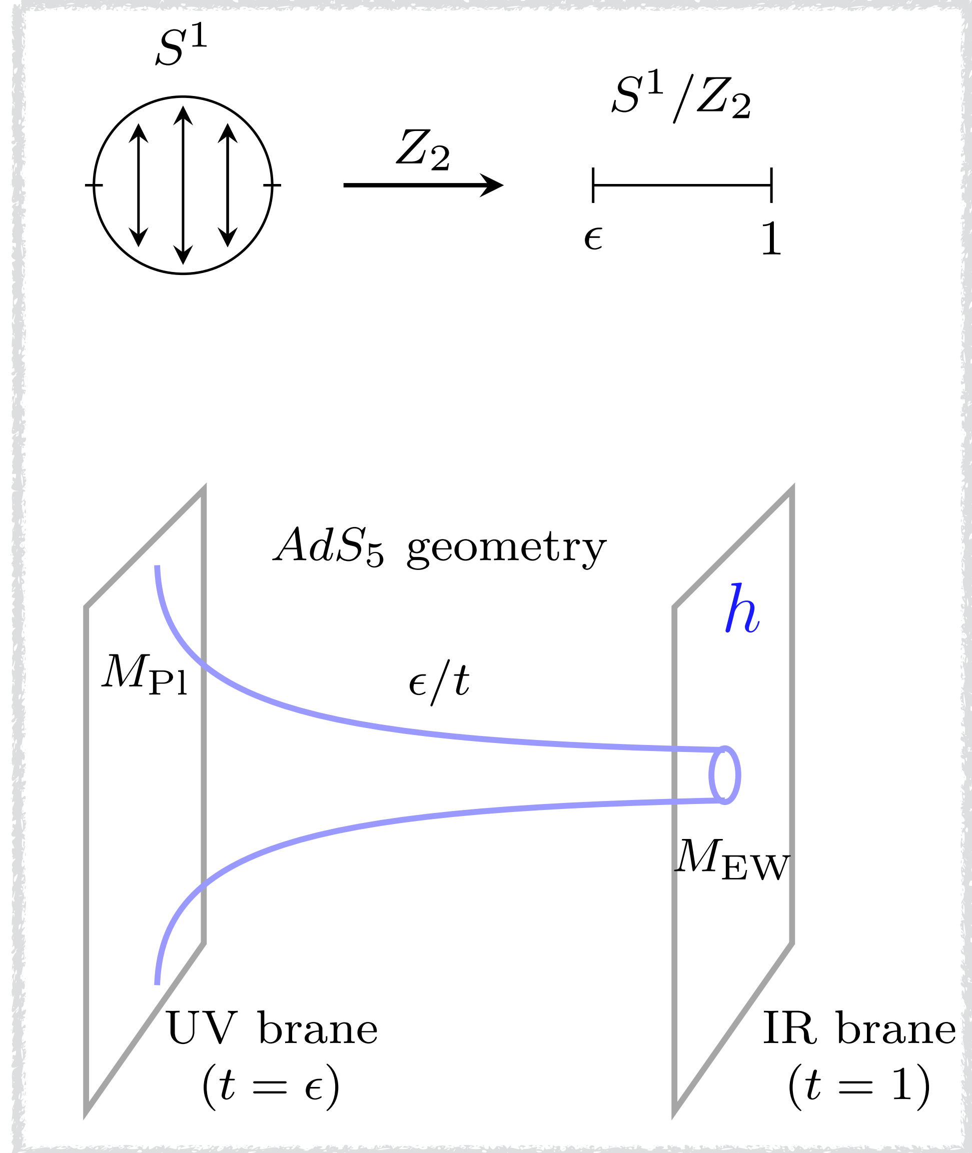
observable	$\mathcal{O}_i$	Λ [TeV]
ϵ_K	$(ds^c)(ds^c)$	$10^4 - 10^5$
Δm_K	$(ds^c)(ds^c)$	$10^3 - 10^3$
Δm_D	$(cu^c)(cu^c)$	$10^2 - 10^3$
Δm_{B_d}	$(bd^c)(bd^c)$	$10^2 - 10^3$

Warped extra dimensions - basics

Setup

[Randall,Sundrum:hep-ph/9905221]

- effective QFT in a slice of AdS_5 space-time, bounded by two 3-branes
- extra dimension: S^1/Z_2 orbifold $(t \in [\epsilon, 1])$
  - Z_2 parity → chiral fermions
- 5D space-time:
  - non-factorizable metric: $ds^2 = \frac{\epsilon^2}{t^2}\left(dx^\mu dx_\mu - \frac{1}{k^2\epsilon^2}\,dt^2\right)$
  - Ricci-scalar (negative scalar curvature): $R = -20k^2$
  - radius of S^1 : $r \sim M_{\rm Pl}^{-1}$
  - warp factor rescaling energy/length: ϵ/t with $\epsilon = e^{-kr\pi}$
  - electroweak hierarchy: $kr \approx 30 \;\rightarrow\; \epsilon \approx \frac{M_{\rm EW}}{M_{\rm Pl}} \approx 10^{-16}$
  - stabilization of radius via bulk scalar [Goldberger,Wise:hep-ph/9907447]
- Higgs sector resides on or near the IR brane
- all 5D fermions and gauge-bosons live in the bulk
- KK decomposition of 5D fields: $\Phi(x,t) \sim \sum_{n=0}^{\infty} \phi_n(x)\chi_n(t)$
- KK mass spectrum: $m_n \sim n\pi M_{\rm KK}$ $\qquad M_{\rm KK} = k\epsilon \sim \text{few TeV}$



Solutions to the hierarchy puzzles

Gauge hierarchy puzzle

[Randall,Sundrum:hep-ph/9905221]

$$S_{\text{Higgs}} \ni \int d^4x \int_\epsilon^1 \frac{dt}{t} \sqrt{|G|}\, \delta(t-1)\, \lambda \left(|\Phi(x)|^2 - v_5^2\right)^2 = \int d^4\, x\, \lambda \left(|\tilde{\Phi}(x)|^2 - v_5^2 e^{-2L}\right)^2$$

- 5D vev is rescaled by the warp factor at the infra-red brane

$$v_5 \sim \mathcal{O}(M_{\text{Pl}}) \quad \Rightarrow \quad v = v_5 e^{-L} \approx 246\,\text{GeV}$$

Fermion hierarchy puzzle

[Grossmann,Neubert:hep-ph/9912408] [Gherghetta,Pomarol:hep-ph/0003129] [Huber,Shafi:hep-ph/0010195]

- 5D fermion bulk-mass parameters: $c_{Q_i}, c_{u_i}, c_{d_i} \sim \mathcal{O}(1)$
- 5D Yukawa matrices: $|(Y_u)_{ij}|, |(Y_d)_{ij}| \sim \mathcal{O}(1)$

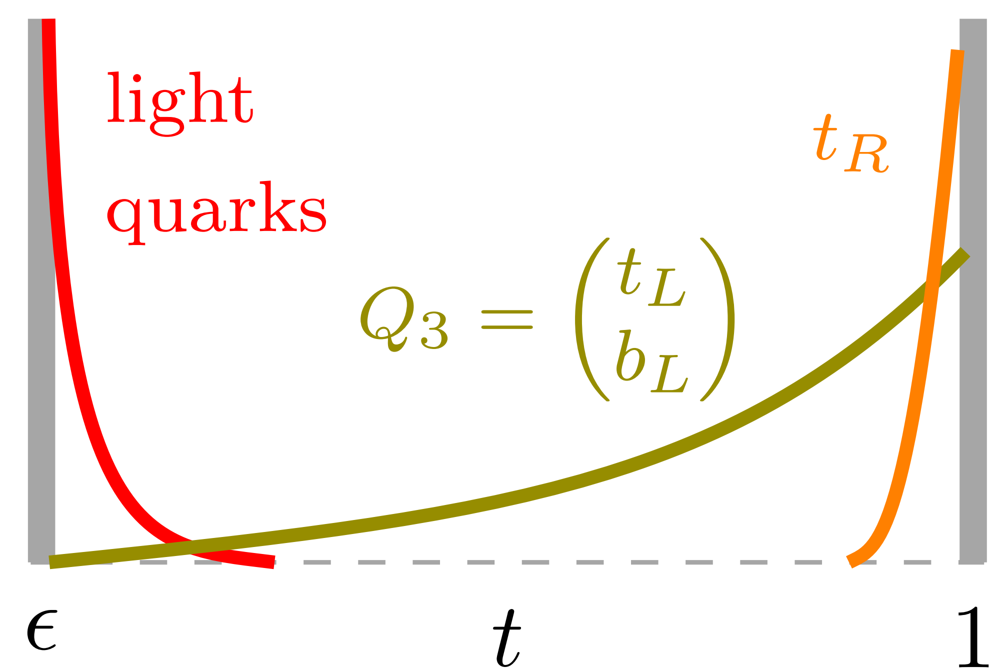
⇒ effective (4D) Yukawa matrix:

$$\boldsymbol{Y}_q^{\text{eff}} \approx F(\boldsymbol{c}_Q)\, \boldsymbol{Y}_q\, F(\boldsymbol{c}_q)$$

$$F(c) \approx \sqrt{|1+2c|} \times \begin{cases} 1 & , c > -1/2 \\ e^{-|\frac{1}{2}+c|L} & , c < -1/2 \end{cases}$$

⇒ top mass:

$$m_t \approx \frac{v}{\sqrt{2}} |(\boldsymbol{Y}_u)_{33}||F(c_{Q_3})F(c_{u_3})|$$



Randall-Sundrum Models - different versions

Minimal RS Model

- based on SM gauge group
- tension with $Zb_L\bar{b}_L$ vertex and electroweak S,T parameters: $M_{\rm KK} \geq 4.0\,\text{TeV (at 95\% CL)}$

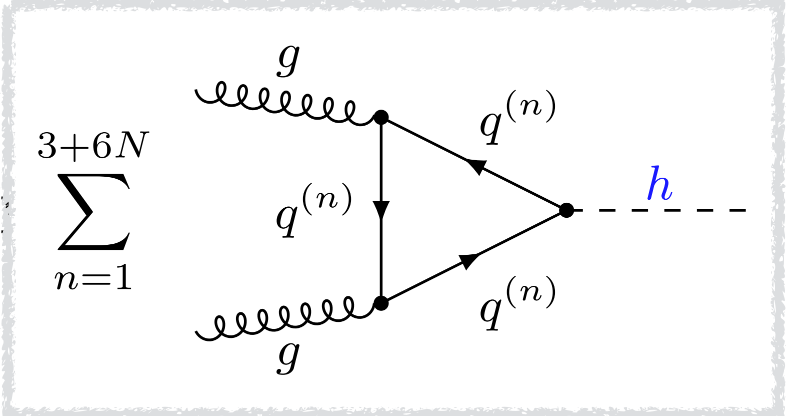
Custodial RS Model

- implement enlarged bulk gauge group: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$
- protect T parameter by a remaining custodial symmetry on the IR brane: $SU(2)_L \times SU(2)_R \to SU(2)_V$
- electroweak symmetry breaking accomplished by a Higgs bi-doublet: $\Phi \sim (\mathbf{2},\mathbf{2})_0$
- protect $Zb_L\bar{b}_L$ vertex by P_{LR} symmetry and: $T_L^{3b_L} = -T_R^{3b_L} = \frac{1}{2}$
- quark sector (Z_2 even fields): $Q_L \sim (\mathbf{2},\mathbf{2})_{\frac{2}{3}},\ u_R^c \sim (\mathbf{1},\mathbf{1})_{\frac{2}{3}},\ \mathcal{T}_R \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1},\mathbf{3})_{\frac{2}{3}}$
  - 15 quark excitations in up-type sector (per KK level)
  - 9 quark excitations in down-type sector (per KK level)
  - 9 exotic fermion excitations with electric charge 5/3 (per KK level)
- lepton sector (minimal embedding): $L_L \sim (\mathbf{2},\mathbf{1})_{-\frac{1}{2}},\ L_R^c \sim (\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$
  - 6 neutrino-like excitations fields (per KK level)
  - 6 charged lepton-like excitations (per KK level)
- tension with electroweak S,T parameter: $M_{\rm KK} \geq 1.9\,\text{TeV (at 95\% CL)}$

Gluon fusion: 4D perspective

Higgs production rate normalized to the SM

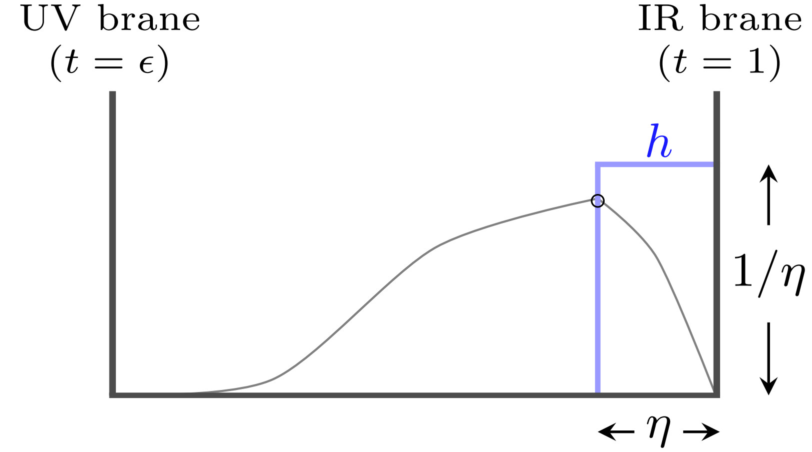
$$R_h = \frac{\sigma(pp \to h)_{\rm RS}}{\sigma(pp \to h)_{\rm SM}}$$



- generic depletion: $R_h < 1$ [Carena,Goertz,Haisch,Neubert,Pfoh:hep-th/1005.4315]
- enhancement: $R_h > 1$ [Azatov,Toharia,Zhu:hep-th/1006.5939]

Subtlety

- Z_2-odd profiles are discontinuous at the IR brane
  - quark overlap integrals with Higgs not well defined
  - regularise Higgs profile: $\chi_h(t) = \delta_h^\eta(t-1) = \dfrac{1}{\eta}\theta(t-1+\eta)$



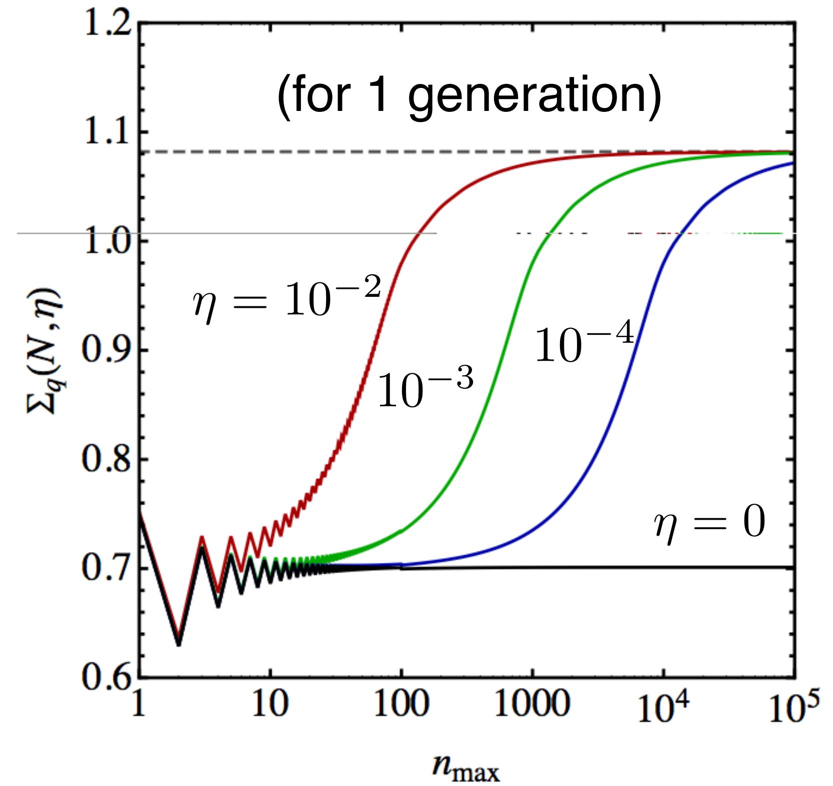
4D KK approach

[Carena,Casagrande,Goertz,Haisch,Neubert:hep-th/1204.0008]

$$\Sigma_q(N,\eta) = \lim_{\substack{N\to\infty \\ \eta\to 0}} \sum_{n=4}^{3+6N} \frac{v\, g_{nn}^q(\eta)}{m_{q_n}}$$

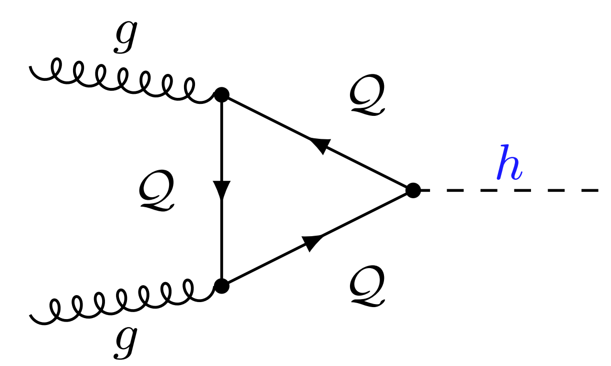
- limits do not commute
  - first $\eta \to 0$: $R_h < 1$
  - first $N \to \infty$: $R_h > 1$
- modes that can penetrate the box: $m_{q_n} \sim \dfrac{M_{\rm EW}}{\eta}$

  (shown for 1 generation)



Gluon fusion: 5D perspective

Calculational steps [RM,Neubert,Novotny,Schmell '13]



- use 5D quark propagators in mixed position-momentum space
- work in dimensional regularisation: $d = 4 - 2\hat{\epsilon}$
- regularize Higgs profile: $\chi_h(t) = \delta_h^\eta(t-1) = \frac{1}{\eta}\theta(t-1+\eta)$
- parametrize the amplitude: $\mathcal{A}(gg \to h) = C_1 \frac{\alpha_s}{12\pi v} \langle 0 | G^a_{\mu\nu} G^{\mu\nu,a} | gg \rangle - C_5 \frac{\alpha_s}{8\pi v} \langle 0 | G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} | gg \rangle$
- coefficents:

$$C_1 = \frac{3}{2} \int_0^1 dx \int_0^1 dy \left(1 - 4xy\bar{y}\right) I_+(xy\bar{y}\, m_h^2) \qquad (\bar{y} = 1 - y)$$

$$C_5 = \int_0^1 dx \int_0^1 dy \; I_-(xy\bar{y}\, m_h^2)$$

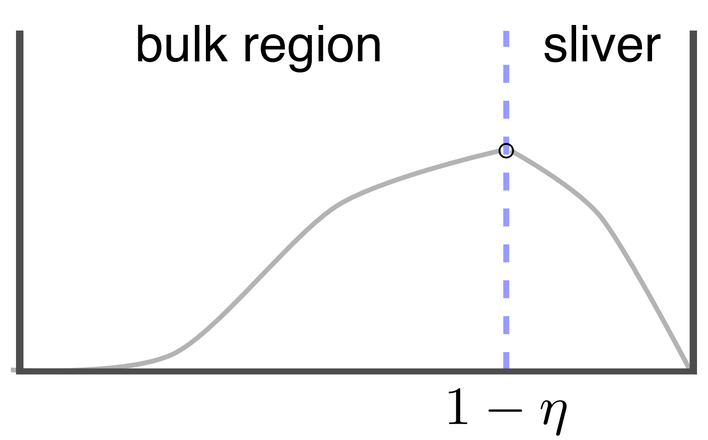
- momentum integration (MSbar scheme):

$$I_\pm(m^2) \equiv -\frac{\mu^{2\hat{\epsilon}} e^{\hat{\epsilon}\gamma_E}}{\Gamma(1-\hat{\epsilon})} \int_0^\infty dp_E \, p_E^{-2\hat{\epsilon}} \frac{\partial}{\partial p_E} T_\pm(p_E^2 - m^2 - i0)$$

Gluon fusion: properties of propagator function

Propagator function

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



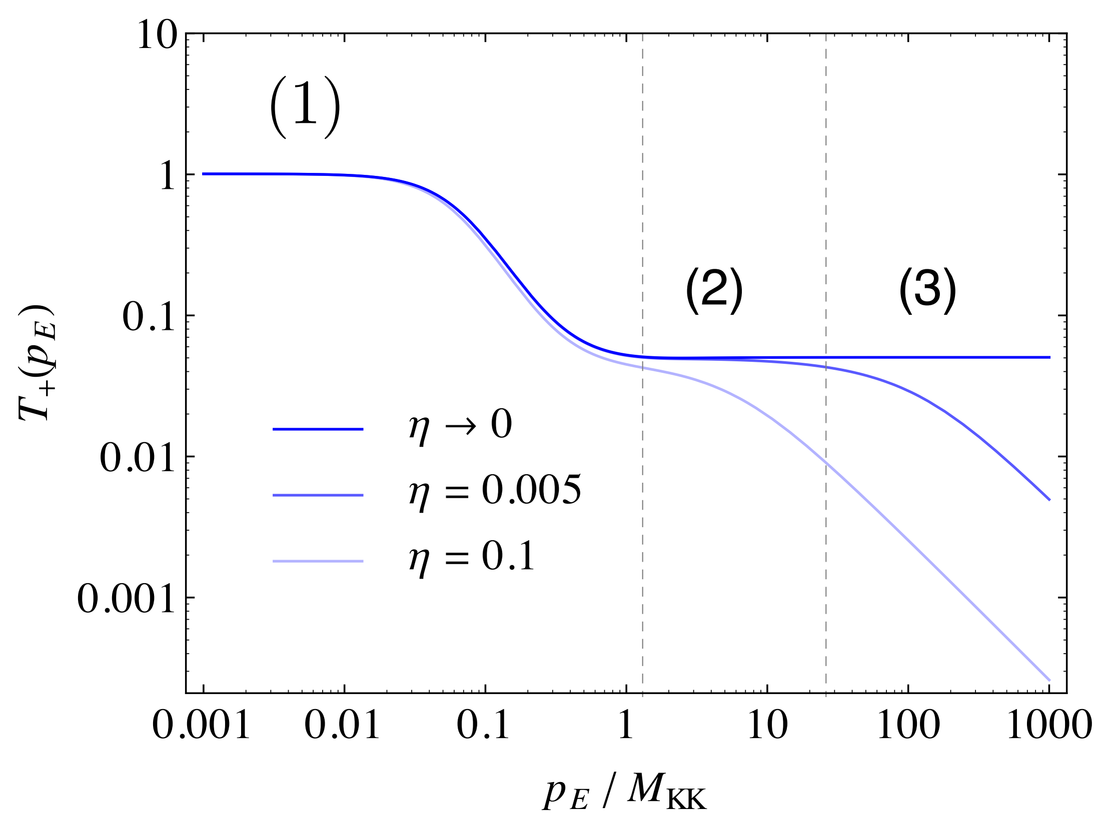
- calculate 5D fermion propagator in the sliver region for 3 generations in the broken Higgs phase
- perform integration with regularised Higgs profile

Asymptotic behaviour

(1) $p_E \ll M_{\mathrm{KK}}$

(2) $M_{\mathrm{KK}} \ll p_E \ll \frac{v|Y_q|}{\eta}$

(3) $p_E \gg \frac{v|Y_q|}{\eta}$



Gluon fusion: analysis of the loop momentum integral

Toy model analysis

- Study to model, that captures all the features of the exact result ($t_i = const$)

$$T_+^{\rm model}(p_E^2) = \frac{t_0 - t_1 - t_2}{1 + \hat{p}_E^2} + \frac{t_2}{\sqrt{1+\hat{p}_E^2}} + \frac{t_3}{\sqrt{(t_3/t_1)^2 + (\eta \hat{p}_E)^2}}$$

- Performing the loop-momentum integration gives

$$I_+^{\rm model}(0) = (t_0 - t_1 - t_2)\left(\frac{\mu}{M_{\rm KK}}\right)^{2\hat{\epsilon}} + t_2 \left(\frac{\mu}{2M_{\rm KK}}\right)^{2\hat{\epsilon}} + t_1 \left(\frac{t_1}{2t_3}\right)^{2\hat{\epsilon}} \left(\frac{\eta\mu}{M_{\rm KK}}\right)^{2\hat{\epsilon}}$$

  - eliminate dim. regulator: momentum integration and $\lim \eta \to 0$ do not commute
  - keep regulator: momentum integration and $\lim \eta \to 0$ commutes → unique result: $R_h < 1$

Interpretation

- different results emerge from two models separated by a (non-calculable) transition region

$$\eta_{\text{brane-localized Higgs}} \ll \frac{v|Y_q|}{\Lambda_{\rm TeV}} \ll \eta_{\text{narrow bulk-Higgs}} \ll \frac{v|Y_q|}{M_{\rm KK}}$$

Gluon fusion: results

Using the exact solutions for the 5D fermion propagator we can obtain results valid to all orders in $v^2/M_{\rm KK}^2$.

Expanding the zero-mode contribution (minimal RS model):

$$C_1 \approx \left[1 - \frac{v^2}{3M_{\rm KK}^2}\,\mathrm{Re}\,\frac{\left(\boldsymbol{Y}_u\boldsymbol{Y}_u^\dagger\boldsymbol{Y}_u\right)_{33}}{(\boldsymbol{Y}_u)_{33}}\right] A_q(\tau_t) + A_q(\tau_b) + \mathrm{Tr}\,g(\boldsymbol{X}_u) + \mathrm{Tr}\,g(\boldsymbol{X}_d)$$

$$C_5 \approx -\frac{v^2}{3M_{\rm KK}^2}\,\mathrm{Im}\left[\frac{\left(\boldsymbol{Y}_u\boldsymbol{Y}_u^\dagger\boldsymbol{Y}_u\right)_{33}}{(\boldsymbol{Y}_u)_{33}}\right] B_q(\tau_t)$$

- $A_q(\tau_t) \approx 1.03$
- $A_q(\tau_b) \approx -0.03 + 0.03i$
- $B_q(\tau_b) \approx -0.02 + 0.02i$

- suppressed zero-mode contribution ($ht\bar{t}$ coupling)
- contribution from KK-quarks

$$g(\boldsymbol{X}_q)\big|_{\text{brane Higgs}} = -\frac{\boldsymbol{X}_q \tanh \boldsymbol{X}_q}{\cosh 2\boldsymbol{X}_q} \approx -\boldsymbol{X}_q^2$$

$$g(\boldsymbol{X}_q)\big|_{\text{narrow bulk Higgs}} = \boldsymbol{X}_q \tanh \boldsymbol{X}_q \approx +\boldsymbol{X}_q^2$$

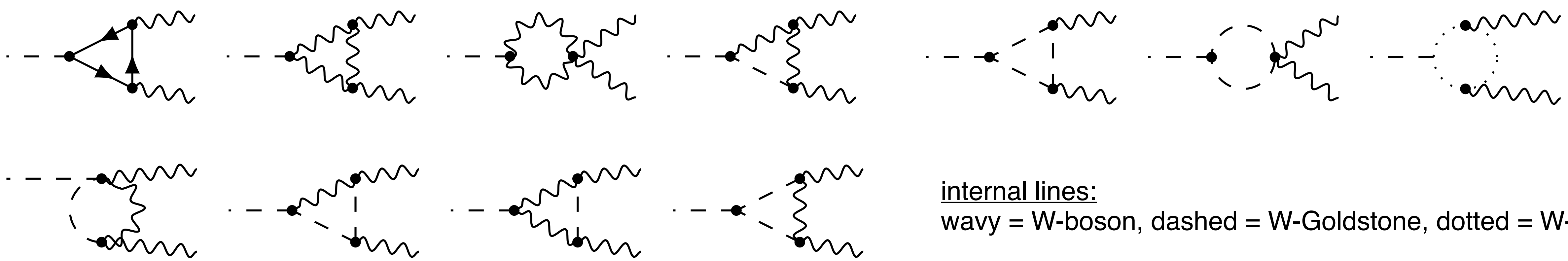
- $\boldsymbol{X}_q^2 = \frac{v^2}{2M_{\rm KK}^2}\boldsymbol{Y}_q\,\boldsymbol{Y}_q^\dagger$

- for a large ensemble of random (anarchic) matrices with $|(\boldsymbol{Y}_q)_{ij}| \le y_\star$: $\langle \mathrm{Tr}\,\boldsymbol{Y}_f\,\boldsymbol{Y}_f^\dagger\rangle = N_g^2\,\frac{y_\star^2}{2}$

- contribution from KK quarks in the custodial RS model (larger by a factor of 4)

$$\mathrm{Tr}\,g(\boldsymbol{X}_u) + \mathrm{Tr}\,g(\boldsymbol{X}_d) \quad\rightarrow\quad \mathrm{Tr}\,g(\sqrt{2}\boldsymbol{X}_u) + 3\,\mathrm{Tr}\,g(\sqrt{2}\boldsymbol{X}_d)$$

Higgs decay into two photons



internal lines:
wavy = W-boson, dashed = W-Goldstone, dotted = W-ghost

W-boson loop contribution

[Hahn,Hoerner,RM,Neubert,Novotny,Schmell,hep-ph/1312.5731]

- calculation in R_ξ gauge: contributions from W-boson, Goldstone and ghost modes
- vertices involving photons are diagonal in KK number → single KK particle in the loop

$$\mathcal{A}_{\rm RS}^W(h\to\gamma\gamma) = \frac{\tilde{m}_W^2}{v} \sum_{n=0}^{\infty} 2\pi \left[\chi_n^W(1)\right]^2 \left[\frac{v_{\rm SM}}{m_W^2}\,\mathcal{A}_{\rm SM}^W(h\to\gamma\gamma)\right]_{m_W\to m_n^W} .$$

- work with 5D propagators in mixed position-momentum space, e.g. W-boson propagator (minimal RS model

$$B_W(t,t';-p^2) \equiv \sum_{n=0}^{\infty} \frac{\chi_n^W(t)\,\chi_n^W(t')}{m_{W_n}^2 - p^2} = \frac{Ltt'}{4M_{\rm KK}^2}\,\frac{\left[\hat{p}D_{10}(t_>,1) - b_1 D_{11}(t_>,1)\right] D_{10}(t_<,\epsilon)}{\hat{p}D_{00}(1,\epsilon) - b_1 D_{10}(1,\epsilon)}$$

  - with: $D_{ij}(t,t') = J_i(\hat{p}t)\,Y_j(\hat{p}t') - Y_i(\hat{p}t)\,J_j(\hat{p}t')$ $\quad \hat{p}\equiv p/M_{\rm KK}, \quad t_> = {\rm Max}(t,t'), \quad t_< = {\rm Min}(t,t')$
  - avoid notion of infinite KK sums and work with compact analytic expressions

Higgs decay into two photons: results

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

W-boson contribution expanded in $v^2/M_{\rm KK}^2$:

$$C_{1\gamma}^W \approx -\frac{21}{4} \left[\left(1 - \frac{\xi L m_W^2}{2M_{\rm KK}^2} \right) A_W(\tau_W) + \frac{\xi L m_W^2}{2M_{\rm KK}^2} \right]$$

- $A_W(\tau_W) \approx 1.19$
- minimal RS model: $\xi = 1$
- custodial RS model: $\xi = 2$

quark contribution (custodial RS model):

(tower contribution larger by factor 9 compared to minimal RS model)

$$C_{1\gamma}^q \approx \left[1 - \frac{2v^2}{3M_{\rm KK}^2} \mathrm{Re} \frac{(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u)_{33}}{(\boldsymbol{Y}_u)_{33}} \right] N_c Q_u^2 \, A_q(\tau_t) \mp \frac{N_c Q_u^2 \, v^2}{M_{\rm KK}^2} \mathrm{Tr} \, \boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \mp \frac{N_c (Q_u^2 + Q_d^2 + Q_\lambda^2) \, v^2}{M_{\rm KK}^2} \mathrm{Tr} \, \boldsymbol{Y}_d \boldsymbol{Y}_d^\dagger$$

$$C_{5\gamma}^q \approx -\frac{2v^2}{3M_{\rm KK}^2} \, \mathrm{Im} \left[\frac{(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u)_{33}}{(\boldsymbol{Y}_u)_{33}} \right] N_c \, Q_u^2 \, B_q(\tau_t)$$

- $A_q(\tau_t) \approx 1.03, \; B_q(\tau_t) \approx 1.05$
- brane Higgs: -
- narrow bulk-Higgs: +

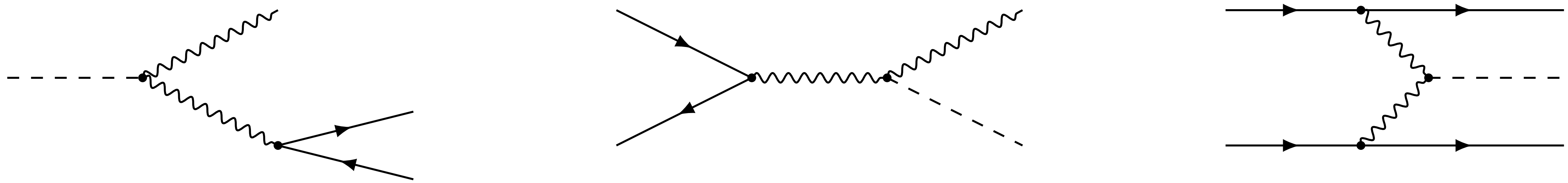
KK lepton contribution (custodial RS model):

- minimal embedding: $C_{1\gamma}^l \approx \mp Q_e^2 \, \frac{v^2}{2M_{\rm KK}^2} \, \mathrm{Tr} \, \boldsymbol{Y}_e \boldsymbol{Y}_e^\dagger$
- enlarged embedding: $C_{1\gamma}^l \approx \mp \left(Q_e^2 + Q_\psi^2 \right) \frac{v^2}{M_{\rm KK}^2} \, \mathrm{Tr} \, \boldsymbol{Y}_e \, \boldsymbol{Y}_e^\dagger$

(larger by factor of 4 w.r.t. to minimal RS model)

Tree-level Higgs production and decay

$h \to WW^*, ZZ^*$ decays — Higgs-strahlung — Vector-boson fusion



Example: $h \to WW^* \to W \bar{f}_1 f_1' \to \bar{f}_2 f_2' \bar{f}_1 f_1'$ [RM,Neubert,Schmell,hep-ph/14xx.xxxx]

- hWW coupling: $c_W \approx 1 - \frac{m_W^2}{2M_{\rm KK}^2}\left(\frac{3}{2}L - 1 + \frac{1}{2L}\right)$
- off-shell 5D W-boson propagator: $\sum_{n=0}^{\infty} \frac{\chi_W^n(1)\chi_W^n(\epsilon)}{m_{W_n}^2 - p^2} \approx \frac{\chi_W(1)\chi_W(\epsilon)}{m_W^2 - p^2} - \frac{1}{2M_{\rm KK}^2}\left(1 - \frac{1}{L}\right)$
- modification of the $W\bar{f}f'$ coupling: $c_{\Gamma_W} = \frac{\Gamma(W \to \bar{f}f')_{\rm RS}}{\Gamma(W \to \bar{f}f')_{\rm SM}} \approx 1 - \frac{m_W^2}{2M_{\rm KK}^2}\frac{1}{2L}$

⇒ To good approximation the main effects can be accounted for by a multiplicative rescaling of the SM decay rates and production cross sections

Higgs couplings

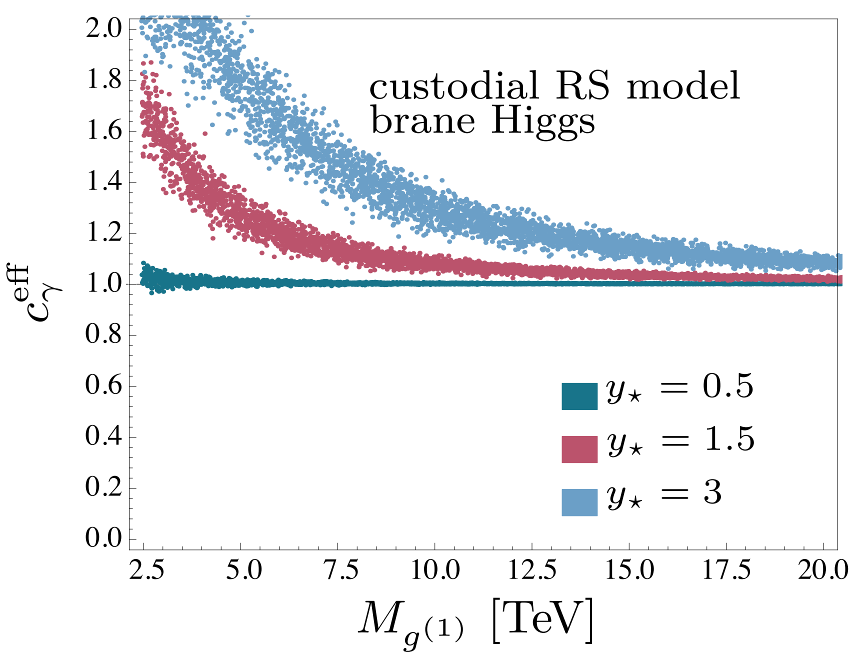
Effective Lagrangian in the broken Higgs phase at the electroweak scale

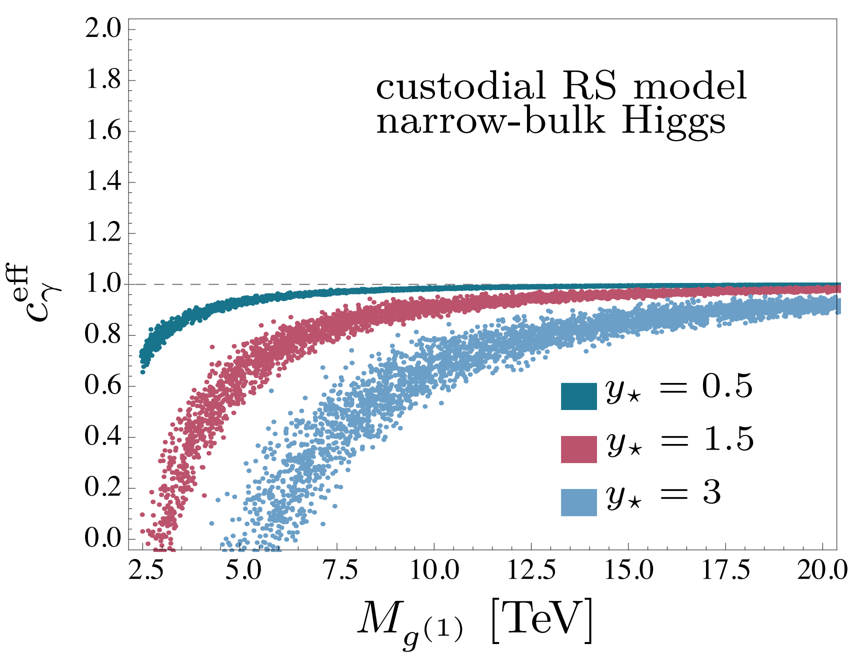
$$\mathcal{L}_{\text{eff}} = c_W \frac{2m_W^2}{v_{\text{SM}}} hW_\mu^+ W^{-\mu} + c_Z \frac{m_Z^2}{v_{\text{SM}}} hZ_\mu Z^\mu - \sum_{f=t,b,\tau} \frac{m_f}{v_{\text{SM}}} h\bar{f}\left(c_f + c_{f5}\, i\gamma_5\right) f$$
$$+ c_g \frac{\alpha_s}{12\pi v_{\text{SM}}} hG_{\mu\nu}^a G^{a,\mu\nu} - c_{g5} \frac{\alpha_s}{8\pi v_{\text{SM}}} hG_{\mu\nu}^a \tilde{G}^{a,\mu\nu} + c_\gamma \frac{\alpha}{6\pi v_{\text{SM}}} hF_{\mu\nu} F^{\mu\nu} - c_{\gamma 5} \frac{\alpha}{4\pi v_{\text{SM}}} hF_{\mu\nu} \tilde{F}^{\mu\nu} + \dots .$$

- SM: $c_W = c_Z = c_f = 1$ and $c_{f5} = c_g = c_{g5} = c_\gamma = c_{\gamma 5} = 0.$
- not complete list of operators; but remaining ones are subdominant, e.g. $hZ_\mu \bar{f}\gamma^\mu f\,,\, hZ_\mu \bar{f}\gamma^\mu \gamma_5 f$

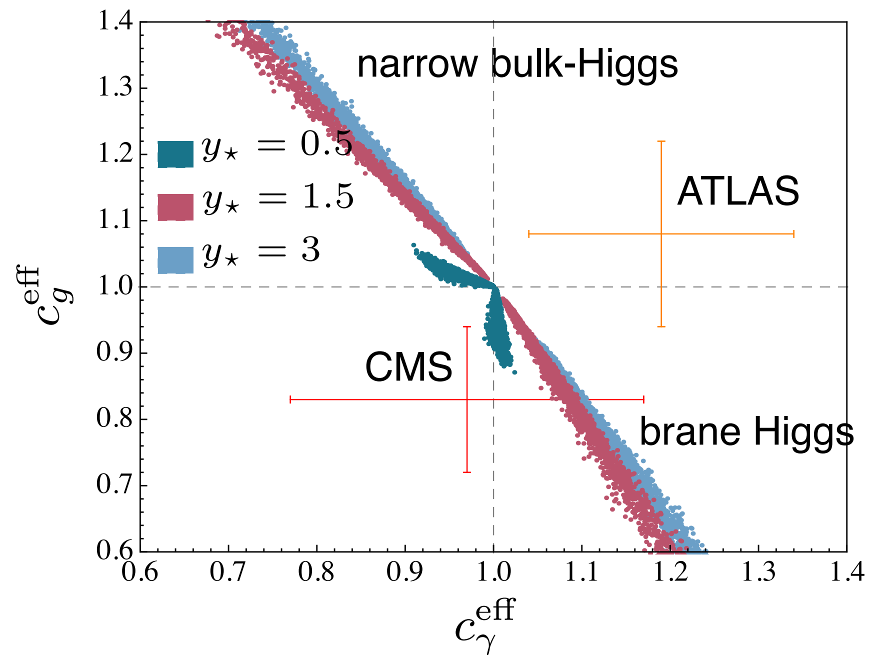
Higgs couplings: loop-induced

$h \to \gamma\gamma$ (custodial RS model)





$h \to \gamma\gamma$ vs. $h \to gg$



- $M_{g^{(1)}} = 2.45\, M_{\rm KK}$
- $|(\boldsymbol{Y}_q)_{ij}| \leq y_\star$

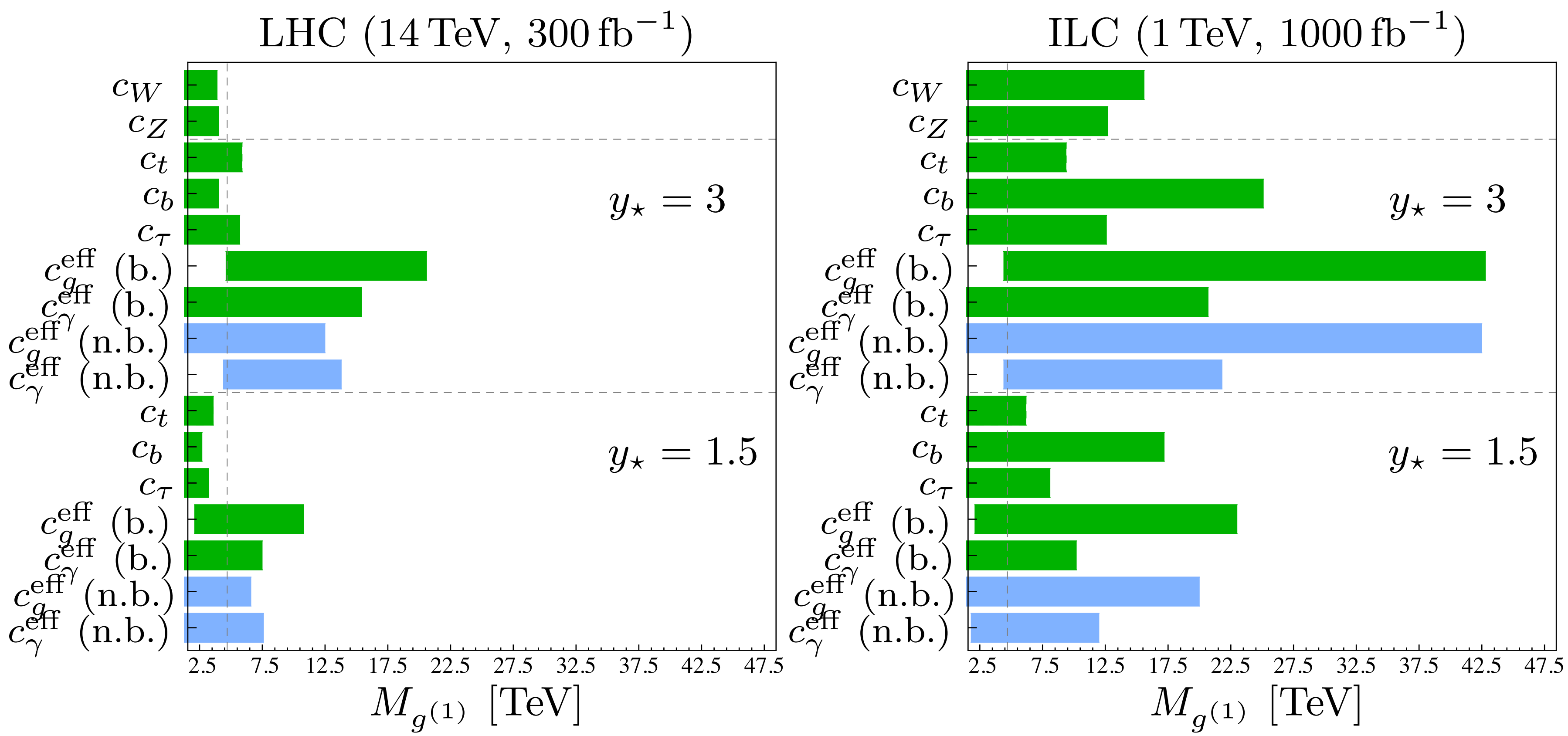
effective couplings

$$c_\gamma^{\rm eff} = \frac{c_\gamma + N_c Q_u^2\, A_q(\tau_t)\, c_t - \frac{21}{4}\, A_W(\tau_W)\, c_W}{N_c Q_u^2\, A_q(\tau_t) - \frac{21}{4}\, A_W(\tau_W)} \approx 1 + \frac{v^2}{2M_{\rm KK}^2} \left[(\pm 21.7 + 0.9)\, y_\star^2 - 5.1 \right]$$

$$c_g^{\rm eff} = \frac{c_g + A_q(\tau_t)\, c_t}{A_q(\tau_t)} \approx 1 + \frac{v^2}{2M_{\rm KK}^2} \left[(\mp 36.0 - 3.3)\, y_\star^2 - 3.6 \right]$$

Higgs couplings: future sensitivities at LHC and ILC

bounds on $M_{g^{(1)}}$ at 95% CL (custodial RS model)



(n.b.) = narrow bulk-Higgs

(b.) = brane Higgs

$$|(\boldsymbol{Y}_q)_{ij}| \leq y_\star$$

$$M_{g^{(1)}} = 2.45\, M_{\rm KK}$$

- LHC analysis:
  - brane Higgs: $M_{g^{(1)}} > 21\,\text{TeV} \times (y_\star/3)$
  - narrow bulk-Higgs: $M_{g^{(1)}} > 13\,\text{TeV} \times (y_\star/3)$
- ILC analysis:
  - brane and narrow bulk-Higgs: $M_{g^{(1)}} > 43\,\text{TeV} \times (y_\star/3)$

[Peskin:hep-ph/1207.2516]

- assume SM outcome
- constraint: $c_{W,Z} \leq 1$

$c_i - 1$	W	Z	t	b
LHC 14 TeV, 300 fb^{-1}	$(-0.069, 0)$	$(-0.077, 0)$	$(-0.154, 0.147)$	$(-0.231, 0.041)$
ILC 1 TeV, 1000 fb^{-1}	$(-0.004, 0)$	$(-0.006, 0)$	$(-0.044, 0.035)$	$(-0.003, 0.011)$
$c_i - 1$	τ	g	γ	
LHC 14 TeV, 300 fb^{-1}	$(-0.093, 0.132)$	$(-0.078, 0.10)$	$(-0.096, 0.059)$	
ILC 1 TeV, 1000 fb^{-1}	$(-0.013, 0.017)$	$(-0.014, 0.014)$	$(-0.032, 0.035)$	

Signal rates

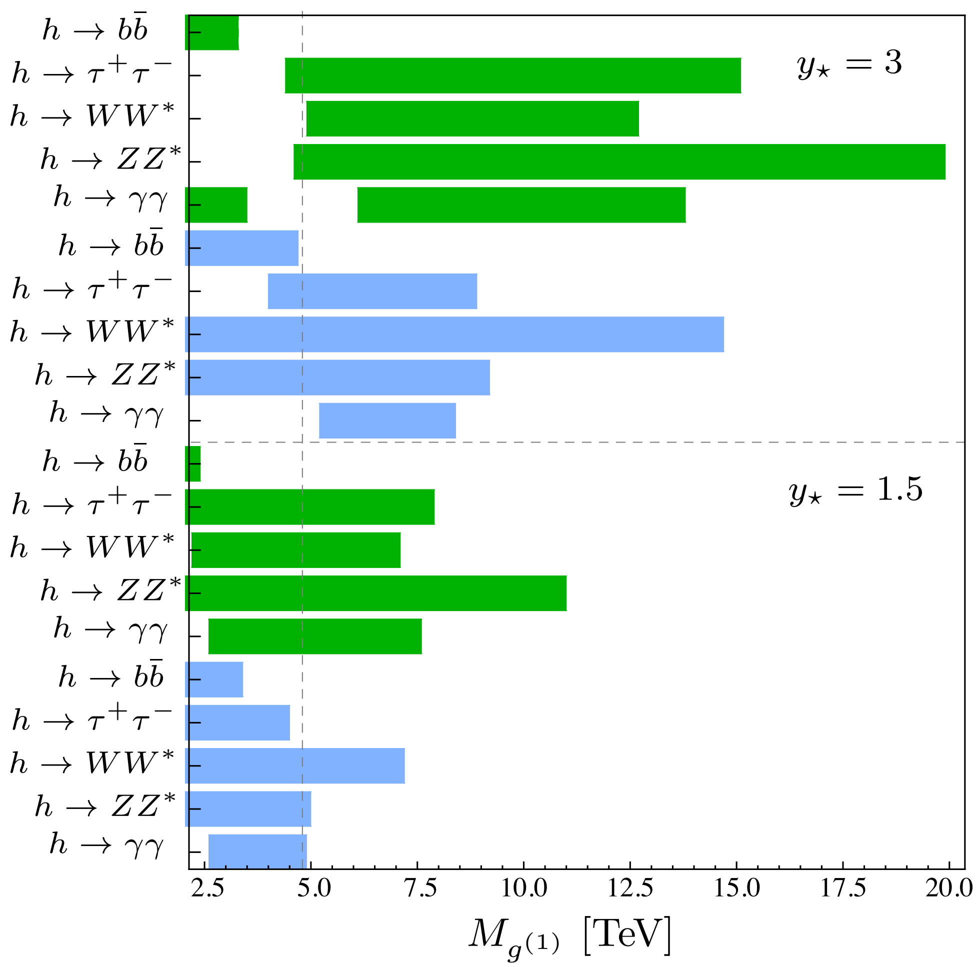
$$R_X \equiv \frac{(\sigma\cdot\mathrm{BR})(pp\to h\to X)_{\mathrm{NP}}}{(\sigma\cdot\mathrm{BR})(pp\to h\to X)_{\mathrm{SM}}} = \frac{\sigma(pp\to h)_{\mathrm{NP}}}{\sigma(pp\to h)_{\mathrm{SM}}}\,\frac{\Gamma(h\to X)_{\mathrm{NP}}}{\Gamma(h\to X)_{\mathrm{SM}}}\,\frac{\Gamma_h^{\mathrm{SM}}}{\Gamma_h^{\mathrm{NP}}}$$

Contribution of new physics

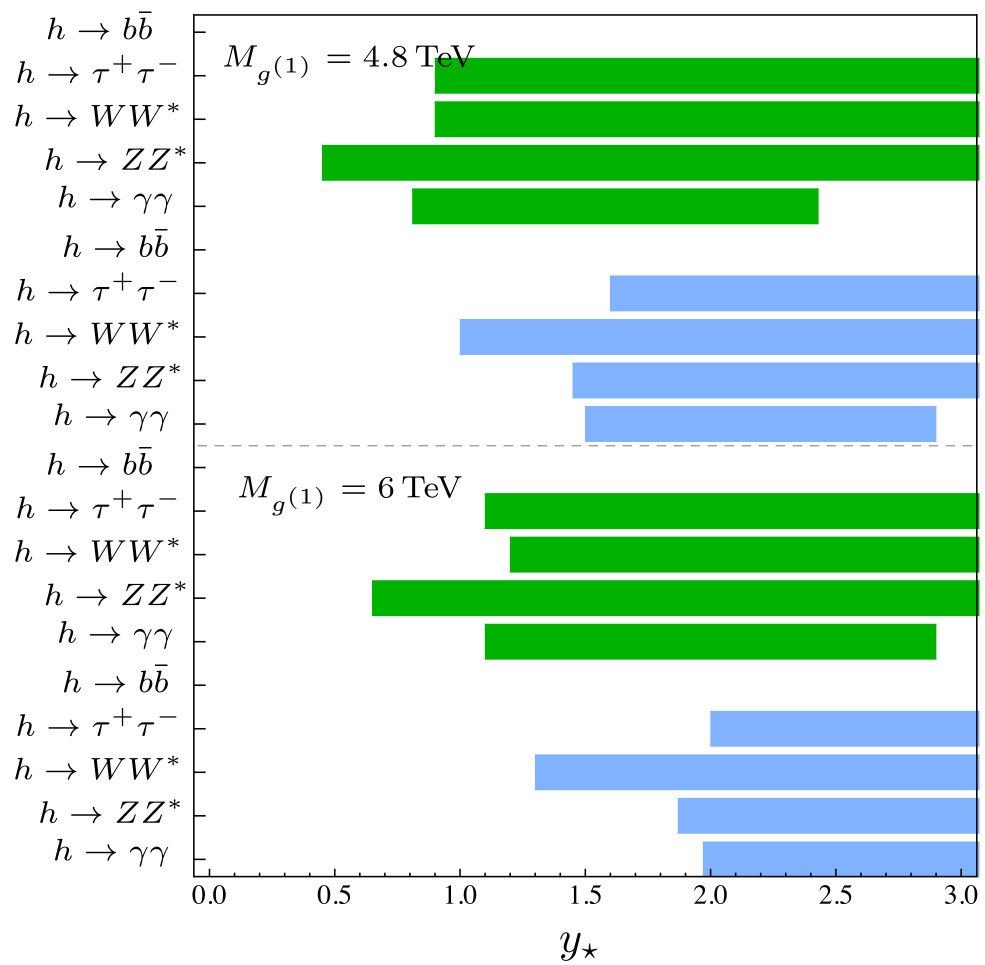
- Higgs production: $$\frac{\sigma(pp\to h)_{\mathrm{RS}}}{\sigma(pp\to h)_{\mathrm{SM}}} \approx \left(|c_g^{\mathrm{eff}}|^2 + |c_{g5}^{\mathrm{eff}}|^2\right) f_{\mathrm{GF}} + c_V^2\, f_{\mathrm{VBF}}$$
  - $f_{\mathrm{GF}} \approx 0.9,\ f_{\mathrm{VBF}} \approx 0.1$
- Higgs decay rates: $$\frac{\Gamma(h\to X)_{\mathrm{RS}}}{\Gamma(h\to X)_{\mathrm{SM}}} \approx |c_X|^2 + |c_{X5}|^2$$
- Higgs width: $$\frac{\Gamma_h^{\mathrm{RS}}}{\Gamma_h^{\mathrm{SM}}} \approx 0.57\,|c_b|^2 + 0.22\,|c_W|^2 + 0.09\left(|c_g^{\mathrm{eff}}|^2 + |c_{g5}^{\mathrm{eff}}|^2\right) + 0.12\,,$$

Signal rates: bounds on KK gluon mass and y_x

bounds on $M_{g^{(1)}}$ at 95% CL (custodial RS model)



bounds on $y_\star$ at 95% CL (custodial RS model)



green = brane Higgs

blue = narrow bulk-Higgs

- brane Higgs: $M_{g^{(1)}} > 19.9\,\text{TeV}$
- narrow bulk-Higgs: $M_{g^{(1)}} > 14.9\,\text{TeV}$

- brane Higgs: $y_\star < 0.4$
- narrow bulk-Higgs: $y_\star < 1.1$

[ATLAS-CONF-2014-009]

[CMS-PAS-HIG-13-005]

R_X	bb	$\tau\tau$	WW	ZZ	$\gamma\gamma$
ATLAS	$0.2^{+0.7}_{-0.6}$	$1.4^{+0.5}_{-0.4}$	$1.00^{+0.32}_{-0.29}$	$1.44^{+0.40}_{-0.35}$	$1.57^{+0.33}_{-0.28}$
CMS	$1.0^{+0.5}_{-0.5}$	$0.78^{+0.27}_{-0.27}$	$0.68^{+0.20}_{-0.20}$	$0.92^{+0.28}_{-0.28}$	$0.77^{+0.27}_{-0.27}$
average	$0.7^{+0.4}_{-0.4}$	$0.92^{+0.24}_{-0.22}$	$0.77^{+0.17}_{-0.16}$	$1.09^{+0.23}_{-0.22}$	$1.09^{+0.21}_{-0.19}$

Conclusion

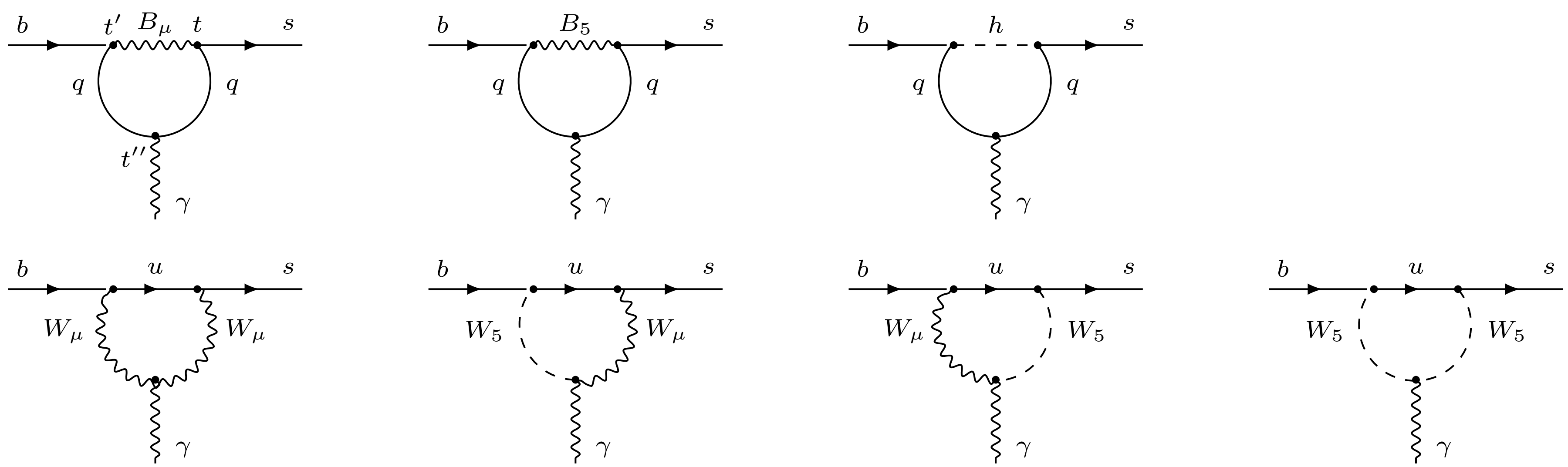
- 5D calculation of the loop-induced Higgs processes $gg \to h,\, h \to \gamma\gamma$ with a distinction between the brane-localized and narrow-bulk Higgs scenario.
- Loop-induced Higgs couplings are very sensitive on the exchange of virtual fermionic KK excitations.
- Higgs physics is well describable by only two parameters, the KK scale and the maximal Yukawa value.
- Signal rates already give stringent bounds on the RS parameter space. These bounds are complementary and often stronger than those from electroweak precision observables and rare flavor-changing processes (custodial RS model).

Outlook

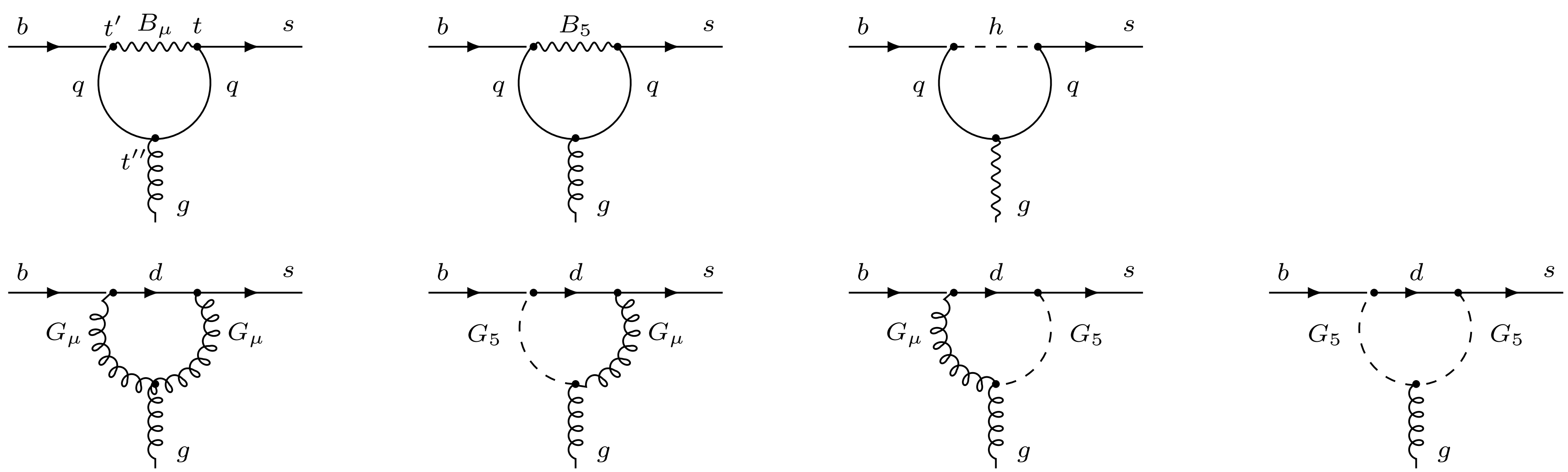
- Calculation of magnetic dipole-operators: $b \to s\gamma,\, \mu \to e\gamma$

magnetic dipole operators

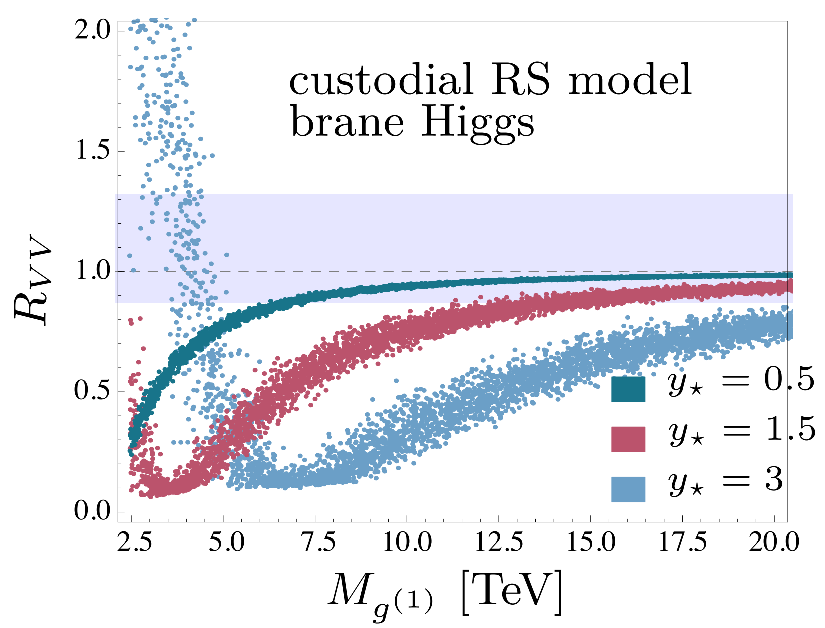
$C_{7\gamma},\, \tilde{C}_{7\gamma}$

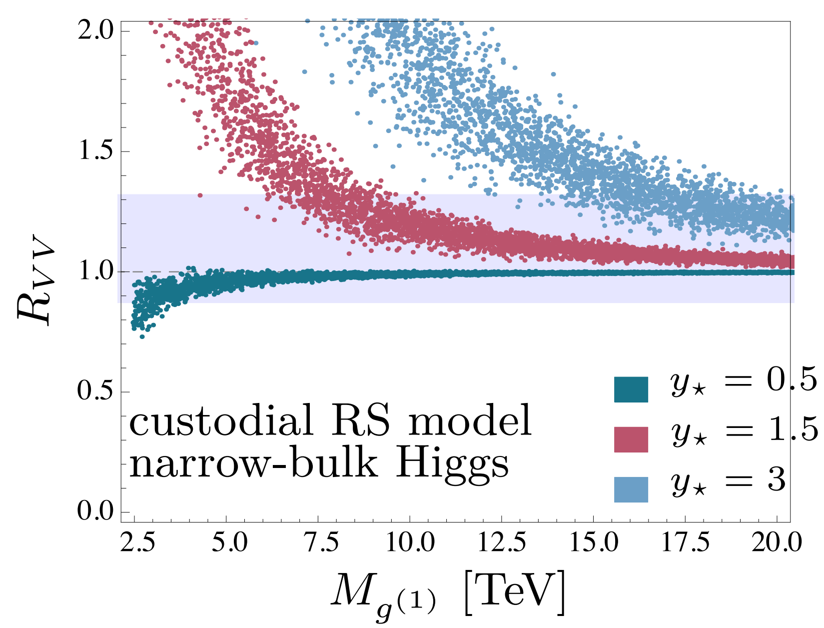


$C_{8g},\, \tilde{C}_{8g}$

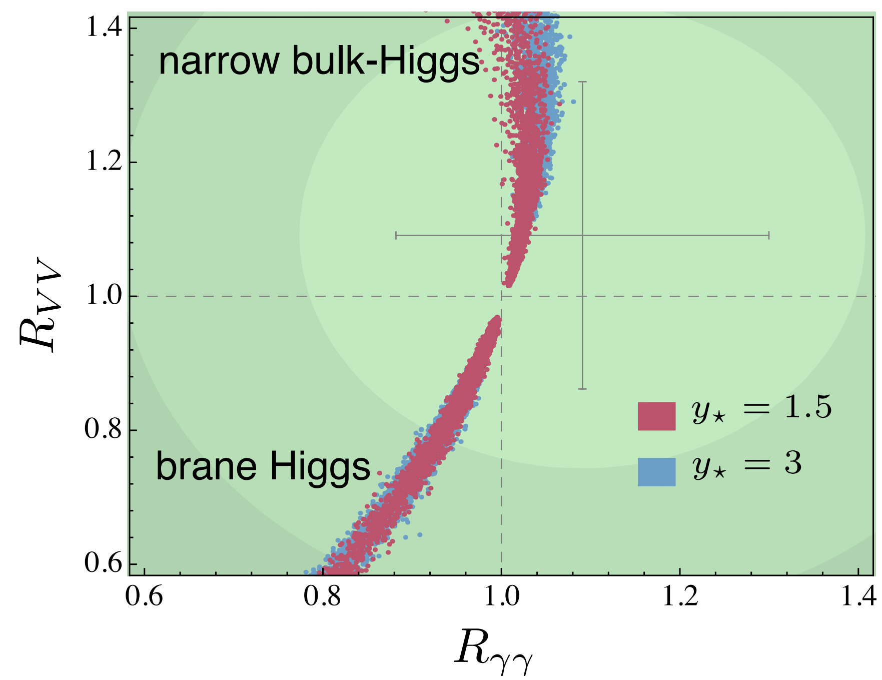


$pp \to h \to VV$





$pp \to h \to VV$ vs. $pp \to h \to \gamma\gamma$

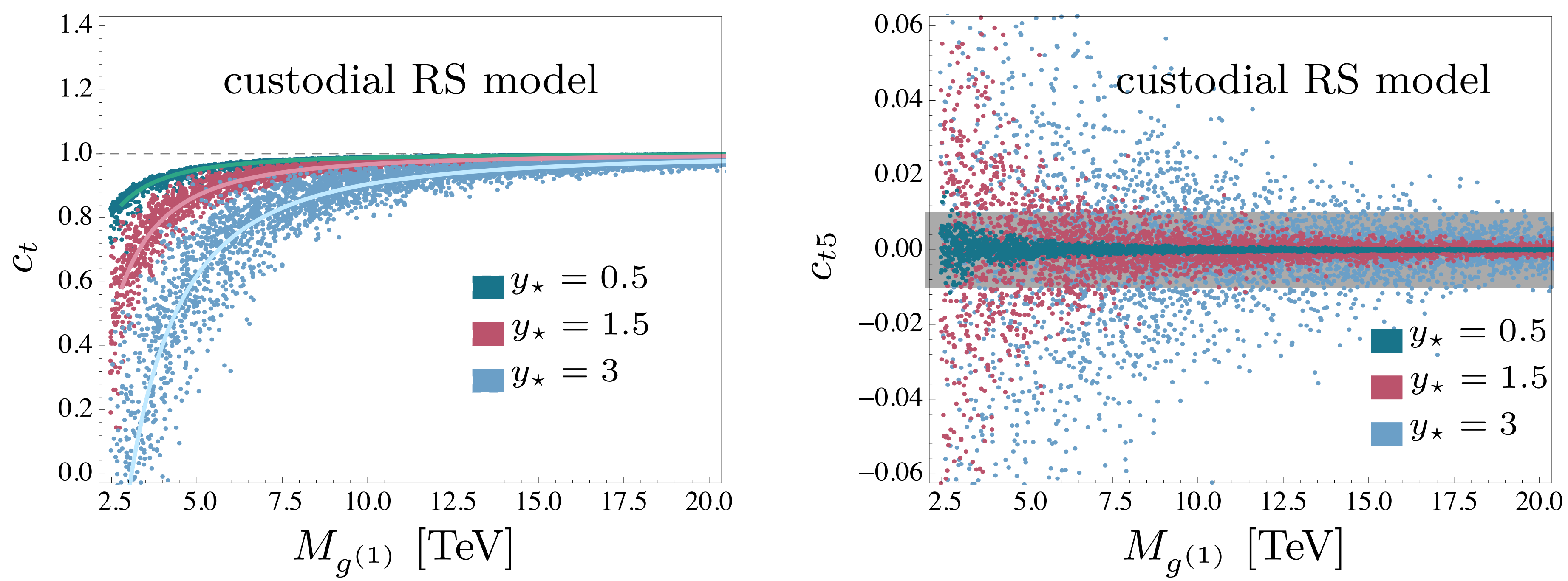


Higgs couplings: tree-level

hVV coupling (custodial RS model): $c_W \approx c_Z \approx 1 - 0.078 \left(\frac{5\,\text{TeV}}{M_{g^{(1)}}}\right)^2$

- directly sensitive on KK gluon mass

$h\bar{t}t$ coupling (custodial RS model) $c_f + i c_{f5} = 1 - \epsilon_f - \frac{L m_W^2}{4 M_{KK}^2} - \frac{v^2}{3 M_{KK}^2} \frac{(\boldsymbol{Y}_f \boldsymbol{Y}_f^\dagger \boldsymbol{Y}_f)_{33}}{(\boldsymbol{Y}_f)_{33}} + \dots$



- 5000 scatter points
- $|(\boldsymbol{Y}_q)_{ij}| \leq y_\star$

- electron EDM (at 90 % CL): $d_e < 8.7 \cdot 10^{-29} e\,cm \quad \rightarrow \quad c_{t5} \leq 0.01$ [Brod,Haisch,Zupan,hep-ph/1310.1385]

Loop calculations in warped extra dimensions

- Randall-Sundrum models are effective field theories:
  - e.g. QED in D dimensions: $[e_D] = \frac{4-D}{2}$
  - position dependent cutoff: $\Lambda(t) = \frac{\epsilon}{t} M_{\rm Pl}$

- work with 5D propagators in mixed position-momentum space, e.g. W-boson propagator

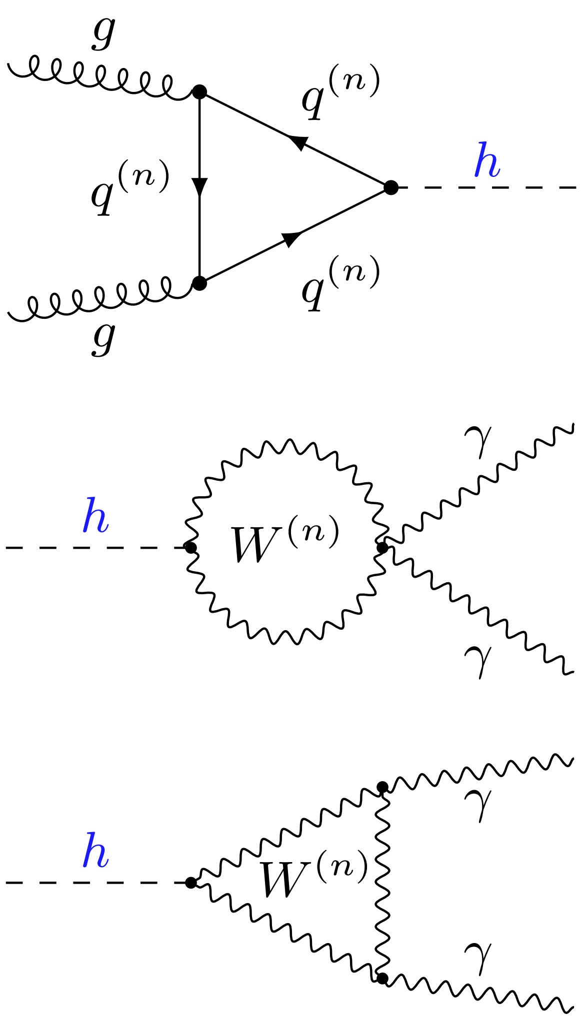
$$B_W(t,t';-p^2) \equiv \sum_{n=0}^{\infty} \frac{\chi_n^W(t)\,\chi_n^W(t')}{m_{W_n}^2 - p^2}$$

  - advantage: avoid notion of infinite KK sums and work with compact analytic expressions

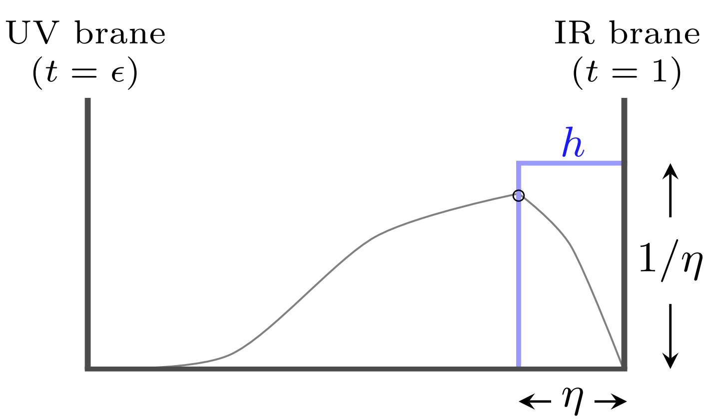
- current status: calculate one-loop processes that are finite (not UV sensitive)
  - magnetic dipole operators: $b \to s\gamma,\ \mu \to e\gamma$
  - anomalous magnetic moment of the muon: $(g-2)_\mu$
  - loop-induced Higgs production and decay: $gg \to h,\ h \to \gamma\gamma$

Loops in Higgs physics

- 4D loop-momentum cutoff: $\Lambda_{\rm TeV} \equiv \Lambda(1) = \epsilon\, M_{\rm Pl} \sim 20\,{\rm TeV}$
- $gg \to h,\ h \to \gamma\gamma$
    - vertices with SM gluons or photons are KK-number diagonal, which follows from the flatness of the profiles
    - only one infinite sum over KK modes per diagram
    - perform the momentum integration analytically and express results in terms of 5D propagators in the broken electroweak phase, valid to all orders in $v^2/M_{\rm KK}^2$
- subtlety: quark Z_2-odd profiles $S_n^{(q)}(t)$ are discontinuous at the IR brane
    - $S_n^{(q)}(1) = 0$ but $S_n^{(q)}(1^-) \neq 0$
    - quark overlap integrals with Higgs profile not well defined
    - regularise Higgs profile: $\chi_h(t) = \delta_h^\eta(t-1) = \frac{1}{\eta}\theta(t-1+\eta)$
    - distinction: brane-localized Higgs or narrow bulk-Higgs scenario



$$\eta_{\text{brane-localized Higgs}} \ll \frac{v}{\Lambda_{\rm TeV}} \ll \eta_{\text{narrow bulk-Higgs}} \ll \frac{v}{M_{\rm KK}}$$



Overview of Higgs localisations

Model	bulk Higgs	narrow bulk-Higgs	transition region	brane Higgs
Higgs profile width	$\eta = \mathcal{O}(1)$	$\frac{v\|Y_q\|}{\Lambda_{\text{TeV}}} \ll \eta \ll \frac{v\|Y_q\|}{M_{\text{KK}}}$	$\eta \sim \frac{v\|Y_q\|}{\Lambda_{\text{TeV}}}$	$\eta \ll \frac{v\|Y_q\|}{\Lambda_{\text{TeV}}}$
Power corrections	$\sim \frac{M_{\text{KK}}}{\Lambda_{\text{TeV}}}$	$\sim \frac{M_{\text{KK}}}{\eta\Lambda_{\text{TeV}}}$	$\sim \frac{M_{\text{KK}}}{v\|Y_q\|}$	$\sim \frac{M_{\text{KK}}}{\Lambda_{\text{TeV}}}$
Higgs profile	resolved by all modes	resolved by high-momentum modes	partially resolved by high-momentum modes	not resolved
$\mathcal{A}(gg \to h)$	enhanced [hep-ph/1006.5939]	enhanced	not calculable	suppressed