What the Higgs can tell us about Warped Extra Dimensions

- in collaboration with R. Malm and M. Neubert
- based on [hep-ph /1303.5703] and current work

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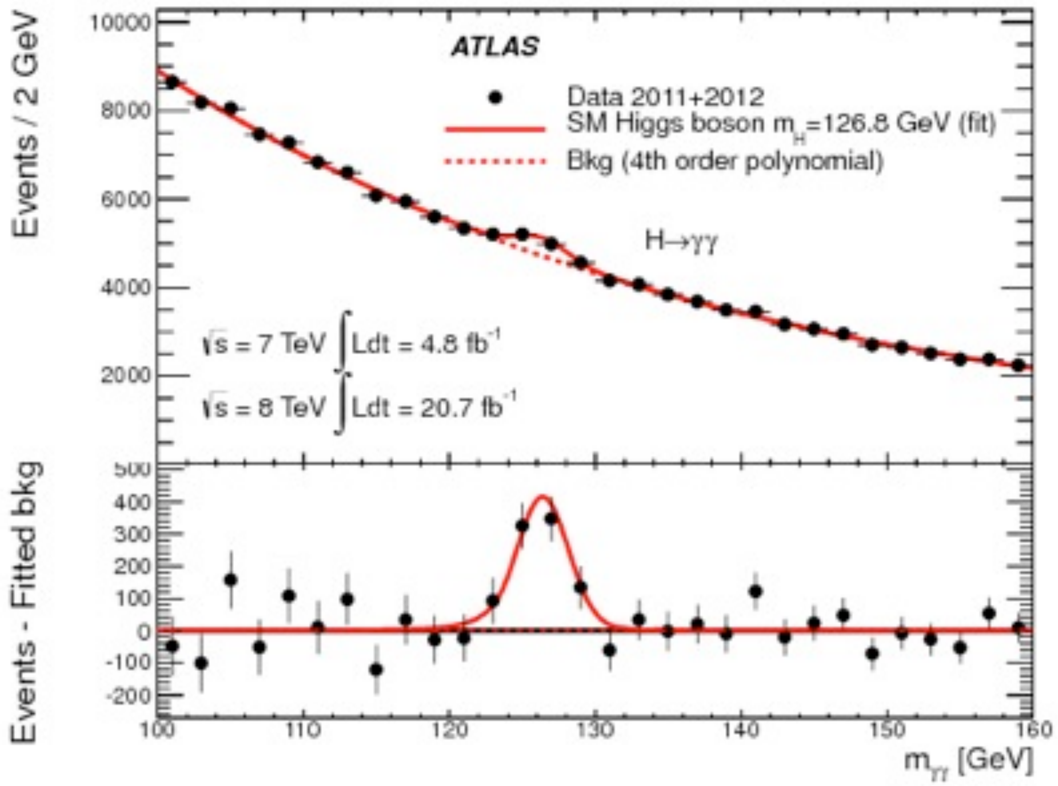
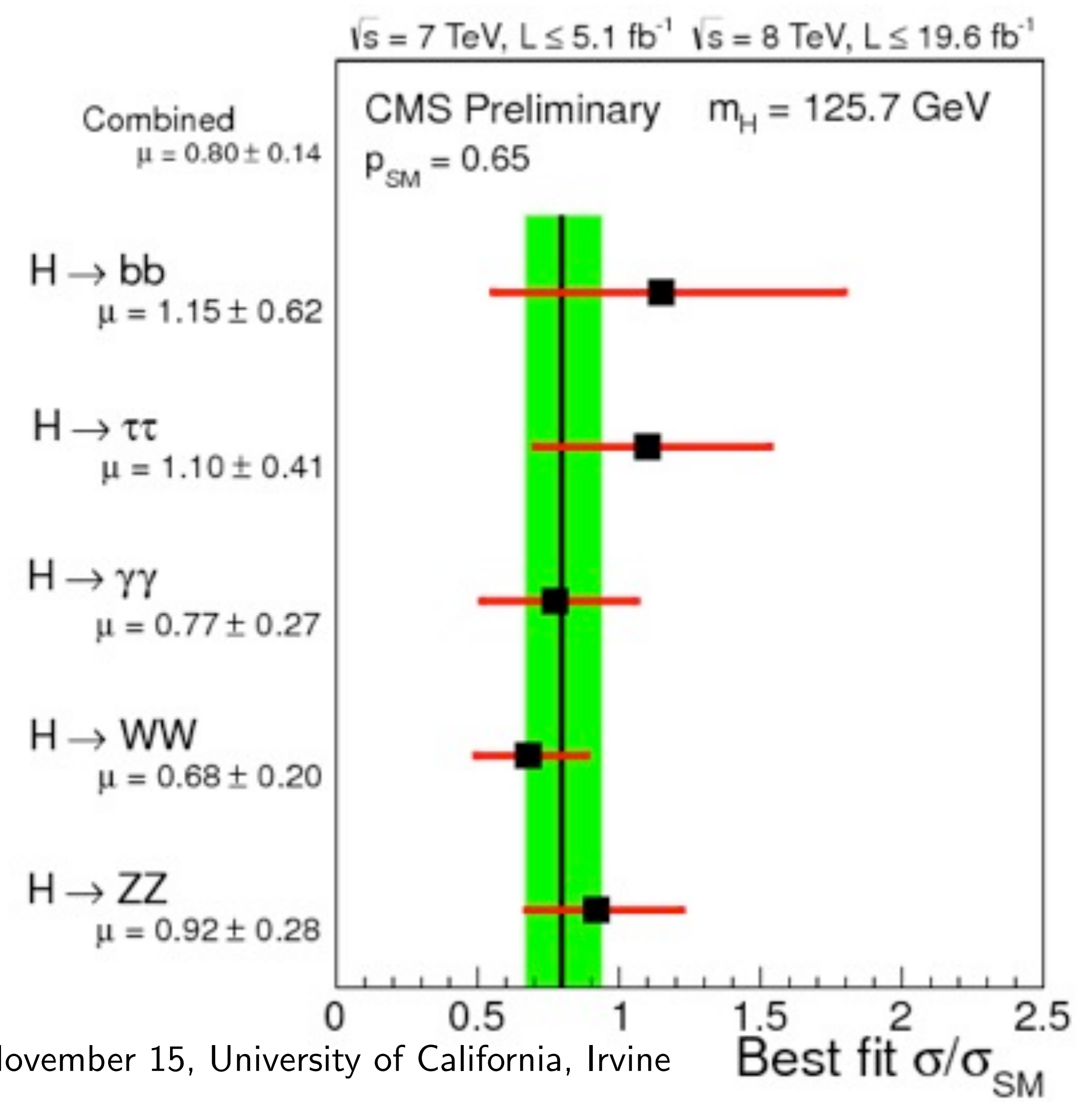
Symmetry Breaking

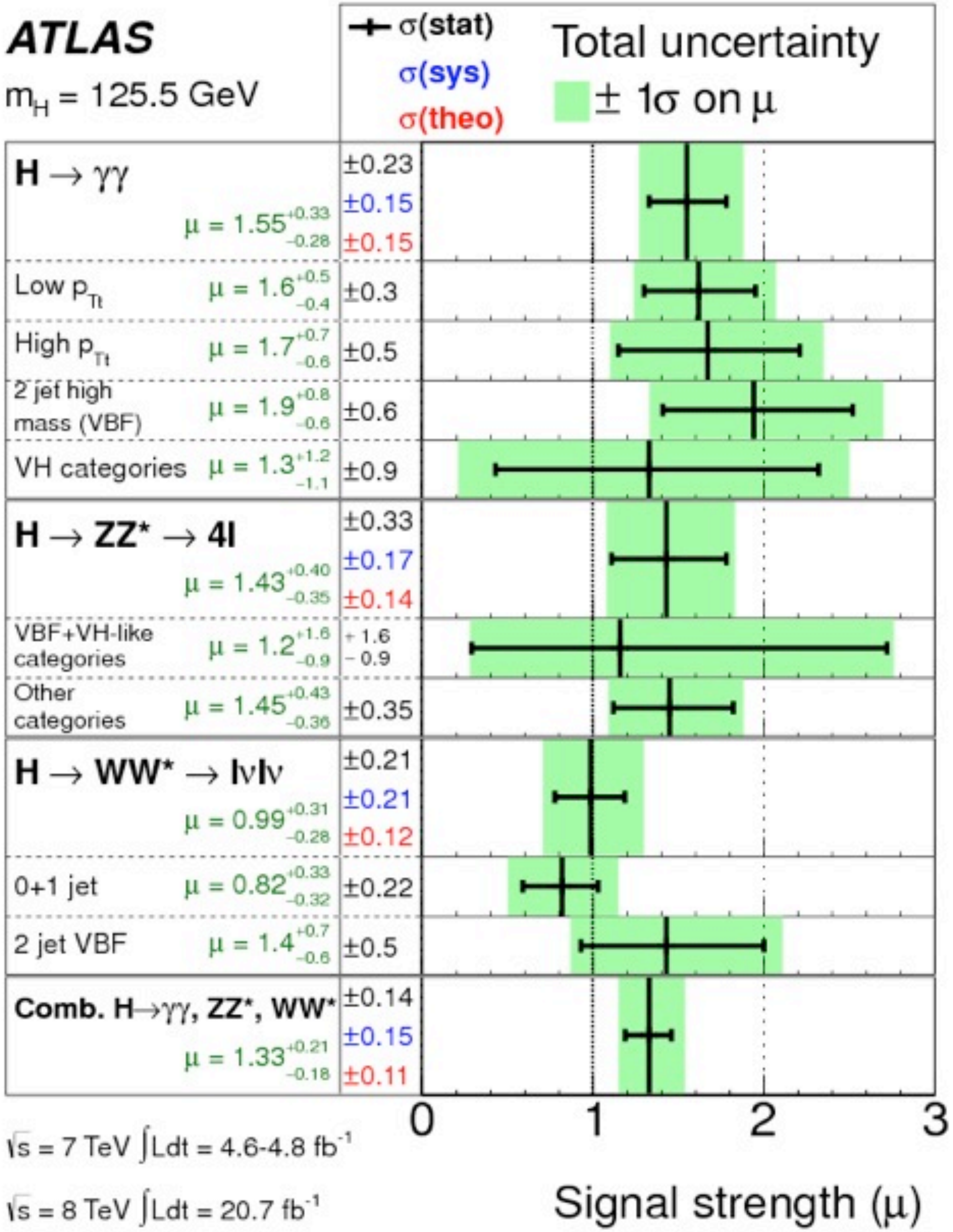
PRISMA

Higgs Results

ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005







Implications for warped extra dimensions?

Outline

1. Basics about Warped Extra Dimensions

2. Higgs Couplings in Warped Extra Dimensions
   - Tree-level Higgs Couplings (W, Z, t, b)
   - Loop-induced Higgs Couplings (g, γ)

3. Higgs Phenomenology in Warped Extra Dimensions
   - Predictions for $pp \to h \to \gamma\gamma, ZZ^{(*)}, WW^{(*)}$
   - Bounds on the Parameter Space from Higgs Physics

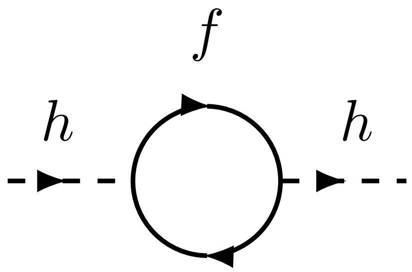
4. Conclusions and Outlook

1. The Randall-Sundrum (RS) Model: Basics

Motivation: The Standard Model suffers from various problems, e.g.

- Gauge hierarchy problem:

  Why is the Higgs light?



$$\Rightarrow \quad \delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2}\left[\Lambda_{\rm UV}^2 + \ldots\right] \qquad\qquad \Lambda_{\rm UV} \overset{?}{=} M_{\rm Pl}$$

- Flavor hierarchy problem:

  Why are the masses and CKM matrix elements hierarchical?

$$m_u : m_c : m_t = 1 : 560 : 75000$$
$$m_d : m_s : m_b = 1 : 20 : 800$$

$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda = 0.23$$

1. The Randall-Sundrum (RS) Model: Basics

Possible solution: Warped Extra Dimensions

[L. Randall, R. Sundrum, hep-ph/9905221]

- Extra dimension: S^1/Z_2 orbifold (for chiral fermions in 5D) in a slice of AdS_5

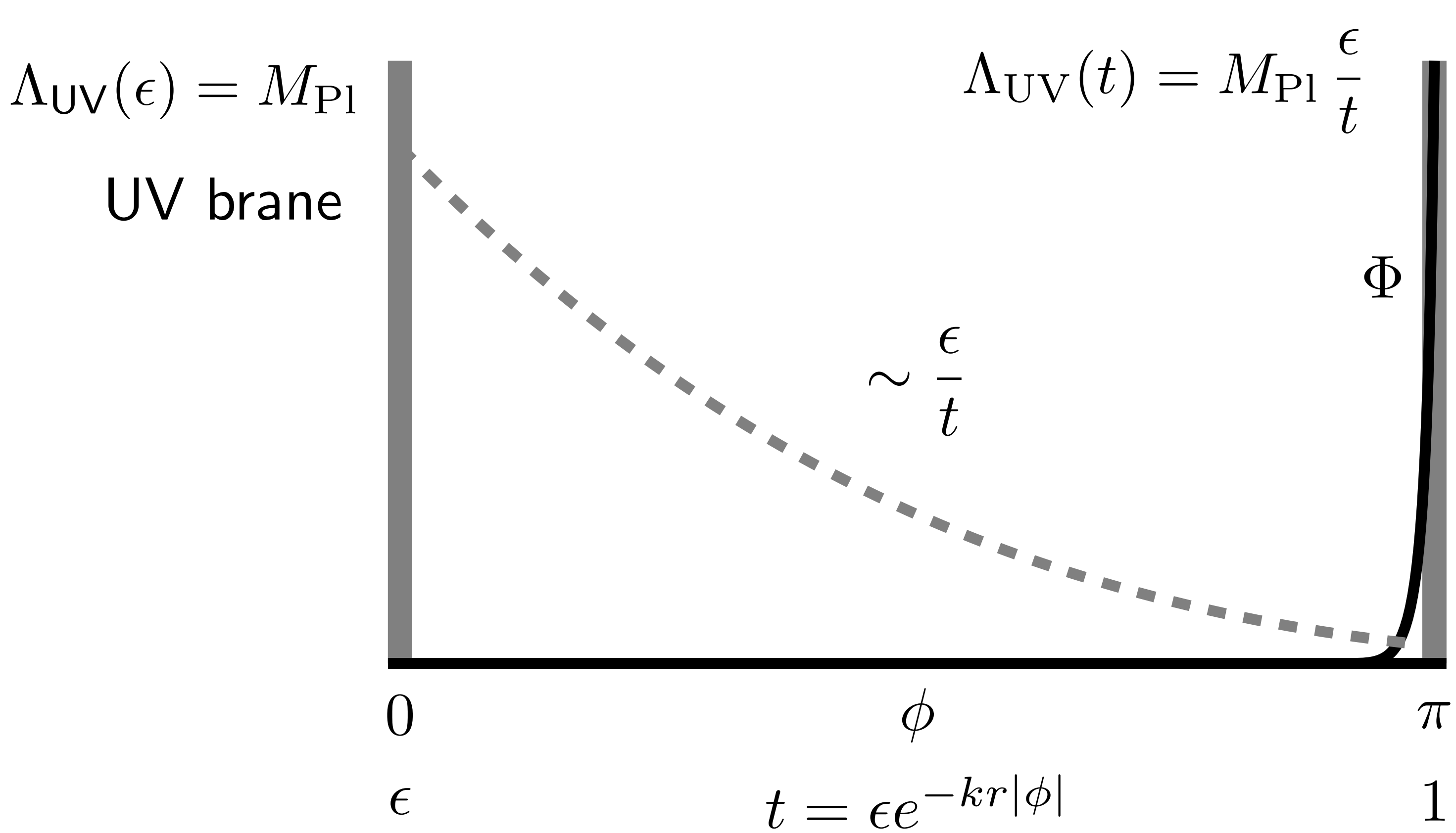
$$\boxed{ds^2 = \frac{\epsilon^2}{t^2}\left(dx_\mu dx^\mu - M_{\mathrm{KK}}^{-2}\, dt^2\right)}$$

warp factor $\epsilon = e^{-L} \approx 10^{-16}$

- Only one scale in theory: Planck mass $M_{\mathrm{Pl}} \sim (k, M_{\mathrm{Pl}(5)}, 1/r)$
- Solution for gauge hierarchy problem by moderate tuning $L = kr\pi \approx 36$

$$\int_\epsilon^1 dt\, \delta(t-1)\, \sqrt{|g(t)|}\, \lambda_5 \left(|\Phi|^2 - v_0^2/2\right)^2 \quad \rightarrow \quad \lambda_5 \left(|\Phi|^2 - (\epsilon v_0)^2/2\right)^2$$

Energy scales are warped down



Higgs doublet localized on IR brane via δ-function at $t = 1$

$\Lambda_{\mathrm{UV}}(1) = \Lambda_{\mathrm{IR}} = \mathcal{O}(\mathrm{TeV})$

$\rightarrow \quad \delta m_h^2 \sim \Lambda_{\mathrm{IR}}^2$

1. The Randall-Sundrum (RS) Model: Basics

Possible solution: Warped Extra Dimensions

[L. Randall, R. Sundrum, hep-ph/9905221]

- All 5D fermion and gauge fields live in the bulk
  $\rightarrow$ *KK decomposition* of 5D fields

$$\Phi(x,t) \sim \sum_{n=0}^{\infty} \phi_n(x)\,\chi_n(t)$$
$$m_n \sim n\pi M_{\rm KK}, \quad M_{\rm KK} = k\epsilon \sim \mathcal{O}(\rm TeV)$$

- Couplings depend on overlap integrals of *profiles* $\sim \int_\epsilon^1 dt\,\chi_i(t)\,\chi_j(t)\,\chi_k(t)$

- Additional parameter in the theory: *bulk-mass parameters* $c_{Q_i,q_i} \sim \mathcal{O}(1)$ $\qquad \mathcal{L}_{\rm quark} \ni k\,\bar{Q}\,\boldsymbol{c}_Q\,Q$

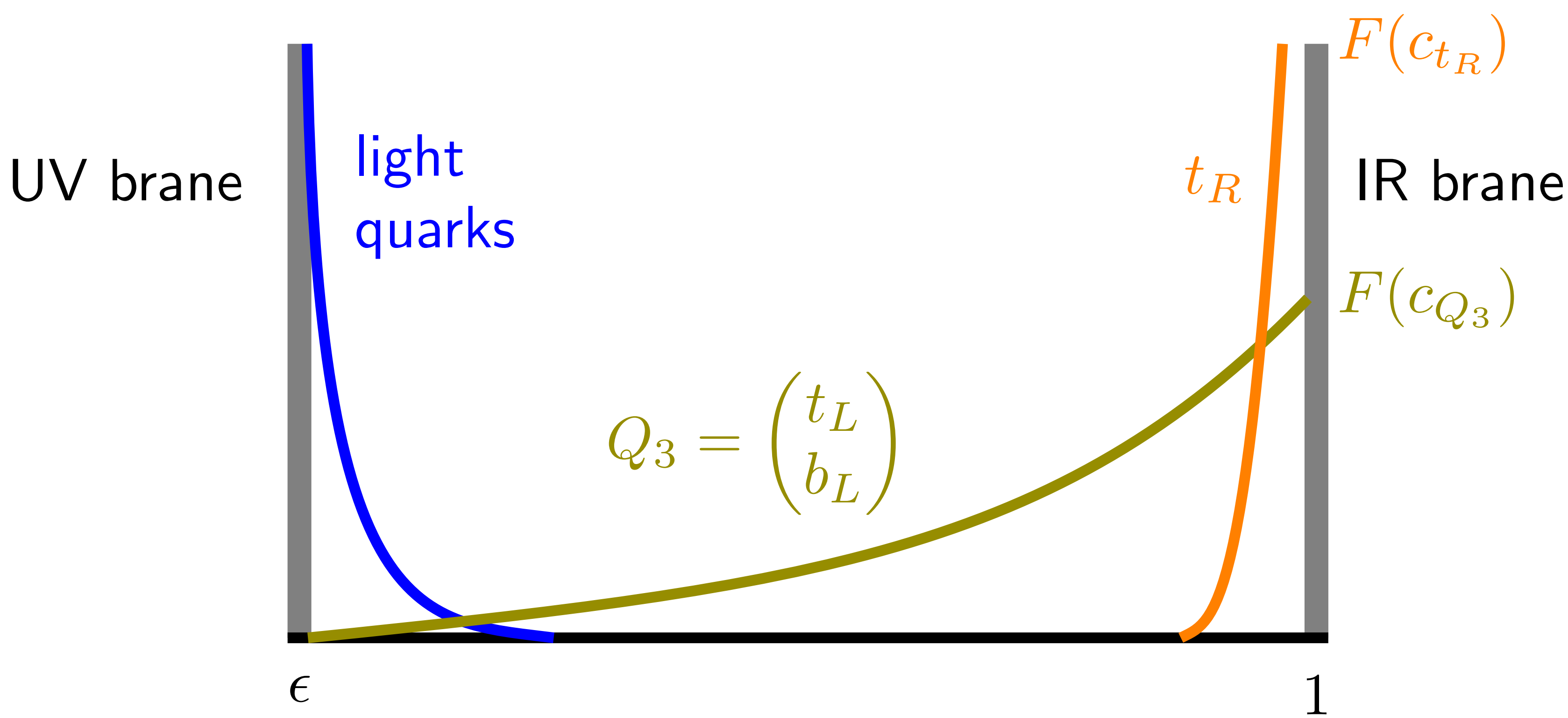
- Explanation for flavor puzzle by localizations along the extra dimension $\qquad$ 5D Yukawas $Y_{q_{ij}} \sim \mathcal{O}(1)$

overlap with Higgs (IR brane)

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

effective Yukawa

$$\boldsymbol{Y}_q^{\rm eff} \sim F(\boldsymbol{c}_Q)\,\boldsymbol{Y}_q\,F(\boldsymbol{c}_q)$$



1. The RS Model: Minimal and Custodial Version

Minimal RS model: [e.g. Casagrande et al, hep-ph/0807.4937]

- Based on SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Gives too large contributions to T parameter and to $Zb\bar{b}$ vertex
- Lower Bound on KK scale: $M_{\rm KK} > 4.0\,{\rm TeV} \quad \rightarrow \quad M_{g^{(1)}} > 9.8\,{\rm TeV}$

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

Custodial RS model: [e.g. Casagrande et al, hep-ph/1005.4315]

- Based on SM group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$
- Reduces contributions to T parameter and to $Zb\bar{b}$ vertex
- Lower Bound on KK scale: $M_{\rm KK} > 1.9\,{\rm TeV} \quad \rightarrow \quad M_{g^{(1)}} > 4.7\,{\rm TeV}$
- Quark Content: up-type, down-type, λ-type (Q=5/3, no zero modes) quarks

Randomized parameters in RS models:

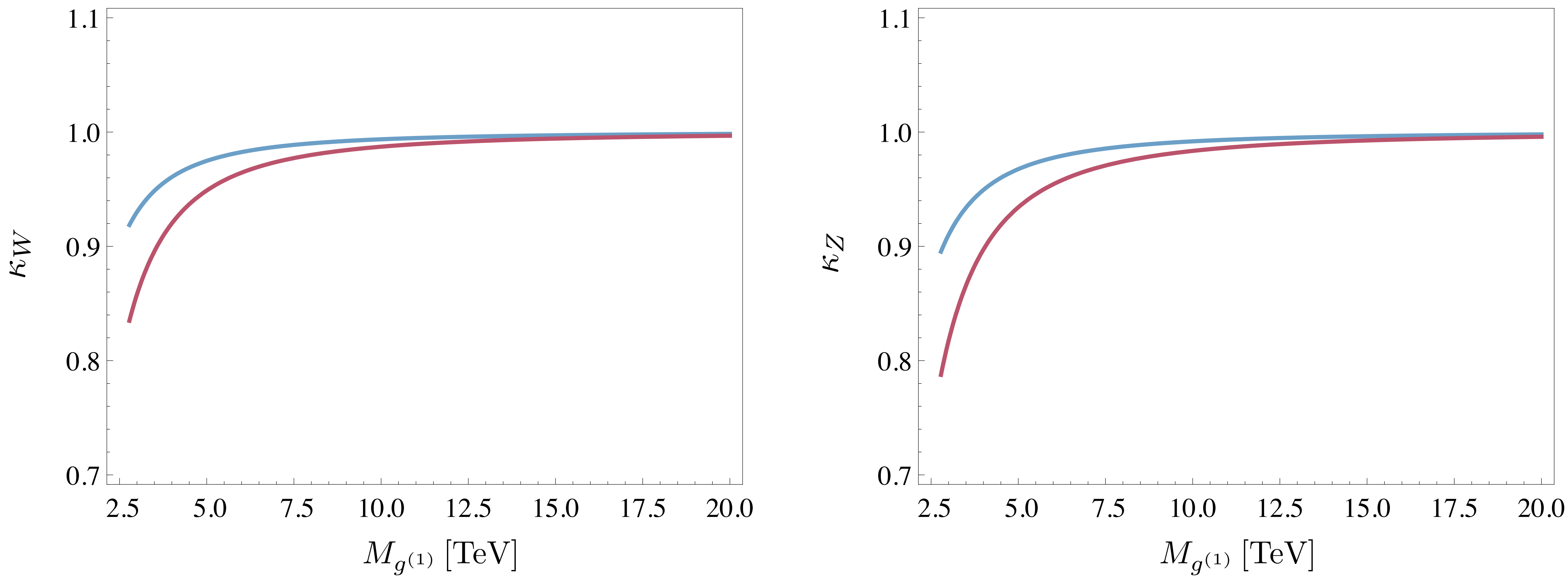
- 2×9 complex Yukawa matrix elements $|(\boldsymbol{Y}_q)_{ij}| \leq y_* \sim \mathcal{O}(1)$
- one free c-parameter $(c_{q_3} \leq 1)$
- KK scale $M_{\rm KK}$, volume $L = kr\pi = 33.5 \quad (\rightarrow \Lambda_{\rm IR} \approx 30\,{\rm TeV})$
- Constraint: Reproduction of SM quark masses and Wolfenstein Parameters

2. Higgs Couplings in RS Models: Tree-level Couplings

- Description via effective Lagrangian: $\mathcal{L}_{\text{eff}} = c_W \, \frac{2m_W^2}{v} \, hW_\mu^+ W^{-\mu} + c_Z \, \frac{2m_Z^2}{v} \, hZ_\mu Z^\mu$
- Couplings are given by overlap integrals: $c_{W,Z} \sim \int_\epsilon^1 dt \, \delta(t-1) \, \chi_{W,Z}(t) \, \chi_{W,Z}(t)$
- Results: $c_{W,Z} = 1 - \frac{m_{W,Z}^2}{2M_{\text{KK}}^2} \left(2L - 1 + \frac{1}{2L}\right)$, for minimal (custodial) RS model
- $\kappa_{W,Z} \equiv \frac{c_{W,Z}}{\kappa_v}$, corrected for vev shift $\kappa_v = \frac{v}{v_{\text{RS}}} = 1 + 2\frac{L m_W^2}{2M_{\text{KK}}^2}$

[Casagrande et al, hep-ph/0807.4937]
[Casagrande et al, hep-ph/1005.4315]
[Bouchart et al, hep-ph/0909.4812]

W boson $\qquad$ Z boson

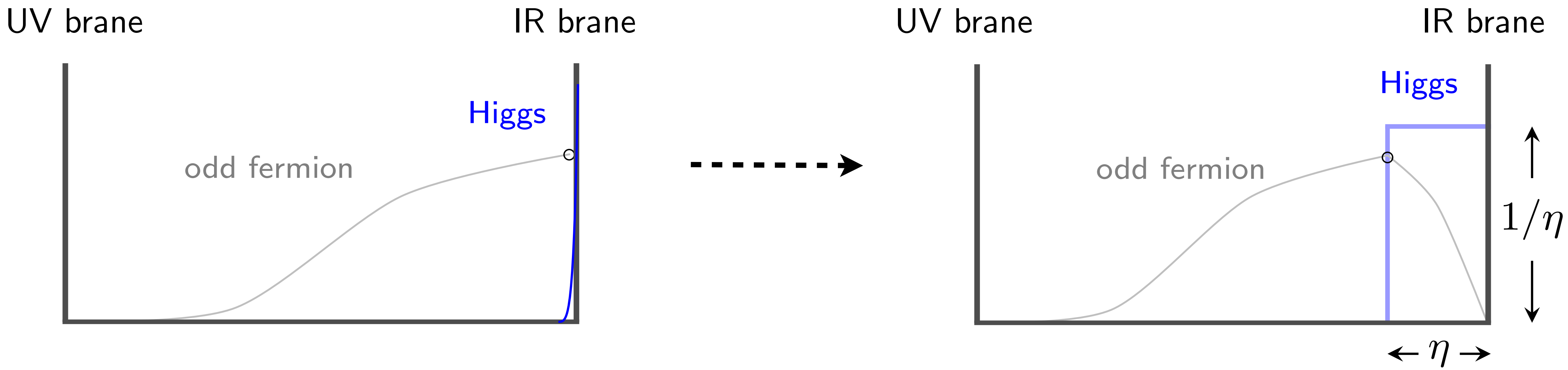


- Only small corrections for $M_{g^{(1)}} \geq 5\,\text{TeV}$, but could be detectable by e.g. ILC

2. Higgs Couplings in RS Models: Tree-level Couplings

- Effective Lagrangian: $\mathcal{L}_{\text{eff}} = -\frac{m_t}{v} h \bar{t} \left(c_t + c_{t5}\, i\gamma_5 \right) t - \frac{m_b}{v} h \bar{b} \left(c_b + c_{b5}\, i\gamma_5 \right) b$
- Couplings are given by overlap integrals: $c_{t,b} \sim \int_\epsilon^1 dt\, \delta(t-1) \left[Q_L^\dagger \, \boldsymbol{Y}_q \, q_R^c + Q_R^\dagger \, \boldsymbol{Y}_q \, q_L^c \right]$
- e.g. 5D doublets: $Q(x,t) = Q_L^0(x)\chi_L^0(t) + Q_L^1(x)\chi_L^1(t) + Q_R^1(x)\chi_R^1(t) + \dots$
- Subtlety: Z_2-odd profiles of Q_R, q_L^c vanish at $t = 1$
  $\rightarrow$ Regularized Higgs profile $\delta^\eta(t-1)$ with width η

[Azatov et al, hep-ph/0906.1990]



- Width η is an unphysical parameter in the case of a brane Higgs
- Gives a finite contribution in the limit $\eta \to 0$

2. Higgs Couplings in RS Models: Tree-level Couplings

- Effective Lagrangian: $\mathcal{L}_{\text{eff}} = -\frac{m_t}{v} h\bar{t}\,(c_t + c_{t5}\, i\gamma_5)\, t - \frac{m_b}{v} h\bar{b}\,(c_b + c_{b5}\, i\gamma_5)\, b$

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[Azatov et al, hep-ph/0906.1990]
[Casagrande et al, hep-ph/1005.4315]

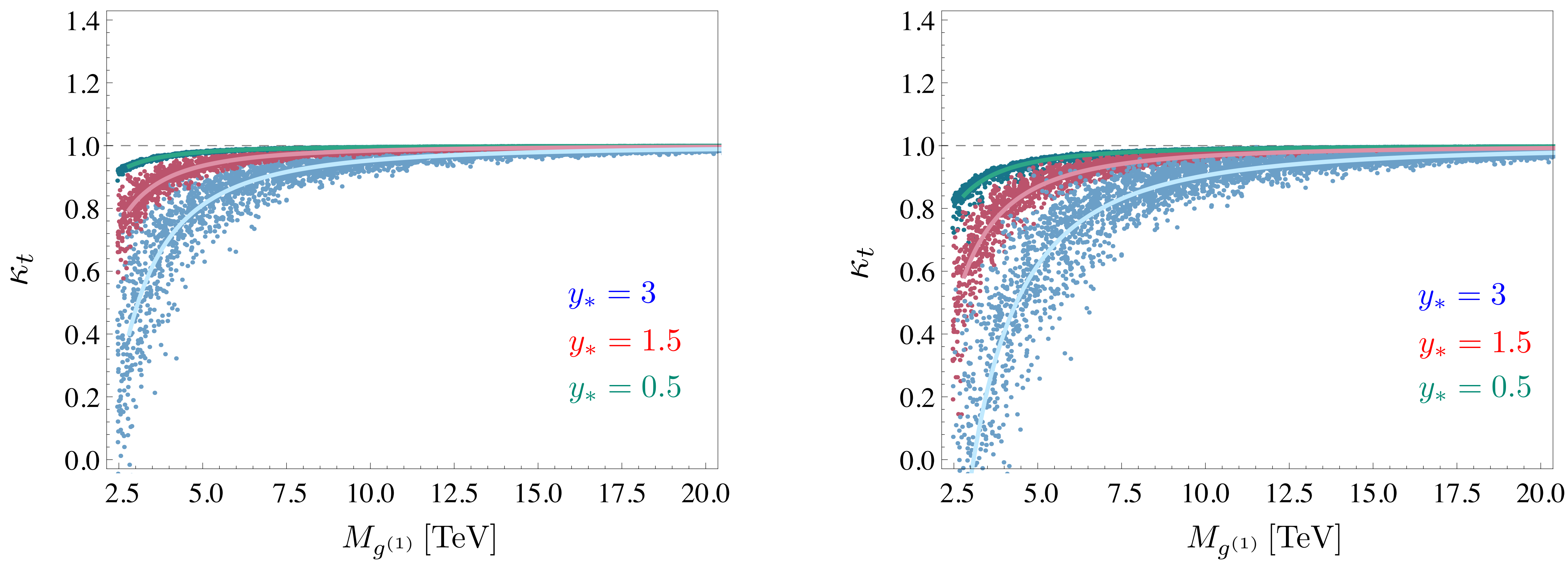
- Results:

$$c_t + ic_{t5} = 1 - (\boldsymbol{\delta}_Q, \boldsymbol{\Phi}_Q)_{33} - (\boldsymbol{\delta}_u, \boldsymbol{\Phi}_u)_{33} - \frac{2v^2}{3M_{\text{KK}}^2} \frac{\left(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u\right)_{33}}{(\boldsymbol{Y}_u)_{33}}$$

$$\sim (2N_g - 1)\,\frac{y_*^2}{2}$$

$$\kappa_{t,b} = \frac{c_{t,b}}{\kappa_v}$$

Minimal RS model | Custodial RS model



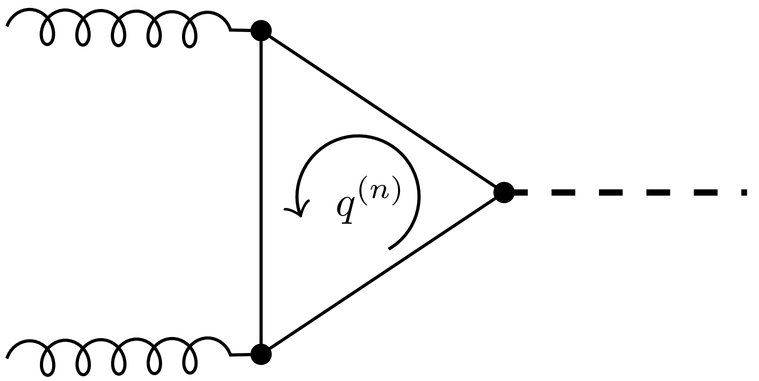
2. Higgs Couplings in RS Models: Loop-induced Couplings

- Effective Lagrangian:

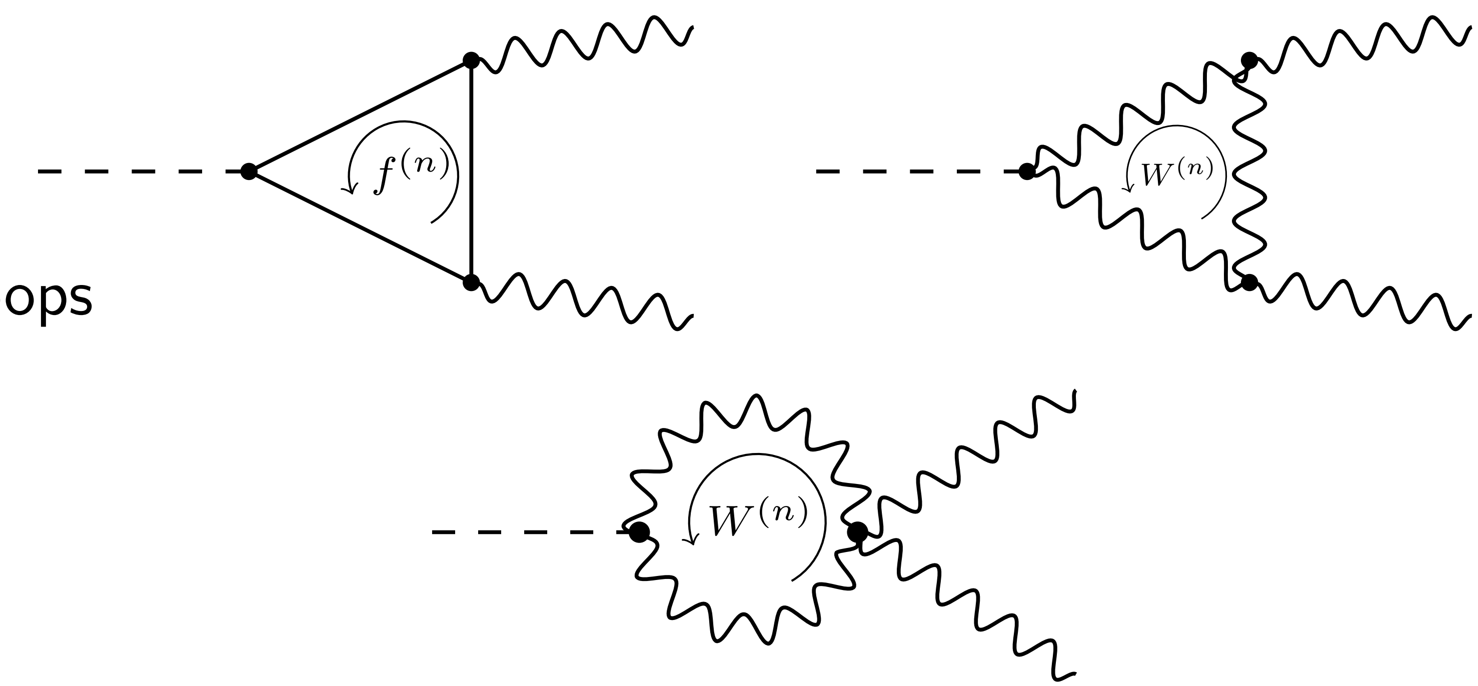
$$\mathcal{L}_{\text{eff}} = c_g \, \frac{\alpha_s}{12\pi v} \, h G^a_{\mu\nu} G^{a,\mu\nu} - c_{g5} \, \frac{\alpha_s}{8\pi v} \, h G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + c_\gamma \, \frac{\alpha_e}{6\pi v} \, h F^a_{\mu\nu} F^{a,\mu\nu} - c_{\gamma 5} \, \frac{\alpha_e}{4\pi v} \, h F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

- Couplings are obtained by calculating loop-level diagrams

- $c_{g,g5}$ from:
- Only quark loop
- Focused on in hep-ph/1303.5702

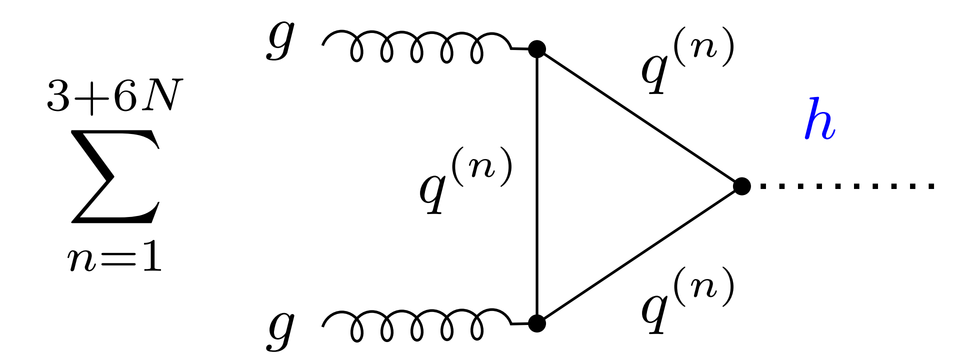


- $c_{\gamma,\gamma 5}$ from:
- Quark, lepton, and W boson loops
- current work



2. Loop-induced Coupling c_g

How large is the KK Contribution for a brane Higgs?
Result insensitive to KK modes above the cutoff?

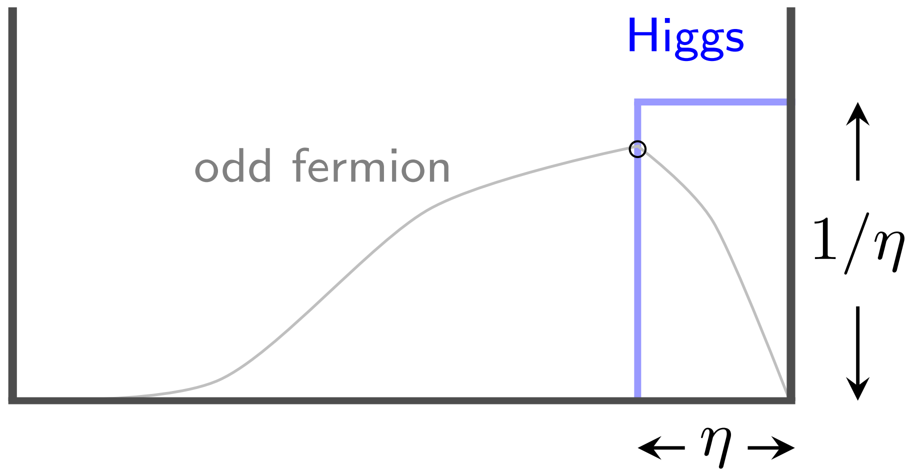


Two contradicting results

[Casagrande et al, hep-ph/1005.4315]

- Contribution of modes below cutoff $\Lambda_{IR} \approx 10\, M_{\rm KK}$
- Higgs coupling to Z_2-odd fermions included
- Result: $c_g^{\rm KK} \approx -\frac{v^2}{2M_{\rm KK}^2}\,{\rm Tr}\left[\boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger\right]$ (negative correction to SM)

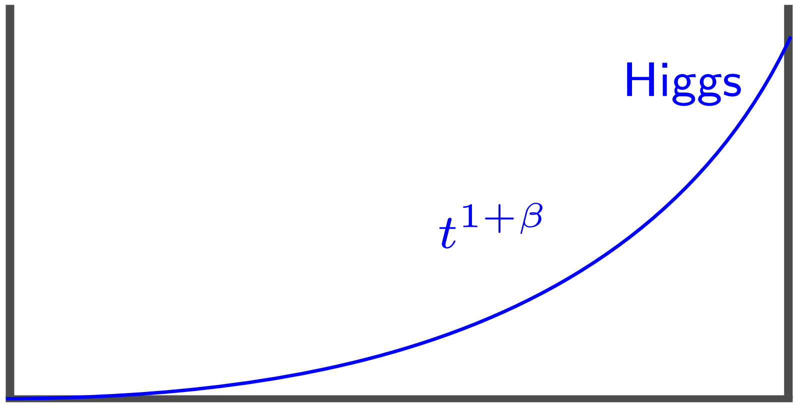
brane-localized Higgs



[Azatov et al, hep-ph/1006.5939]

- Calculation with Bulk Higgs
- Narrow-bulk Higgs: Moving Higgs profile towards IR brane ($\beta \to \infty$)
- Result: $c_g^{\rm KK} \approx +\frac{v^2}{2M_{\rm KK}^2}\,{\rm Tr}\left[\boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger\right]$ (positive correction to SM)

narrow-bulk Higgs



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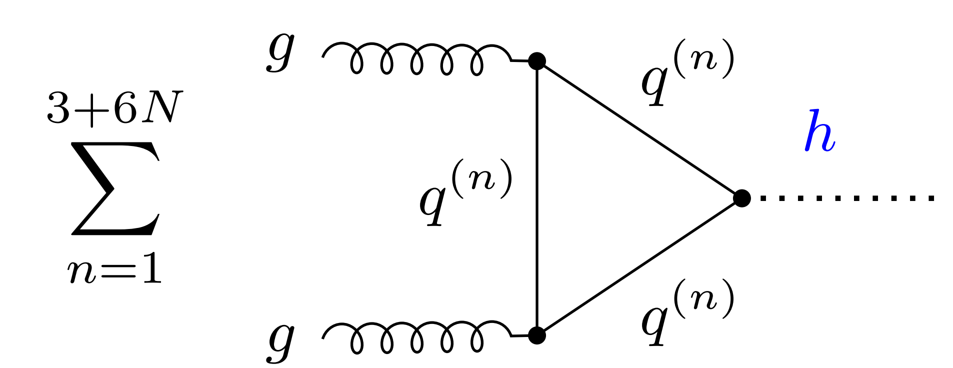

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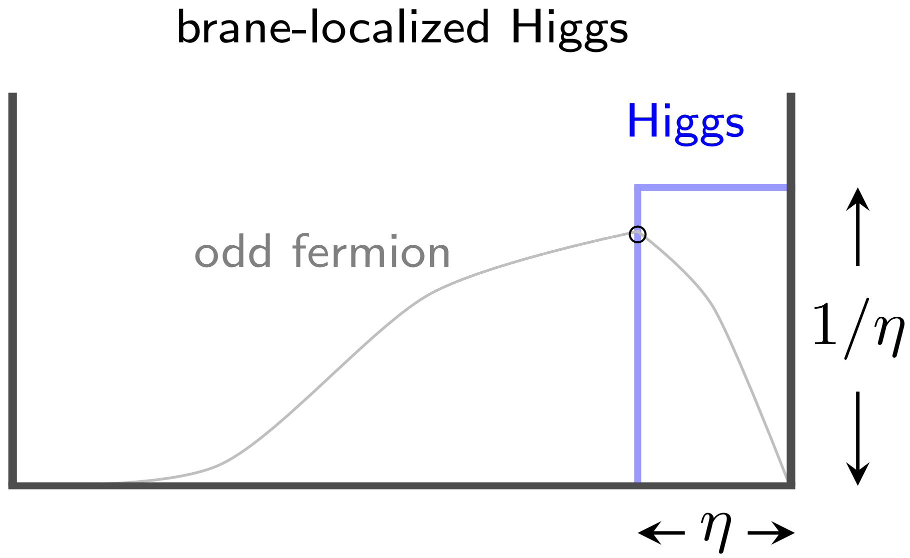

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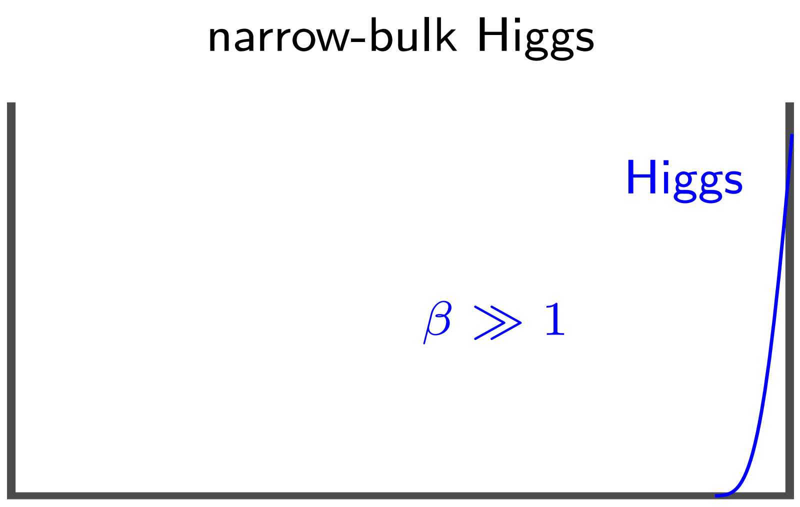

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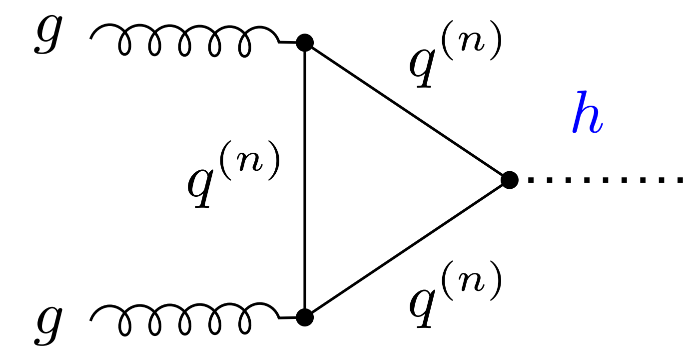
Two contradicting results

$$\sum_{n=1}^{3+6N}$$



Explanation from the 4D perspective [Carena et al, hep-ph/1204.0008]

$$\lim_{N\to\infty,\eta\to 0} \sum_{n=4}^{3+6N} \frac{v\, g^q_{nn}(\eta)}{m_{q_n}} \left(\frac{\mu}{m_{q_n}}\right)^{4-d}$$

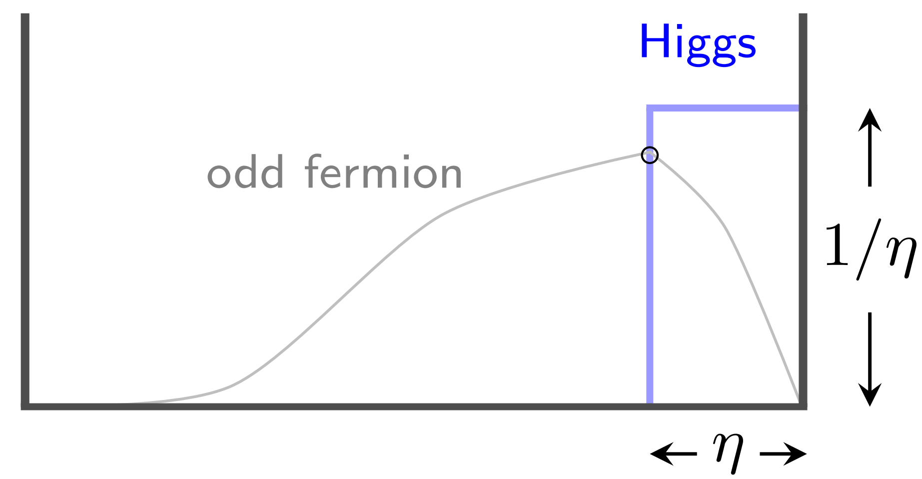
$d < 4$, with cutoff

- limits $N \to \infty$ and $\eta \to 0$ commute
- unique result: $c_g^{\rm KK} \approx -\frac{v^2}{2M_{\rm KK}}\,{\rm Tr}\left[\boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger\right]$

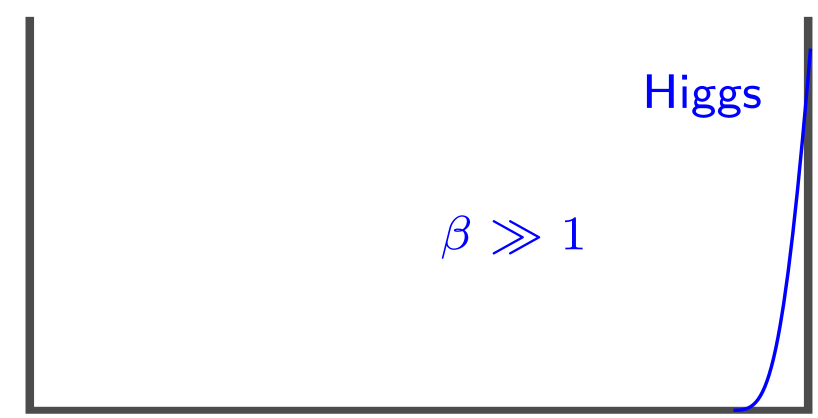
$d = 4$, without cutoff

- limits $N \to \infty$ and $\eta \to 0$ do not commute
- KK modes with $m_{q_n} \sim v|Y_q|/\eta$ contribute significantly

brane-localized Higgs



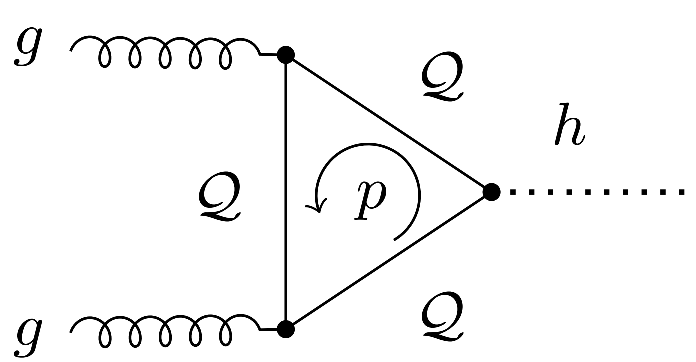
narrow-bulk Higgs



2. Loop-induced Coupling c_g

Idea of our work (hep-ph/1303.5703):

- Derive 5D fermion propagator for three generations and with exact dependence on the Yukawas $\rightarrow$ KK modes implicitly summed up
- Use regularized δ-function for Higgs profile
- Use dimensional regularization ($d = 4 - 2\hat{\epsilon}$) for the 4D loop-momentum integral
- Check explicitly how high-momentum modes decouple

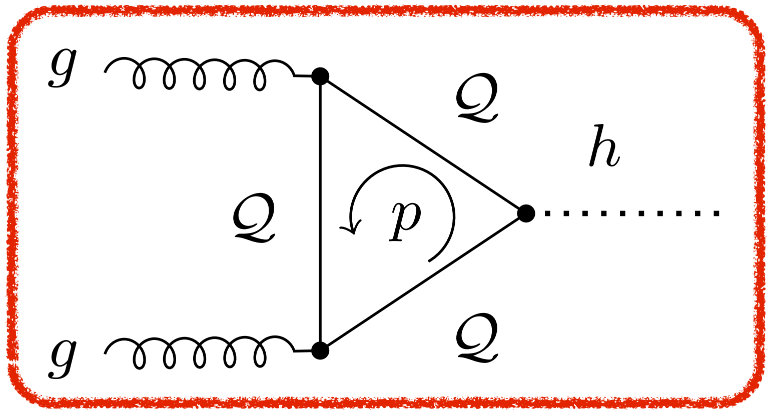


$$\mathcal{A}(gg \to h) = c_g \, \frac{\alpha_s}{12\pi v} \, \langle 0 | G^a_{\mu\nu} G^{\mu\nu,a} | gg \rangle - c_{g5} \, \frac{\alpha_s}{8\pi v} \, \langle 0 | G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} | gg \rangle$$

$$c_{g,g5} \sim I_\pm(m^2) = -\frac{e^{\hat{\epsilon}\gamma_E} \, \mu^{2\hat{\epsilon}}}{\Gamma(1-\hat{\epsilon})} \int_0^\infty dp_E \, p_E^{-2\hat{\epsilon}} \, \frac{\partial}{\partial p_E} T_\pm(p_E^2 + m^2)$$

- Functions $T_\pm$ are integrals over the mixed-chirality components $\boldsymbol{\Delta}_{LR,RL}$ of the 5D quark propagator with the regularized Higgs profile along the extra dimension

2. Loop-induced Coupling c_g



$$\mathcal{A}(gg \to h) = c_g \frac{\alpha_s}{12\pi v} \langle 0|G^a_{\mu\nu} G^{\mu\nu,a}|gg\rangle - c_{g5} \frac{\alpha_s}{8\pi v} \langle 0|G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}|gg\rangle$$

$$c_{g,g5} \sim I_\pm(m^2) = -\frac{e^{\hat\epsilon \gamma_E} \mu^{2\hat\epsilon}}{\Gamma(1-\hat\epsilon)} \int_0^\infty dp_E \, p_E^{-2\hat\epsilon} \frac{\partial}{\partial p_E} T_\pm(p_E^2 + m^2) \Big|_{p_E^2 = -p^2}$$

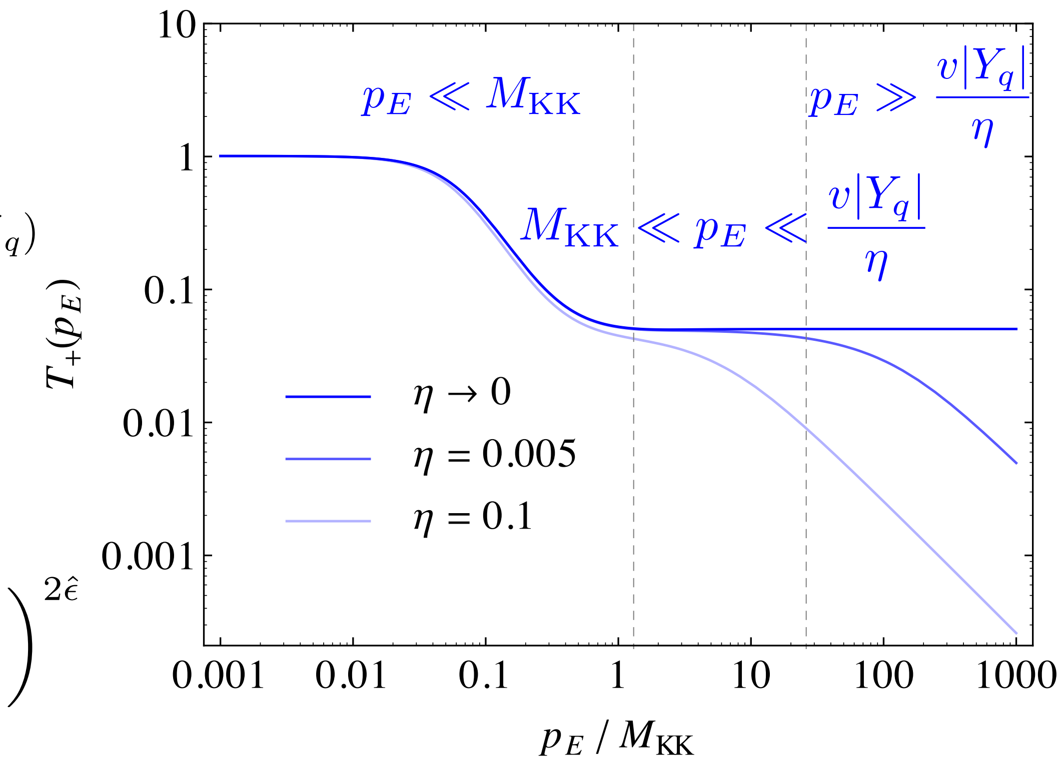
Function $T_+(p_E^2)$:

- three characteristic regions
- can be approximated by toy model $t_{0,1,3} \equiv t_{0,1,3}(\boldsymbol{Y}_q)$ $t_2 \equiv t_2(\boldsymbol{c}_j, \boldsymbol{Y}_q)$

$$T_+^{\text{toy}}(p_E^2) = \frac{t_0 - t_1 - t_2}{1 + \hat p_E^2} + \frac{t_2}{\sqrt{1 + \hat p_E^2}} + \frac{t_3}{\sqrt{(t_3/t_1)^2 + (\eta \hat p_E)^2}}$$

- Performing loop momentum integral gives

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



Two different choices lead to two different models! Transition region not calculable!

- send $\eta \to 0$, then remove regulator: $I_+^{\text{toy}}(0) = t_0 - t_1$ $(R_h < 1)$ *brane Higgs*
- keep η finite, then remove regulator: $I_+^{\text{toy}}(0) = t_0$ $(R_h > 1)$ *narrow-bulk Higgs*

2. Loop-induced Coupling c_g

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- keep η finite, then remove regulator: $I_+^{\rm toy}(0) = t_0 \; (R_h > 1)$ *narrow-bulk Higgs*

Regulator dependent result? What about transition region?

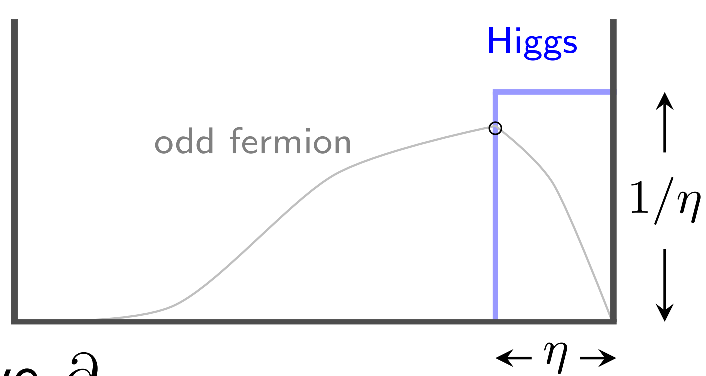
- Repeat analysis with hard-momentum cutoff $\Lambda_{\rm TeV}$
- Threshold corrections explicitly visible
- Results:

$$I_+^{\rm toy} = t_0 - t_1 - \frac{3t_2}{2}\frac{M_{\rm KK}}{\Lambda_{\rm TeV}}$$ *brane Higgs*

$$I_+^{\rm toy} = t_0 - \frac{3t_3}{2}\frac{M_{\rm KK}}{\eta\Lambda_{\rm TeV}}$$ *narrow-bulk Higgs*

Threshold corrections in the narrow bulk-Higgs scenario

- explode for $\eta \to 0$
- can be attributed to higher-dimensional operators involving derivative ∂_t



Transition region not calculable!

2. Loop-induced Coupling c_g

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

$$\downarrow$$

$$\boxed{\begin{aligned} I_+(m^2) &= \sum_{q=u,d}\left\{\mathrm{Tr}\,g(\boldsymbol{X}_q)+\frac{1}{2}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)}+\frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]\right\} \\ I_-(m^2) &= \sum_{q=u,d}\frac{1}{2i}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)}-\frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]\end{aligned}}$$

2. Loop-induced Coupling c_g

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

$$I_+(m^2) = \sum_{q=u,d}\left\{\mathrm{Tr}\, g(\boldsymbol{X}_q) + \frac{1}{2}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\right.\right.$$

$$I_-(m^2) = \sum_{q=u,d}\frac{1}{2i}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\right.$$

$\boldsymbol{X}_q^2 = \frac{v^2}{2M_{\mathrm{KK}}^2}\,\boldsymbol{Y}_q\boldsymbol{Y}_q^\dagger$, with 5D Yukawa matrices $\boldsymbol{Y}_q$

- $\mathcal{L}_Y \ni \int_\epsilon^1 dt\,\bar{Q}_L(t,x)\cdot\Phi(x,t)\,\boldsymbol{Y}_d\,d_R^c(t,x)+\dots$
- anarchic 3×3 matrices in generation space
- $(\boldsymbol{Y}_q)_{ij}$ are random complex numbers
- $|(\boldsymbol{Y}_q)_{ij}| \le y_* \sim \mathcal{O}(1)$

2. Loop-induced Coupling c_g

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

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

$$I_+(m^2) = \sum_{q=u,d}\left\{ \mathrm{Tr}\, g(\boldsymbol{X}_q) + \frac{1}{2}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)} + \frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]\right\}$$

$$I_-(m^2) = \sum_{q=u,d}\frac{1}{2i}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)} - \frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]$$

- Depends on the RS scenario

$$g(\boldsymbol{X}_q)\big|_{\rm brane} = -\frac{\boldsymbol{X}_q\tanh\boldsymbol{X}_q}{\cosh\boldsymbol{X}_q} = -\boldsymbol{X}_q{}^2+\dots$$

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

- Independent of bulk mass parameters $\boldsymbol{c}_{Q,q}$
- Dependent on rank of matrix $\boldsymbol{X}_q^2 = \frac{v^2}{2M_{\rm KK}^2}\boldsymbol{Y}_q\boldsymbol{Y}_q^\dagger$
- Vanishes in the limit $M_{\rm KK}\to\infty$

  $\to$ Contribution from KK tower

2. Loop-induced Coupling c_g

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

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

$$I_+(m^2) = \sum_{q=u,d}\left\{\text{Tr}\, g(\boldsymbol{X}_q) + \frac{1}{2}\text{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)} + \frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]\right\}$$

$$I_-(m^2) = \sum_{q=u,d}\frac{1}{2i}\text{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)} - \frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]$$

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

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

- Independent of bulk mass parameters $\boldsymbol{c}_{Q,q}$
- Dependent on rank of matrix $\boldsymbol{X}_q^2 = \frac{v^2}{2M_{\text{KK}}^2}\boldsymbol{Y}_q\boldsymbol{Y}_q^\dagger$
- Vanishes in the limit $M_{\text{KK}}\to\infty$

  $\to$ Contribution from KK tower

$$\boldsymbol{Z}_q(p_E^2) = \frac{v^2}{2M_{\text{KK}}^2}\frac{\tanh\boldsymbol{X}_q}{\boldsymbol{X}_q}\boldsymbol{Y}_q\boldsymbol{R}_q(\hat p_E)\boldsymbol{Y}_q^\dagger\frac{\tanh\boldsymbol{X}_q}{\boldsymbol{X}_q}\boldsymbol{R}_Q(\hat p_E)$$

$$\hat p_E = \frac{p_E}{M_{\text{KK}}}$$

- $\boldsymbol{R}_{Q,q}$ are ratios of Bessel functions
- $\boldsymbol{R}_{Q,q}$ include bulk mass parameters $\boldsymbol{c}_{Q,q}$
- Small momentum behavior $\boldsymbol{R}_{Q,q} = \frac{F^2(\boldsymbol{c}_{Q,q})}{\hat p_E} + \mathcal{O}(\hat p_E)$
- Non-vanishing contributions in the limit $M_{\text{KK}}\to\infty$

  $\to$ $\boldsymbol{Z}_q$ includes zero-mode contribution

2. Loop-induced Coupling c_g

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

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

$$I_+(m^2) = \sum_{q=u,d}\left\{\mathrm{Tr}\,g(\boldsymbol{X}_q) + \frac{1}{2}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)} + \frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]\right\}$$

$$I_-(m^2) = \sum_{q=u,d}\frac{1}{2i}\mathrm{Tr}\left[\frac{2\boldsymbol{X}_q}{\sinh 2\boldsymbol{X}_q}\left(\frac{\boldsymbol{Z}_q(-m^2)}{1+\boldsymbol{Z}_q(-m^2)} - \frac{\boldsymbol{Z}_q^\dagger(-m^2)}{1+\boldsymbol{Z}_q^\dagger(-m^2)}\right)\right]$$

$g(\boldsymbol{X}_q$

$g(\boldsymbol{X}_q)|_{\rm nar}$

- Indepen
- Depend
- Vanishe

$\rightarrow$ Cont

$(\hat p_E)$

$\mathcal{O}(\hat p_E)$

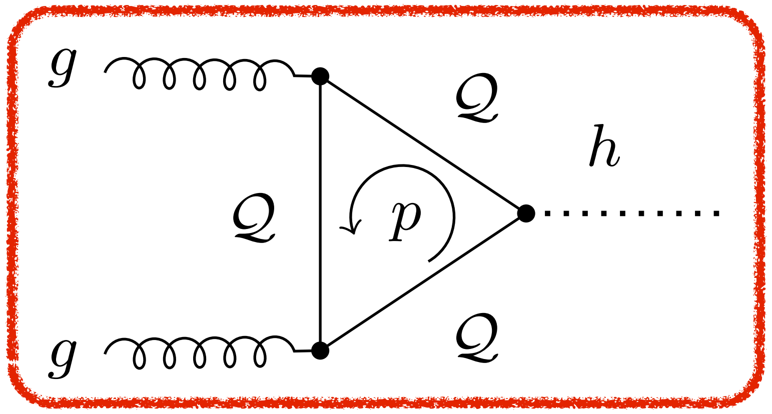
Integration over the Feynman parameter yields the Wilson coefficients

$$c_g = \frac{3}{2}\int_0^1 dz\,(1-z)\,f(z)\,I_+\left(-z\frac{m_h^2}{4}-i0\right)$$

$$c_{g5} = \int_0^1 dz\,f(z)\,I_-\left(-z\frac{m_h^2}{4}-i0\right)$$

$$f(z) = \mathrm{arctanh}\sqrt{1-\mathrm{z}}$$

2. Loop-induced Coupling c_g



$$\mathcal{A}(gg \to h) = c_g \frac{\alpha_s}{12\pi v} \langle 0 | G^a_{\mu\nu} G^{\mu\nu,a} | gg \rangle - c_{g5} \frac{\alpha_s}{8\pi v} \langle 0 | G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} | gg \rangle$$

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

minimal

custodial

$$c_{g5} \approx -\frac{2v^2}{3M_{\mathrm{KK}}^2} \mathrm{Im} \frac{(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u)_{33}}{(\boldsymbol{Y}_u)_{33}} B(\tau_t)$$

$$g(\boldsymbol{X}_q)\big|_{\mathrm{brane}} = -\frac{\boldsymbol{X}_q \tanh \boldsymbol{X}_q}{\cosh \boldsymbol{X}_q} = -\boldsymbol{X}_q{}^2 + \dots$$

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

- Independent of bulk mass parameters $\boldsymbol{c}_{Q,q}$
- Dependent on rank of matrix $\boldsymbol{X}_q^2 = \frac{v^2}{2M_{\mathrm{KK}}^2} \boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger$
- Vanishes in the limit $M_{\mathrm{KK}} \to \infty$

  $\to$ Contribution from KK tower

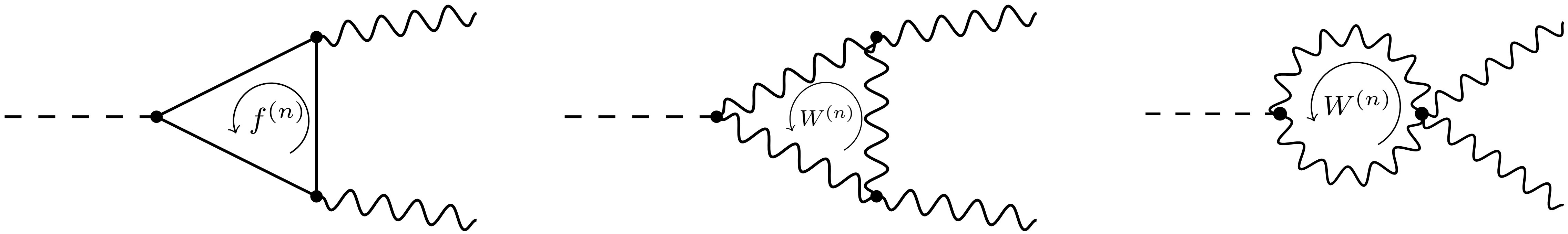
Factor of 4 larger!

$$A(\tau) = \frac{3\tau}{2} \left[1 + (1-\tau) \arctan^2 \frac{1}{\sqrt{\tau - 1}} \right] \qquad \tau_i = 4m_{q_i}^2/m_h^2 - i0$$

$$B(\tau) = \tau \arctan^2 \frac{1}{\sqrt{\tau - 1}}$$

- Contribution from SM quarks
- Only top and bottom quark relevant
- Modified couplings to top due to mixing with KK modes

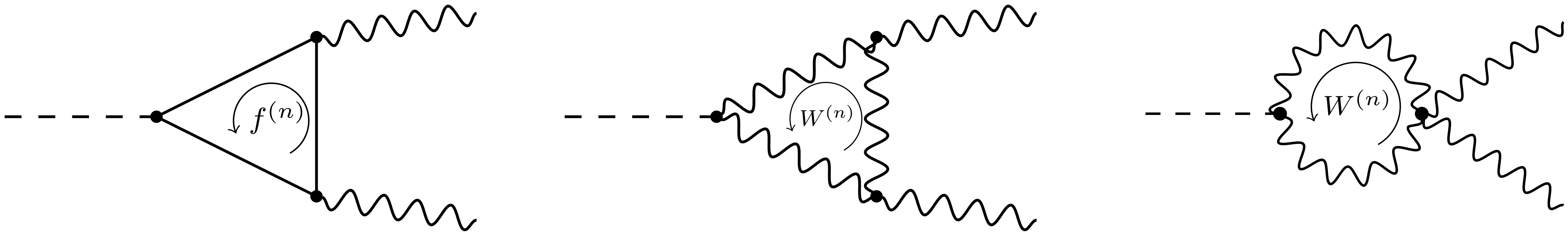
2. Loop-induced Coupling c_γ



- $c_{\gamma,\gamma 5} = c^q_{\gamma,\gamma 5} + c^l_{\gamma,\gamma 5} + c^W_{\gamma,\gamma 5}$ [$c^{q,l}_{\gamma,\gamma 5}$ from $c_{g,g5}$ $(g_s t_a \to eQ_f)$]
- Idea to determine $c^W_{\gamma,\gamma 5}$:
  - Calculate each diagram in R_ξ gauge
  - Show that at each KK level the sum of all diagrams is gauge-independent
  - Only the two diagrams above contribute [Marciano et al, hep-ph/1109.5304]
  - Relate amplitude to expressions involving 5D boson propagator
- Result:

$$c^W_\gamma = -3\pi \tilde{m}^2_W \left[T_W(0) + 3\int_0^1 dz \left(1 - \frac{z}{2}\right) \operatorname{arctanh}(\sqrt{1-z})\, I_W\left(z\frac{m_h^2}{4}\right)\right]$$

2. Loop-induced Coupling c_γ



$$c_\gamma^W = -3\pi\tilde{m}_W^2 \left[T_W(0) + 3\int_0^1 dz \left(1 - \frac{z}{2}\right) \operatorname{arctanh}(\sqrt{1-z})\, I_W\left(z\frac{m_h^2}{4}\right)\right]$$

$$T_W(p_E^2) = \int_\epsilon^1 dt\, \delta_h^\eta(t-1)\, D_W^{\xi=1}(t,t;p_E^2)$$

$$I_W(m^2) = -\frac{e^{\hat{\epsilon}\gamma_E}\mu^{2\hat{\epsilon}}}{\Gamma(1-\hat{\epsilon})} \int_0^\infty dp_E\, p_E^{-2\hat{\epsilon}} \frac{\partial}{\partial p_E} T_W(p_E^2 - m^2 - i0)$$

- Integral over regularized Higgs profile and 5D propagator
- $T_W(0) = \frac{1}{2\pi\tilde{m}_W^2}$
- $T_W(p_E^2) = \frac{L}{2\pi M_{\rm KK}^2}\frac{1}{\hat{p}_E}$ for $p_E \gg M_{\rm KK}$
- No plateau! Unambiguous result!

Correction to W boson c_W

SM result

KK tower contribution

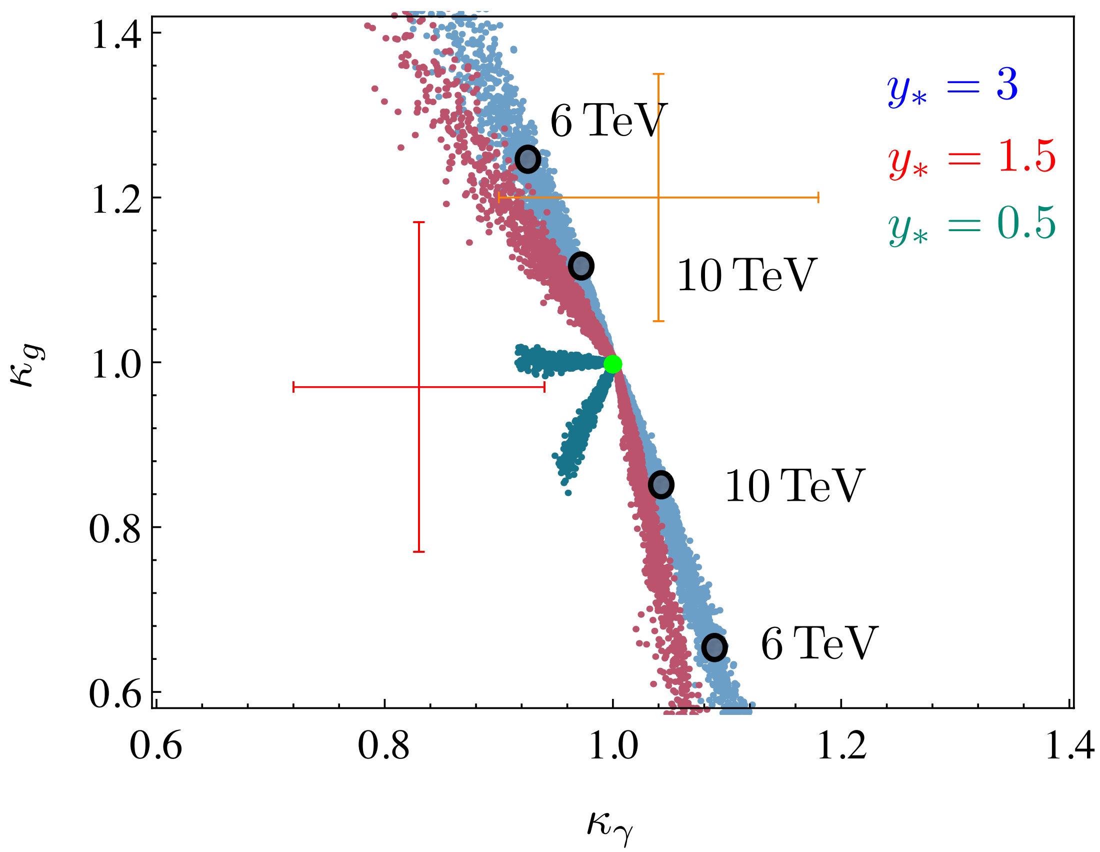
$$c_\gamma^W \approx \left[1 - \frac{m_W^2}{2M_{\rm KK}^2}\left(L - 1 + \frac{1}{2L}\right)\right] A_W^h(\tau_W) - \frac{21}{8}\frac{m_W^2}{M_{\rm KK}^2}\left(L - 1 + \frac{1}{2L}\right)$$

2. Loop-induced Couplings c_g and c_γ

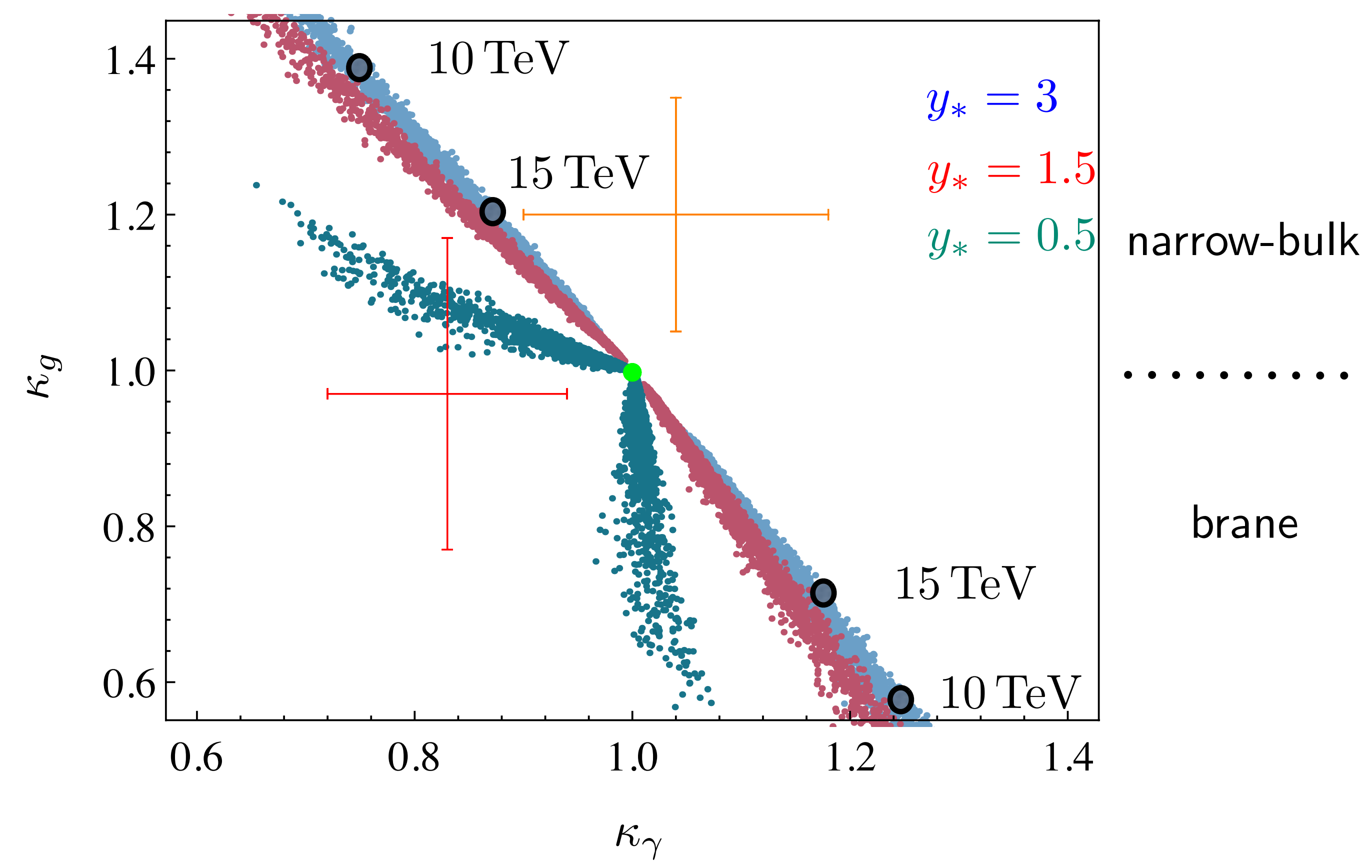
ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005

$$\kappa_{g,\gamma} = \frac{c_{g,\gamma}}{c_{g,\gamma}^{\rm SM}\,\kappa_v}$$

Minimal model



Custodial model



$$\kappa_g \approx 1 - \frac{v^2}{2M_{\rm KK}^2}\left[4\left(\pm 4N_g^2 + 2\frac{2}{3}N_g - 2\frac{1}{3}\right)\langle|\boldsymbol{Y}_{ij}|^2\rangle + \frac{2Lm_W^2}{v^2}\right]$$

$$\kappa_\gamma \approx 1 - \frac{v^2}{2M_{\rm KK}^2}\left[\frac{1}{\hat{c}_\gamma^{\rm SM}}\left(\pm 9\,\frac{8}{3}N_g^2 + 2\frac{16}{9}N_g - 2\frac{8}{9}\right)\langle|\boldsymbol{Y}_{ij}|^2\rangle + \frac{2Lm_W^2}{\hat{c}_\gamma^{\rm SM}\,v^2}\left(\frac{23}{4} + A_h^W(\tau_W)\right)\right]$$

$$\mp\,{\rm Tr}\,\boldsymbol{X}_q^2 = \mp\frac{v^2}{2M_{\rm KK}^2}\sum_{i,j=1}^{N_g}|(\boldsymbol{Y}_q)_{ij}|^2 \approx \mp\frac{v^2}{2M_{\rm KK}^2}\frac{N_g^2 y_*^2}{2}$$

Factor of 4 (9, electric charge of λ-quarks!) larger!

Compensates for suppression by $\hat{c}_\gamma^{\rm SM} \approx -4.9$

3. Higgs Phenomenology in Warped Extra Dimensions

- Investigate $pp \to h \to BB = \gamma\gamma, WW^{(*)}, ZZ^{(*)}$

Gluon fusion $f_{\rm GF} = 0.9$

Vector boson fusion $f_{\rm VBF} = 0.1$

$$R_{BB} \equiv \frac{(\sigma \cdot \mathrm{BR})(pp \to h \to BB)_{\rm RS}}{(\sigma \cdot \mathrm{BR})(pp \to h \to BB)_{\rm SM}} = \frac{\left[\left(|\kappa_g|^2 + |\kappa_{g5}|^2\right) f_{\rm GF} + \kappa_V^2\, f_{\rm VBF}\right]\left[|\kappa_B|^2 + |\kappa_{B5}|^2\right]}{\kappa_h}$$

Correction to Higgs width $\quad \kappa_h = \frac{\Gamma_h^{\rm RS}}{\Gamma_h^{\rm SM}} = 0.57\,|\kappa_b|^2 + 0.22\,|\kappa_W|^2 + 0.06\left(|\kappa_g|^2 + |\kappa_{g5}|^2\right) + 0.15$

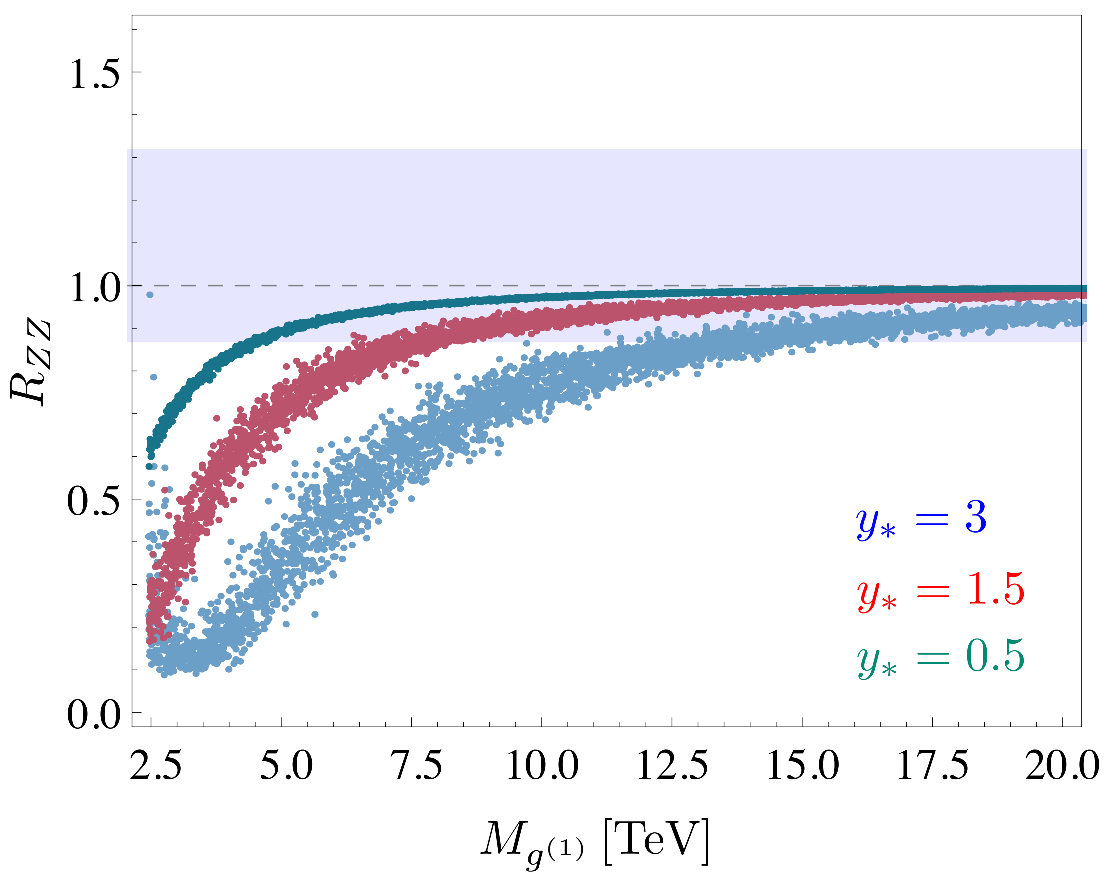
- Plot R_{BB} as a function of $M_{g^{(1)}}$ for $y_* = 0.5, 1.5$ and 3
- Compare with data, calculate $R_{BB}^{\rm th}/R_{BB}^{\rm exp}$ and check compatibility with 1
- Derive exclusion ranges in $y_* - M_{g^{(1)}}$ parameter space

3. Phenomenology: RS predictions for $pp \to h \to ZZ^{(*)}$

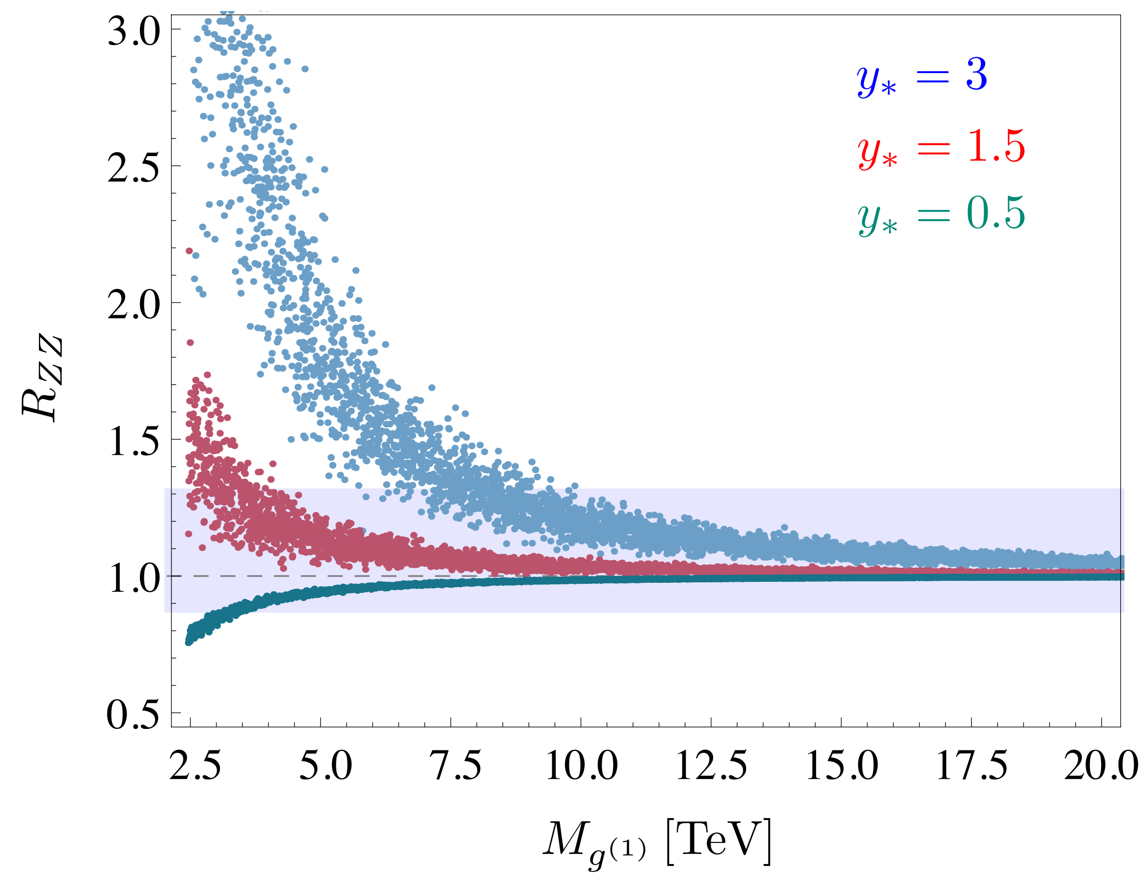
ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005

Minimal model

Brane Higgs



Narrow Bulk Higgs



- R_h strictly below 1

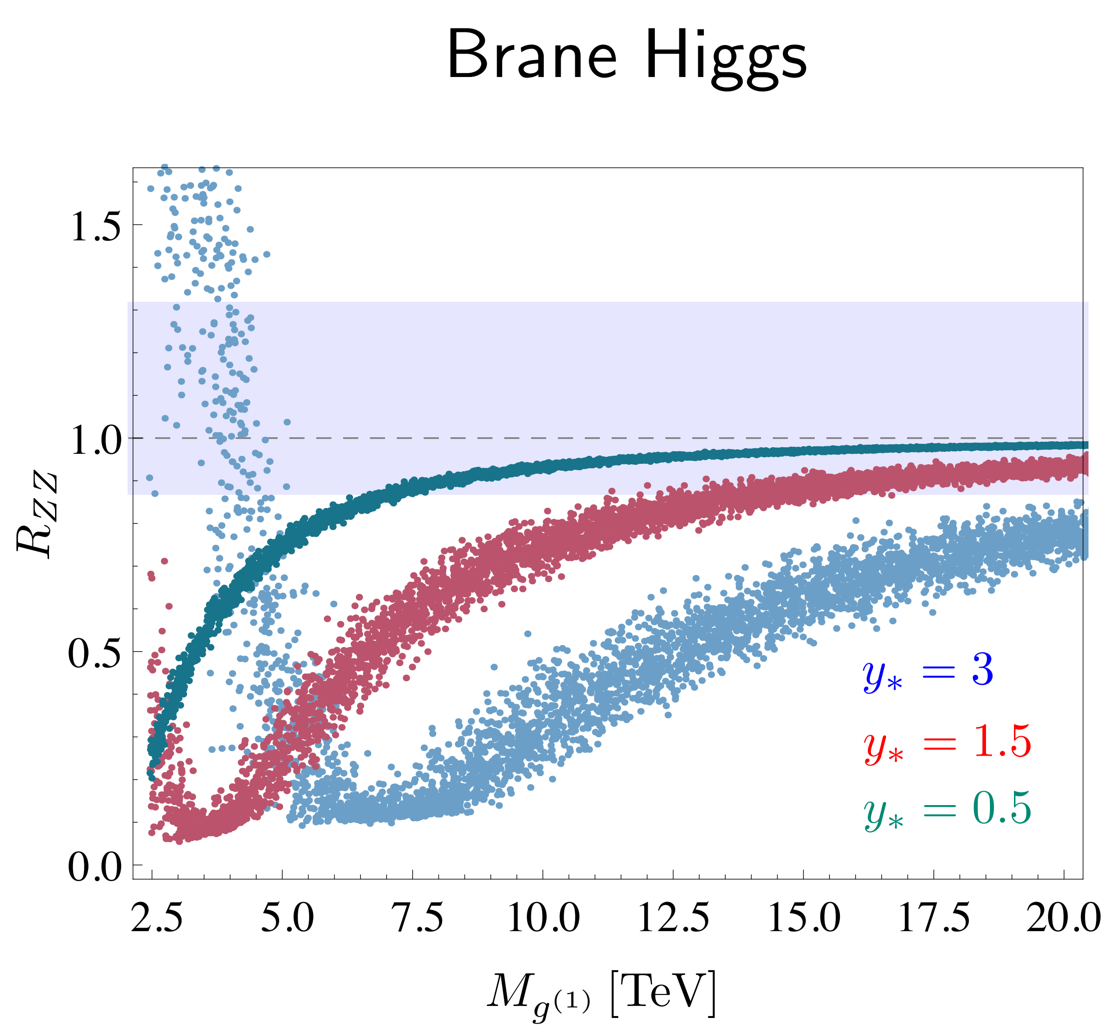
- R_h above 1

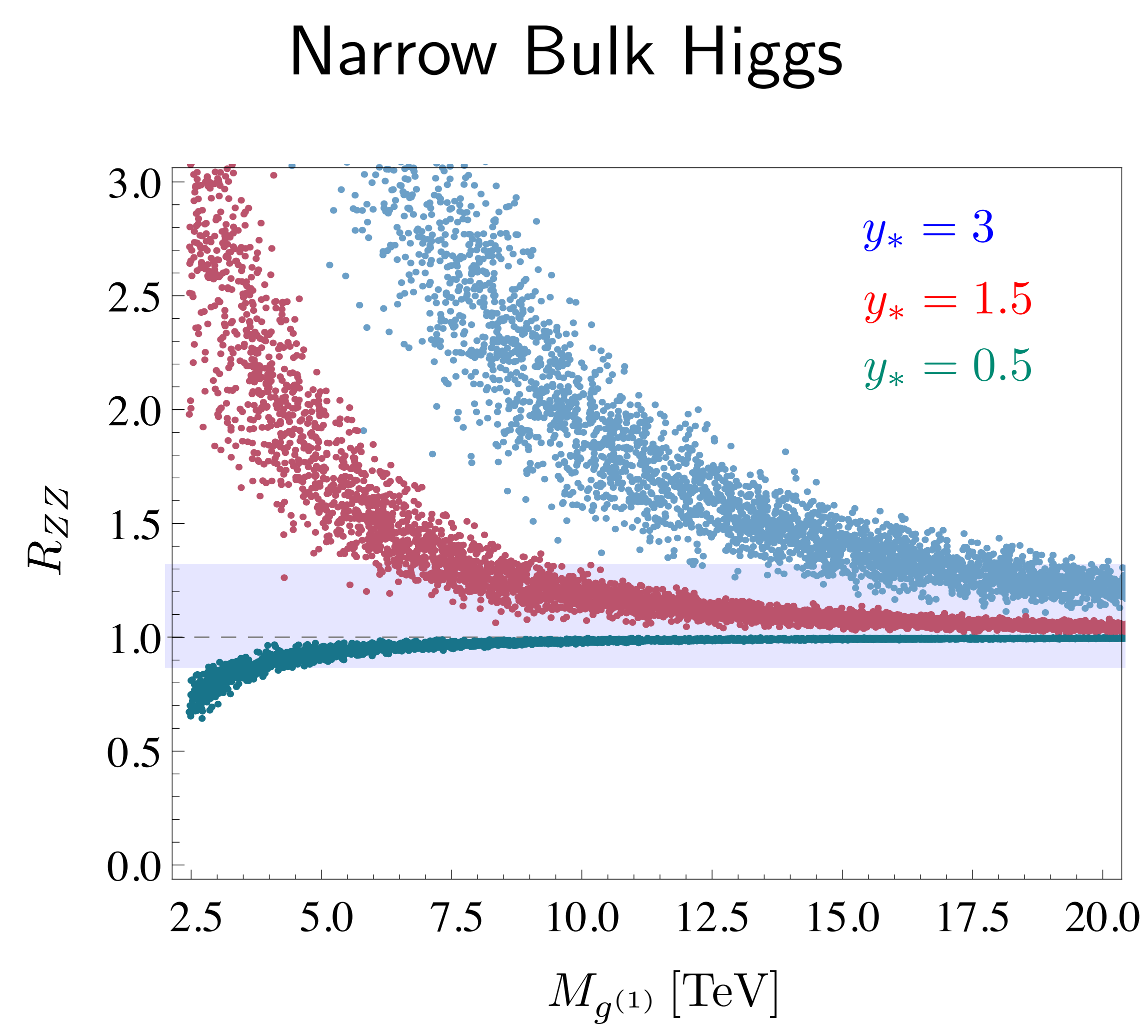
- Effect increases with larger y_*
- Possible to set limits on mass of lightest KK gluon $M_{g^{(1)}} = 2.45\, M_{\text{KK}}$
- Data disfavor KK gluon masses in the low TeV range

3. Phenomenology: RS predictions for $pp \to h \to ZZ^{(*)}$

ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005

Custodial model





- R_h below or above 1

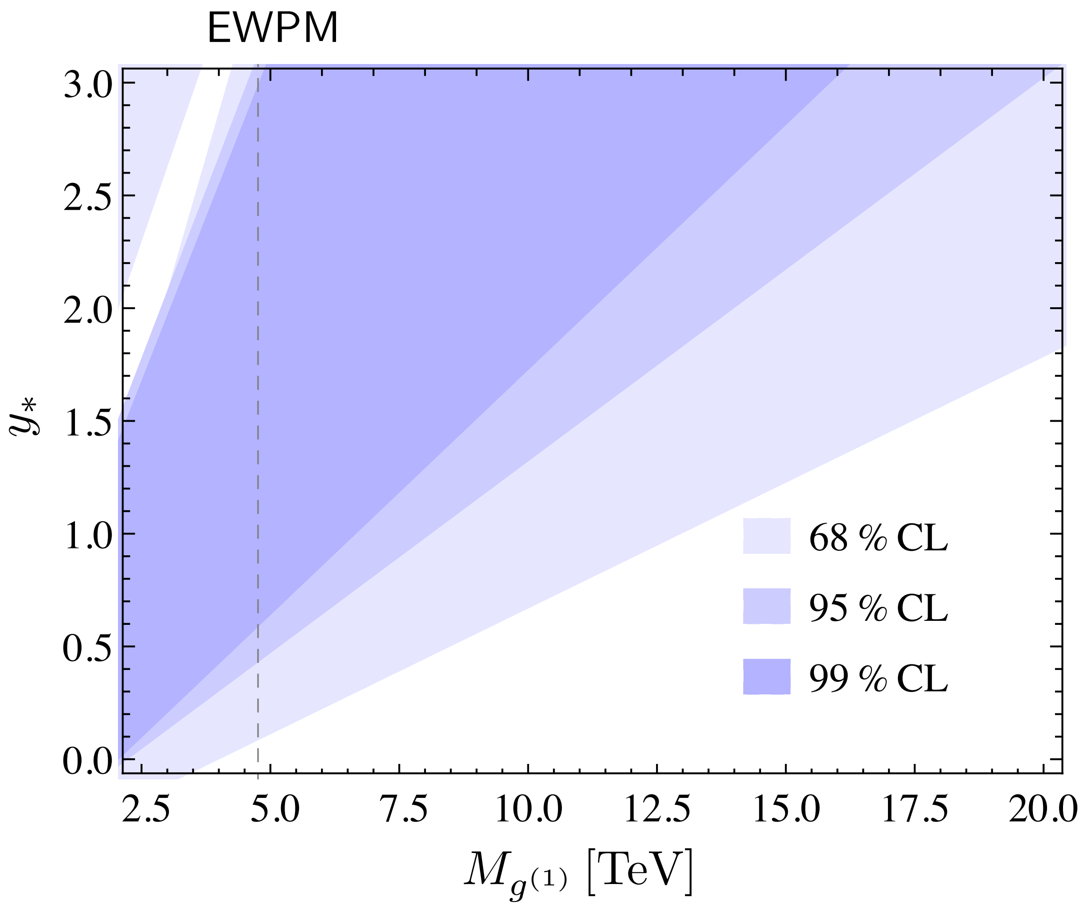
- R_h above 1

- Even larger effect due to factor of 4
- For large y_* KK contribution exceeds SM contribution
- Data disfavor KK gluon masses in the low TeV range

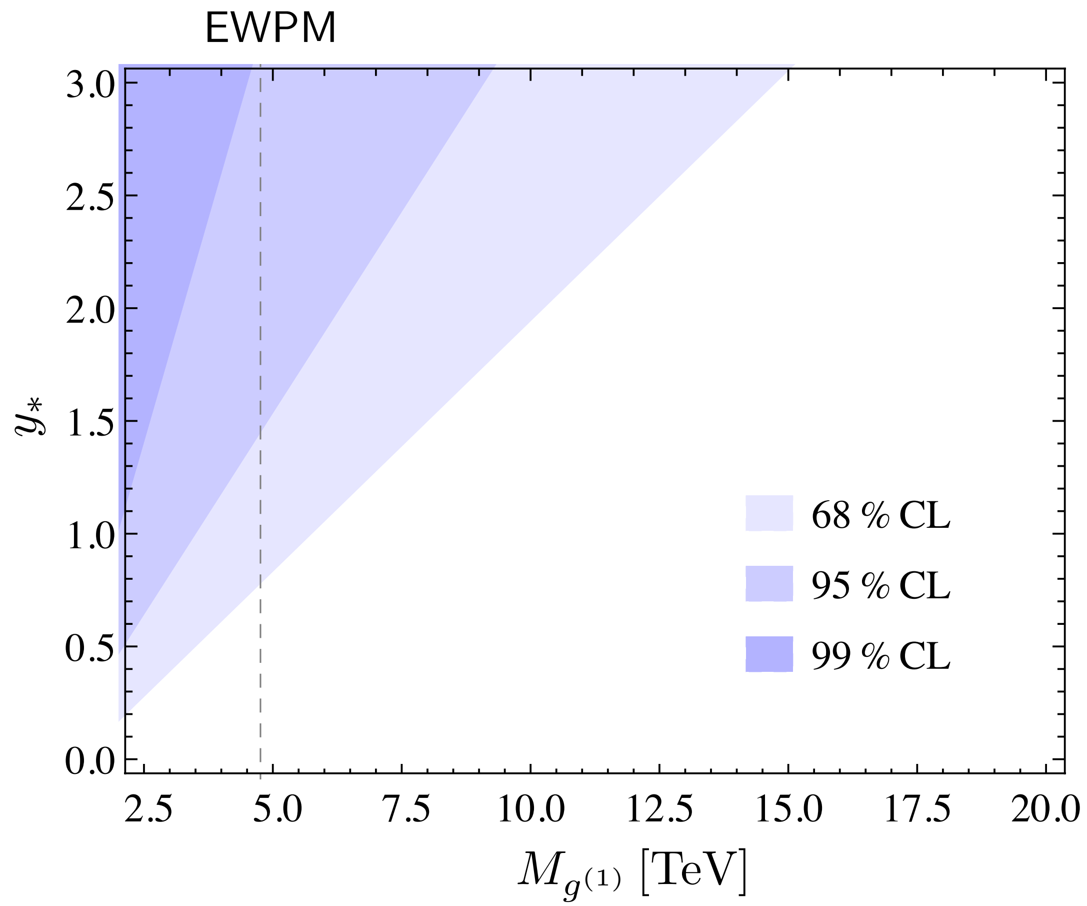
3. Phenomenology: RS predictions for $pp \to h \to ZZ^{(*)}$

Exclusion plots: Custodial model

Brane Higgs



Narrow Bulk Higgs



- Huge range of KK masses disfavored for not too small y_*
- For large y_* low TeV-range KK gluon masses allowed
- But: Low KK scales disfavored by EWPM
- Custodial model loses its advantage of lowering the KK scale

3. Phenomenology: Bounds on KK gluon mass

minimal RS model

model	brane Higgs	narrow bulk-Higgs
$h \to WW^{(*)}$	$M_{g^{(1)}} > 6.4\,\text{TeV}$	$M_{g^{(1)}} > 7.3\,\text{TeV}$
$h \to ZZ^{(*)}$	$M_{g^{(1)}} > 10.1\,\text{TeV}$	$M_{g^{(1)}} > 4.4\,\text{TeV}$
$h \to \gamma\gamma$	$M_{g^{(1)}} > 8.5\,\text{TeV}$	–

95% CL

$y_* = 3$

custodial RS model

model	brane Higgs	narrow bulk-Higgs
$h \to WW^{(*)}$	$2.9\,\text{TeV} < M_{g^{(1)}} < 5.1\,\text{TeV}$ or $M_{g^{(1)}} > 12.9\,\text{TeV}$	$M_{g^{(1)}} > 15.0\,\text{TeV}$
$h \to ZZ^{(*)}$	$3.4\,\text{TeV} < M_{g^{(1)}} < 4.6\,\text{TeV}$ or $M_{g^{(1)}} > 19.9\,\text{TeV}$	$M_{g^{(1)}} > 9.1\,\text{TeV}$
$h \to \gamma\gamma$	$3.5\,\text{TeV} < M_{g^{(1)}} < 5.9\,\text{TeV}$ or $M_{g^{(1)}} > 13.4\,\text{TeV}$	$3.8\,\text{TeV} < M_{g^{(1)}} < 5.2\,\text{TeV}$ or $M_{g^{(1)}} > 8.4\,\text{TeV}$

- Strongest bounds from $h \to ZZ^{(*)}$ (brane) and $h \to WW^{(*)}$ (narrow-bulk)
- Bounds in minimal model weaker than those from EWPM
- Bounds in custodial model much stronger than those from EWPM
- Custodial model loses its advantage of lowering the KK scale

3. Phenomenology: Bounds on maximal value of Yukawas

minimal RS model

model	brane Higgs	narrow bulk-Higgs
$h \to WW^{(*)}$	$y_* < 2.1$	$y_* < 2.2$
$h \to ZZ^{(*)}$	$y_* < 1.1$	–
$h \to \gamma\gamma$	$y_* < 1.5$	–

95% CL

$M_{g^{(1)}} = 5\,\mathrm{TeV}$

custodial RS model

model	brane Higgs	narrow bulk-Higgs
$h \to WW^{(*)}$	$y_* < 0.9$ or $y_* > 2.9$	$y_* < 1.0$
$h \to ZZ^{(*)}$	$y_* < 0.5$	$y_* < 1.5$
$h \to \gamma\gamma$	$y_* < 0.9$ or $y_* > 2.5$	$y_* < 1.7$ or $y_* > 2.9$

- Strongest bounds from $h \to ZZ^{(*)}$ (brane) and $h \to WW^{(*)}$ (narrow-bulk)
- Small values preferred, in particular for custodial model
- Too small values for y_* problematic for ϵ_K
- KK particles probably too heavy for direct detection at the LHC

4. Conclusions

- The RS model is able to explain the hierarchy problems of the SM (by warp factor and different localization of fermions in bulk)

- Could explain the contradictory results for $gg \to h$ in the RS model
  $\to$ Narrow bulk vs. brane Higgs (two different models!)
  $\to$ Transition region not calculable!

- Loop-induced couplings very sensitive on virtual effects of KK excitations

- Large Effects possible even for high KK masses, in particular in custodial RS model

- Current measurements: R_{WW}, R_{ZZ}, and $R_{\gamma\gamma}$ excellent quantities to distinguish between RS scenarios and to give bounds on RS parameter space

- Direct detection of KK particles at the LHC disfavored (in either scenario)

- Thus, (more precise) measurements of R_{WW}, R_{ZZ}, and $R_{\gamma\gamma}$ and the couplings κ_i desirable $\quad\to\quad$ indirect detection

4. Outlook

- Complete the discussion of Higgs physics in warped extra dimensions by studying Higgs processes in bulk-Higgs RS models
- Use solutions for 5D propagators to study $b \to s\gamma$ or $\mu \to e\gamma$

Thank you for your attention!

Backup: Classification of Models

Model	bulk Higgs	narrow bulk-Higgs	transition region	brane Higgs
Higgs profile width	$\eta = \mathcal{O}(1)$	$\frac{v\lvert Y_q\rvert}{\Lambda_{\rm TeV}} \ll \eta \ll \frac{v\lvert Y_q\rvert}{M_{\rm KK}}$	$\eta \sim \frac{v\lvert Y_q\rvert}{\Lambda_{\rm TeV}}$	$\eta \ll \frac{v\lvert Y_q\rvert}{\Lambda_{\rm TeV}}$
Power corrections	$\sim \frac{M_{\rm KK}}{\Lambda_{\rm TeV}}$	$\sim \frac{M_{\rm KK}}{\eta\Lambda_{\rm TeV}}$	$\sim \frac{M_{\rm KK}}{v\lvert Y_q\rvert}$	$\sim \frac{M_{\rm KK}}{\Lambda_{\rm TeV}}$
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

Backup: Derivation of 5D quark propagator

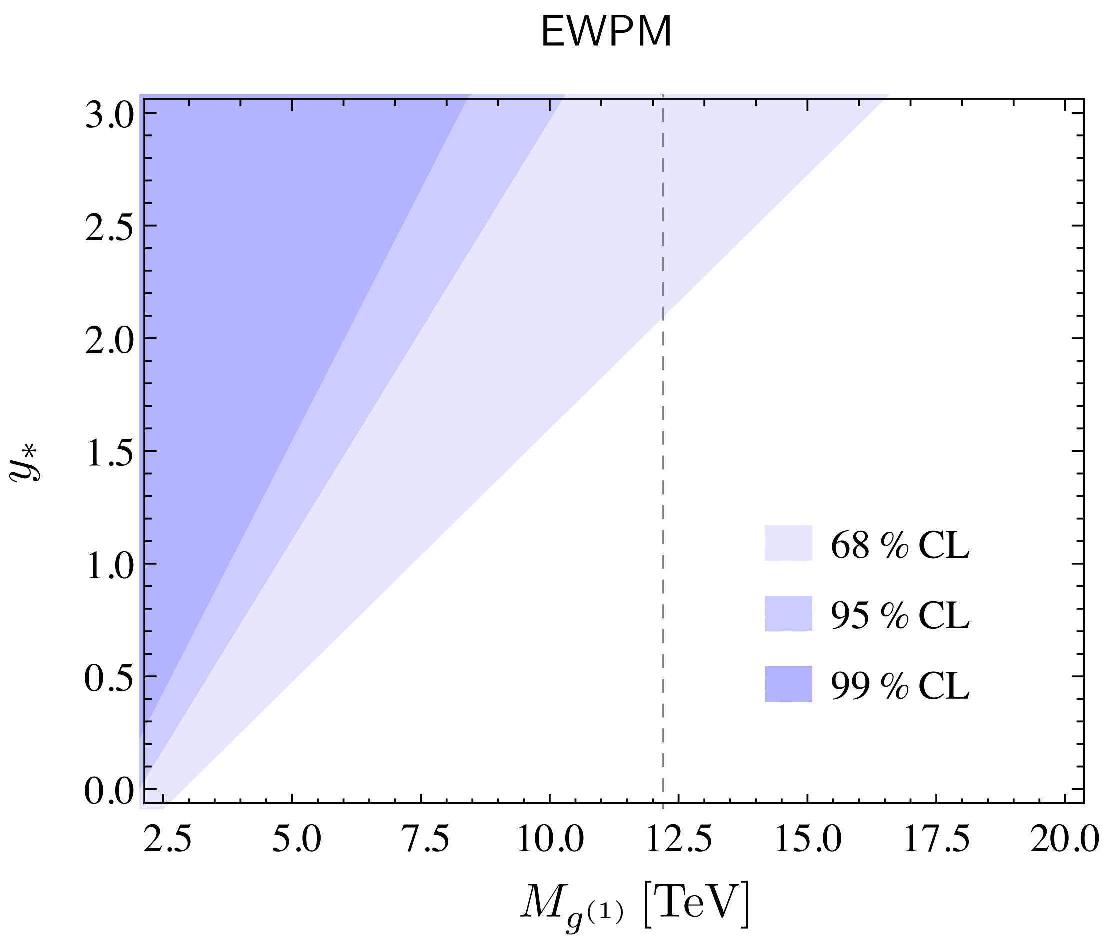
- 5D Dirac equation $\mathcal{D}\,\boldsymbol{S}^q(t,t';p) = \delta(t-t')$
- 5D Dirac operator $\mathcal{D} = \not{p} - M_{\mathrm{KK}}\gamma_5\partial_t - M_{\mathrm{KK}}\,\mathcal{M}_q(t)$
- Mass matrix $\mathcal{M}_q(t) = \frac{1}{t}\begin{pmatrix}\boldsymbol{c}_Q & 0\\ 0 & -\boldsymbol{c}_q\end{pmatrix} + \frac{v}{\sqrt{2}M_{\mathrm{KK}}}\delta^\eta(t-1)\begin{pmatrix}0 & \boldsymbol{Y}_q\\ \boldsymbol{Y}_q^\dagger & 0\end{pmatrix}$
- Propagator $\boldsymbol{S}^q(t,t';p) = \left[\boldsymbol{\Delta}^q_{LL}(t,t';-p^2)\not{p} + \boldsymbol{\Delta}^q_{RL}(t,t';-p^2)\right]P_R + L \leftrightarrow R$
- This gives coupled differential equations for $\boldsymbol{\Delta}^q_{RL,LL}$
- UV/IR Boundary conditions given by BC for fermion profiles
- Together with jump conditions at $t = t'$ (due to $\delta(t-t')$) we get unique solutions for bulk ($t < 1-\eta$) and sliver ($t > 1-\eta$)
- Then: Evaluate (with sliver solution)

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

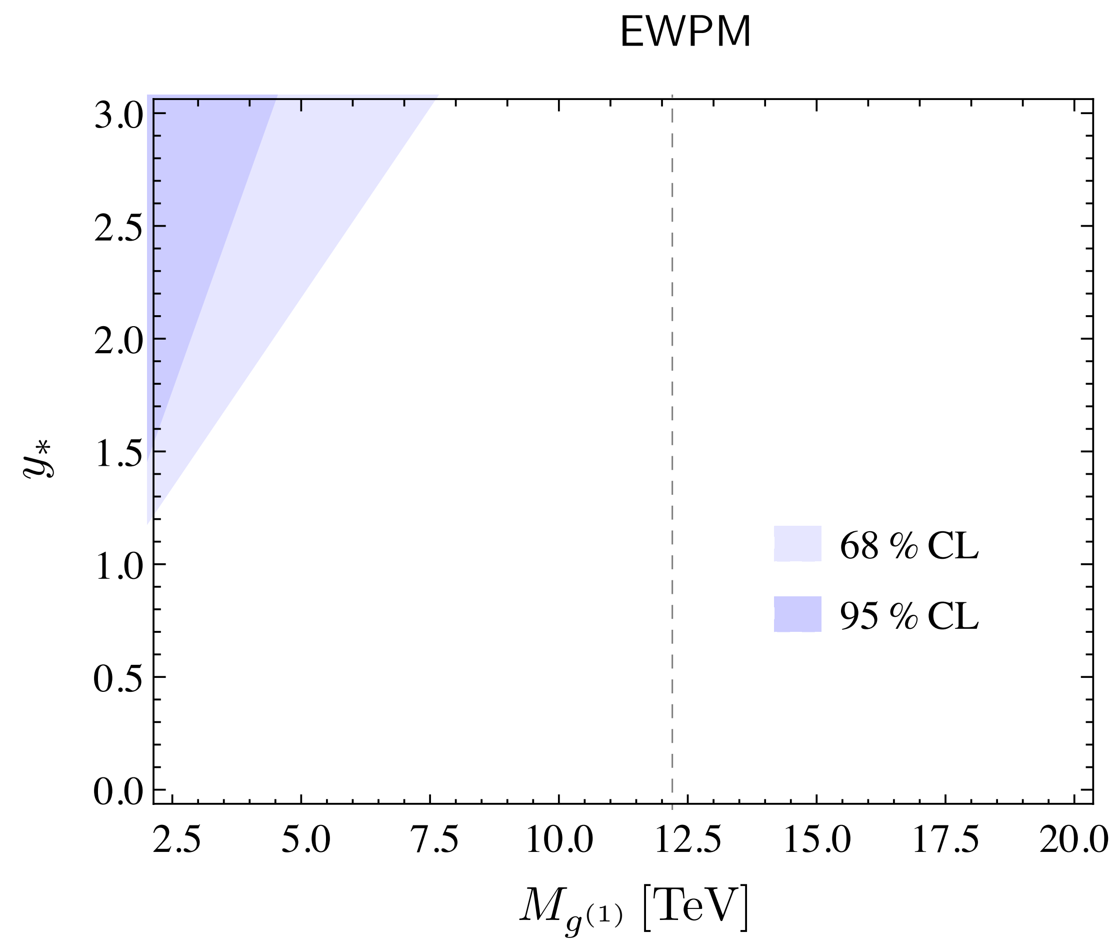
3. Phenomenology: RS predictions for $pp \to h \to ZZ^{(*)}$

Exclusion plots: Minimal model

Brane Higgs



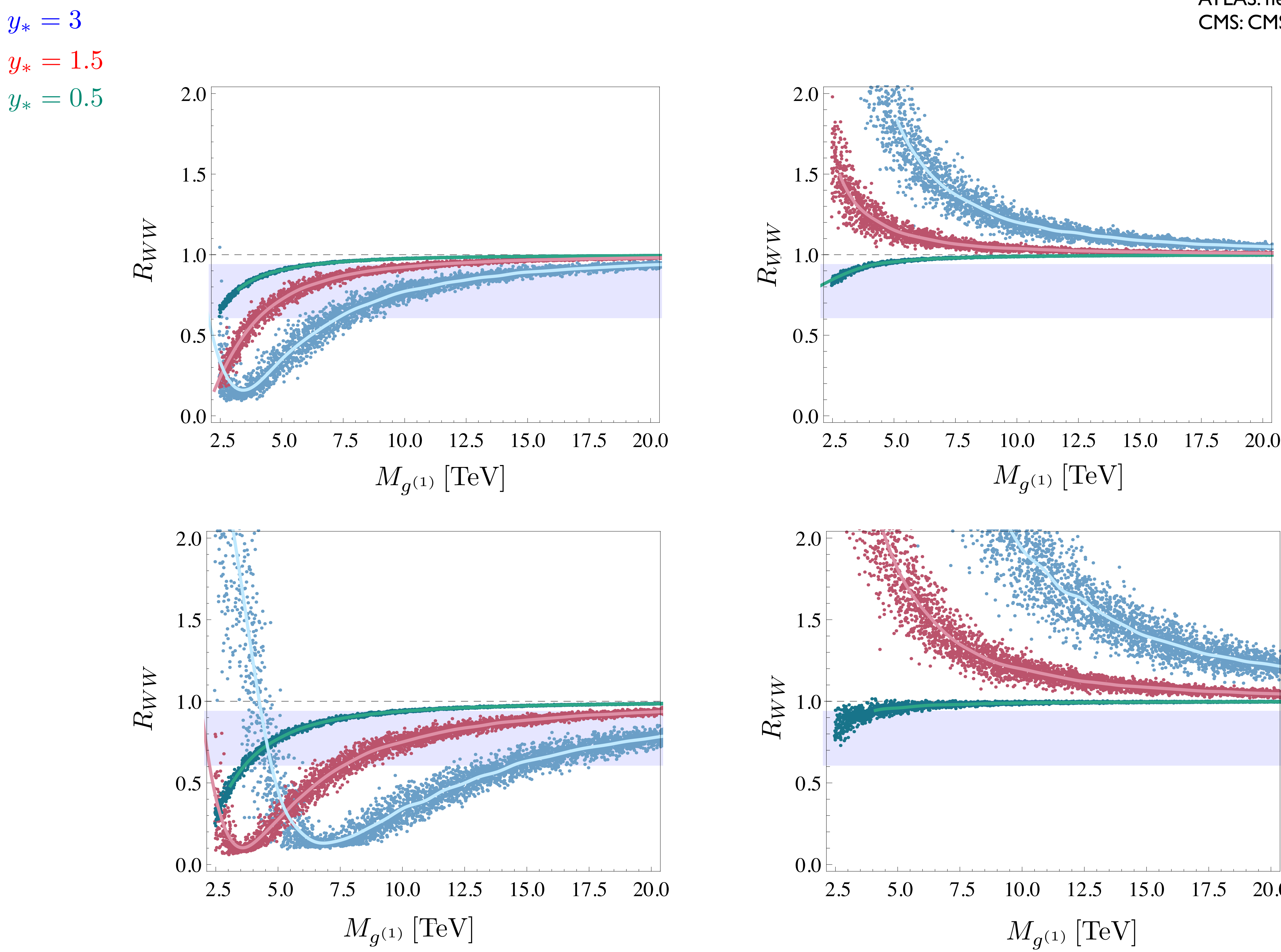
Narrow Bulk Higgs



- For large (small) y_* low TeV-range KK gluon masses disfavored (favored)
- Brane Higgs: constraints comparable with those from EWPM
- Narrow-bulk Higgs: weaker constraints than those from EWPM

Backup: RS predictions for $pp \to h \to WW^{(*)}$

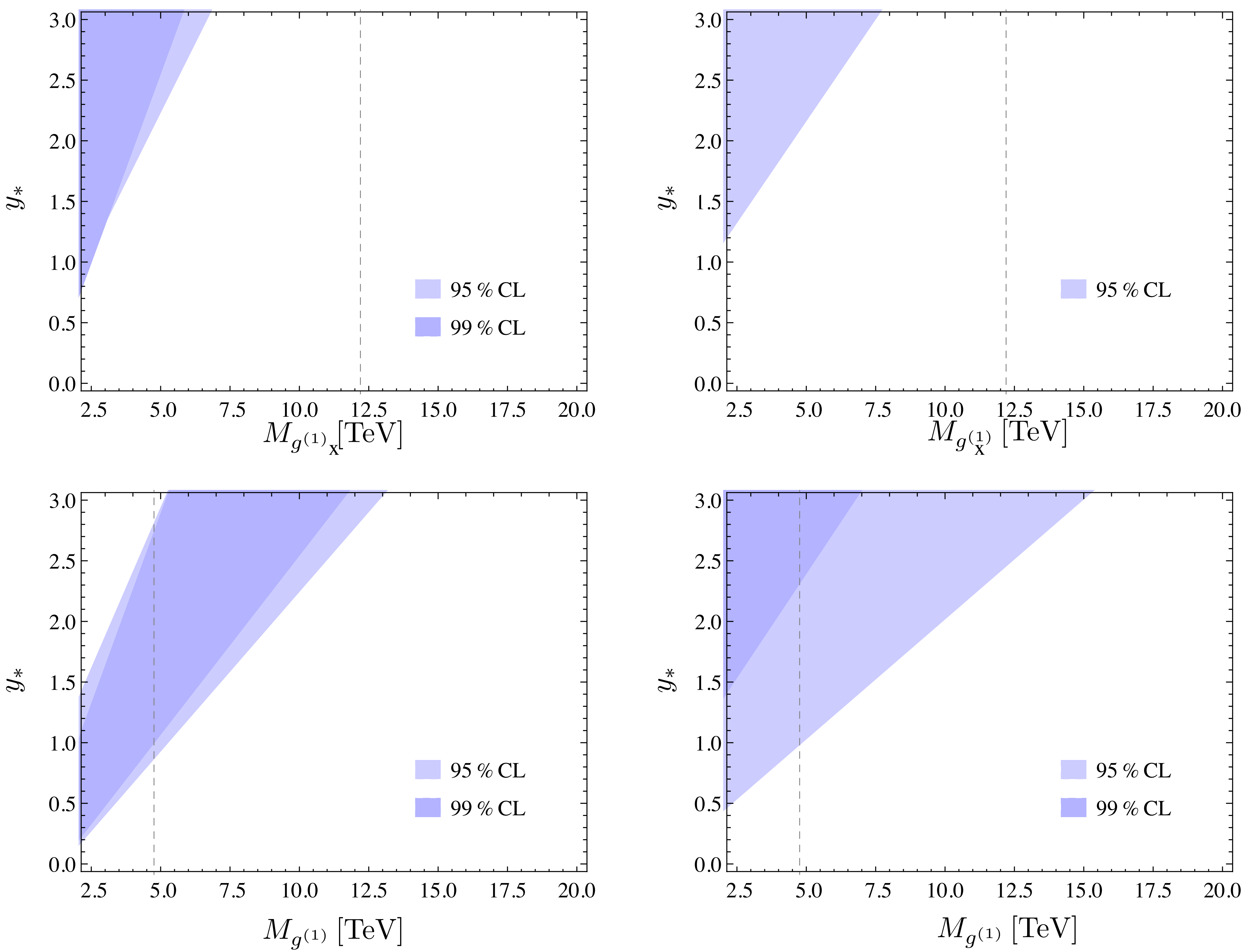
ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005



Backup: RS predictions for $pp \to h \to WW^{(*)}$

Exclusion plots

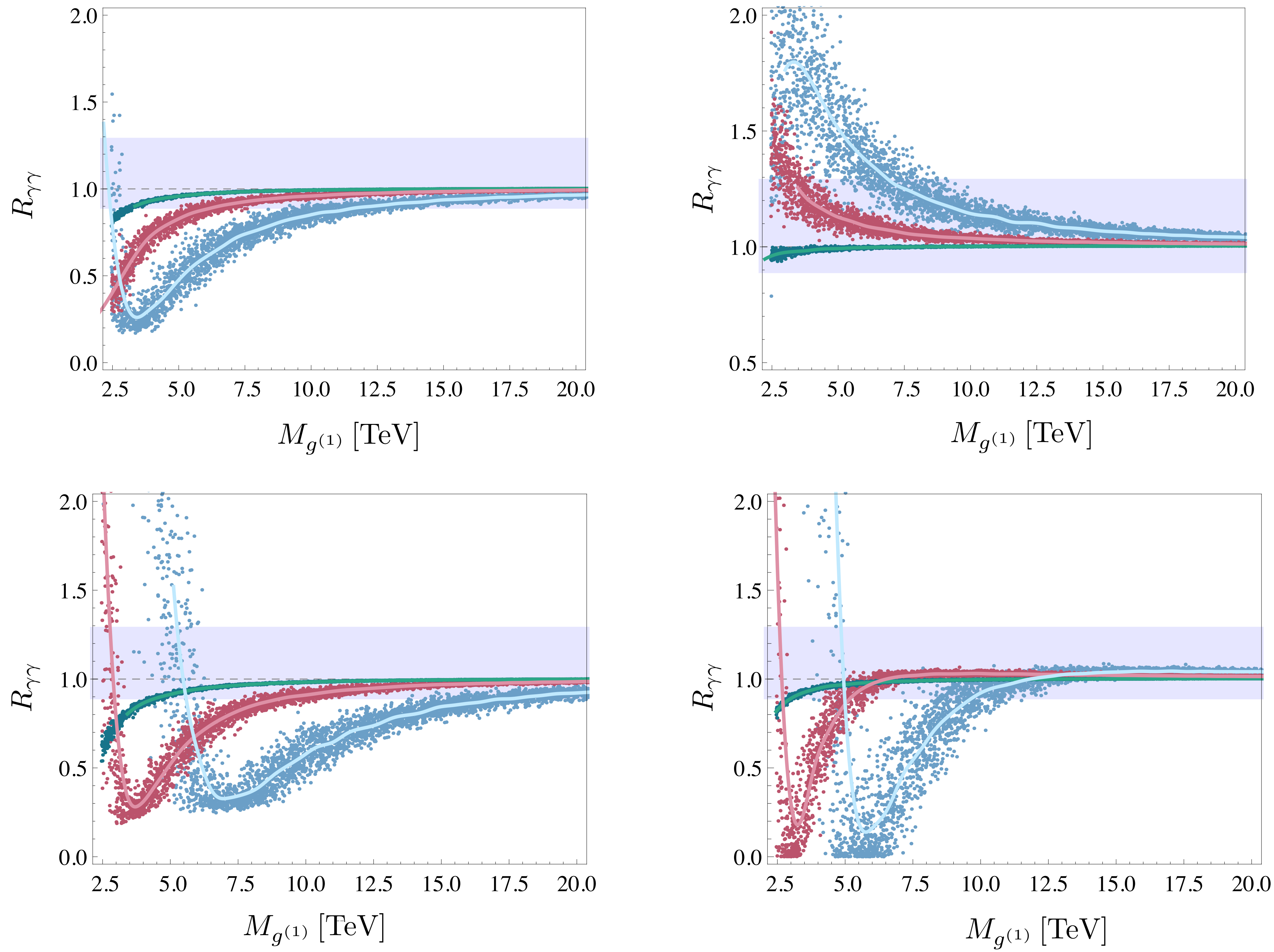
ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005



Backup: RS predictions for $pp \to h \to \gamma\gamma$

ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005

$y_* = 3$
$y_* = 1.5$
$y_* = 0.5$



Backup: RS predictions for $pp \to h \to \gamma\gamma$

Exclusion plots

ATLAS: hep-ex/1307.1427
CMS: CMS-PAS-HIG-13-005