# 5D Perspective on Higgs Production at the Boundary of a Warped Extra Dimension

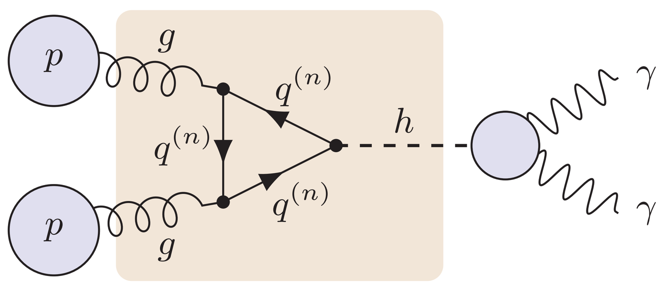
Raoul Malm in collaboration with M. Neubert, K. Novotny and C. Schmell

## 1. Searching for new physics

The discovery of a Higgs-like boson at the LHC marks the beginning of a new era in particle physics. While the properties of the new particle appear to be close (at the $\sim 10\%$ level) to those predicted for an elementary scalar with couplings as given by the Standard Model (SM), there are still open questions the SM does not answer.

From the theoretical perspective, the most pressing questions concern the mechanisms for explaining the *radiative stability of the Higgs mass* as well as the *hierarchy of the Yukawa couplings*, also known as the flavor puzzle. One attractive solution to both problems is provided by Randall-Sundrum models [1], that embed the SM into a compact and warped extra dimension (WED) of anti-de Sitter space ($AdS$).

In general, extensions of the SM predict new heavy particles, that can be searched for by direct or indirect measurements. In the latter case, especially loop mediated processes like the Higgs production via gluon-fusion $gg \to h$




are sensitive on new particles and therefore present unique opportunities to search for hints of new physics. One can parametrize the new contributions by the ratio

$$R_h = \frac{\sigma(gg\to h)_{\rm NP}}{\sigma(gg\to h)_{\rm SM}},$$

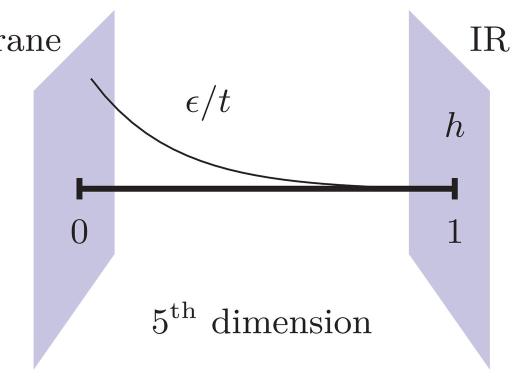
where $\sigma_{\rm NP}$ denotes the new physics cross section.

## 2. The minimal RS model

Proposed in 1999 by Lisa Randall and Raman Sundrum [1], the Randall-Sundrum (RS) model enlarges four-dimensional space-time by one small and compact extra dimension in a slice of $AdS_5$. In terms of the metric, this is expressed by

$$ds^2 = \frac{\epsilon^2}{t^2}\Big(\eta_{\mu\nu}dx^\mu dx^\nu - \frac{1}{M_{\rm KK}^2}dt^2\Big),$$

where the fifth dimension is parametrized by the dimensionless coordinate $t \in [\epsilon, 1]$ with $\epsilon \equiv M_{\rm EW}/M_{\rm Pl}$ and $M_{\rm KK}$ denotes the




new physics scale. The warp factor $\epsilon/t$ rescales the units of length and mass in such a way, that the fundamental Planck scale $M_{\rm Pl}$ is warped down to the TeV scale as $t$ varies between $\epsilon$ (UV brane) and 1 (IR brane). Consequently the Higgs mass is stabilized around the electroweak scale, as long as the Higgs particle is localized near the IR brane.

All other particles of the SM are extended to five-dimensional fields, that are allowed to propagate along the extra dimension, and that can be decomposed into a sum of 4D modes times profile functions, only depending on the coordinate $t$. The lightest modes resemble the SM particle content, which are accomplished by massive resonances called Kaluza-Klein (KK) states.

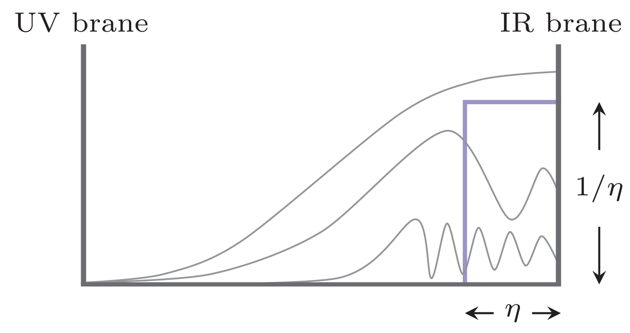
## 3. Higgs production via gluon fusion

Due to recent publications [2], [3] there have been controversies about the reliability of calculations concerning the Higgs production cross section via gluon fusion, in the regime where the Higgs boson is localized very close to or at the IR brane.

*regularized δ-function*

$$\delta_h^\eta(t-1) = \theta(t-1+\eta)$$

with $0 < \eta \ll 1$




Applying a 5D perspective allows for an understanding and clarification of the problem without the notion of KK modes [4]. In view of the five-dimensional description, the amplitude of the process $gg \to h$ can be formulated by

$$\mathcal{A}(gg\to h) = i\frac{4\pi\alpha_s}{\sqrt{2}}\delta_{ab}\int\frac{d^dp}{(2\pi)^d}\int_\epsilon^1 dt_1\int_\epsilon^1 dt_2\int_\epsilon^1 dt\,\delta_h^\eta(t-1)\sum_{q=u,d}\mathrm{Tr}\left[\begin{pmatrix}0 & \boldsymbol{Y}_q\\ \boldsymbol{Y}_q^\dagger & 0\end{pmatrix}\boldsymbol{S}_q(t,t_2;p-k_2)\not\varepsilon_{k_2}\boldsymbol{S}_q(t_2,t_1;p)\not\varepsilon_{k_1}\boldsymbol{S}_q(t_1,t;p+k_1)\right],$$

where four-dimensional regularization with $d = 4 - 2\hat\epsilon$ is used for the loop integral to ensure gauge invariance. After some manipulations one can arrive at an expression, where the key object that contains all the physics is given by

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

which is an integral in euclidean momentum space over the functions $T_\pm(p_E^2)$. In the following analysis, it turns out that the physically relevant function is $T_+(p_E^2)$, which is defined by

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

where $\boldsymbol{\Delta}_{RL}^q$ and $\boldsymbol{\Delta}_{LR}^q$ denote components of the 5D propagator. Since the integrand in (1) involves essentially a derivative, the value of the integral depends on the asymptotic behavior for small and large euclidean momenta of $T_\pm(p_E^2)$.

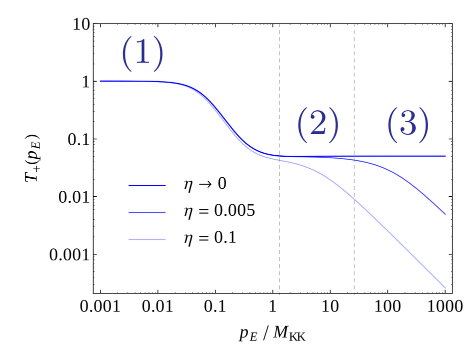
## 4. Analysis of $T_+(p_E^2)$ and $I_+(m^2)$

Concerning the interesting function $T_+(p_E^2)$, there are three characteristic regions, represented by the figure below.

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

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

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




Denoting the limiting value in region 1 by $T_+(p_E^2) \approx t_0$, in region 2 by $T_+(p_E^2) \approx t_1$ and in region 3 by $T_+(p_E^2) \approx t_3/\eta p_E$, where $t_0, t_1$ and $t_3$ are in general functions depending on the Yukawa matrices and the bulk mass parameters, one can perform the momentum integration given in equation (1).

*Keeping the dimensional regulator $\hat\epsilon$*

$\eta \to 0$ commutes with $p$ integral : $I_+ = t_0 - t_1$ $(R_h < 1)$

*Removing the dimensional regulator $\hat\epsilon$*

first $\eta \to 0$, then $p$ integration : $I_+ = t_0 - t_1$ $(R_h < 1)$

first $p$ integration, then $\eta \to 0$ : $I_+ = t_0$ $(R_h > 1)$

Keeping the dimensional regulator $\hat\epsilon$, one always obtains a unique result independent of the order of taking $\eta \to 0$ or performing the loop-momentum integration. This result represents the case where the cross section $R_h$ is generally suppressed. Instead, if one first sends the regulator $\hat\epsilon$ to zero, the limit $\eta \to 0$ and the momentum integral do not commute and one can reproduce both results of an enhanced and suppressed cross section.

## 5. Physical interpretation

One can understand the different results in view of two distinct models, that can be distinguished by the scale $\eta$ in relation to the vev $v$, the new physics scale $M_{\rm KK}$ and the cutoff $\Lambda_{\rm TeV}$ at the IR brane,

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

The range of $\eta$ can be interpreted in a qualitative manner.

| *treat $\eta$ as an unphysical parameter:* | *interpret $\eta$ as the width of the Higgs profile:* |
|---|---|
| brane-localized Higgs | narrow bulk-Higgs |

In one model, one treats $\eta$ as an unphysical parameter, just introduced for technical reasons. The condition is that $\eta$ must be smaller than the electroweak scale divided by the cutoff $\Lambda_{\rm TeV}$ - otherwise KK modes with masses $\sim v|Y_q|/\eta$ belong to the theory. For such a range of $\eta$, one speaks of a brane-localized Higgs, and one always obtains a suppressed contribution. On the other hand, one can treat $\eta$ as a physical parameter, representing the small but finite width of the Higgs profile. The condition is that it is larger than $v|Y_q|/\Lambda_{\rm TeV}$ but smaller than $v|Y_q|/M_{\rm KK}$. For such a value of $\eta$, one speaks of a narrow-bulk Higgs.

In order to determine the reliability of the obtained results for $I_+(m^2)$ within the framework of an EFT, it is convenient to use a hard momentum-cutoff instead of a dimensional regularization. Repeating the calculations, one finds

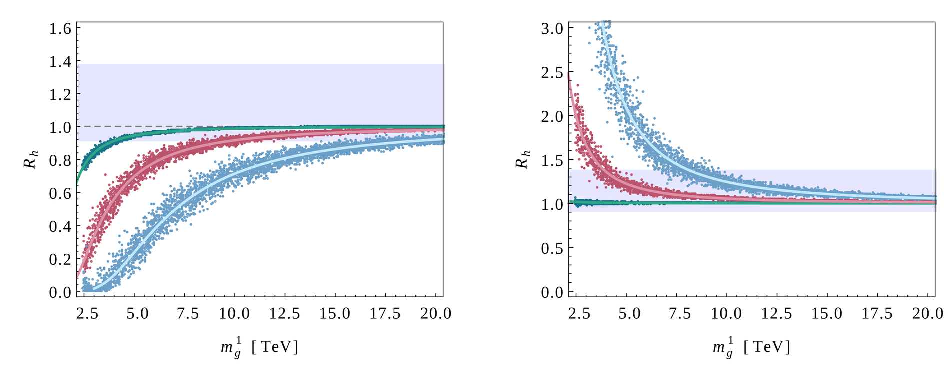
brane-localized Higgs $\qquad I_+^{\rm model}(0) = t_0 - t_1 - \frac{3t_2}{2}\frac{M_{\rm KK}}{\Lambda_{\rm TeV}},$

narrow bulk-Higgs $\qquad I_+^{\rm model}(0) = t_0 - \frac{3t_3}{2}\frac{M_{\rm KK}}{\eta\Lambda_{\rm TeV}},$

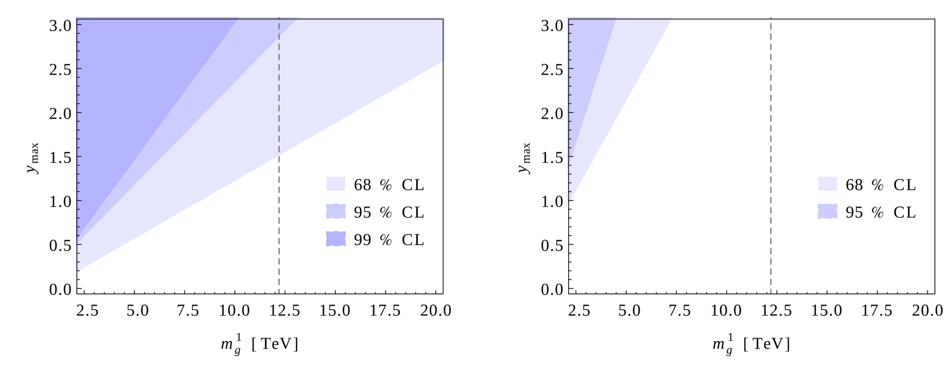
where the power corrections for the narrow bulk-Higgs scenario are enhanced by $1/\eta$. This behavior shows that higher dimensional operators yield unsuppressed contributions in the narrow-bulk Higgs scenario for too small values of $\eta$.

## 6. Phenomenology

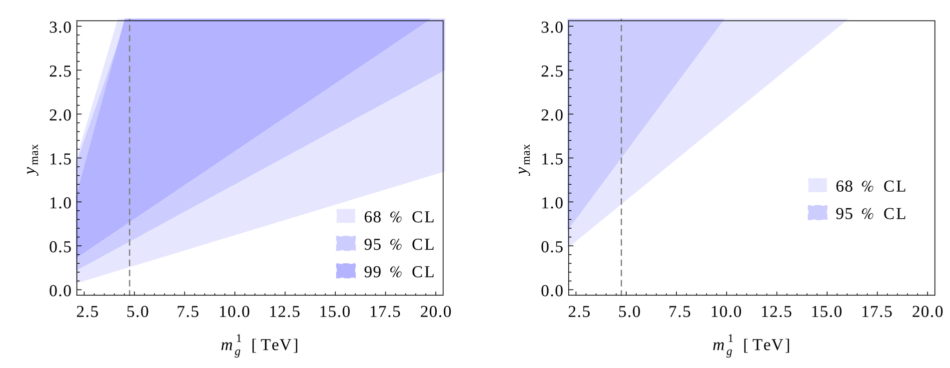
The plots below show the results for the ratio $R_h$ in the minimal RS model for the cases of a brane-localized Higgs boson (left) and a narrow bulk-Higgs field (right) as a function of the lightest KK gluon mass $m_g^1 \approx 2.45\,M_{\rm KK}$. The green, red, and blue scatter points refer to the three different values of $y_{\rm max} = 0.5, 1.5$ and 3, that define the allowed ranges $0 \le |Y_{ij}| \le y_{\rm max}$ for each Yukawa matrix entry, when randomized with a flat distribution.




Comparing with the experimental data for the process $pp \to h \to ZZ^{(*)} \to 4l$ [5], denoted by the band, colored in light blue, one arrives at the following exclusion plots for both Higgs scenarios.




Switching to the custodial RS model, the higher multiplicity of fermion KK modes generically enlarges the observable effects.




The vertical dashed lines show lower bounds at the 95% CL, stemming from electroweak precision parameters $S$ and $T$.

## 7. Classification of models and conclusion

The following table summarizes the qualitative results of the analysis concerning the Higgs production via gluon fusion ($gg \to h$) for different localizations of the Higgs particle along the extra dimension within the minimal Randall-Sundrum model.

| Model | bulk Higgs | narrow bulk-Higgs | transition region | brane Higgs |
|---|---|---|---|---|
| Higgs profile width | $\eta \sim \mathcal{O}(1)$ | $\frac{v\lvert Y_q\rvert}{\Lambda_{\rm TeV}} \ll \eta \ll \frac{v\lvert Y_q\rvert}{M_{\rm KK}}$ | $\eta \sim \frac{v\lvert Y_q\rvert}{\Lambda_{\rm TeV}}$ | $\eta \ll \frac{v\lvert Y_q\rvert}{\Lambda_{\rm TeV}}$ |
| 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 |
| Result | model-dependent | model-independent | unreliable | model-independent |

There is no reliable interpolation between the narrow bulk and the brane-localized Higgs scenario in the sense that the EFT concept breaks down within the transition region.

## Prospective work

- Further interesting loop processes are Higgs decays $h \to \gamma\gamma$, $h \to \gamma Z$, the anomalous magnetic moment $g_\mu - 2$, the $T$ parameter and the flavor-changing neutral current $b \to s\gamma$.
- Due to the AdS/CFT conjecture, Randall-Sundrum models are connected to four dimensional strongly coupled theories. In this context, one can study the holographic interpretation of 5D propagators.

## References


[1] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).

[2] S. Casagrande, F. Goertz, U. Haisch, M. Neubert and T. Pfoh, JHEP **1009**, 014 (2010) [arXiv:1005.4313 [hep-ph]].

[3] A. Azatov, M. Toharia and L. Zhu, Phys. Rev. D **82**, 056004 (2010) [arXiv:1006.5939 [hep-ph]].

[4] R. Malm, M. Neubert, K. Novotny and C. Schmell, arXiv:1303.5702 [hep-ph].

[5] Talks presented by F. Hubaut (ATLAS Collaboration) and M. G. Gomez-Ceballos (CMS Collaboration) at the Rencontres de Moriond, *Electroweak Interactions and Unified Theories*, La Thuile, Aosta Valley (Italy), 2–9 March 2013; slides for download at: `https://indico.in2p3.fr/conferenceOtherViews. py?view=standard&confId=7411`