The Origin of Mass Hierarchies

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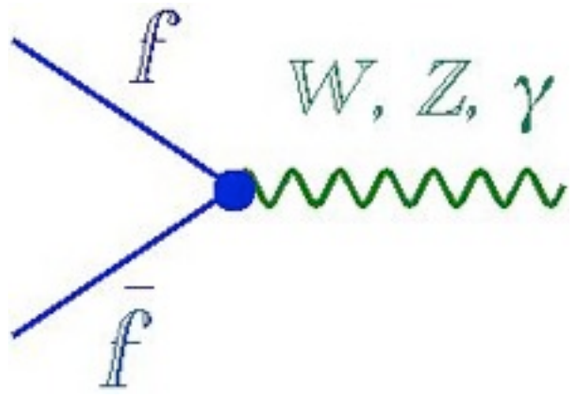
The Electroweak Standard Model

SM gauge interactions ⟶



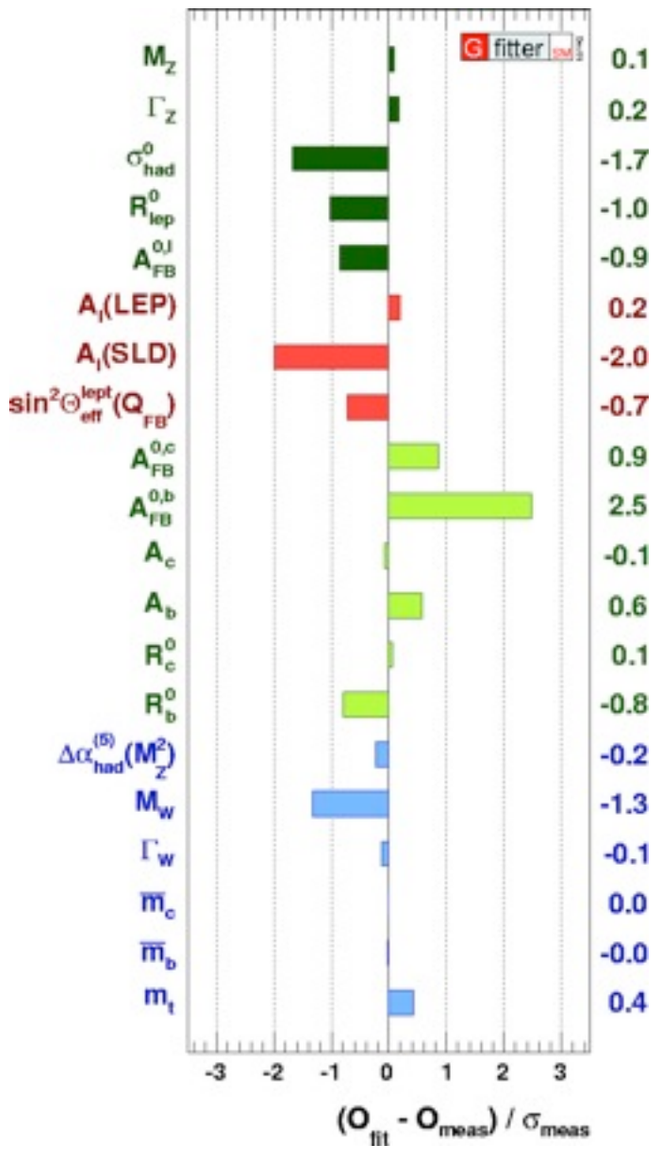
Tested with precision at *LEP I, II, Tevatron, Low Energy, ...*

Symmetry Breaking Sector: Higgs mechanism ⟶ M_W, M_Z

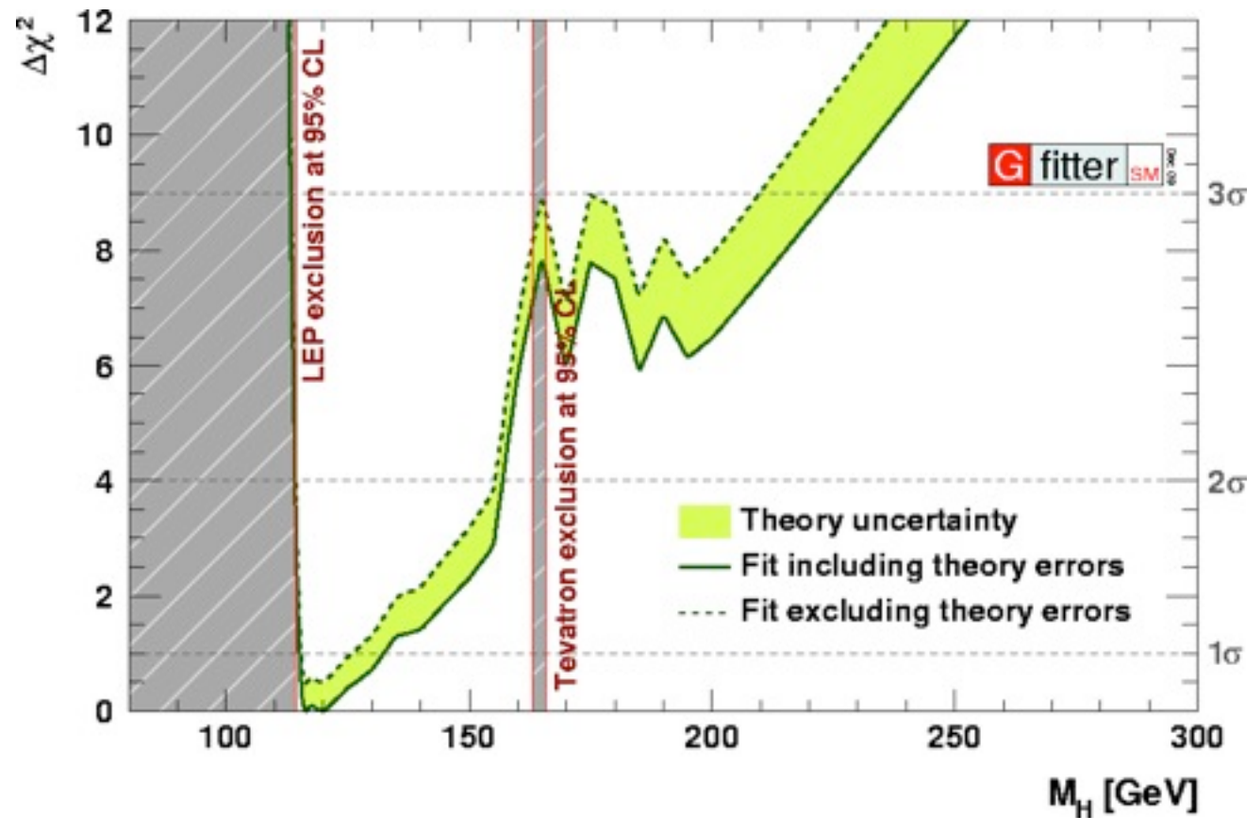
H only enters through loops

The Success of the Standard Model

Tests of the gauge sector



The SM Higgs is light

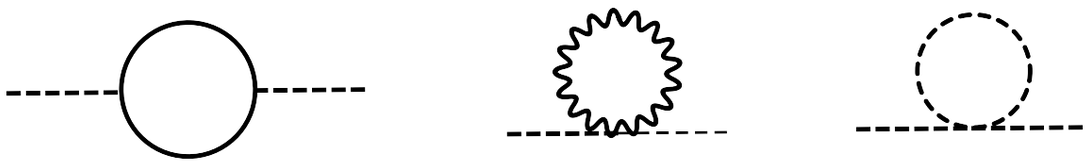


The Standard Model and the Origin of Mass

What is the origin of Electroweak Symmetry Breaking ?

- In the SM Higgs sector is elementary
- But elementary Higgs has hierarchy problem:

Weak scale is not radiatively stable



$$\delta m_h^2 \sim \frac{c}{16\pi^2}\,\Lambda^2$$

$\longrightarrow$ SM is natural up to $\Lambda \simeq O(1)\mathrm{TeV}$

Stabilizing a Large Hierarchy

New Physics at the TeV scale is

Weakly Coupled

- Supersymmetry
- Little Higgs, Twin Higgs, ...
- Large Extra Dimensions
- ⋮

Strongly Coupled

- Technicolor, WTC
- Topcolor, Top See-saw, ...
- Composite Higgs
- Randall-Sundrum, AdS_5
- ⋮

The Standard Model and the Origin of Mass

What is the origin of the fermion mass hierarchy ?

- In the SM, Yukawa couplings of elementary scalar

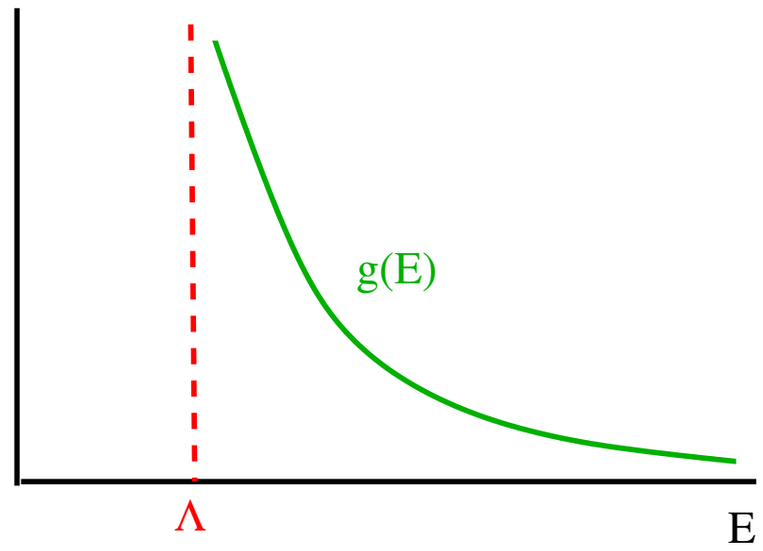
$$Y_f \, \bar{f}_L H f_R$$

- But $Y_t \sim O(1)$ and $Y_u \sim 10^{-5}$, $Y_e \sim 10^{-6}$, ...

$\longrightarrow$ *Large hierarchy of fermion Yukawas*

Dynamical Generation of a Mass Hierarchy

Dimensionless gauge coupling $g(E)$ gets strong at low energy Λ



- QCD: Hadronic scale generated at low energy $m_P \ll \Lambda_{UV}$ is natural.

- Technicolor: Generate v_{EW} dynamically from new AF gauge interaction

- In general: strong interaction leads to

$$\langle \bar{F}_L F_R \rangle \neq 0 \Longrightarrow \text{Spontaneous Symmetry Breaking}$$

Dynamical Electroweak Symmetry Breaking

Ingredients

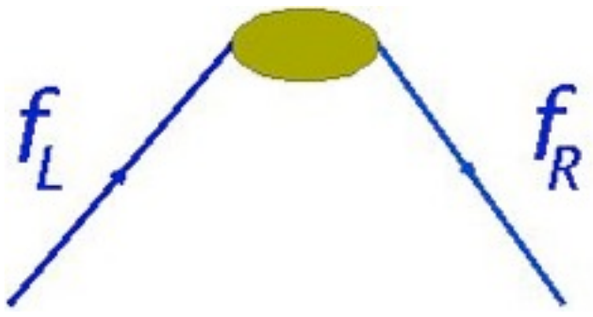
- New interaction strong at TeV scale
- Fermion condensation:

$\langle \bar{F}_L F_R \rangle \neq 0$ where F_L, F_R carry EW quantum #'s

- Condensing F_L, F_R can be confined (Technicolor)

  or un-confined (Top, Fourth-generation condensation)

- Fermion mass generation:

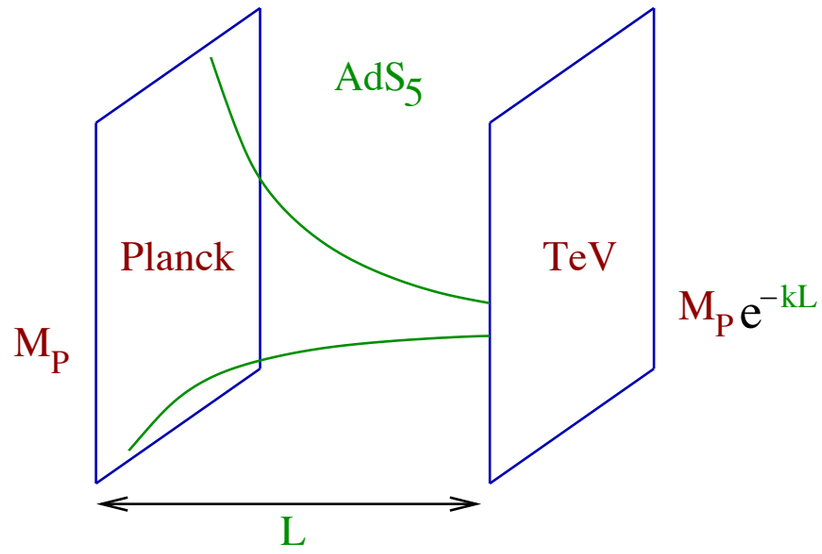


$\Longrightarrow \quad \mathcal{O} \bar{f}_L f_R$

with $\dim[\mathcal{O}] \geq 1$

E.g. Composite Higgs $\Longrightarrow \dim[\mathcal{O}] > 1$

Strong Dynamics from AdS in 5D



$$ds^2 = e^{-2k|y|}\eta^{\mu\nu}dx_\mu dx_\nu - dy^2$$

(Randall-Sundrum)

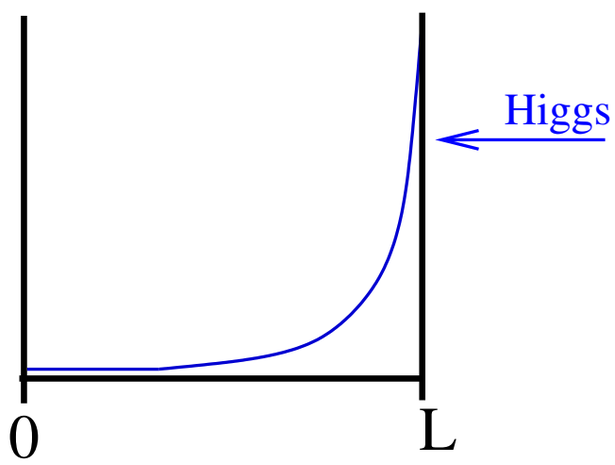
- $k \simeq M_P$ only scale fundamental scale
- To solve the hierarchy problem: m_h localized close to TeV brane
- Fermions and Gauge fields can be in the 5D bulk

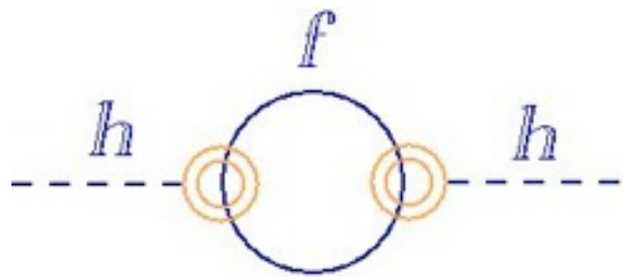
Strong Dynamics from AdS in 5D

Theories with compact extra dimensions are dual to 4D strongly coupled theories

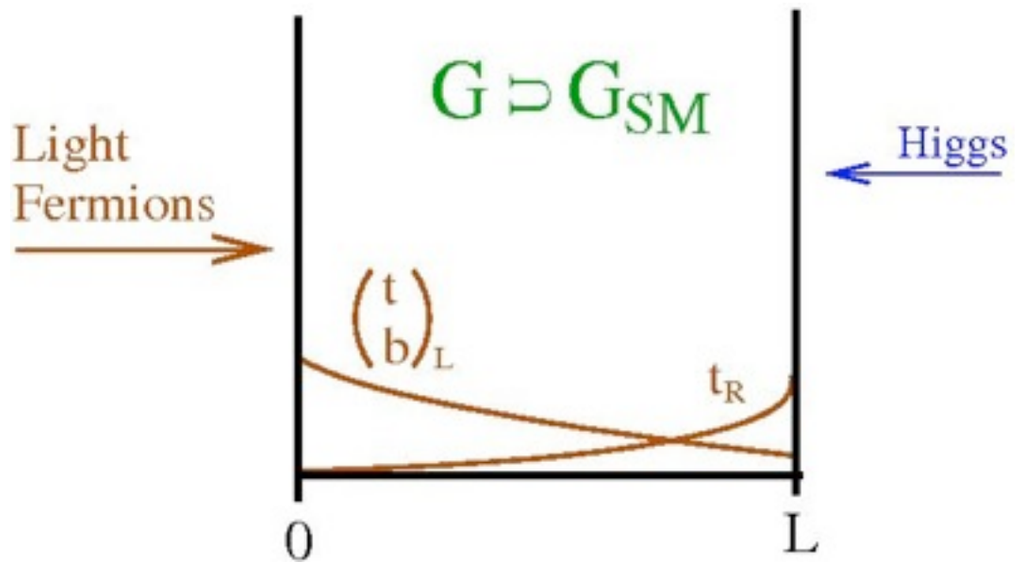
- With AdS metric:
  localization in 5D $\longleftrightarrow$ energy flow in 4D
- Build strongly coupled 4D theories of the weak scale using 5D weakly coupled theories (AdS_5)

- Higgs is TeV-localized $\Longrightarrow$ is composite





Model Building in AdS_5



- Lighter fermion is Planck-localized ⇔ small Higgs overlap
- 3rd Generation is TeV-localized ⇔ large Yukawa
- Heavier fermions are strongly coupled to TeV scale
  ⇒ strongly coupled to gauge KK modes
- Gauge group in 5D bulk must contain custodial symmetry to protect ρ parameter (Agashe-Delgado-May-Sundrum)

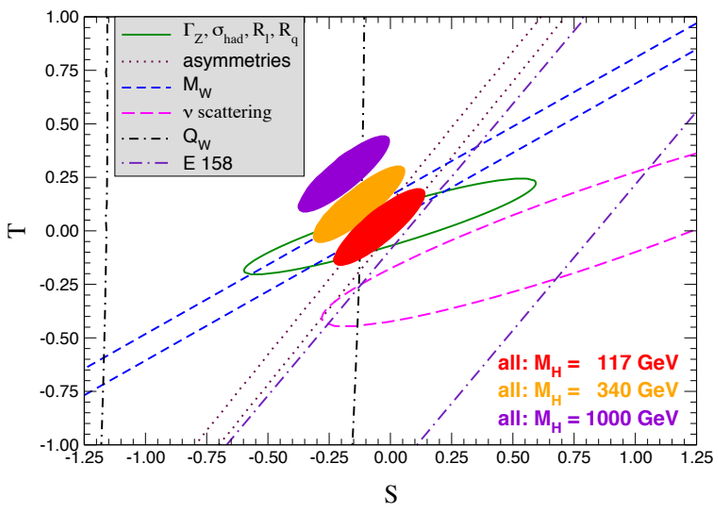
Model Building Issues in AdS_5

Higgs Localization:

- Gauge-Higgs Unification: Higgs comes from extra components of 5D gauge field. Light composite Higgs. (Agashe-Contino-Pomarol)
- H is composite of TeV-localized zero-mode fermions (Eg 4th generation) ⇒ Heavier composite Higgs. (GB-Da Rold)
- Higgsless. Dual to Technicolor. (Grojean-Murayama-Pilo-Terning)

Constraints:

- EW precision bounds. S,T, $Z \to \bar{b}b$



- Flavor constraints:

Flavor violation at tree level with KK gauge bosons (Eg KKgluons)

Model Building and Strong Dynamics

Future Directions:

- Departure from AdS_5:

  Can we build 4D models with these 5D features ?

- What is the role of conformal invariance ?
  How is it broken ?

- How much can we learn from QCD ?

Signals

- KK gauge bosons at the LHC prefer top pairs
- Flavor violation at tree level in high pT processes
  Eg. $pp \to t\bar{c}$ (Aquino-GB-Eboli)
- New sources of CP violation in B physics
- KK fermion spectrum, some of them light

Strong Dynamics and Dark Matter

- In AdS_5 : we can always implement a discrete symmetry

  (*Agashe-Servant, Ponton-Randall, ...*).

- More natural in strong dynamics scenarios:

  Asymmetric Dark Matter (Talk by Mads Frandsen)

Naturally explain $\dfrac{\Omega_{DM}}{\Omega_B} \simeq 5$

by generating n_B and n_{DM} from same source } (Kaplan '90)

- $\dfrac{\Omega_{DM}}{\Omega_B} = \dfrac{m_{DM}}{m_P}\,\dfrac{n_{DM}}{n_B}$ {

  Low mass: $m_{DM} \simeq 5$ GeV

  High mass: $m_{DM} \simeq O(1)\mathrm{TeV}$

  (Nardi, Sanino,Strumia)

Strong Dynamics and Dark Matter

ADM in AdS:

- Still no model in AdS
- Need to build conserved topological current such as Goldstone-Wilczek for baryons, but in 5D theory.

- Lessons from QCD: building baryon current in AdS/QCD

Conclusions/Outlook

- New methods to approach strongly coupled theories of the TeV scale

- Mass hierarchies can be generated in AdS_5 for both gauge and fermion masses

- LHC will test these models starting early on

- Asymmetric Dark Matter may be the natural framework for DM in these scenarios