Running 5d masses and radiative localization

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Outline

Introduction

- Compact extradimensional theories: fields propagate in $\mathcal{M}_4 \times \mathcal{C}_{D-4}$

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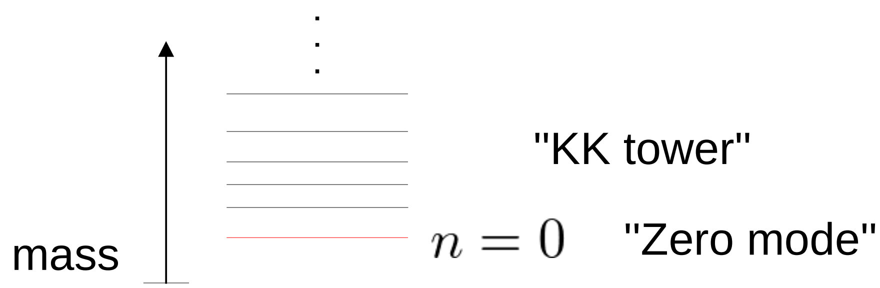
- A compact space always features the existence of a Kaluza Klein spectrum.



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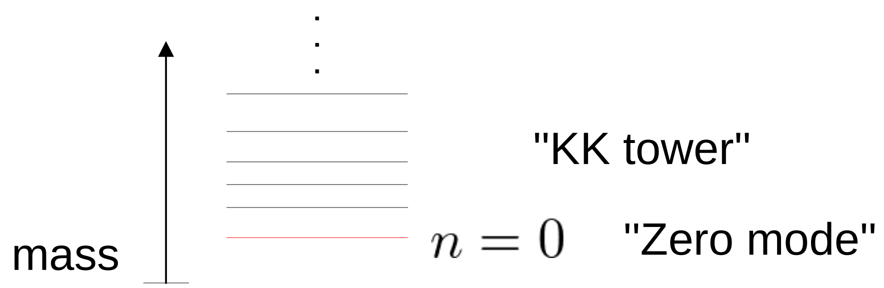
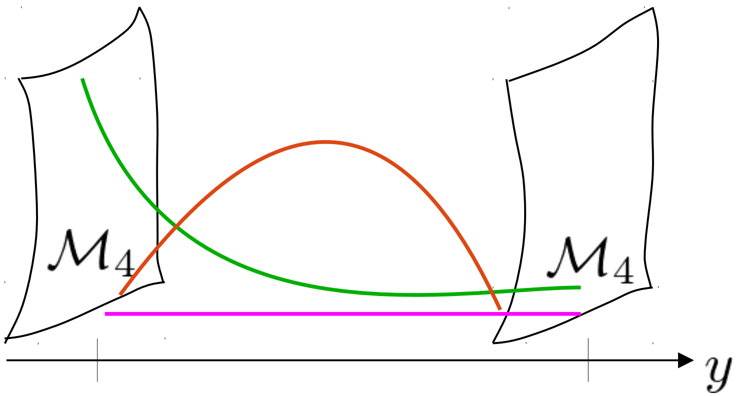


- If Poincaré symmetry is broken, e.g. in presence of branes, fields can also have non-trivial profiles along the extradimensions.



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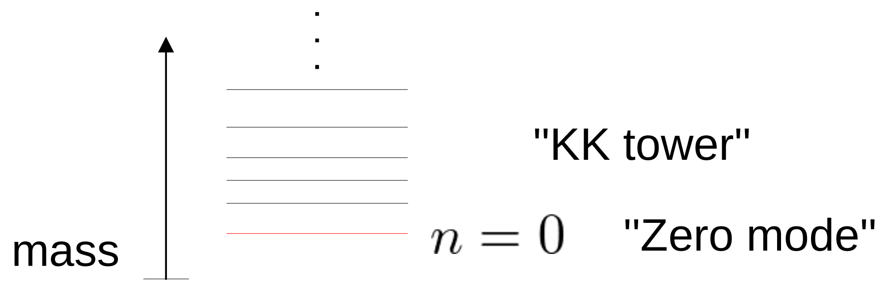
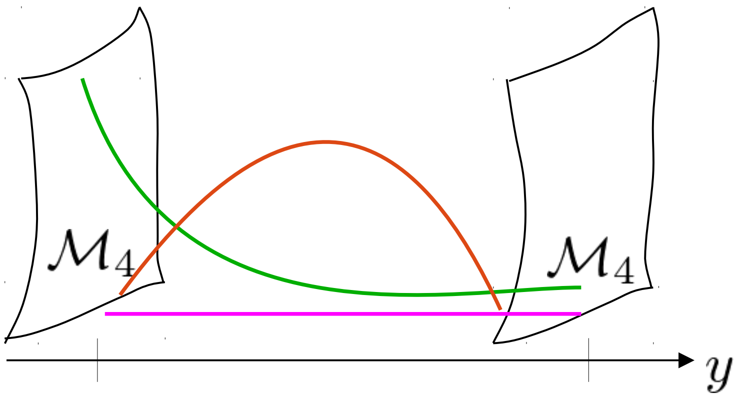


- If Poincaré symmetry is broken, e.g. in presence of branes, fields can also have non-trivial profiles along the extradimensions.
- These two features are influenced by bilinear operators.



- Bilinear parameters in 5d, scalars and fermions can have a a 5d mass ("bulk mass"):

$$\mathcal{L}_5 \supset -\int d^4x^\mu dy \sqrt{-g}\ \left\{ m_\Phi^2 |\Phi|^2 + m_\Psi \bar{\Psi}\Psi \right\}$$

- It influences both KK spectrum and profiles. In particular it controls localization of zero modes.
  In a flat space : exponential wave-functions like $\Psi^0(x^\mu, y) \propto \psi^0(x^\mu) e^{-m_\Psi y}$

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- Localization features propose many possibilites for BSM physics : flavour structure, neutrinos, proton decay, hierarchy problem, hidden sectors...

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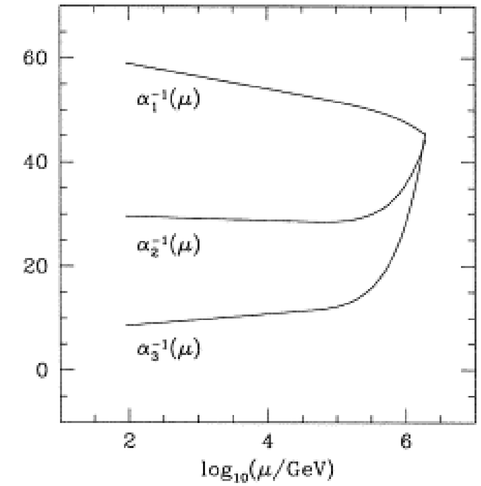
- All these mechanisms are considered at the classical level.

What happens at the quantum level ?



- [Dienes/Dudas/Gherghetta '99]:
  Accelerated running of gauge couplings because of KK loops

- [Randall/Schwartz '01, Goldberger/Rothstein '02] :
  4d-like running of gauge couplings in AdS_5

- Yukawa couplings have also been studied. (more model-dependence...)
  [Cornell/Deandrea/Liu/Tarhini '11]

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$$\rightarrow \frac{Z^{(5)}}{Z^{(4)}} \partial_5^2 \Phi - \frac{Z_m}{Z^{(4)}} m_\Phi^2 \Phi = m_{4d}^2 \Phi \, . \qquad \eta_{\mu\nu} \partial^\mu \partial^\nu \Phi = m_{4d}^2 \Phi$$

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- But for $m_\Phi^2 \neq 0$, the equation of motion itself is modified. Whatever the eigenvalue, the ratio $Z_m/Z^{(5)}$ modifies the differential operator. Even for a light or zero mode, one has

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➡ Not only the KK spectrum, but also profiles are possibly renormalized.

So the plan is to investigate:

- General quantum corrections from 2-point functions
- Bulk masses RG flow
- Implications of all that

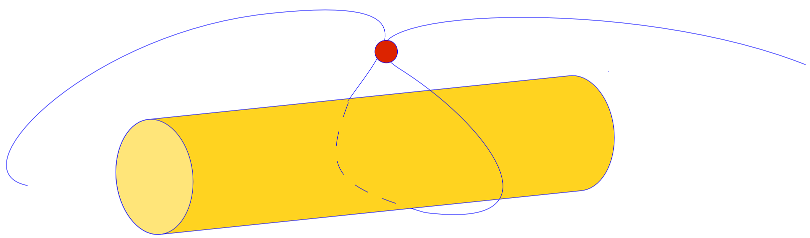
Setup

- A convenient formalism to derive 5d self-energies: keep position space for the compact dimension.

$$S(x_1 - x_2, y_1, y_2) = \int \frac{d^4p}{(2\pi)^4} S_p(y_1, y_2) e^{-ip.(x_1 - x_2)} \, .$$

- KK modes are replaced by winding modes. In the UV i.e 5d limit, only the zero winding mode remains because other modes are non-local. Scalar propagator:

$$S_p^{S_1}(y_1, y_2) = \frac{e^{i\chi|y_1 - y_2|}}{2\chi} + \frac{e^{i\chi|y_1 - y_2|} + e^{-i\chi|y_1 - y_2|}}{2\chi(e^{(-i\chi(2\pi R)} - 1))} \qquad \chi^2 = p^2 - m_\Phi^2$$



- UV divergences arise only from the zero winding modes. Other modes induce finite corrections.

- We consider spin 0, ½, 1 particles with generic interactions,

$$S_5 = \int_{\mathcal{C}} dy \int d^4x\, \sqrt{-g} \left\{ |D^M \Phi|^2 + i\bar{\Psi}\gamma^M D_M \Psi - \frac{1}{4g^2} F^a_{MN} F_a^{MN} \right.$$
$$\left. - m_\Phi^2 |\Phi|^2 - m_\Psi^2 \bar{\Psi}\Psi - \lambda |\Phi|^4 - (y\Phi\bar{\Psi}\Psi + h.c) \right\} + S_{\partial\mathcal{C}}[\Phi, \Psi, F_{MN}]\,.$$

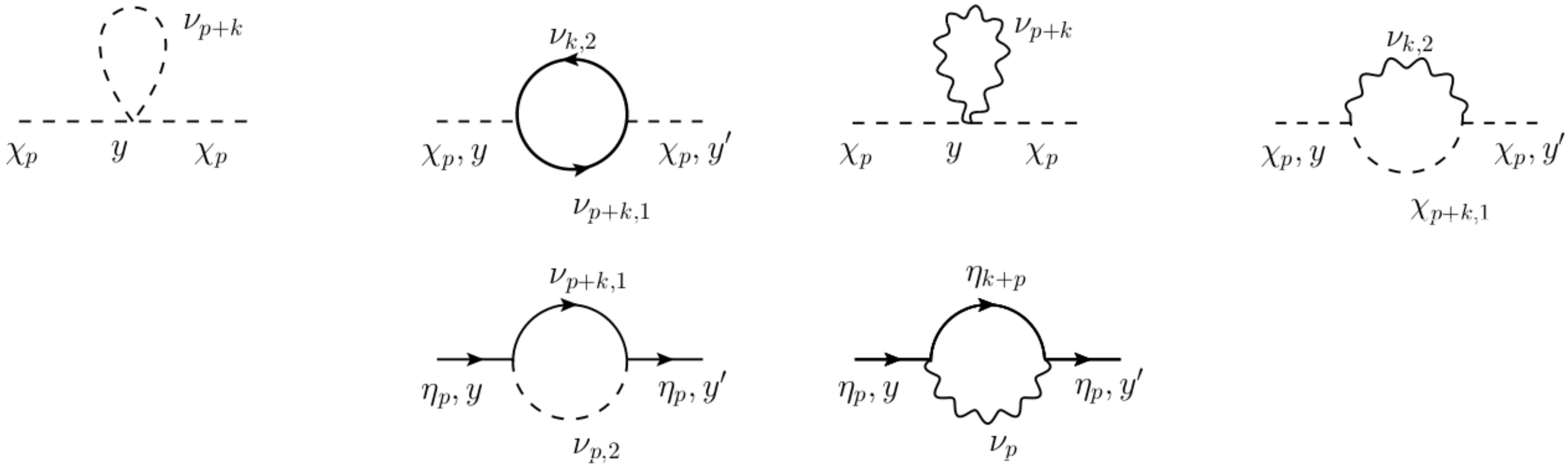
- In the present study, we focus on the circle and the interval with flat 5d metric. Compactification scale is $(\pi R)^{-1}$. (the following formalism works for any metric)

- For a generic compact space, all renormalization coefficients can be obtained from derivatives with respect to p_μ and primitives with respect to y. General formula is

$$\delta Z = \pm i^n \frac{\partial^m}{\partial p_\mu^m} \int_{\mathcal{C}} dy_1 \int_{y_1}^{(n)} X^{\mathcal{C}}(0, \tilde{y}_1, y_2) d\tilde{y}_1$$

- We will be interested in renormalization of the operator $\partial_5^2 + \frac{Z_m}{Z^{(5)}} m^2_{\Phi,\Psi}$, which modifies the profiles.

Bulk masses renormalization



- For our purposes we discuss only the leading corrections (cubic, quadratic, linear). Subleading corrections may give symmetry breaking mass thresholds, depending on the regulation scheme.

- We use a 4d cutoff $$\int_{\mathcal{C}} dy \int dk_E k_E^3 \to \int_{\mathcal{C}} dy \int_0^{\Lambda} dk_E k_E^3$$

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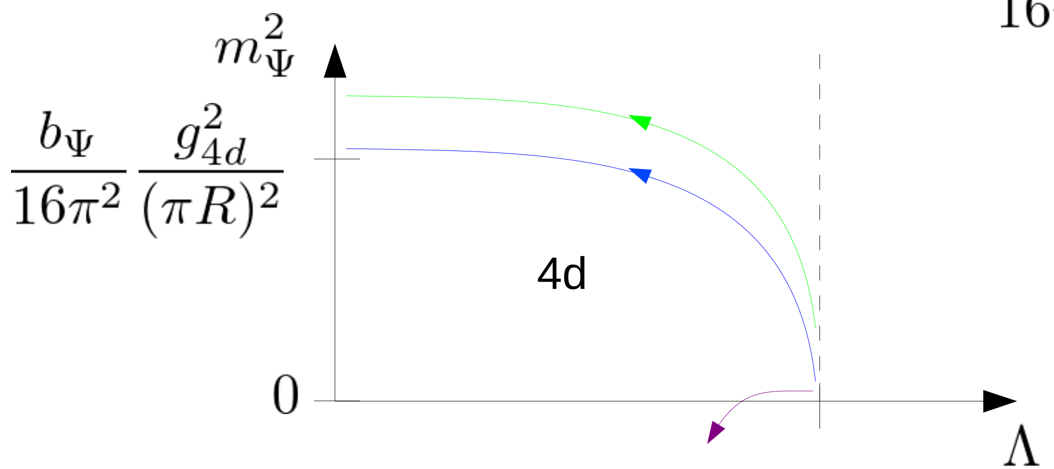
- 5d fermions are not chiral, but fermion bulk mass is protected by a $\mathbb{Z}_2$ symmetry of the kinetic term $\Psi_+ \to \Psi_+,\ \Psi_- \to -\Psi_-,\ y \to -y,$

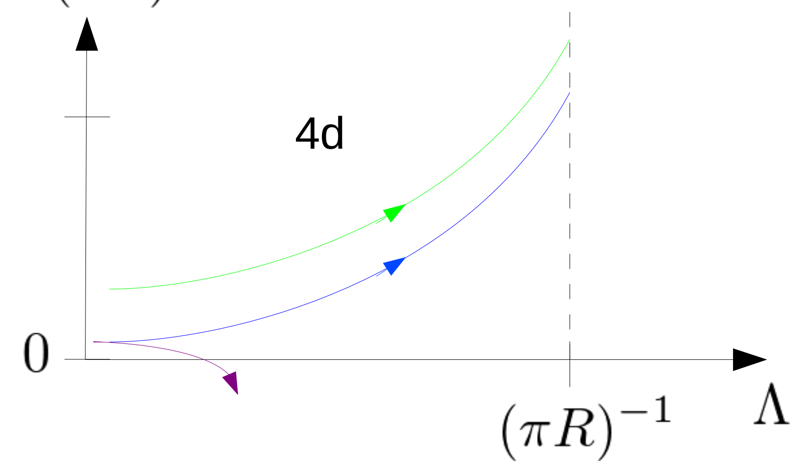
- In the 4d regime, quadratic corrections for fermion bulk masses appear from wave-function renormalization.

- The 4d and 5d limit have been used for various consistency checks.

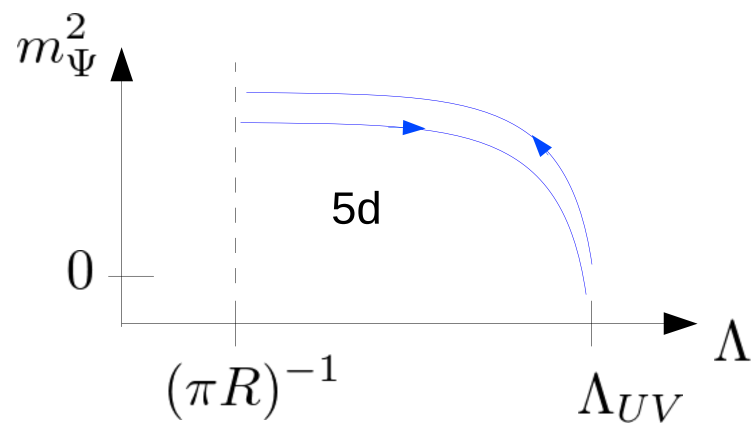
- $m_\Phi^2 = \mathcal{O}(\Lambda_{UV}^2)$ ➡ No light 4d scalar neither on the circle nor the interval. (Except with fine-tuning, which can be enforced by some symmetry)

- Fermion bulk mass, 4d regime: shift of $\approx \dfrac{b_\Psi}{16\pi^2}\dfrac{g_{4d}^2}{(\pi R)^2}$





- Fermion bulk mass, 5d regime: factor of $e^{b_{\Psi,\mathcal{H}} g_{5d}^2 \Lambda_{UV}/(16\pi^2)}$ when going from UV to IR



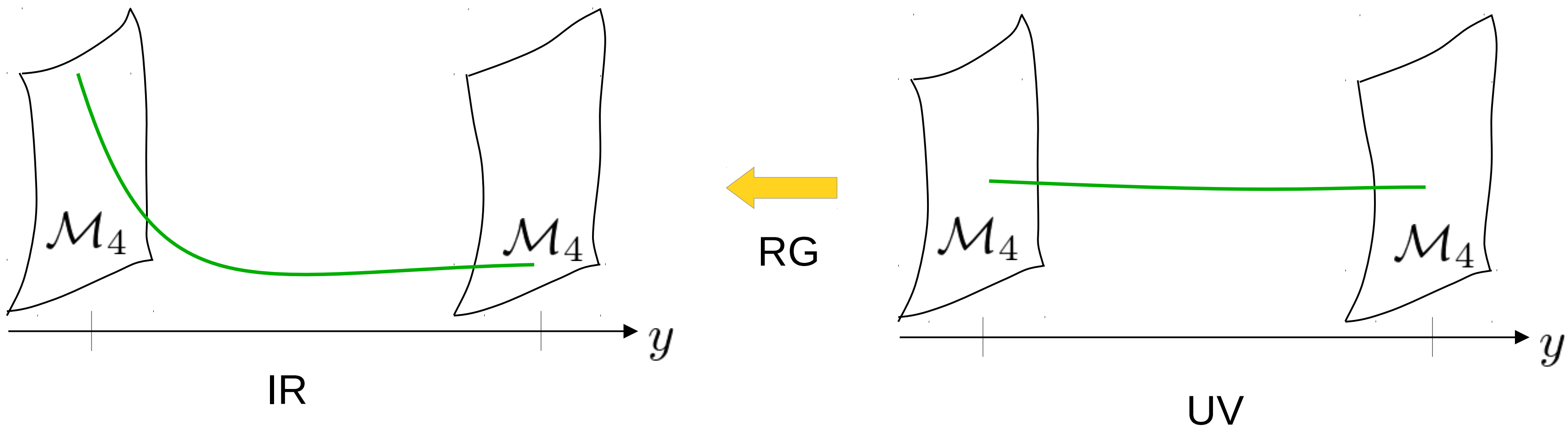
Radiative localization

Radiative localization

- Profiles of light modes depend on the renormalization scale Λ, as

$$f^{light}(y) = \frac{1}{\sqrt{N}} e^{-m_{\Psi,\mathcal{H}} y}$$

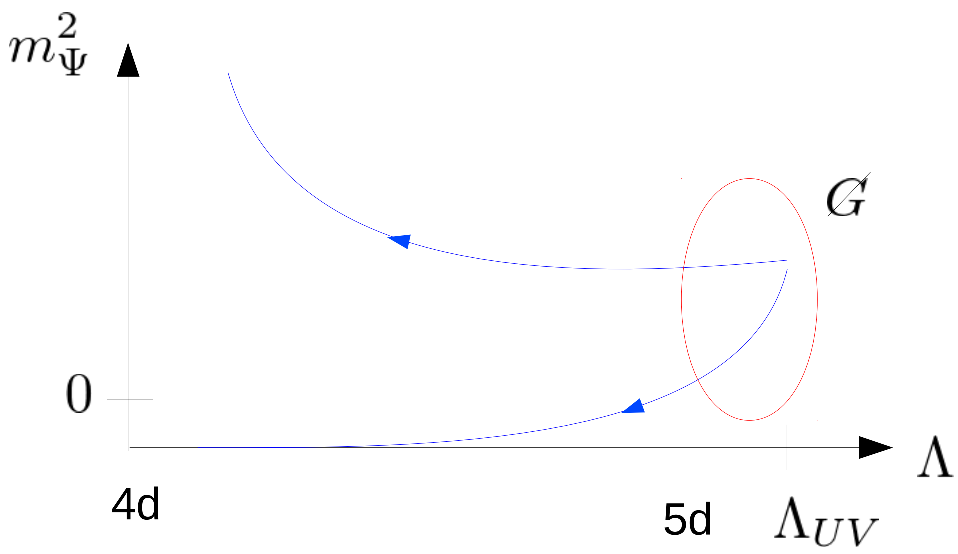
- Apart fine-tuned RG intial conditions, fields tend to be delocalized in the UV and localized in the IR.



- Effective couplings arising from operators involving zero modes will experience some kind of exponential RG because of the localization.
  Ex: $\mathcal{L}^{5d} \supset \delta(y)\lambda_{\mathcal{O}}\mathcal{O}\Psi(y) \Longrightarrow \mathcal{L}^{4d} \supset \lambda_{eff}\mathcal{O}\psi^{light}$ with $\lambda_{eff} = \lambda_{\mathcal{O}} f^{light}(0)$

- Breaking from the UV: in the 5d regime, bulk masses are sensitive to the UV physics. (as they are enhanced by a factor $e^{b_{\Psi,\mathcal{H}} g_{5d}^2 \Lambda_{UV}/(16\pi^2)}$ in the IR)

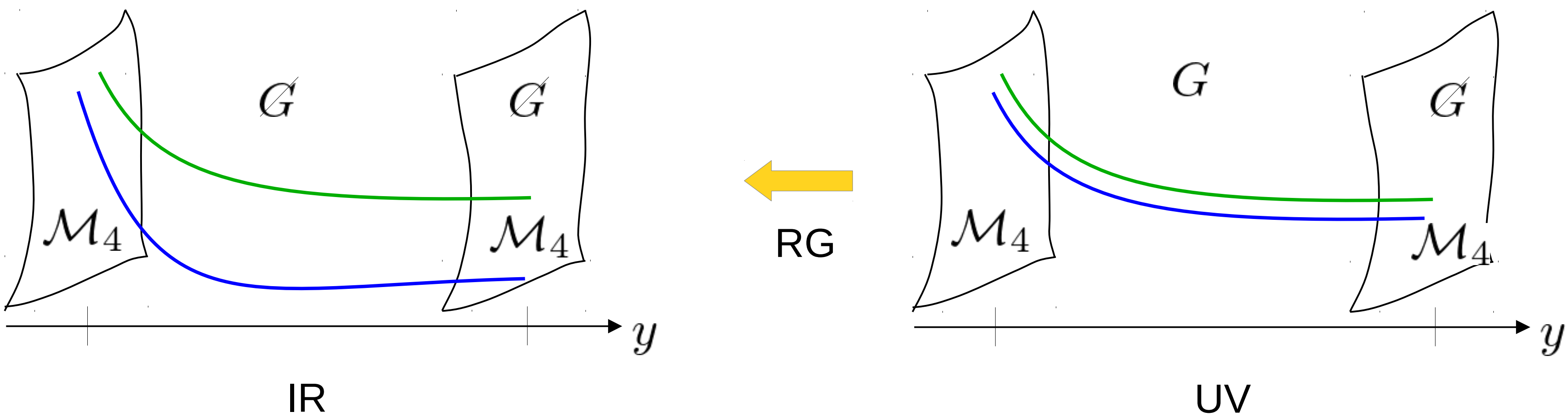
  Bulk masses (coming from the relevant set of UV operators) can be invariant under some global group G , while irrelevant operators do not respect it. But through loops, close from the cutoff, this breaking is transmitted to the bulk masses.



Example: flavour group broken by a four-fermion interaction in the UV.

- Brane-induced bulk symmetry breaking: Take a set of bulk fields with arbitrary bulk masses, and a global symmetry group G. Assume that G is broken on a brane.

  At tree level, bulk masses do not run: G remains exact in the bulk. (only BCs are G - breaking). At loop-level, the breaking is transmitted to bulk masses.



Example: flavour group breaking by brane kinetic terms

- We investigate renormalization of bilinear parameters in 5d theories.
- We set up a formalism in mixed 5d position-momenta space, and calculate the RG flow of bulk masses in flat 5d theories.
- Bulk masses and profiles are indeed renormalized.
- Fermion bulk masses always receive quadratic corrections in the 4d regime. Strong effects can happen in the 5d regime.
- Radiative localization might lead to many applications for BSM model-building.
- Many developments are possible !

Thank you for your attention !!!

More

- Scalar on the circle:

$$S_p^{S_1}(y_1,y_2) = \sum_{n=-\infty}^{\infty} S_p^{\mathbb{R}}(\tau^n y_1, y_2) = \frac{i\cos\chi_p(|y_1-y_2|-\pi R)}{2\chi_p \sin(\chi_p \pi R)}\,,$$

- On the interval: one uses the orbifold picture to implement Neumann/Dirichlet boundary conditions on each brane,

$\mathbb{Z}_2$ projection

$$\Rightarrow\quad S_p^{S_1/\mathbb{Z}_2}(y_1,y_2) = \frac{1}{2}\left(S_p^{S_1}(y_1,y_2) + P_\Phi S_p^{S_1}(\gamma(y_1),y_2)\right),$$

Scherk-Schwarz twist

$$\Rightarrow\quad S_p^{S_1,\,T=-1}(y_1,y_2) = \sum_{n=-\infty}^{\infty} T^n S_p^{\mathbb{R}}(\tau^n y_1,y_2) = \frac{i\sin\chi_p(|y_1-y_2|-\pi R)}{2\chi_p\cos\chi_p \pi R}\,.$$

- Parities are given by $Z_0 = P \quad , \quad Z_\pi = TP\,.$

- We will be interested in renormalization of the operator $\partial_5^2 + \frac{Z_m}{Z^{(5)}} m^2_{\Phi,\Psi}$, which modifies the profiles.

- Mass corrections: $\delta m^2_\Phi = \int dy_1 \Pi(0, y_1, y_2) \qquad \delta m_\Psi = \int dy_1 \Sigma(0, y_1, y_2)$

- WFR : $\delta Z^{(5)}_\Phi = i^2 \int_{\mathcal{C}} dy_1 \int_{y_1}^{(2)} \Pi^{\mathcal{C}}(0, \tilde{y}_1, y_2) d\tilde{y}_1$ ...

- And define bulk mass beta-functions as

$$\beta_{m^2_\Phi} = \frac{\partial}{\log \Lambda} \delta m^2_\Phi - m^2_\Phi \frac{\partial}{\log \Lambda} \delta Z^{(5)}_\Phi \qquad \beta_{m_\Psi} = \frac{\partial}{\log \Lambda} \delta m_\Psi - m_\Psi \frac{\partial}{\log \Lambda} \delta Z^{(5)}_\Psi$$

- This is still an EFT view, these beta-functions show how the parameters vary depending on the scale at which UV physics is integrated out.

Why are we speaking of extradimensionality in a 4d regime ?

- We have two manifestations of the existence of a compact extradimension : a KK spectrum, and (possibly) field localization.

- A KK spectrum comes from 5d Lorentz symmetry breaking, caracterized by $\mathcal{M}_{5N}\pi R$ which has dimension -1. This is a classicaly irrelevant feature, i.e it vanishes in the 4d limit.

- Profiles come from 5d Poincaré breaking, caracterized by $\mathcal{P}_5\pi R$, which has dimension 0. This is a classicaly marginal feature, i.e it remains invariant at any scale.

- (In presence of quantum effects, KK spectrum remains an irrelevant feature(at least perturbatively), while localization can be either marginal, relevant, or irrelevant. This we will discover in the calculation.)

Answer : in the 4d limit, KK modes are not observable, but profiles are still there.

- On the circle: $\delta m_\Psi \approx 0$ and

$$\delta m_\Phi^{2,\,s} = a^s \frac{\lambda_s}{16\pi^2} \int dk_E k_E^3 \begin{cases} \dfrac{1}{\nu_s \tanh \nu_s \pi R} & \text{if } s \text{ integer,} \\ \dfrac{1}{\nu_{1,s} \tanh \nu_{1,s}\pi R} \dfrac{\chi^2 - \nu_{1,s}^2}{\nu_{2,s}^2 - \nu_{1,s}^2} - (\nu_{1,s} \leftrightarrow \nu_{2,s}) & \text{if } s = 1/2. \end{cases} .$$

- Corrections positive for bosonic loops, negative for fermion loops. One gets indeed $\Delta m_\Phi^2 = \mathcal{O}(\Lambda^3 \pi R)$ in the 5d limit and $\Delta m_\Phi^2 = \mathcal{O}(\Lambda^2)$ in the 4d limit.

- On the circle: $a^s = (2, -4, 4)$

- 4d limit: $\Delta m_\Phi^{2,\,\Phi} \approx (\lambda_{4d}/8\pi^2)\Lambda_{UV}^2$ as expected for a complex scalar

- On the interval: same coefficients (up to a factor 2) in the 5d limit, different coefficients in the 4d limit because of the $\mathbb{Z}_2$ projection

- Fermion wave-function renormalization

$$\delta Z_{\Psi}^{(5),\,s} = b_{\Psi}^{s} \frac{\lambda_s}{16\pi^2} \int dk_E k_E^3 \frac{1}{k_E(\nu_s^2 - \nu_{1/2}^2)^2} \left(\frac{\nu_s^2 + \nu_{1/2}^2}{\tanh \nu_s \pi R} - \frac{2\nu_s \nu_{1/2}}{\tanh \nu_{1/2} \pi R} \right)$$

with $b_{\Psi}^{s} = (0, -1, 2)$

- 5d limit: mass corrections are $\Delta m_{\Psi}^2 = \mathcal{O}(m_{\Psi}^2 \Lambda \pi R)$ and have the sign of b_{Ψ}^{s}

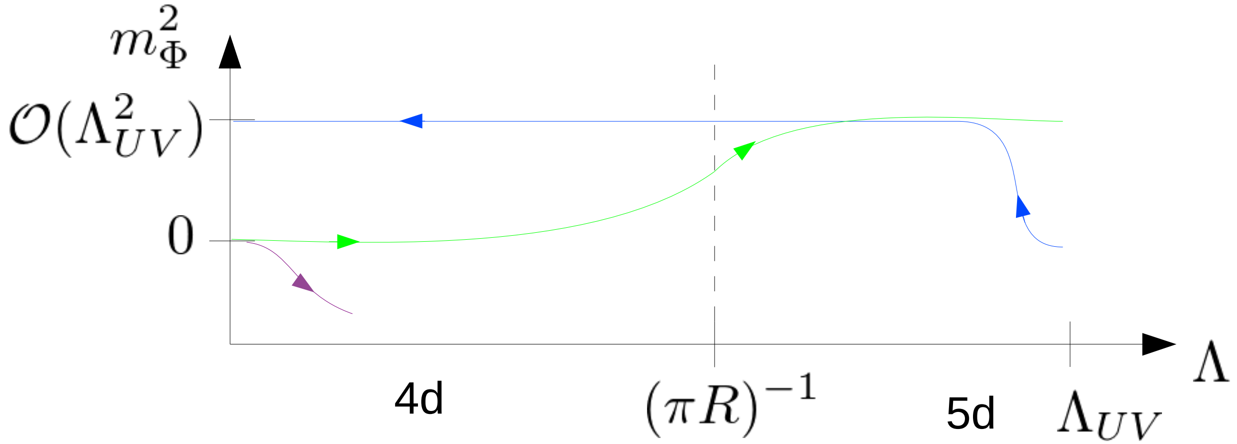
- 4d limit: mass corrections are $\Delta m_{\Psi}^2 = \mathcal{O}(\Lambda^2)$ and signs depend on mass differences.

- In the 4d regime, quadratic corrections for fermion bulk masses appear from wave-function renormalization.

- Unless miraculous cancellations i.e fine-tuned initial conditions in the RG flow, one has

$$m_\Phi^2 = \mathcal{O}(\Lambda_{UV}^2)$$

➡ No light 4d mode on the circle or on the interval.



- On the interval, heavy 4d mode(s) are bulk localized. A tuning of boundary conditions would be necessary to have a light mode. This can be enforced by a symmetry. (SUSY, 5d gauge symmetry, shift symmetry, ...)

- One may investigate what happens in presence of a breaking of such symmetry at an intermediate scale Λ_{SB} . In a top-down view, one expects

$$m_\Phi^2 \approx \frac{g_{4d}^2}{16\pi^2}\Lambda_{SB}^2$$

Radiative localization

- Localization in 4d regime: starting in the UV, the bulk mass increases in the IR, such that exponential suppression on one of the branes is amplified by a factor

$$f(0\,\mathrm{or}\,\pi R) \approx f^{tree}(0\,\mathrm{or}\,\pi R)e^{-b_\Psi g_{4d}^2/16\pi^2}$$

- The effect becomes sizeable near the strong coupling regime. At the limit of validity, one has

$$f(0\,\mathrm{or}\,\pi R) \approx f^{tree}(0\,\mathrm{or}\,\pi R)e^{-\mathcal{O}(1)}$$

- Localization in 5d regime: starting in the UV, the exponential suppression at the KK scale is amplified by a power

$$f(0\,\mathrm{or}\,\pi R) \approx \left[f^{tree}(0\,\mathrm{or}\,\pi R)\right]^{\exp(b_{\Psi,\mathcal{H}}g_{5d}^2\Lambda_{UV}/(16\pi^2))}$$

- Near strong coupling, effect can be large :

$$f(0\,\mathrm{or}\,\pi R) \approx \left[f^{tree}(0\,\mathrm{or}\,\pi R)\right]^{\exp(\mathcal{O}(1))}$$

For example...

- Consider an SU(5) type GUT matter sector $10=(Q,U,E)$, $\bar{5}=(L,D)$, coupled to a Higgs $\Sigma\supset(H_u,H_d)$ localized on the $y=0$ brane.

- Matter fields have bulk masses repecting the flavour group G_F in the UV. Matter couple to the Higgs through anarchical brane Yukawas $\mathcal{L}\supset y_1\,10\,10\,\Sigma+y_2\,10\,\bar{5}\,\Sigma$. Matter fields also have anarchical brane kinetic terms.

- In the RG flow, BKTs transmit G_F- breaking to the bulk masses. From radiative localization, one can get a suppression factor $\varepsilon\approx e^{-3}$. Taking $f^i_{10}(0)\approx(1,\varepsilon,\varepsilon^2)$ $f^i_{\bar{5}}(0)\approx(1,1,1)$, the 4d Yukawa matrices $\mathcal{L}\supset y_u QUH_u+y_dQDH_d+y_eLEH_d$ are

$$y_u\approx\begin{pmatrix}\varepsilon^4 & \varepsilon^3 & \varepsilon^2\\ \varepsilon^3 & \varepsilon^2 & \varepsilon\\ \varepsilon^2 & \varepsilon & 1\end{pmatrix},\quad y_d\approx y_e^t\approx\begin{pmatrix}\varepsilon^2 & \varepsilon^2 & \varepsilon^2\\ \varepsilon & \varepsilon & \varepsilon\\ 1 & 1 & 1\end{pmatrix}.$$

(see also [Nomura/Poland/Tweedie 06'], [Brümmer/SF/Kraml 11'] for details about this structure)

- Finish the SUSY checks
- Set up a 5d Lorentz respecting regularization scheme
- Compute corrections for vector fields with broken gauge symmetry $m_{\mathcal{A}} \neq 0$
- Carry on the same work in warped metric
- Investigate radiative localization at strong coupling with SUSY
- Exploit properties for BSM model-building
- ...