Composite Higgs Phenomenology and Naturalness

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Precision Physics, Fundamental Interactions and Structure of Matter

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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 unsolved mysteries of particle 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

→ for a detailed analysis of flavor bounds from dipole operators on various composite Higgs models, see: König, MN, Straub: 1403.2756

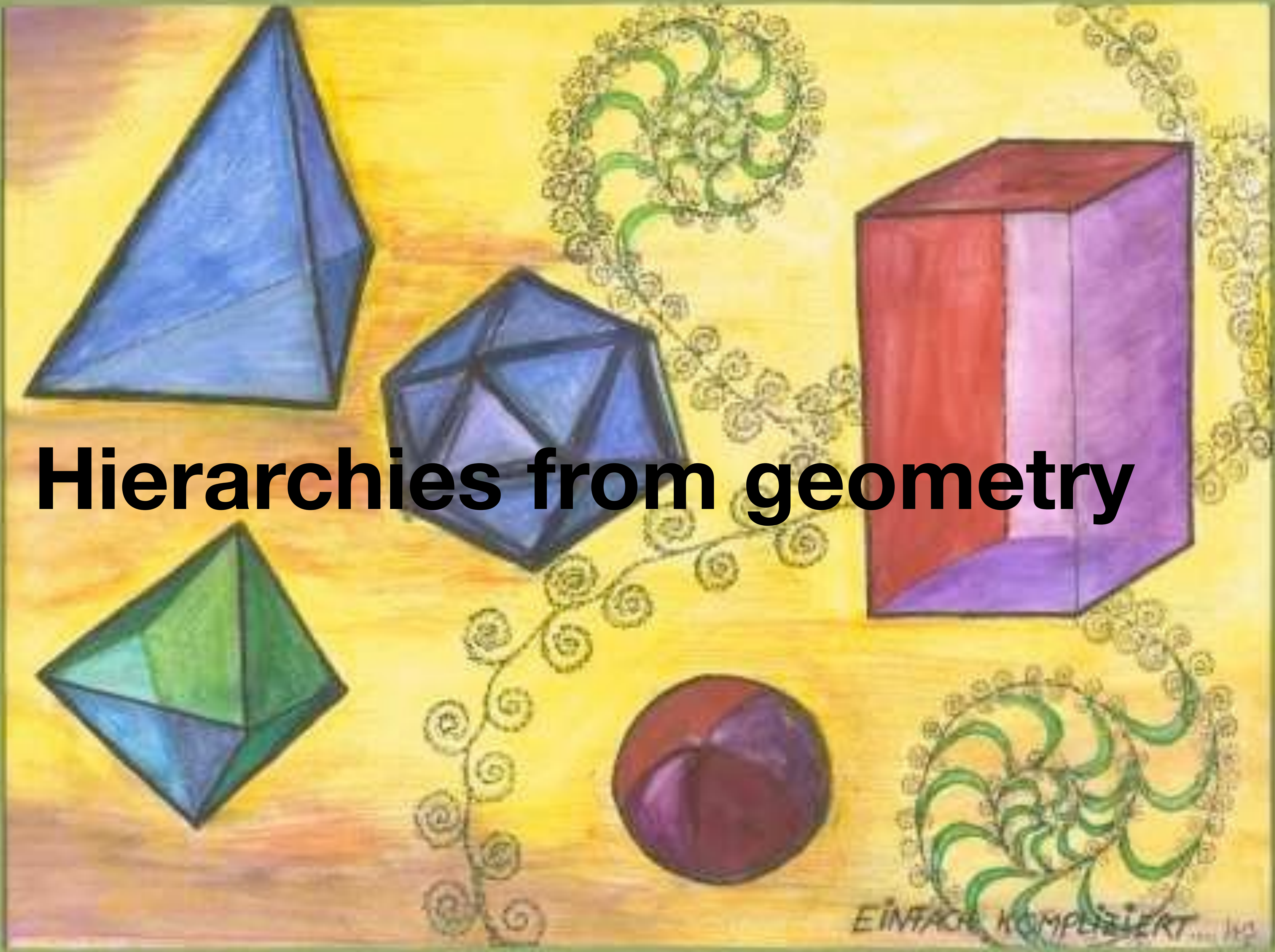
Outline

Part I: Higgs phenomenology in custodial Randall-Sundrum models with the scalar sector near the IR brane (composite Higgs)

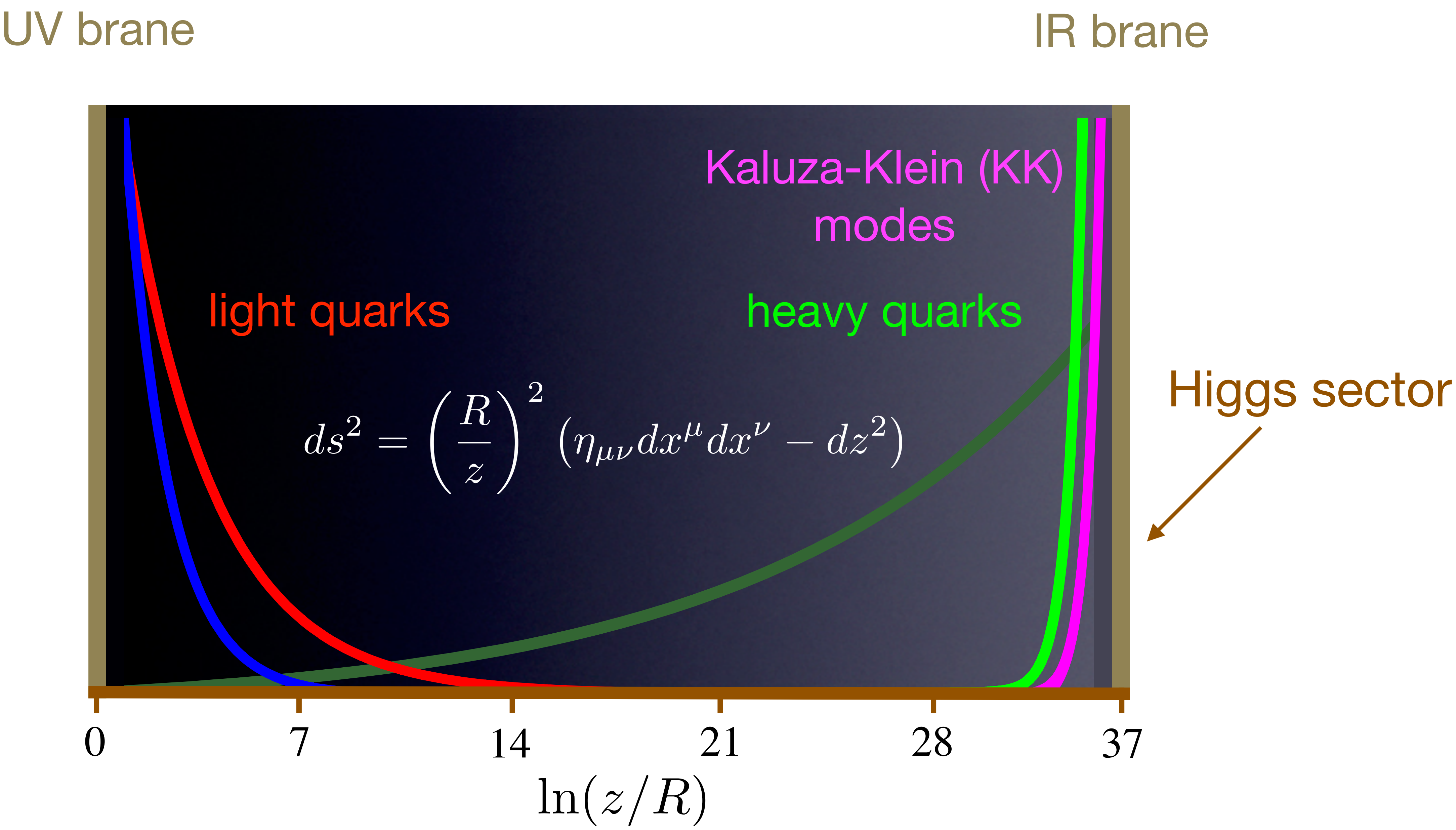
Part II: Moving the Higgs into the bulk in the minimal RS model (partially composite Higgs)

Part III: Minimal composite pNGB Higgs models

Hierarchies from geometry



Warped extra dimension (RS models)



Randall-Sundrum (RS) models with a **warped extra dimension** address the hierarchy problem and the flavor puzzle by means of the same **geometrical mechanism**

Randall, Sundrum (1999)

Warped extra dimension (RS models)

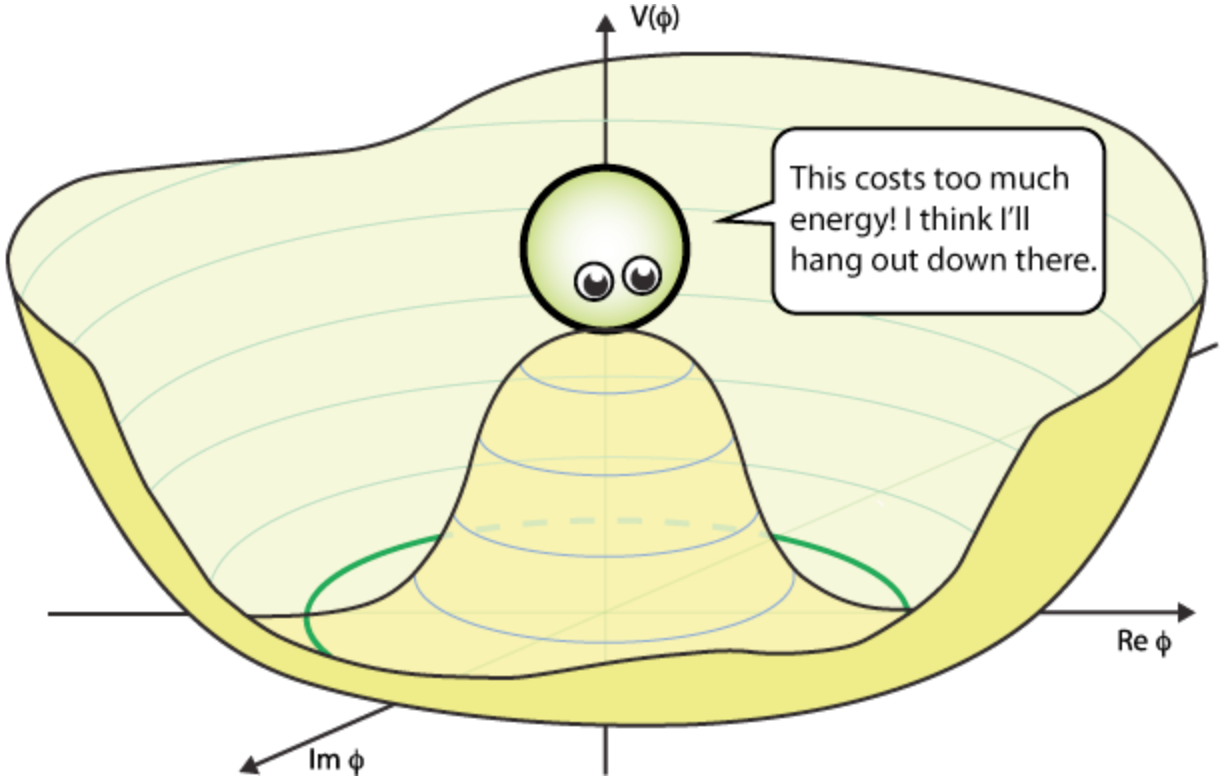
RS models provide a toolbox to study different variants of **4D composite Higgs models**, to which they are **dual by AdS/CFT** Luty, Okui (2004)

- dual composite Higgs operator O_h has **scaling dimension $\Delta_h = 2+\beta$**, implying that the Higgs mass operator $O_h^\dagger O_h$ is no longer a relevant operator if $\beta \geq 0$ Witten (1998)
- for AdS geometries $\beta \geq 0$ is required by Breitenlohner-Freedman bound Breitenlohner, Freedman (1982)

In RS models, β is related to the **localization of the 5D scalar field** along the extra dimension

- limit $\beta \to \infty$ correspond to an **IR-brane localized Higgs** field (composite Higgs)
- limit $\beta \to 0$ corresponds to a **broad bulk Higgs** field (partially composite Higgs)

Higgs Properties as an Indirect Probe for Extra Dimensions



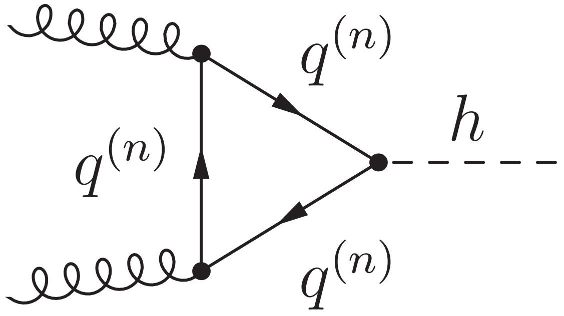
Malm, MN, Novotny, Schmell: arXiv:1303.5702 (JHEP)
Hahn, Hörner, Malm, MN, Novotny, Schmell: arXiv:1312.5731 (EPJC)
Malm, MN, Schmell: arXiv:1408.4456 (today)
Archer, Carena, Carmona, MN: arXiv:1408.nnnn (Monday)

Higgs properties 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 effects of new particles

In RS models, **large number of bulk fermionic fields** in 5D theory can give rise to large corrections to 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 symmetry

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

Effective Higgs couplings

Most important Higgs couplings to SM particles can be parameterized by the **effective Lagrangian**:

$$\mathcal{L}_{\text{eff}} = c_W \frac{2m_W^2}{v_{\text{SM}}} hW_\mu^+ W^{-\mu} + c_Z \frac{m_Z^2}{v_{\text{SM}}} hZ_\mu Z^\mu - \sum_{f=t,b,\tau} \frac{m_f}{v_{\text{SM}}} h\bar{f}\left(c_f + c_{f5}\, i\gamma_5\right) f$$

$$- c_{3h} \frac{h^3}{6} - c_{4h} \frac{h^4}{24} + c_g \frac{\alpha_s}{12\pi v_{\text{SM}}} hG_{\mu\nu}^a G^{a,\mu\nu} - c_{g5} \frac{\alpha_s}{8\pi v_{\text{SM}}} hG_{\mu\nu}^a \tilde{G}^{a,\mu\nu}$$

$$+ c_\gamma \frac{\alpha}{6\pi v_{\text{SM}}} hF_{\mu\nu} F^{\mu\nu} - c_{\gamma 5} \frac{\alpha}{4\pi v_{\text{SM}}} hF_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$

- SM: $c_{W,Z,f} = 1\,, \qquad c_{f5} = 0\,, \qquad c_{g(5),\gamma(5)} = 0$
- deviations from integrating out new, heavy particles (KK resonances)

Custodial RS model with IR-localized Higgs

Extended RS model with **custodial symmetry** protecting the *T* parameter, the left-handed $Zd_i\bar{d}_j$ couplings

Agashe, Delgado, May, Sundrum (2003)
Csaki, Grojean, Pilo, Terning (2003)
Agashe, Contino, Da Rold, Pomarol (2006)

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:

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

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

Tree-level analysis of EWP observables implies $M_{g^{(1)}} > 4.8\,\mathrm{TeV}\ \ (\mathrm{at}\ 95\%\ \mathrm{CL})$ compared with 12.3 TeV in the minimal model

Carena, Delgado, Ponton, Tait, Wagner (2003)
Update: Malm, MN, Novotny, Schmell (2013)

“Tree-level” couplings to W & Z bosons

Malm, MN, Schmell: 1408.4456

One finds:

$$c_W = 1 - \frac{m_W^2}{2M_{\text{KK}}^2}\left(3L - 1 + \frac{1}{2L}\right) + \dots$$

$$c_Z = 1 - \frac{m_W^2}{2M_{\text{KK}}^2}\left(3L + 1 - \frac{1}{2L}\right) + \dots$$

$\rightarrow$ $\frac{\sqrt{L}}{M_{\text{KK}}}$

where $L = \ln(M_{\text{Pl}}/\Lambda_{\text{TeV}}) \approx 34$, and the KK mass scale is such that in terms of the lowest-lying KK gluon (photon) resonance:

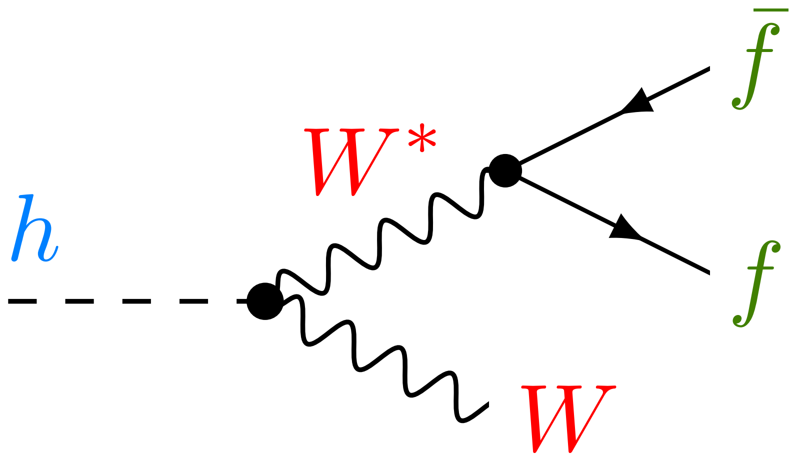
$$M_{g^{(1)}} \approx 2.45 M_{\text{KK}} \qquad \Rightarrow \qquad \boxed{c_W \approx c_Z \approx 1 - 0.078\left(\frac{5\,\text{TeV}}{M_{g^{(1)}}}\right)^2}$$

Both couplings can be **suppressed by up to 8%** in view of EWPT bounds

Higgs decay rates to WW* and ZZ*

Malm, MN, Schmell: 1408.4456

Different sources of new-physics effects:



- modification of Higgs coupling to gauge-boson pairs: c_W
- modification of W- and Z-boson couplings to fermions: c_{Γ_W}
- contribution of heavy KK bosons

Expression for the decay rate:

$$\Gamma(h \to WW^*) = \frac{m_h^3}{16\pi v_{\rm SM}^2}\,\frac{c_{\Gamma_W}\Gamma_W^{\rm SM}}{\pi m_W}\,c_W^2\left[g\left(\frac{m_W^2}{m_h^2}\right) - \frac{m_h^2}{2M_{\rm KK}^2}\left(1-\frac{1}{L}\right)h\left(\frac{m_W^2}{m_h^2}\right) + \dots\right]$$

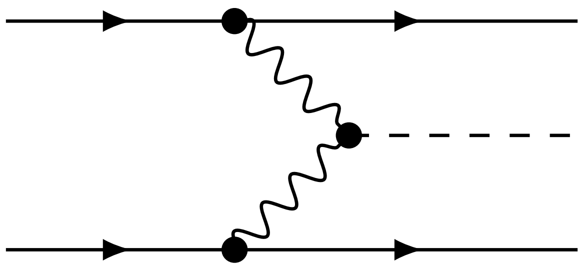
Only c_W contains ***L*-enhanced terms**, so to very good approximation:

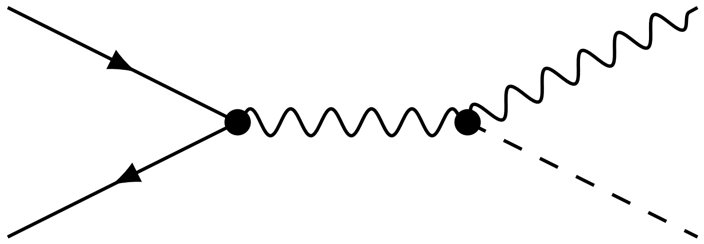
$$\Gamma(h \to VV^*) \approx c_V^2\,\Gamma(h \to VV^*)_{\rm SM}$$

Higgs production in VBF and Higgs-strahlung

Malm, MN, Schmell: 1408.4456

Two important Higgs production processes:


Vector-boson fusion


Higgs-strahlung

Analogous analysis shows that, at level of *L*-enhanced terms:

$$\sigma(pp \to hqq') \approx c_V^2 \, \sigma(pp \to hqq')_{\rm SM} \qquad\qquad \sigma(pp \to hV) \approx c_V^2 \, \sigma(pp \to hV)_{\rm SM}$$

“Tree-level” couplings to fermions

One finds:

VEV shift　　subleading effects

$$c_f + ic_{f5} = 1 - \frac{2v^2}{3M_{\mathrm{KK}}^2}\,\frac{\left(\boldsymbol{Y}_f\boldsymbol{Y}_f^\dagger\boldsymbol{Y}_f\right)_{33}}{\left(\boldsymbol{Y}_f\right)_{33}} - \frac{Lm_W^2}{2M_{\mathrm{KK}}^2} - \varepsilon_f + \dots$$

Csagrande, Goertz, Haisch, MN, Pfoh (2010)

For anarchic 5D Yukawa matrices with $|(\boldsymbol{Y}_f)_{ij}| \le y_\star$, we obtain **on average**:

$$\left\langle \frac{\left(\boldsymbol{Y}_f\boldsymbol{Y}_f^\dagger\boldsymbol{Y}_f\right)_{33}}{\left(\boldsymbol{Y}_f\right)_{33}} \right\rangle = (2N_g - 1)\,\frac{y_\star^2}{2} \quad \longrightarrow \quad \boxed{\frac{y_*}{M_{\mathrm{KK}}}}$$

For vast majority of points in parameter space, the CP-even couplings *c*c_f are **suppressed** compared with the SM, by an amount $\sim (y_*/M_{\mathrm{KK}})^2$

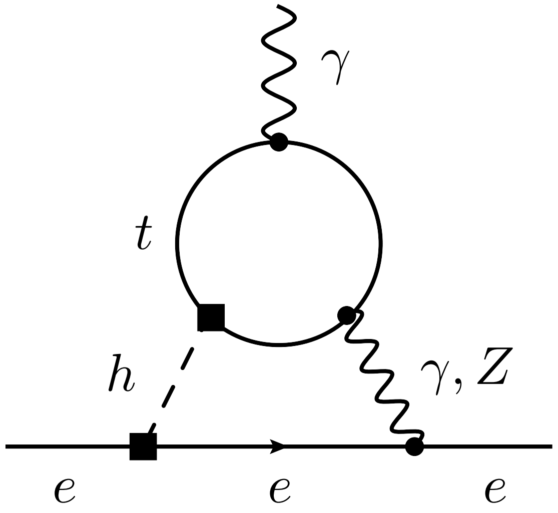
“Tree-level” couplings to fermions

Malm, MN, Schmell: 1408.4456

Distribution of imaginary part (CP-odd couplings c_{f5}) is approximately Gaussian (with non-Gaussian tails), with standard deviation:

$$\sigma_{c_{f5}} \approx \frac{v^2\, y_\star^2}{3M_{\rm KK}^2} \approx 0.044 \left(\frac{y_\star}{3}\right)^2 \left(\frac{5\,\rm TeV}{M_{g^{(1)}}}\right)^2$$

Non-trivial upper bound from **electron EDM** via Barr-Zee two-loop diagrams:



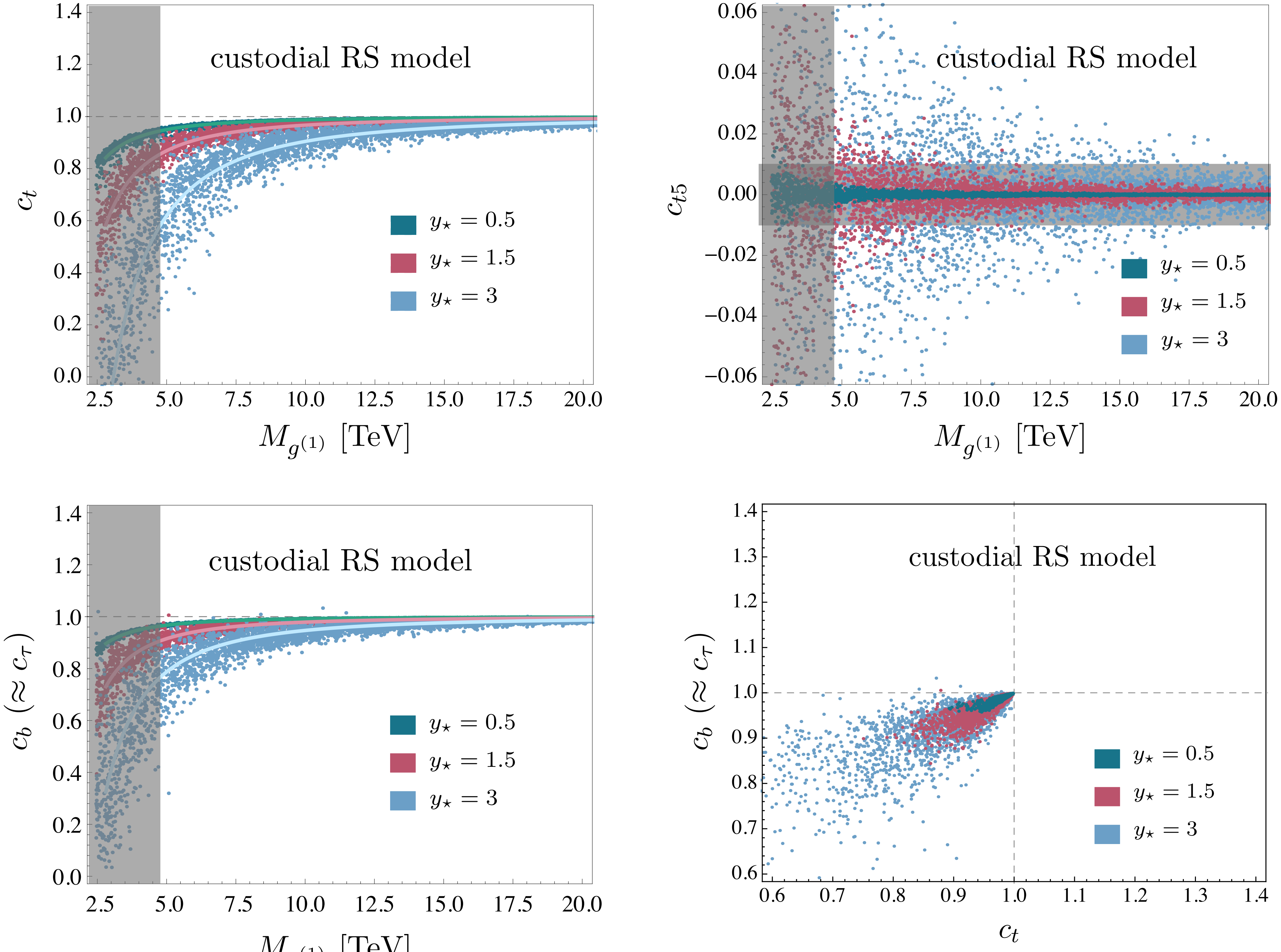
$d_e < 8.7 \cdot 10^{-29} e\,\rm cm$ $\longrightarrow$ $|c_{t5}|_{e\rm EDM} < 0.01$ (90% CL)

Brod, Haisch, Zupan (2013)

“Tree-level” couplings to fermions

Malm, MN, Schmell: 1408.4456

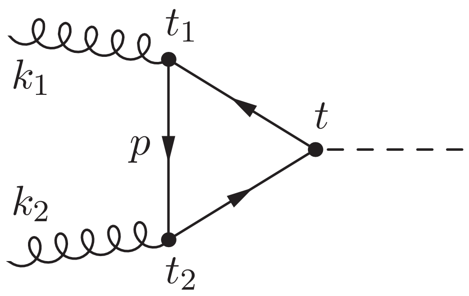
Numerical results with anarchic Yukawa matrices:



EDM bound

Loop-induced couplings to gluons & photons

Computing 5D loop graph with KK quarks gives:



$$c_g = \mathrm{Tr}\, g(\sqrt{2}\boldsymbol{X}_u) + 3\,\mathrm{Tr}\, g(\sqrt{2}\boldsymbol{X}_d) + (\boldsymbol{\Phi}_U)_{33} + (\boldsymbol{\Phi}_u)_{33} + (\boldsymbol{\Phi}_D)_{33}$$

$$c_{g5} = 0$$

Casagrande, Goetrz, Haisch, MN, Pfoh (2010)
Azatov, Toharia, Zhu (2010)
Carena, Casagrande, Goertz, Haisch, MN (2012)
Malm, MN, Novotny, Schmell (2013)

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

Result depends on **localization of Higgs profile** on or near the IR brane:

$$g(\boldsymbol{X}_q)\big|_{\text{brane Higgs}} = -\frac{\boldsymbol{X}_q \tanh \boldsymbol{X}_q}{\cosh 2\boldsymbol{X}_q} = -\boldsymbol{X}_q^2 + \mathcal{O}\left(\frac{v^4}{M_{\mathrm{KK}}^4}\right)$$

$$g(\boldsymbol{X}_q)\big|_{\text{narrow bulk Higgs}} = \boldsymbol{X}_q \tanh \boldsymbol{X}_q = \boldsymbol{X}_q^2 + \mathcal{O}\left(\frac{v^4}{M_{\mathrm{KK}}^4}\right)$$

indicates a UV sensitivity to the scale *vβ* for *β*→∞

For anarchic 5D Yukawa matrices with $|(\boldsymbol{Y}_f)_{ij}| \le y_\star$, we obtain **on average**:

$$\left\langle \mathrm{Tr}\, \boldsymbol{Y}_f\boldsymbol{Y}_f^\dagger \right\rangle = N_g^2\,\frac{y_\star^2}{2}$$

Loop-induced couplings to gluons & photons

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** $v\beta$ $(\text{with }\beta \gg 1)$ is larger or smaller than the cutoff scale:

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

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

Carena, Casagrande, Goertz, Haisch, MN (2012)
Delaunay, Kamenik, Perez, Randall (2012)
Malm, MN, Novotny, Schmell (2013)

Loop-induced couplings to gluons & photons

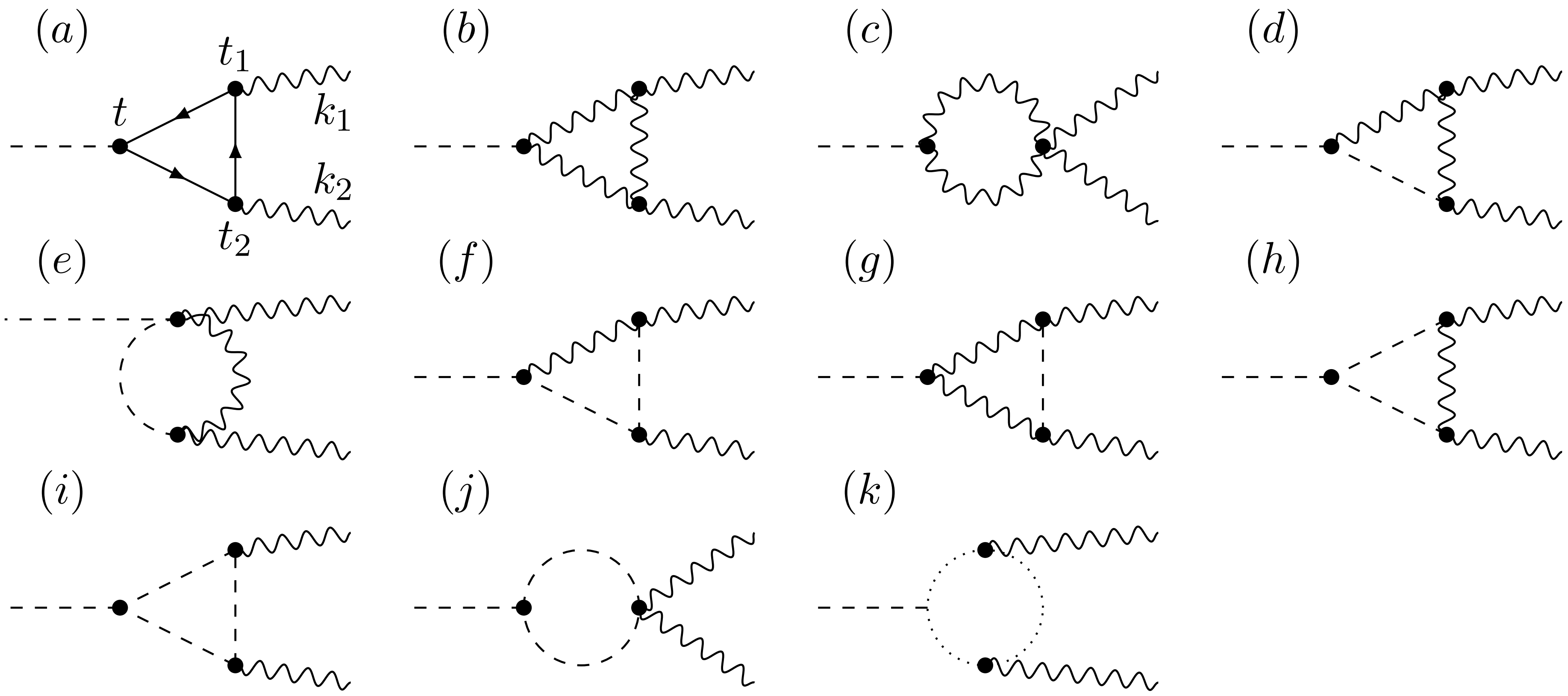
Computing 5D loop graph with KK fermions and gauge fields gives:

$$c_\gamma = N_c\, Q_u^2 \,\mathrm{Tr}\, g(\sqrt{2}\boldsymbol{X}_u) + N_c\,(Q_d^2 + Q_u^2 + Q_\lambda^2)\,\mathrm{Tr}\, g(\sqrt{2}\boldsymbol{X}_d) + Q_l^2\,\mathrm{Tr}\, g(\boldsymbol{X}_l)$$

$$+ N_c\, Q_u^2 \left[(\boldsymbol{\Phi}_U)_{33} + (\boldsymbol{\Phi}_u)_{33} \right] + N_c\, Q_d^2\, (\boldsymbol{\Phi}_D)_{33} - \frac{21}{4}\,\nu_W$$

$$c_{\gamma 5} = 0$$

Casagrande, Goertz, Haisch, MN, Pfoh (2010)
Azatov, Toharia, Zhu (2010)
Hahn, Hörner, Malm, MN, Novotny, Schmell (2013)



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$$+ N_c\, Q_u^2 \left[(\boldsymbol{\Phi}_U)_{33} + (\boldsymbol{\Phi}_u)_{33} \right] + N_c\, Q_d^2\, (\boldsymbol{\Phi}_D)_{33} - \frac{21}{4}\, \nu_W$$

$$c_{\gamma 5} = 0$$

Casagrande, Goertz, Haisch, MN, Pfoh (2010)
Azatov, Toharia, Zhu (2010)
Hahn, Hörner, Malm, MN, Novotny, Schmell (2013)

Contribution of KK gauge bosons and scalars:

$$\nu_W = \frac{m_W^2}{2M_{\mathrm{KK}}^2} \left(2L - 1 + \frac{1}{2L} \right) + \dots$$

Bouchart, Moreau (2009)
Casagrande, Goetrz, Haisch, MN, Pfoh (2010)

Effective couplings after integrating out top & W

Effective couplings relevant for Higgs production in gluon fusion:

$$c_g^{\rm eff} = \frac{c_g + A_q(\tau_t)\, c_t}{A_q(\tau_t)}\,, \qquad c_{g5}^{\rm eff} = \frac{c_{g5} + B_q(\tau_t)\, c_{t5}}{A_q(\tau_t)}$$

Effective couplings relevant for $h \to \gamma\gamma$ decay:

$$c_\gamma^{\rm eff} = \frac{c_\gamma + N_c Q_u^2\, A_q(\tau_t)\, c_t - \frac{21}{4}\, A_W(\tau_W)\, c_W}{N_c Q_u^2\, A_q(\tau_t) - \frac{21}{4}\, A_W(\tau_W)}$$

$$c_{\gamma 5}^{\rm eff} = \frac{c_{\gamma 5} + N_c Q_u^2\, B_q(\tau_t)\, c_{t5}}{N_c Q_u^2\, A_q(\tau_t) - \frac{21}{4}\, A_W(\tau_W)}$$

CP-violating couplings inherited from top quark (c_{t5}), such that the electron EDM bound implies:

$$|c_{\gamma 5}^{\rm eff}| \approx 0.28\, |c_{t5}| < 0.003$$

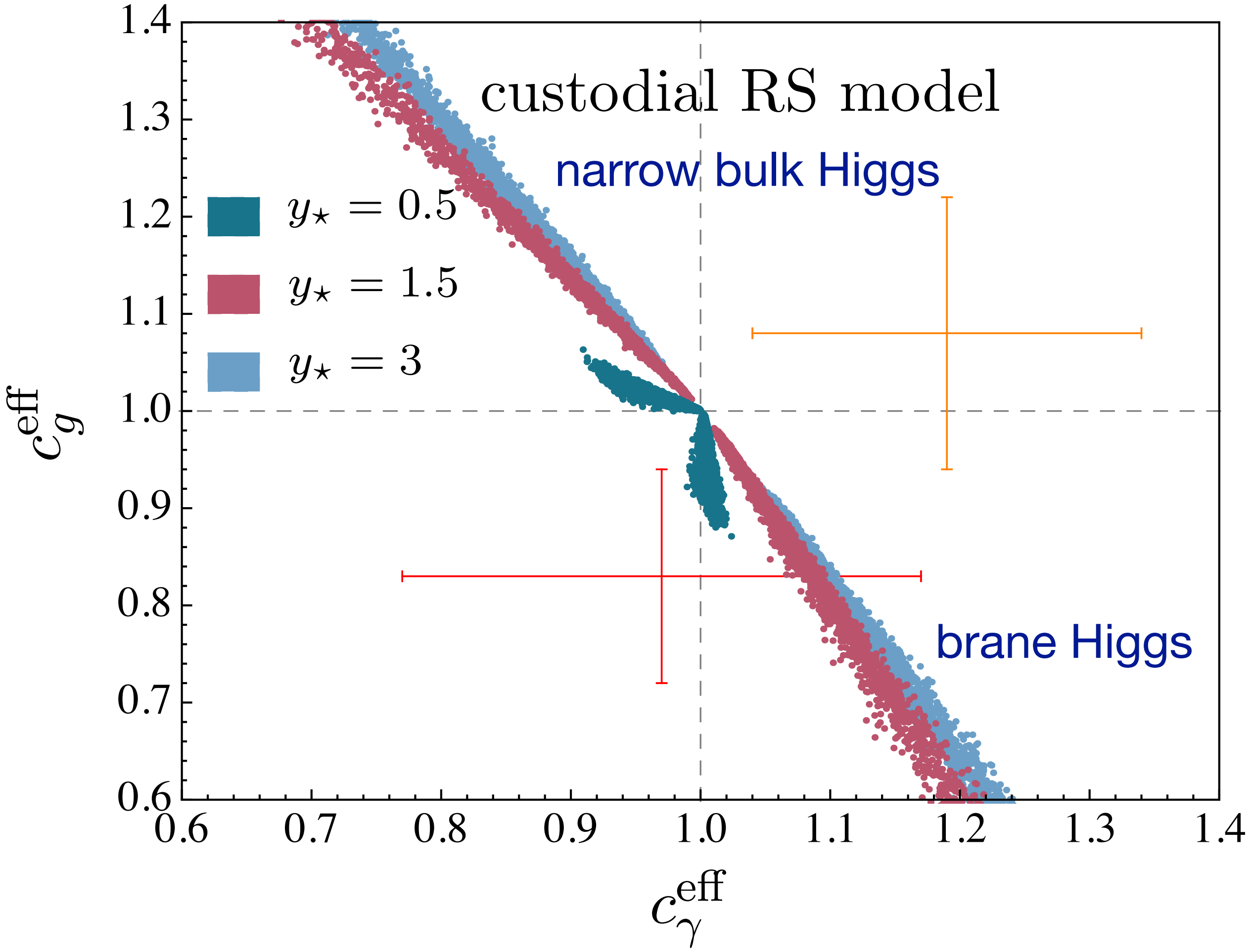
Too small to be detectable at LHC

For a detailled analysis, see: Bishara, Grossman, Harnik, Robinson, Shu, Zupan (2013)

Loop-induced couplings to gluons & photons

Malm, MN, Schmell: 1408.4456

CP-conserving couplings:

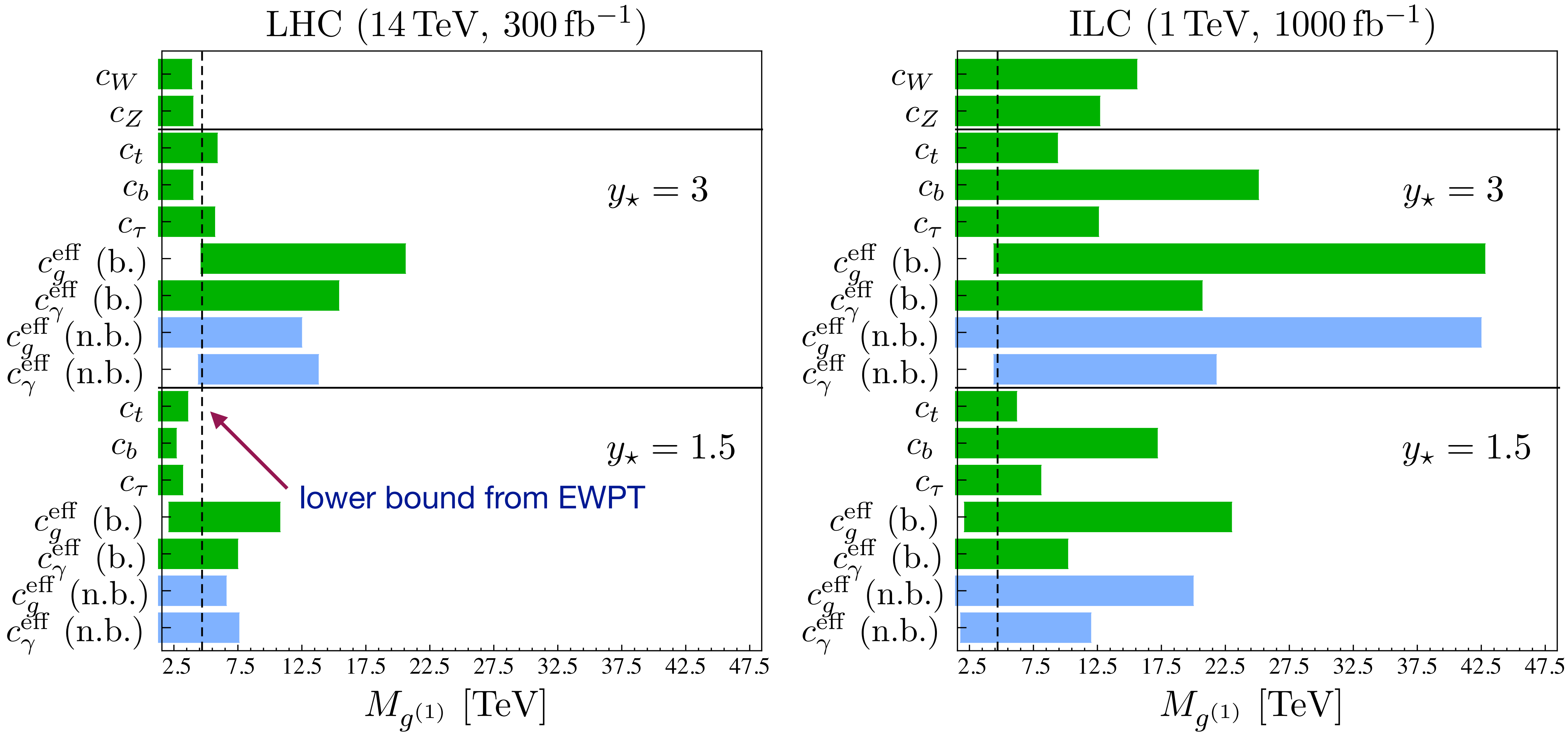


- strong **anti-correlation** due to fermion loop contributions!

New physics reach in Higgs couplings

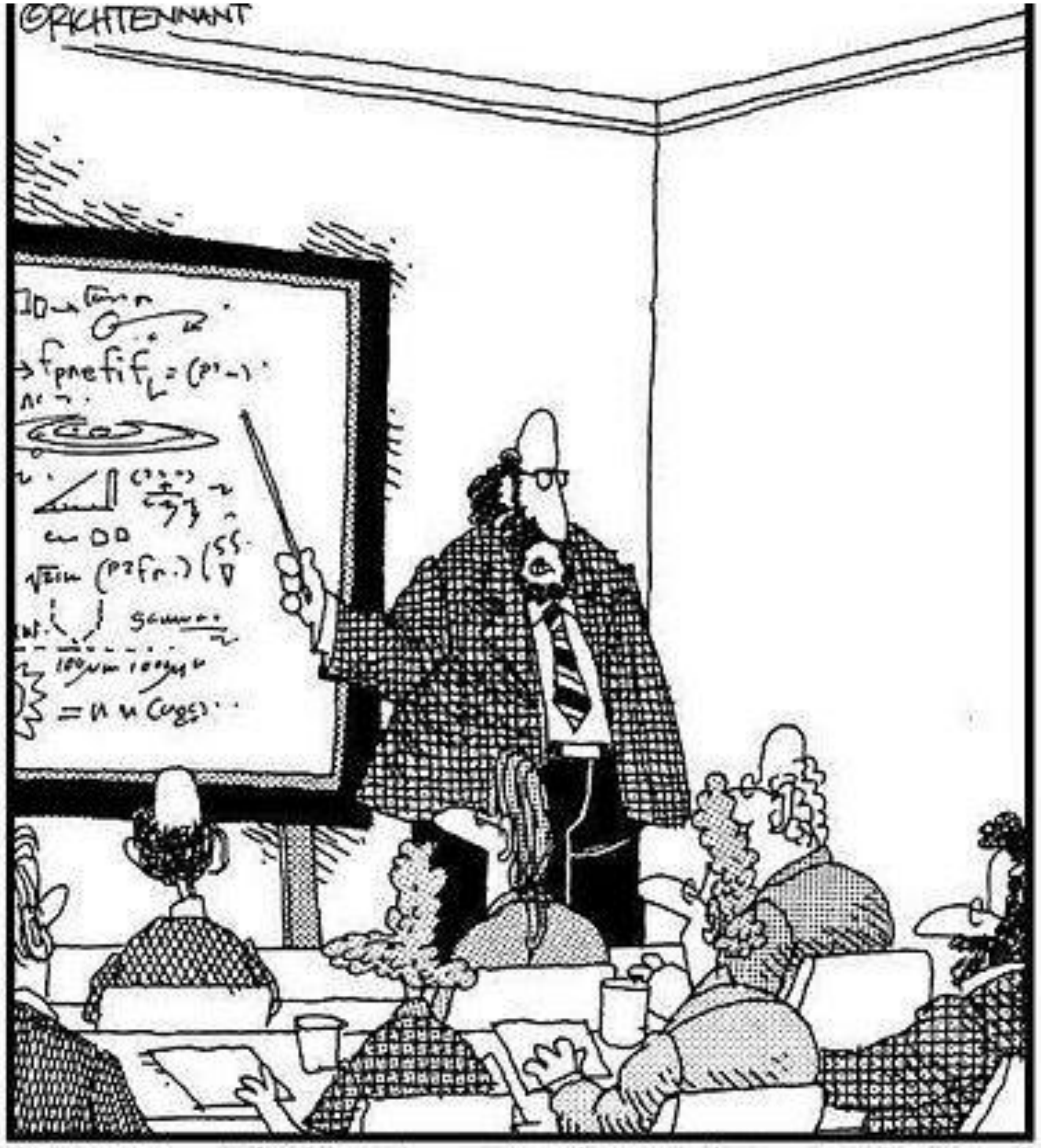
Malm, MN, Schmell: 1408.4456

Exclusion bounds derived from a **global analysis** of all relevant Higgs couplings, assuming SM-like measurements: Peskin (2012)



⇒ will be possible to probe mass scales in the **10-40 TeV** range!

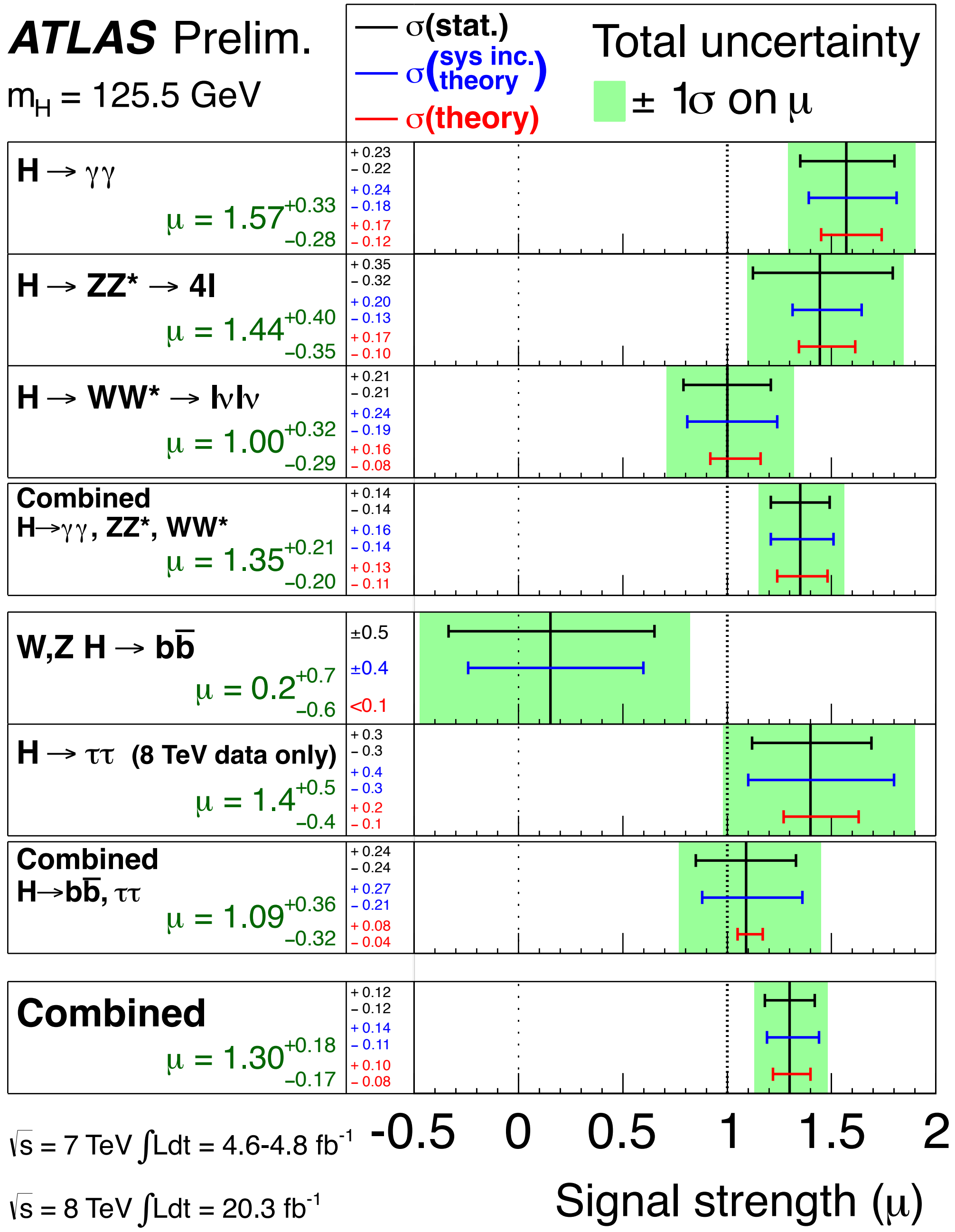
Observations and current bounds

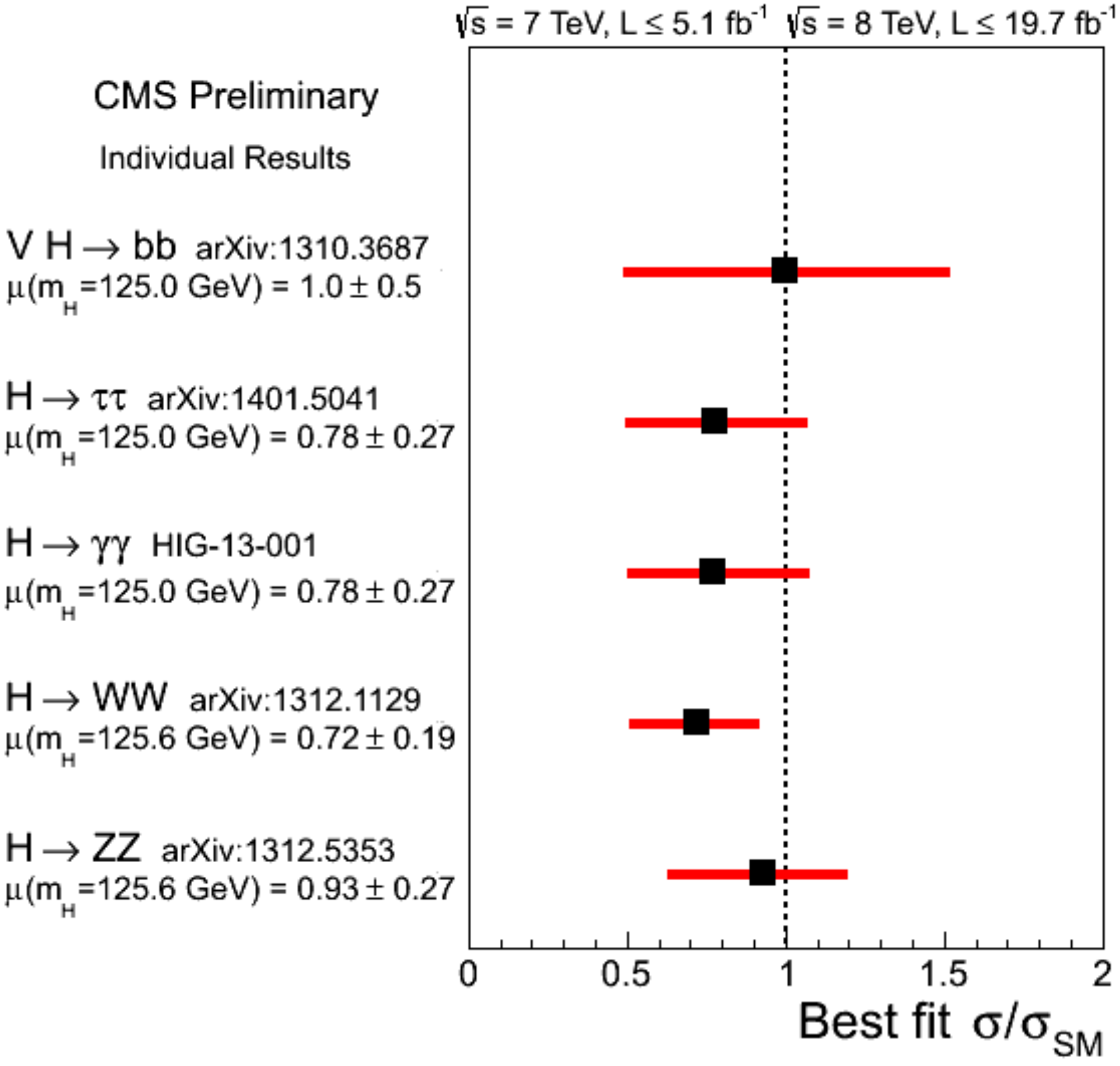


“Along with ‘Antimatter,’ and ‘Dark Matter,’ we’ve recently discovered the existence of ‘Doesn’t Matter,’ which appears to have no effect on the universe whatsoever.”

Phenomenological predictions and LHC data

Use Run-I date sets from ATLAS and CMS:





Phenomenological predictions and LHC data

Perform poor theorist's **naive averages** (no correlations):

R_X	bb	$\tau\tau$	WW	ZZ	$\gamma\gamma$
ATLAS [51]	$0.2^{+0.7}_{-0.6}$	$1.4^{+0.5}_{-0.4}$	$1.00^{+0.32}_{-0.29}$	$1.44^{+0.40}_{-0.35}$	$1.57^{+0.33}_{-0.28}$
CMS [52]	$1.0^{+0.5}_{-0.5}$ [55]	$0.78^{+0.27}_{-0.27}$ [56]	$0.68^{+0.20}_{-0.20}$	$0.92^{+0.28}_{-0.28}$	$0.77^{+0.27}_{-0.27}$
Average	$0.7^{+0.4}_{-0.4}$	$0.92^{+0.24}_{-0.22}$	$0.77^{+0.17}_{-0.16}$	$1.09^{+0.23}_{-0.22}$	$1.09^{+0.21}_{-0.19}$

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

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

- Higgs **production cross section** (~87% gluon fusion, <7% vector-boson fusion, 5% *V*+*h* production)
- Higgs **decay rate** to the observed final state *X*
- **total Higgs width** (mainly sensitive to $h \to bb$, $h \to WW$, also $h \to$ invisible)

Phenomenological predictions and LHC data

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Theory predictions:

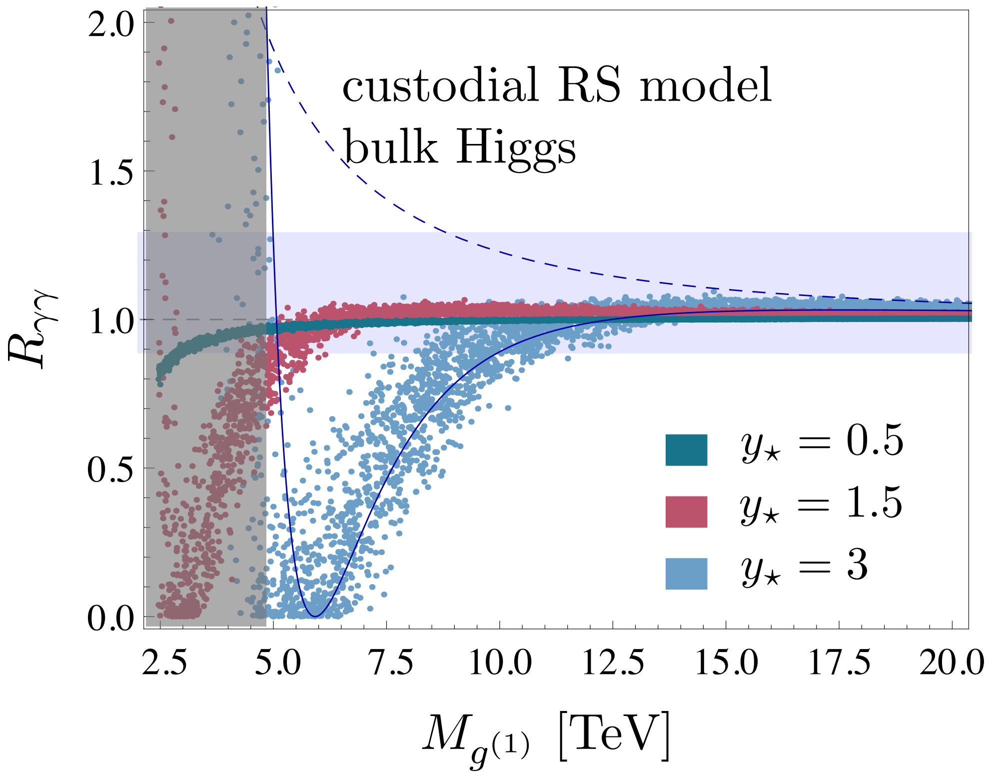
$$R_X \equiv \frac{(\sigma\cdot\mathrm{BR})(pp\to h\to X)_{\mathrm{RS}}}{(\sigma\cdot\mathrm{BR})(pp\to h\to X)_{\mathrm{SM}}} = \frac{\Big[\big(|c_g^{\mathrm{eff}}|^2+|c_{g5}^{\mathrm{eff}}|^2\big)\overset{\sim 0.9}{f_{\mathrm{GF}}}+c_V^2\,\overset{\sim 0.1}{f_{\mathrm{VBF}}}\Big]\Big[|c_X^{(\mathrm{eff})}|^2+|c_{X5}^{(\mathrm{eff})}|^2\Big]}{c_h}$$

with correction to the total Higgs width: Denner, Heinemeyer, Puljak, Rebuzzi, Spira (2011)

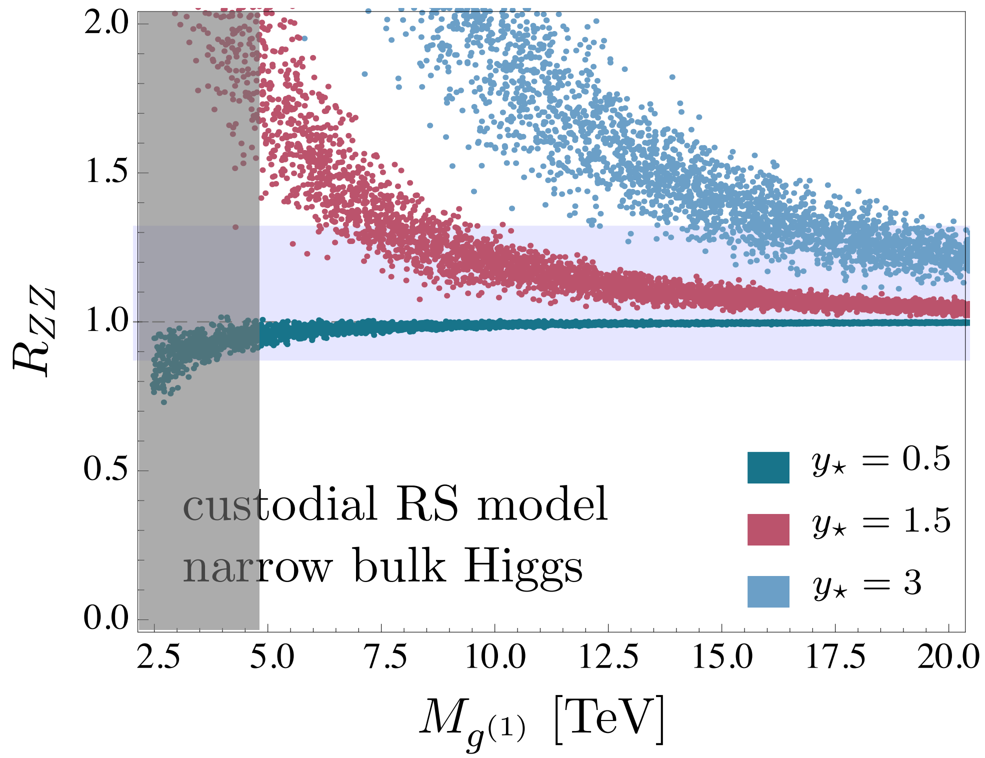
$$c_h = \frac{\Gamma_h^{\mathrm{RS}}}{\Gamma_h^{\mathrm{SM}}} \approx 0.57(c_b^2+c_{b5}^2)+0.22c_W^2+0.03c_Z^2+0.09\big(|c_g^{\mathrm{eff}}|^2+|c_{g5}^{\mathrm{eff}}|^2\big)+0.06(c_\tau^2+c_{\tau5}^2)+0.03$$

Higgs decays to γγ and ZZ* (WW*)

Malm, MN, Schmell: 1408.4456

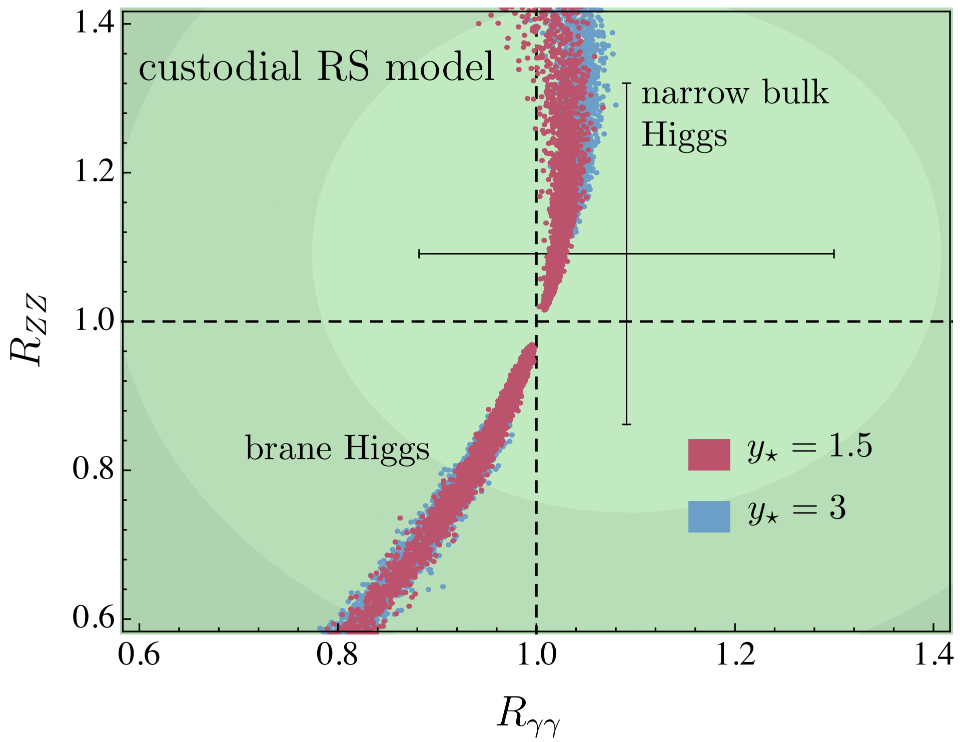


Malm, MN, Novotny, Schmell (2013)



Observe a **strong correlation** of the two quantities:

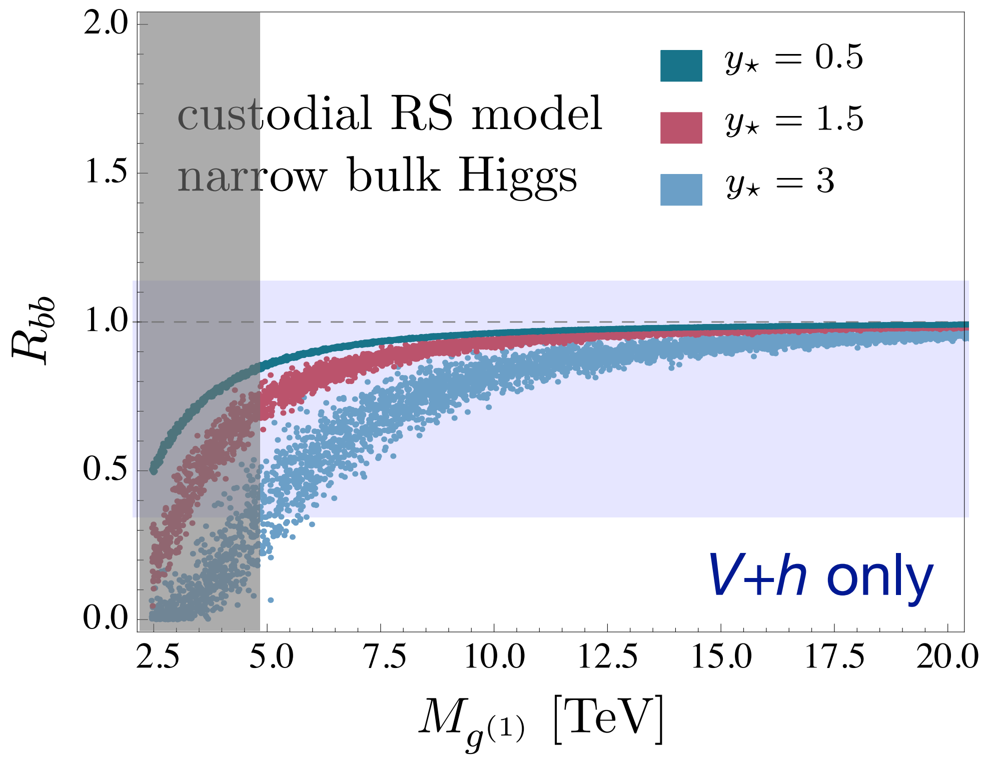
⇒ more precise measurements at LHC and ILC will allow one to differentiate between different variants of RS models

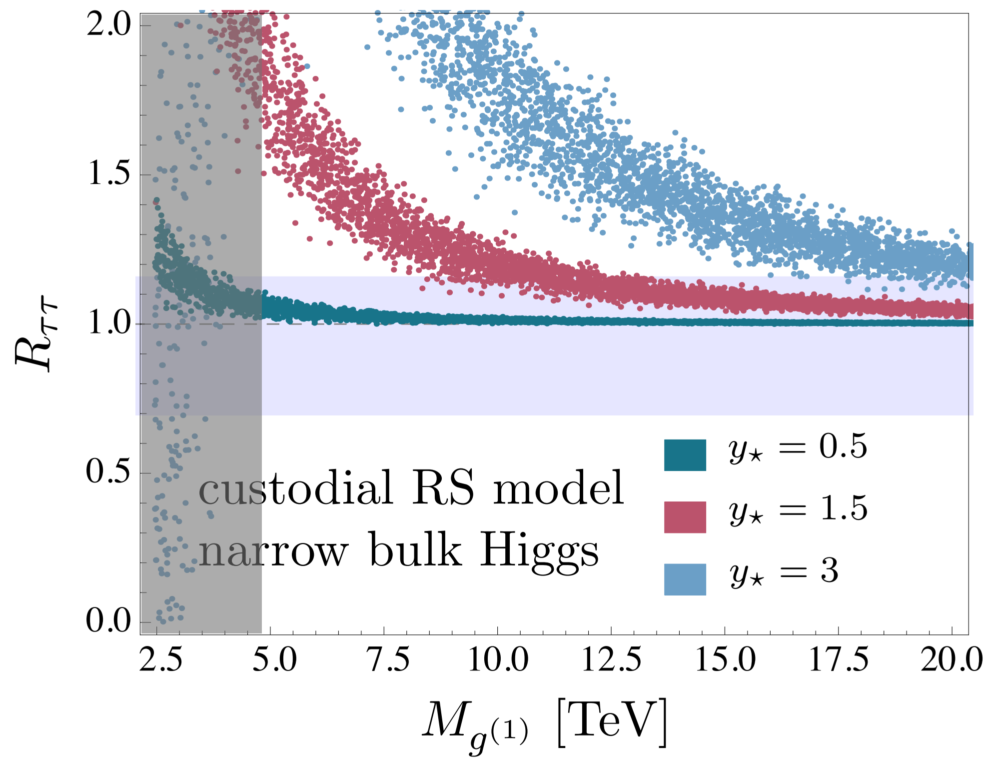


Higgs decays to third-generation fermions

Malm, MN, Schmell: 1408.4456

Model predictions compared with LHC data (ATLAS & CMS) on *b*-quark pair production in vector-boson fusion and inclusive $\tau^+\tau^-$ production:

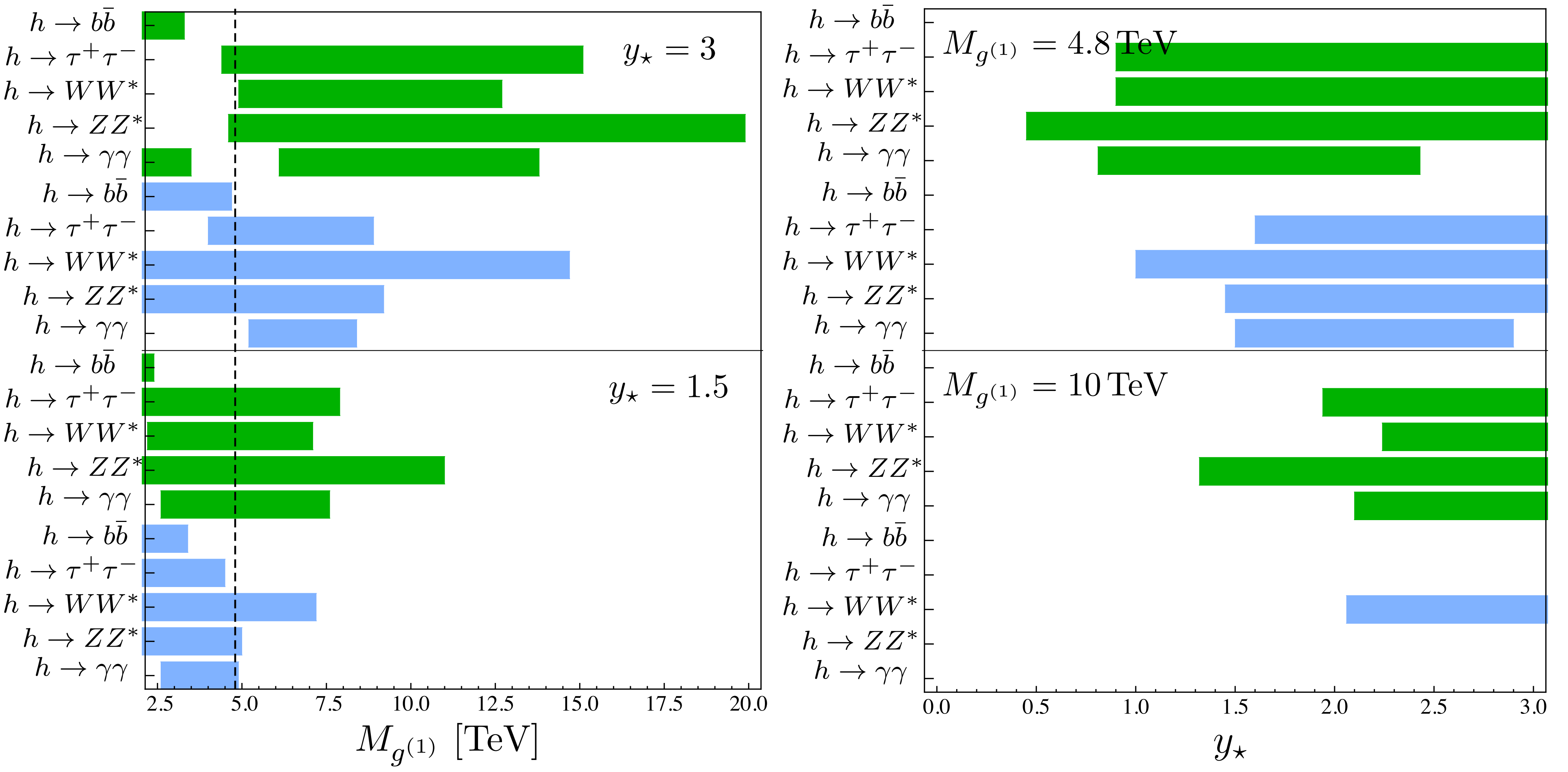




Summary of present constraints from LHC

Malm, MN, Schmell: 1408.4456

Exclusion regions (95% CL) for the lightest KK gluon mass and y_*:



🟦 : narrow bulk Higgs 🟩 : brane-localized Higgs

⇒ some bounds are **much stronger** than those from EWPT

Moving the Higgs into the bulk

RS models with a bulk Higgs

No compelling reason why the Higgs field should be the only brane-localized field in an RS models

Models with the Higgs in the bulk can still solve the hierarchy problem (dual to **4D partially composite Higgs** models)

Cacciapaglia, Csaki, Marandella, Terning (2007)
Archer (2012)

Setup:

$$S_h = \int d^4x \int_{-r\pi}^{r\pi} dx_5\, e^{-4\sigma(\phi)} \left[g^{MN} D_M \Phi^\dagger D_N \Phi - \mu^2 \, |\Phi|^2 - V_{\rm UV}(\Phi)\, \delta(x_5) - V_{\rm IR}(\Phi)\, \delta(|x_5| - r\pi) \right]$$

$$V_{\rm UV}(\Phi) = M_{\rm UV} \, |\Phi|^2 \,, \qquad V_{\rm IR}(\Phi) = -M_{\rm IR} \, |\Phi|^2 + \lambda_{\rm IR} \, |\Phi|^4$$

- Higgs scaling dimension $\beta = \sqrt{4 + \mu^2/k^2}$ by the ratio of two Planck-scale parameters
  Witten (1998); Luty, Okui (2004)
- limit $\beta \to \infty$ is unnatural as it requires a large hierarchy between the 5D scalar mass μ and the AdS curvature k

RS models with a bulk Higgs

Profile functions of scalar VEV and Higgs field are still IR localized:

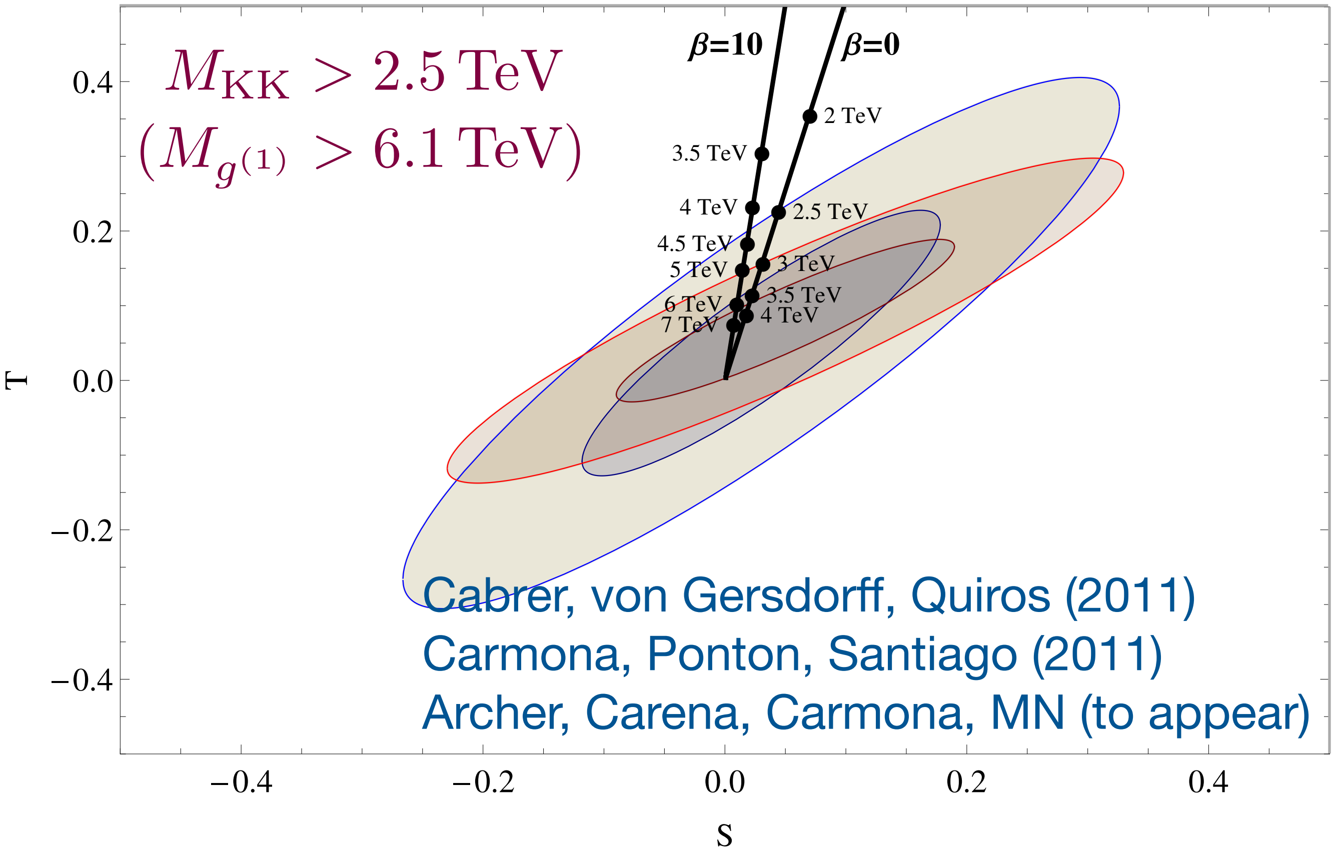
Cacciapaglia, Csaki, Marandella, Terning (2007)
Malm, MN, Novotny, Schmell (2013)

$$v(t) = v_4 \sqrt{\frac{L}{\pi}(1+\beta)}\, t^{1+\beta}; \quad t = \frac{z}{R'}$$

$$\chi_h(t) = \sqrt{\frac{L}{\pi}(1+\beta)}\, t^{1+\beta} \left[1 - \frac{m_h^2}{4M_{\text{KK}}^2} \left(\frac{t^2}{1+\beta} - \frac{1}{2+\beta} \right) + \dots \right]$$

Advantages:

- β = O(1) more natural
- tames constraints from EWPTs (correction to the *T* parameter can be reduced by factor 3)
- can consider a more minimal model with custodial symmetry



$M_{\text{KK}} > 2.5\,\text{TeV}$
$(M_{g^{(1)}} > 6.1\,\text{TeV})$

Cabrer, von Gersdorff, Quiros (2011)
Carmona, Ponton, Santiago (2011)
Archer, Carena, Carmona, MN (to appear)

RS models with a bulk Higgs

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Advantages:

- softens perturbativity bound on dimensionless 5D Yukawa couplings (from NDA), thus allowing for larger values

Csaki, Falkowski, Weiler (2008)
Malm, MN, Novotny, Schmell (2013)

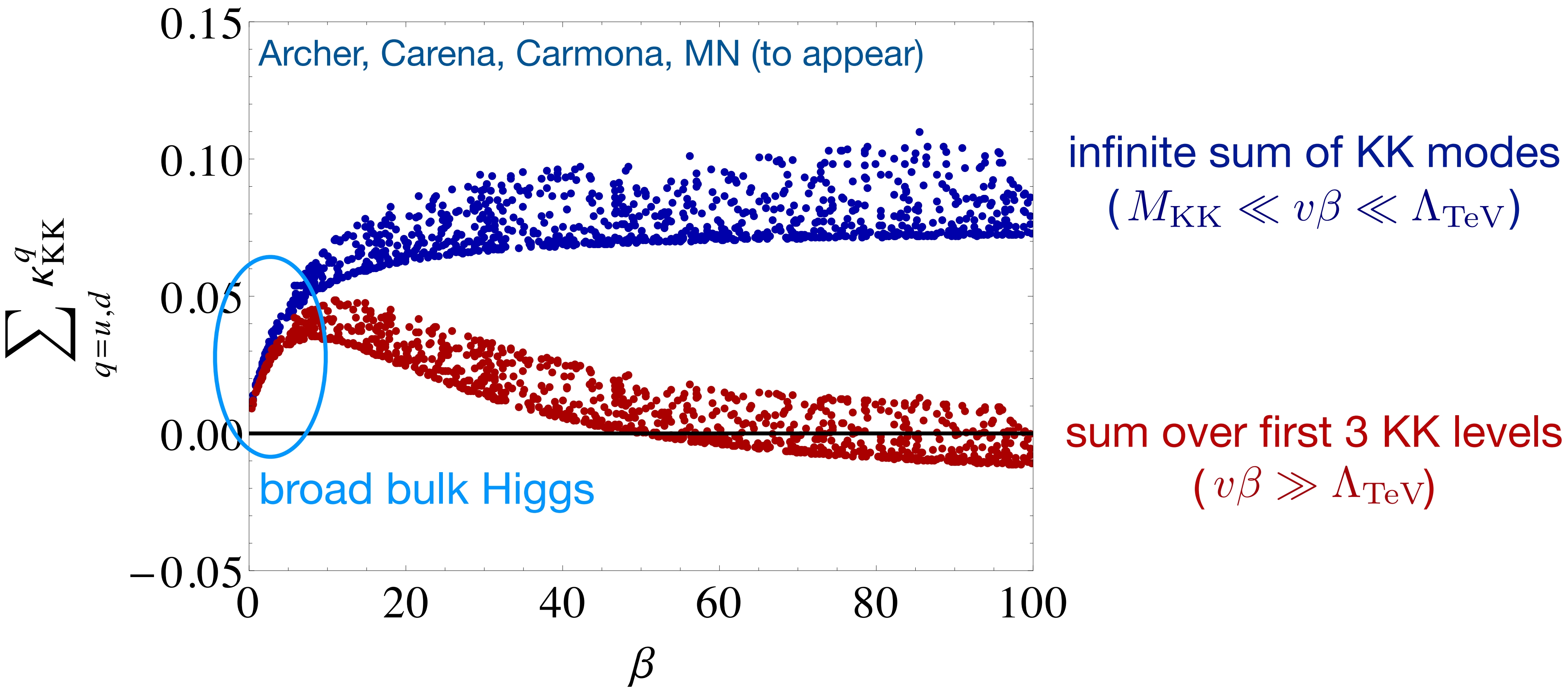
$$y_{\max} \sim \begin{cases} \dfrac{6\pi^2}{\sqrt{5}} \dfrac{M_{\text{KK}}}{\Lambda_{\text{TeV}}} \sim 3.0\,; & \text{brane Higgs} \\[2ex] \sqrt{\dfrac{96\pi^3}{5}} \sqrt{\dfrac{M_{\text{KK}}}{(1+\beta)\Lambda_{\text{TeV}}}} \sim \dfrac{8.3}{\sqrt{1+\beta}}\,; & \text{bulk Higgs} \end{cases}$$

- help to alleviate flavor constraints

Agashe, Azatov, Zhu (2008)
Archer, Huber, Jäger (2011)
Cabrer, von Gersdorff, Quiros (2011)

RS models with a bulk Higgs

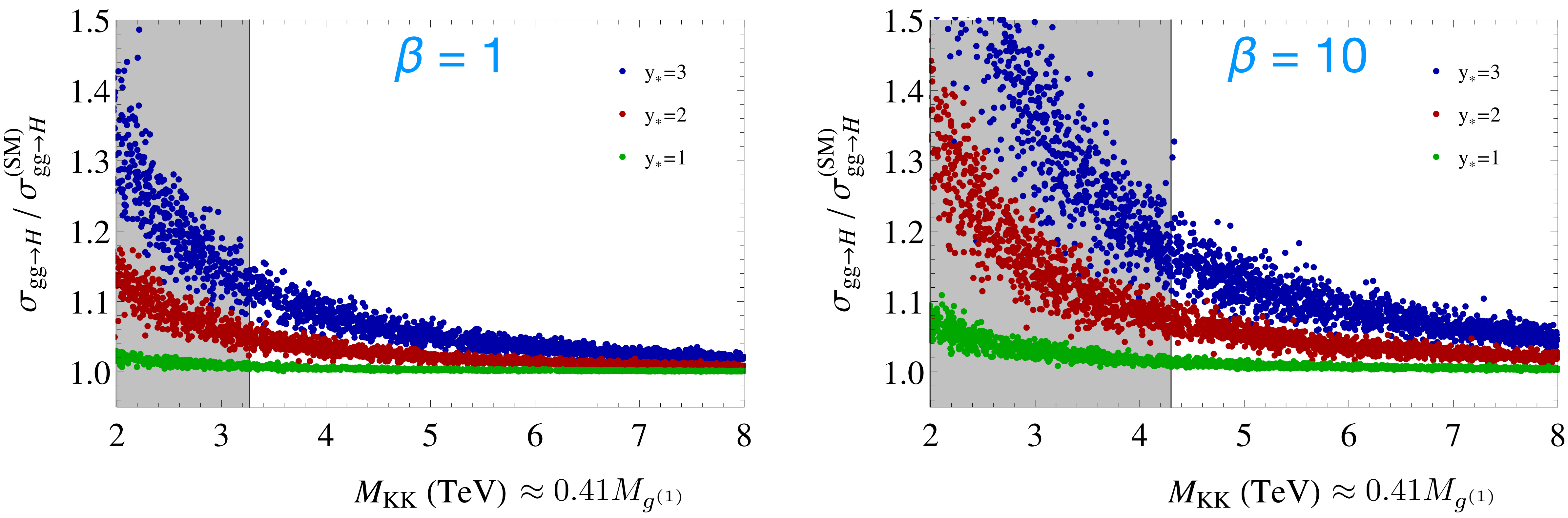
Moving the Higgs into the bulk also eliminates the UV sensitivity of the $gg \to h$ and $h \to \gamma\gamma$ (as well as $b \to s\gamma$) amplitudes to the precise localization mechanism of the Higgs field on or near the IR brane:



KK contribution to the gluon-fusion amplitude (for $N_g=1$) versus β, approaching asymptotically the values for a brane-localized Higgs and a narrow bulk Higgs

Higgs production in gluon fusion

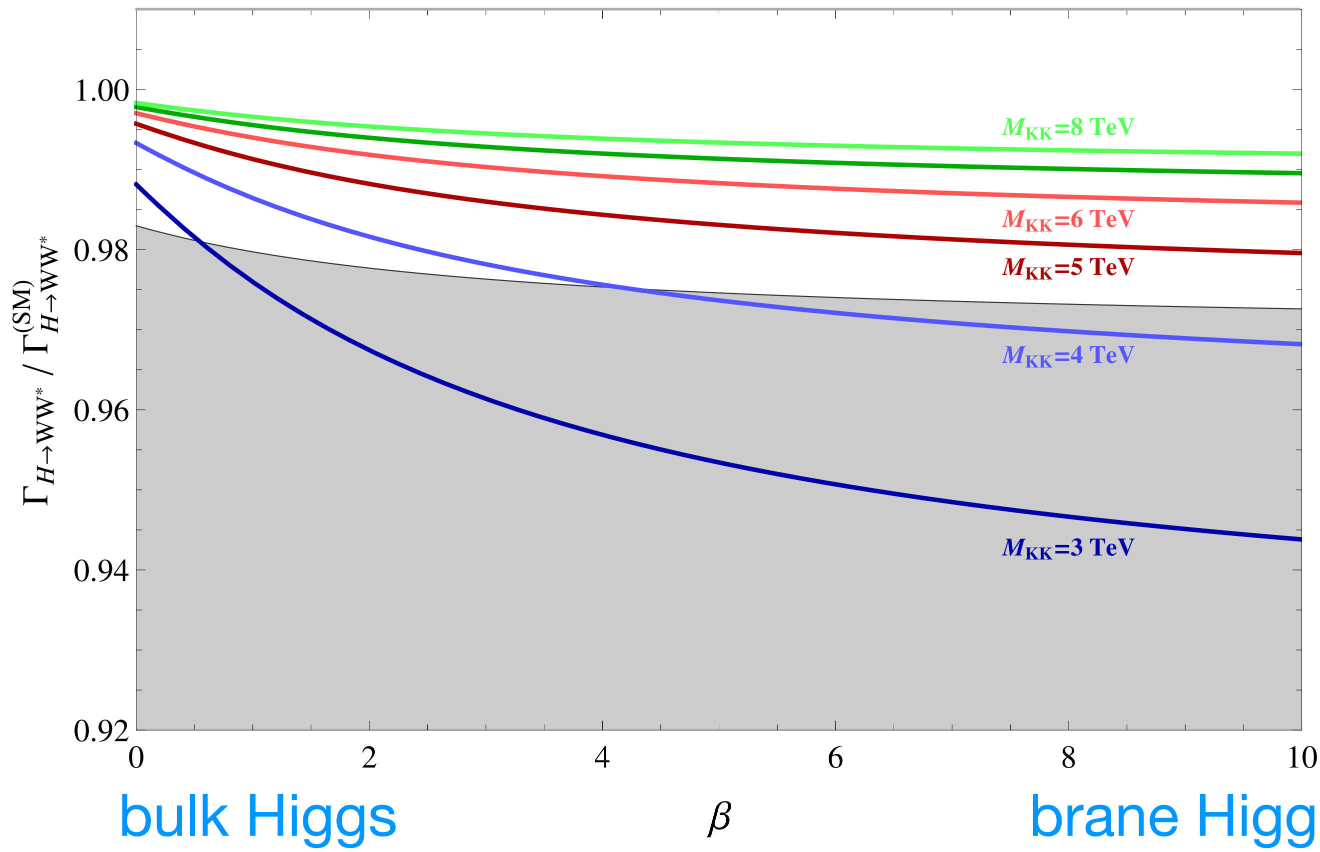
Archer, Carmona, Carena, MN (to appear)



Moving the Higgs field further into the bulk **reduces** the magnitude of the corrections significantly, while at the same time allowing for **lighter KK resonances**

Higgs decays to WW* and ZZ*

Archer, Carmona, Carena, MN (to appear)

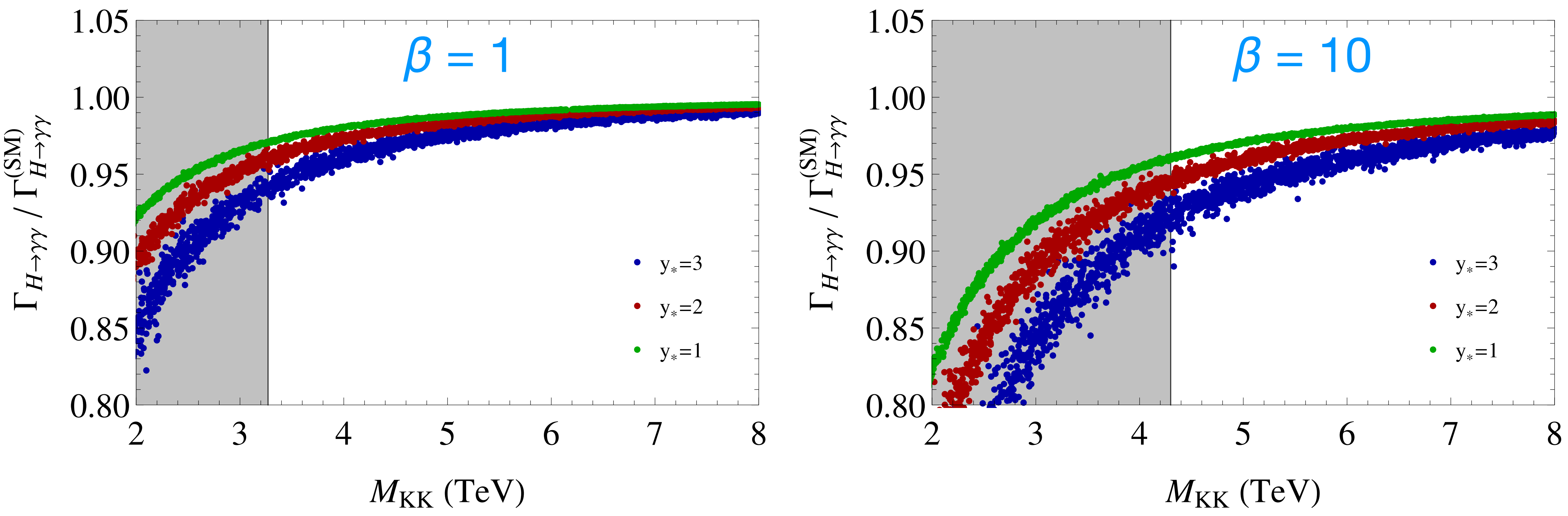


bulk Higgs brane Higgs

Moving the Higgs field further into the bulk **reduces** the magnitude of the corrections significantly, while at the same time allowing for **lighter KK resonances**

Higgs decays to $\gamma\gamma$

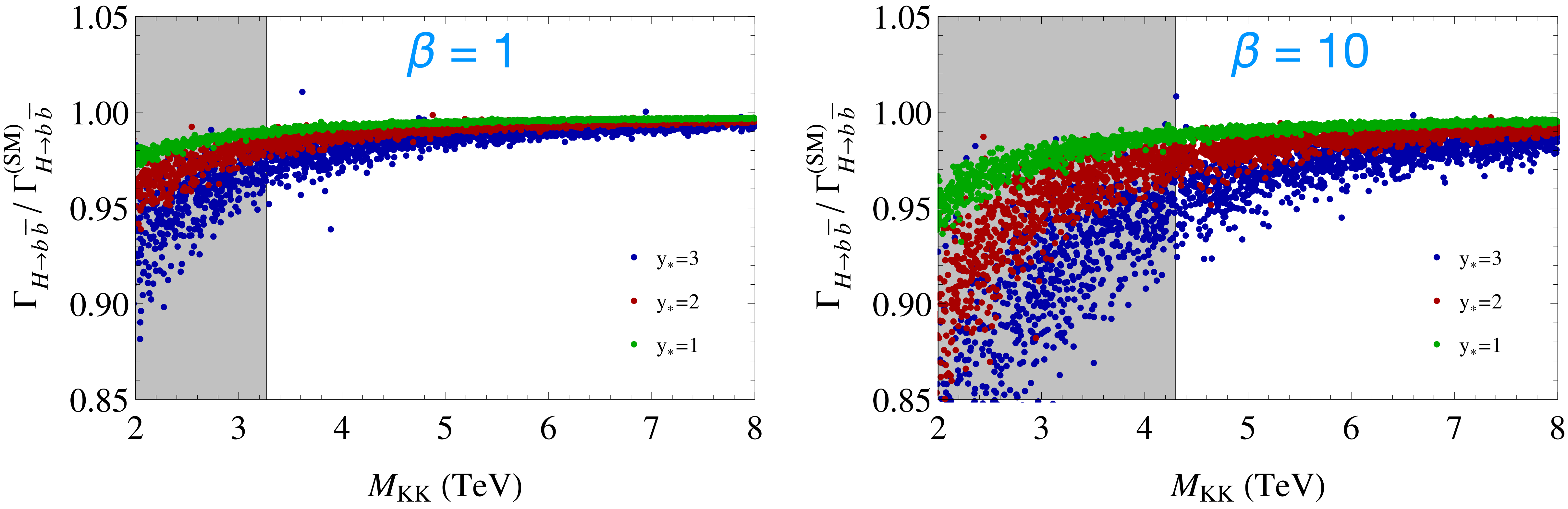
Archer, Carmona, Carena, MN (to appear)



Moving the Higgs field further into the bulk **reduces** the magnitude of the corrections significantly, while at the same time allowing for **lighter KK resonances**

Higgs decays to $b\bar{b}$ and $\tau^+\tau^-$

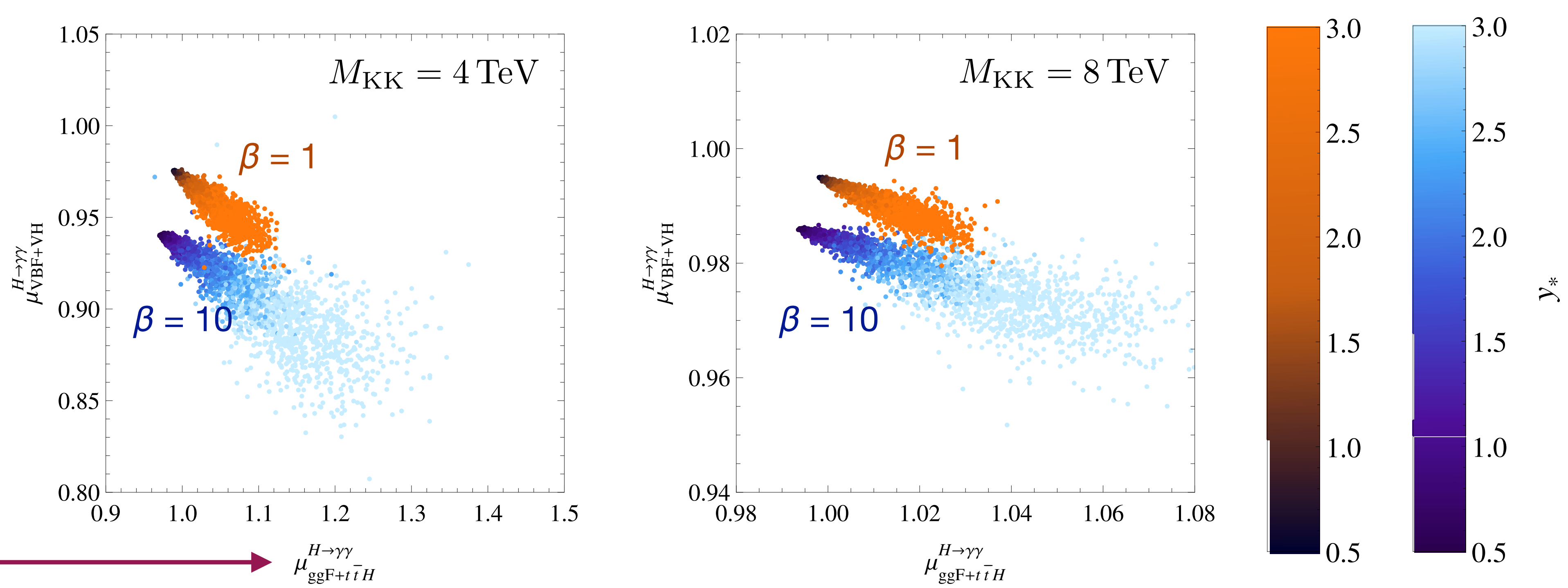
Archer, Carmona, Carena, MN (to appear)



Moving the Higgs field further into the bulk **reduces** the magnitude of the corrections significantly, while at the same time allowing for **lighter KK resonances**

Correlated $h\to\gamma\gamma$ signal strengths in GF and VBF

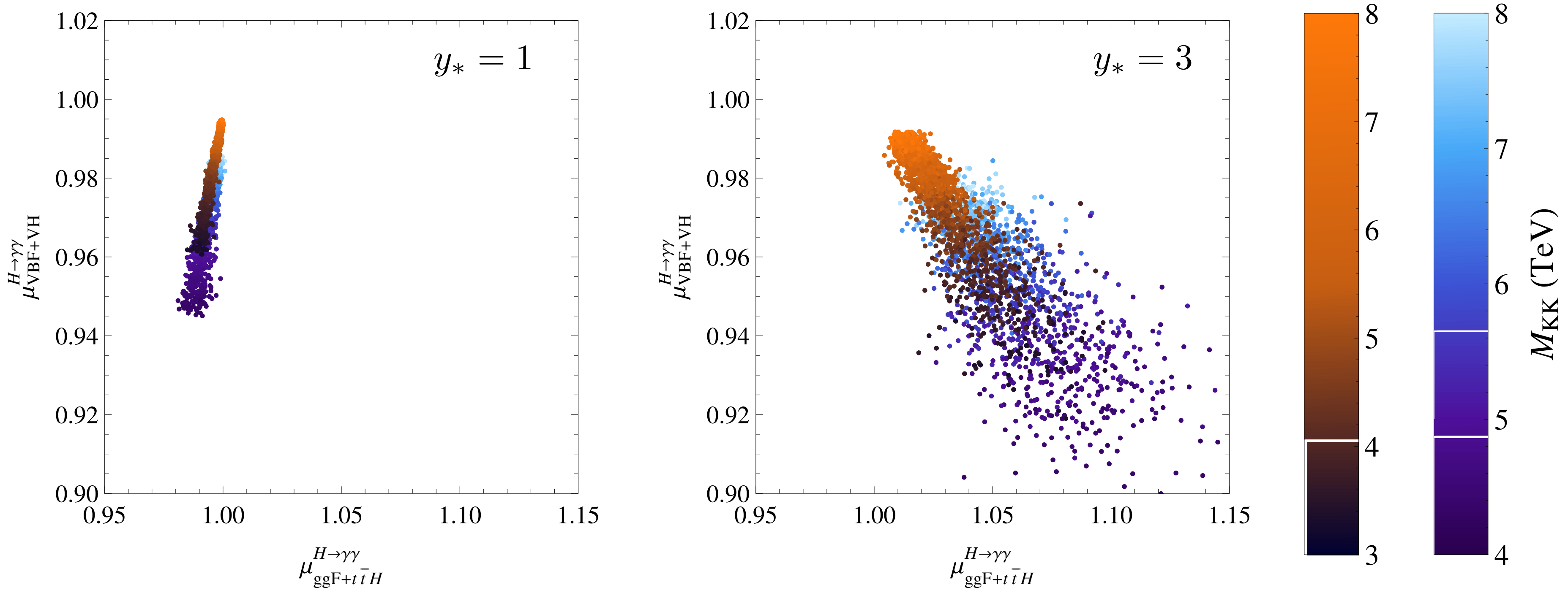
Archer, Carmona, Carena, MN (to appear)



VBF + *Vh* →

gluon fusion →

(a) $M_{\rm KK} = 4\,{\rm TeV}$ (left) and $M_{\rm KK} = 8\,{\rm TeV}$ (right) with $\beta = 1$ (orange-brown) and $\beta = 10$ (white-blue).



(b) $y_* = 1$ (left) and $y_* = 3$ (right) with $\beta = 1$ (orange-brown) and $\beta = 10$ (white-blue).

Minimal composite pNGB Higgs models

Minimal composite pNGB Higgs models

Higgs as a pseudo Nambu-Goldstone boson of a **spontaneously broken global symmetry SO(5)/SO(4)**, which contains the SM+custodial symmetry

Kaplan, Georgi (1984)
Contino, Nomura, Pomarol (2003)
Agashe, Contino, Pomarol (2004)
Giudice, Grojean, Pomarol, Rattazzi (2007)

Eliminates the little hierarchy problem (why $m_h \ll M_{\rm KK}$?) and gives a naturally light Higgs boson (but m_h=125 GeV requires some tuning)

Main differences:

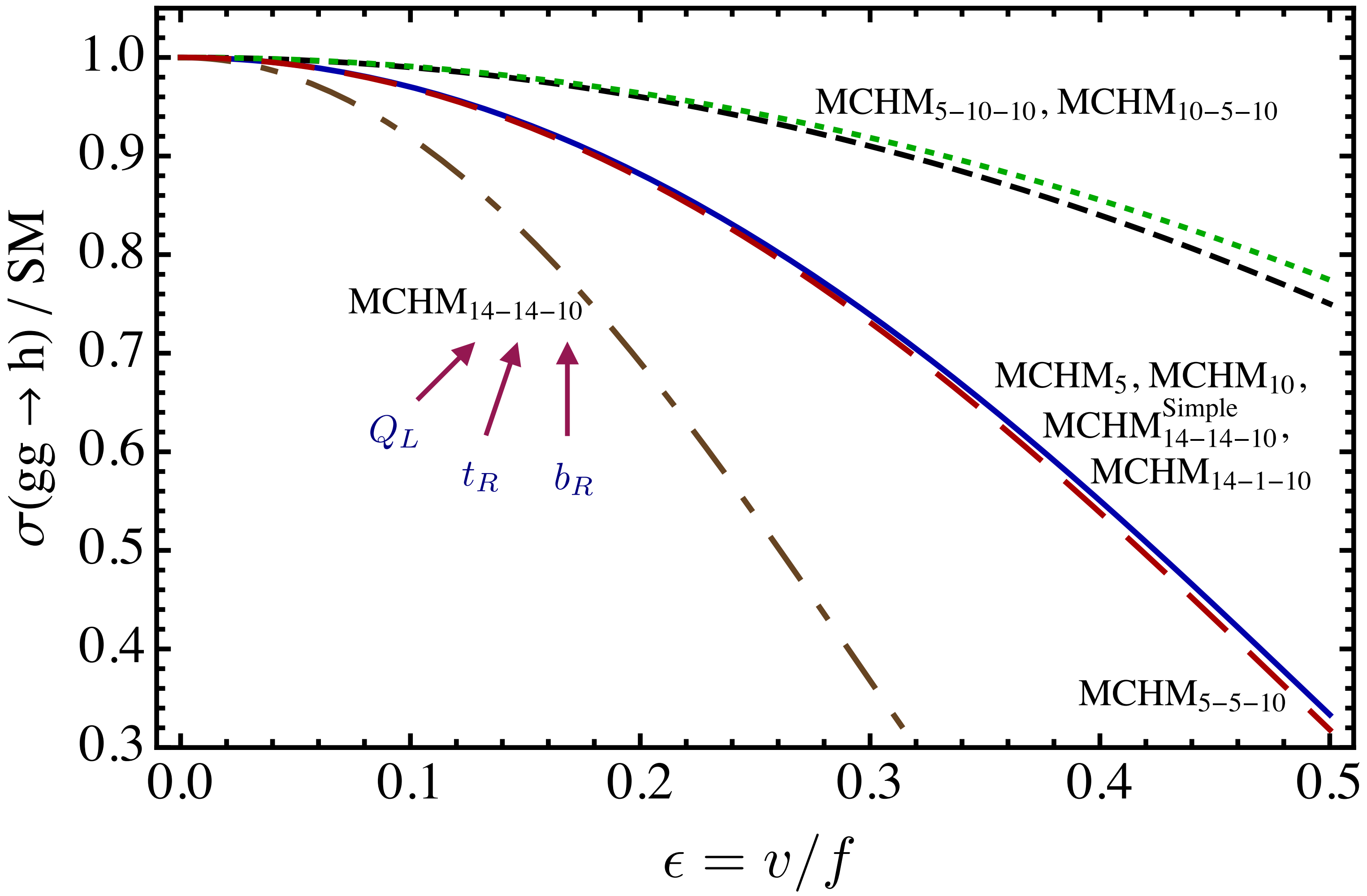
- (broken) **shift symmetry** forbids large contributions $\sim N_g^2 y_*^2/M_{\rm KK}^2$ from KK resonances to loop-induced *hgg* and *hγγ* couplings
- in **gauge-Higgs unification models**, the Yukawa couplings originate from 5D gauge interactions
- $hf\bar{f}$ couplings strongly depend on the **fermion representations** under the global symmetry group

Carena, Da Rold, Ponton: 1402.2987

Minimal composite Higgs models

Carena, Da Rold, Ponton: 1402.2987

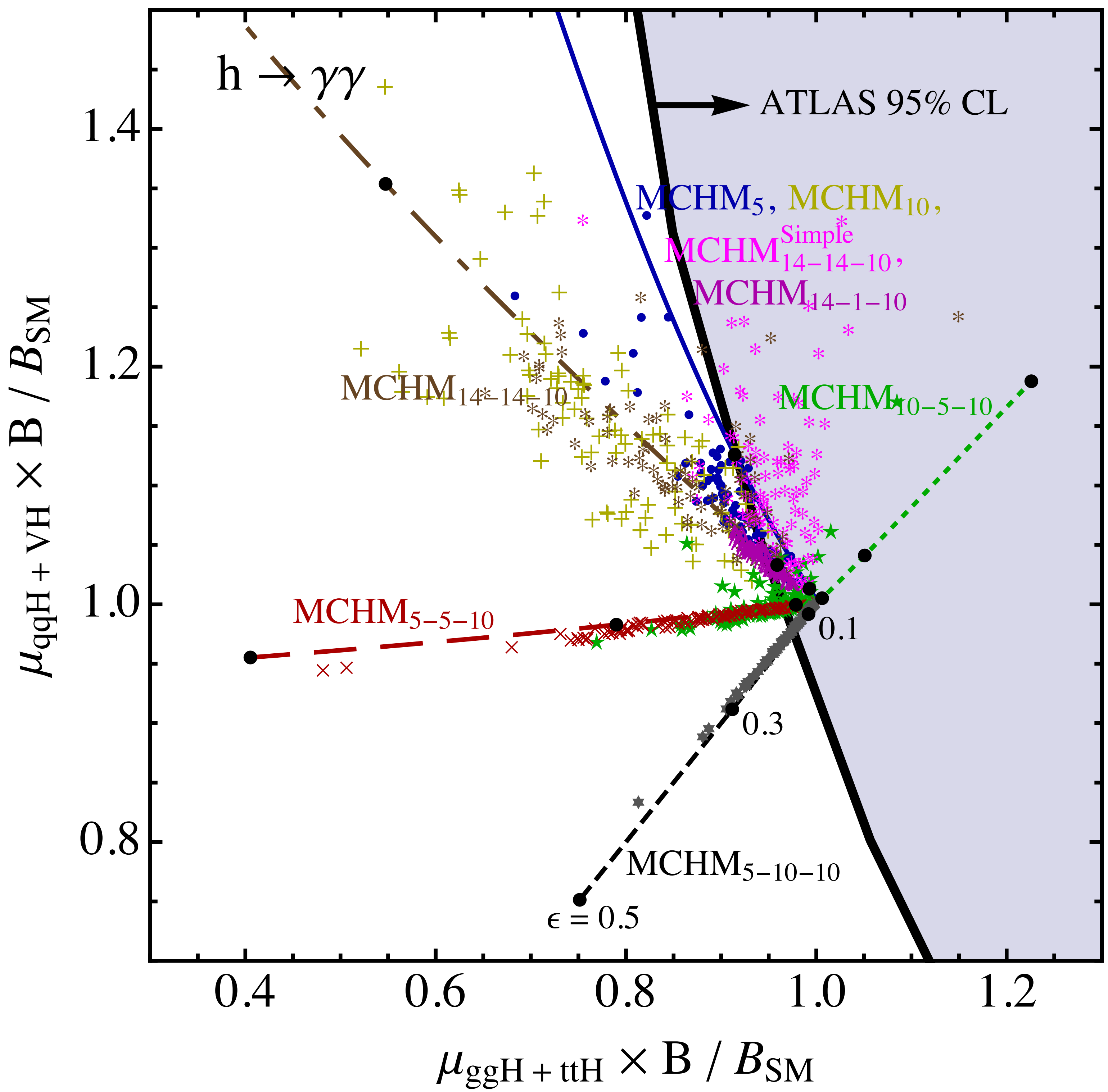
Higgs phenomenology quite different from RS models, in particular one finds a **suppression** of the gluon-fusion cross section:



(resonance masses $m_\rho \sim g_\rho f$ with $g_\rho \lesssim 4\pi$)

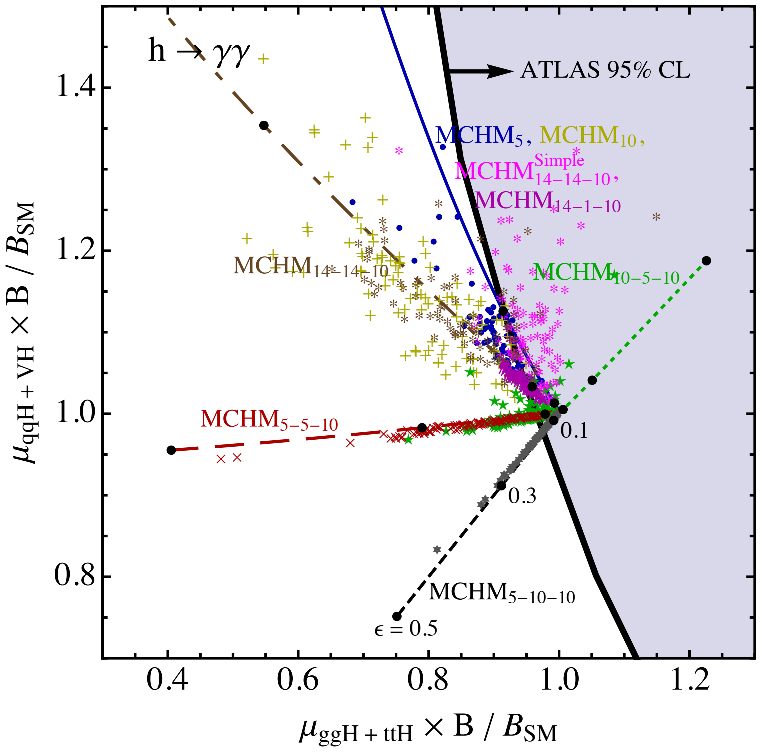
Correlated $h\to\gamma\gamma$, VV*, $\tau^+\tau^-$ signal strengths

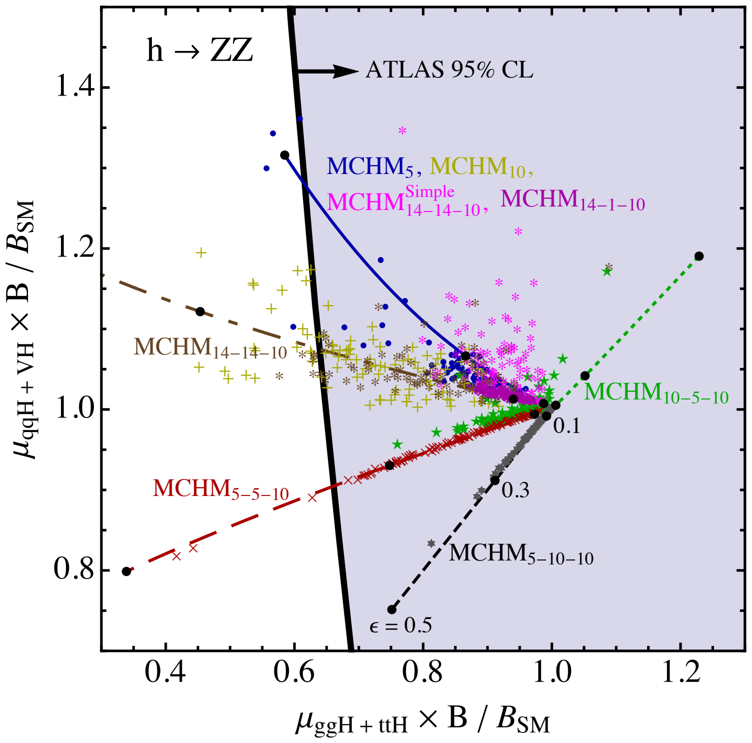
Carena, Da Rold, Ponton: 1402.2987

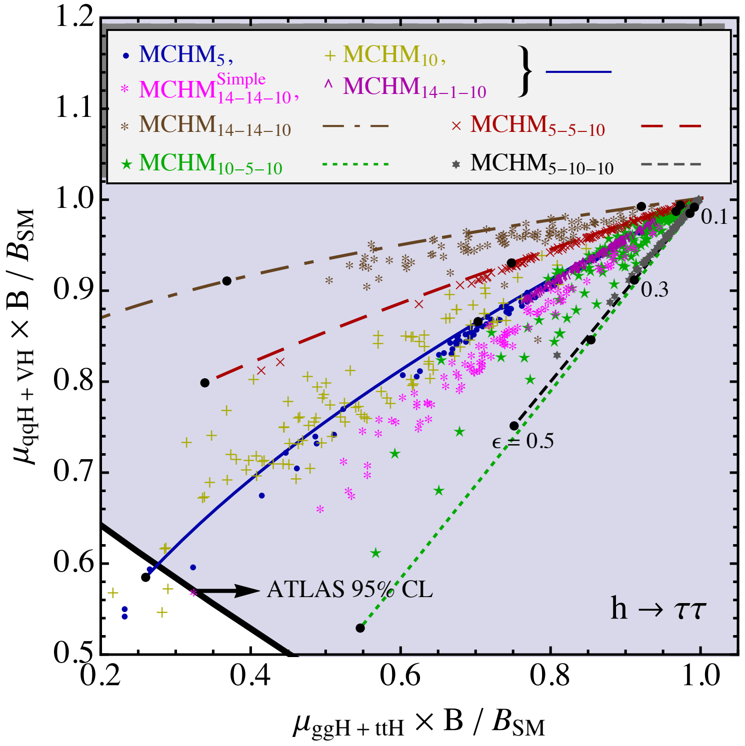


Correlated $h \rightarrow \gamma\gamma$, VV*, $\tau^+\tau^-$ signal strengths

Carena, Da Rold, Ponton: 1402.2987







Correlated $h \to \gamma\gamma$, VV*, $\tau^+\tau^-$ signal strengths

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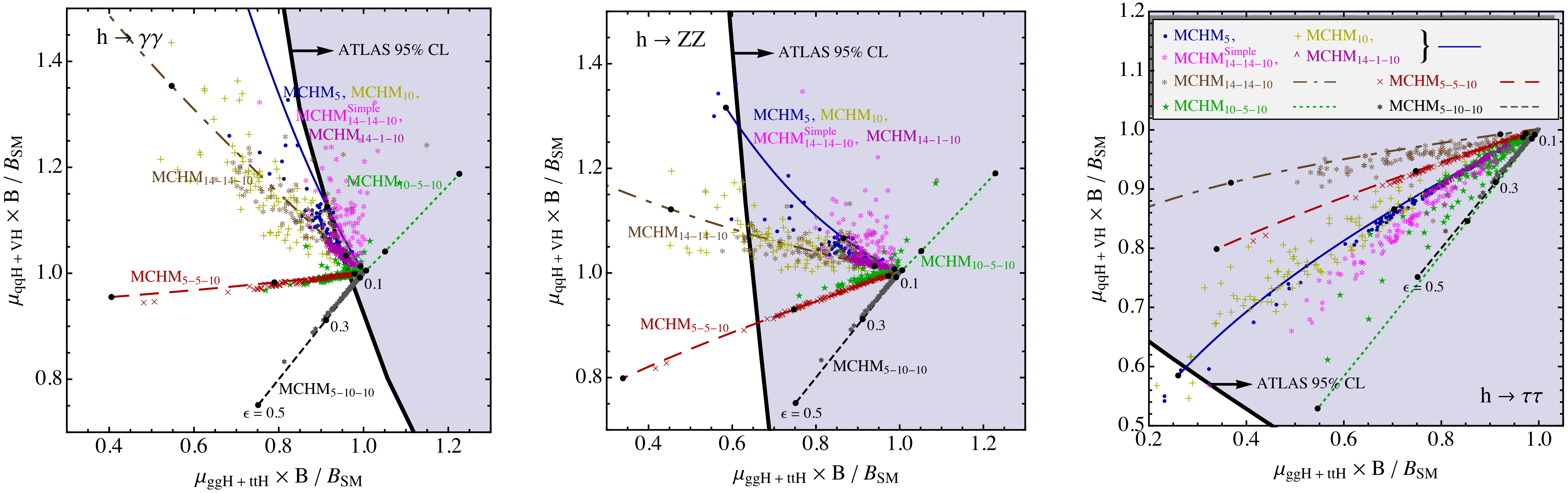
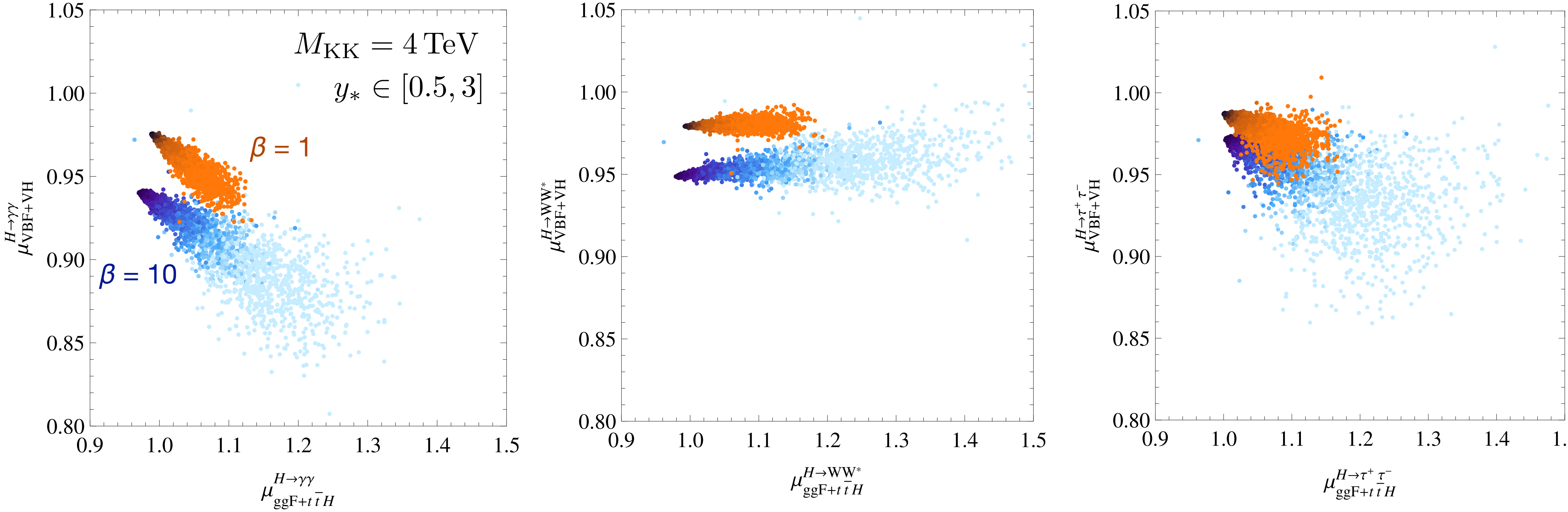
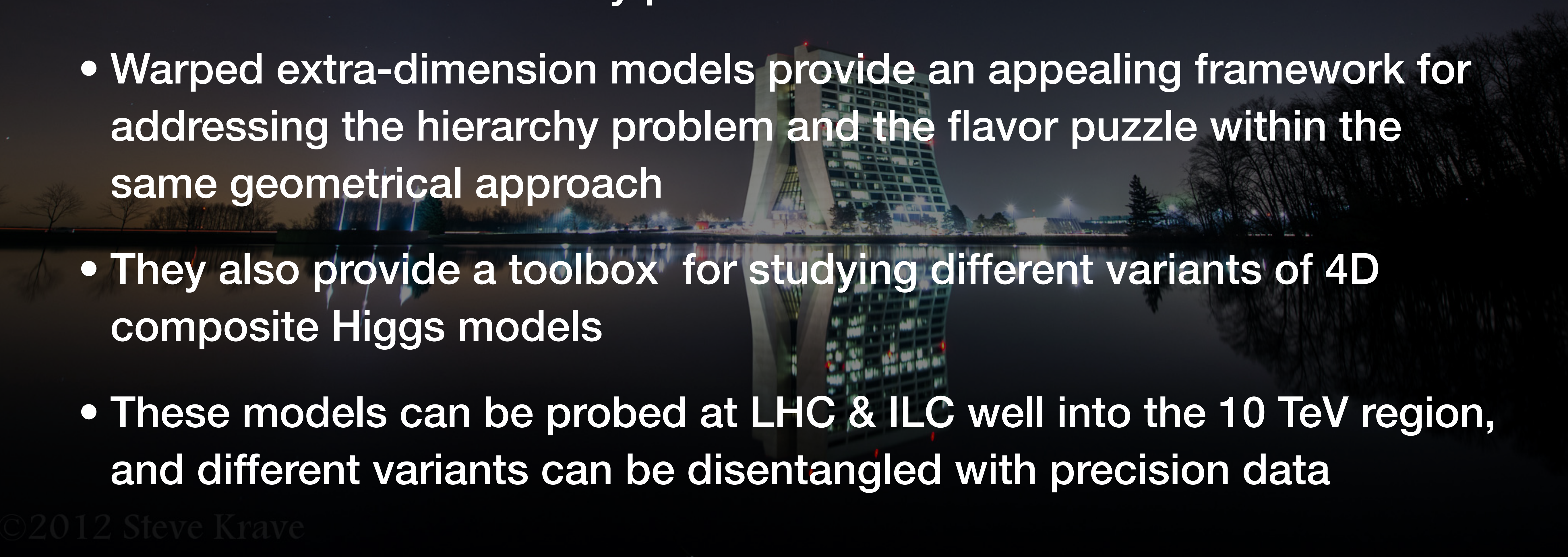




Conclusions

- 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
- They also provide a toolbox for studying different variants of 4D composite Higgs models
- These models can be probed at LHC & ILC well into the 10 TeV region, and different variants can be disentangled with precision data



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