Crunching Away the Hierarchy Problem

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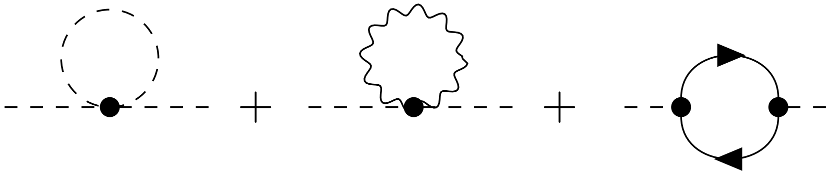
2021 La Thuile Conference
March 11, 2021

Hierarchy problem

All elementary scalars expected to be **ultra heavy**

$$\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$$



Mass of Higgs not protected by symmetries (like fermion, gauge boson)

• Sensitive to any UV scale physics - Λ a stand-in for mass of whatever new physical particle appears there

Symmetry based approach

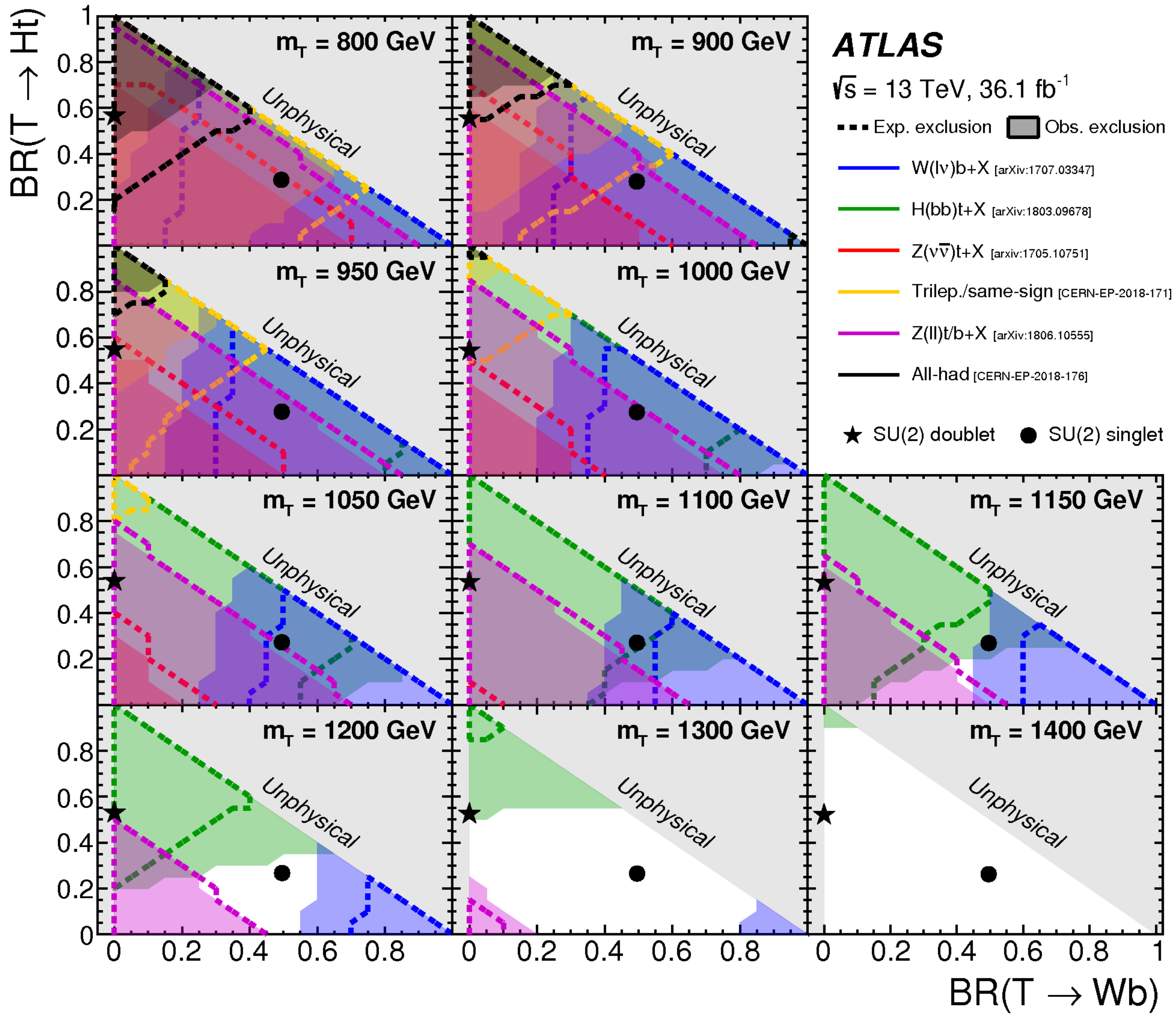
- New physics at the TeV scale shields from UV corrections - SUSY, compositeness/XD

- Typically expect new colored particles at the TeV scale ``top partners"

- Not observed at the LHC - putting these models under serious stress

• Direct bounds

Spin 1/2 top partners



Symmetry based approach

- New physics at the TeV scale shields from UV corrections - SUSY, compositeness/XD
- Typically expect new colored particles at the TeV scale ``top partners”
- Not observed at the LHC - putting these models under serious stress
- Could still avoid them via ``neutral naturalness/ Twin Higgs” type models
- Those still possible, though deviation to Higgs coupling will test those eventually as well

Cosmological selection/relaxation

- Correction to Higgs mass not suppressed

- Cosmological dynamics of some light field leads to selection of realistic vacuum

- Examples: relaxion, N-naturalness, …

- Very interesting direction, quite baroque models (or regions of parameter space)

Anthropic approach

- Multiverse with different patches - each patch has a different Higgs mass and O(1) quartics.

- Only patches with small Higgs VEV can support life (otherwise no chemistry?)

- No way to experimentally verify

- Also motivation for split SUSY

Crunching solution to hierarchy problem

- Our proposal: somewhere in between, take best aspects of each approach

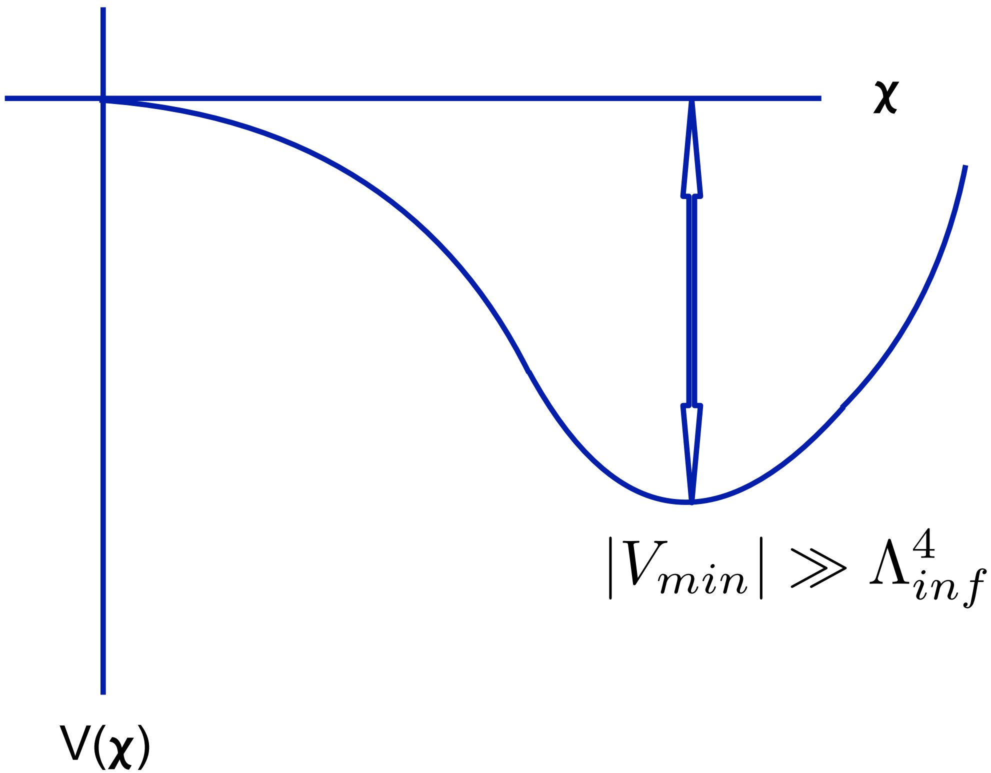
- Assume we still have a multiverse with the various patches having different Higgs masses/VEVs

- There is also a hidden CFT that is spontaneously broken - producing a (light) dilaton

- True ground state of CFT has large negative vacuum energy leading to the rapid crunch of the patch in that vacuum

Crunching solution to hierarchy problem

- The true minimum has a very large negative CC



Crunching solution to hierarchy problem

- The techniquarks of the CFT charged under SU(2) EW symmetry - leads to interaction between dilaton and SM Higgs

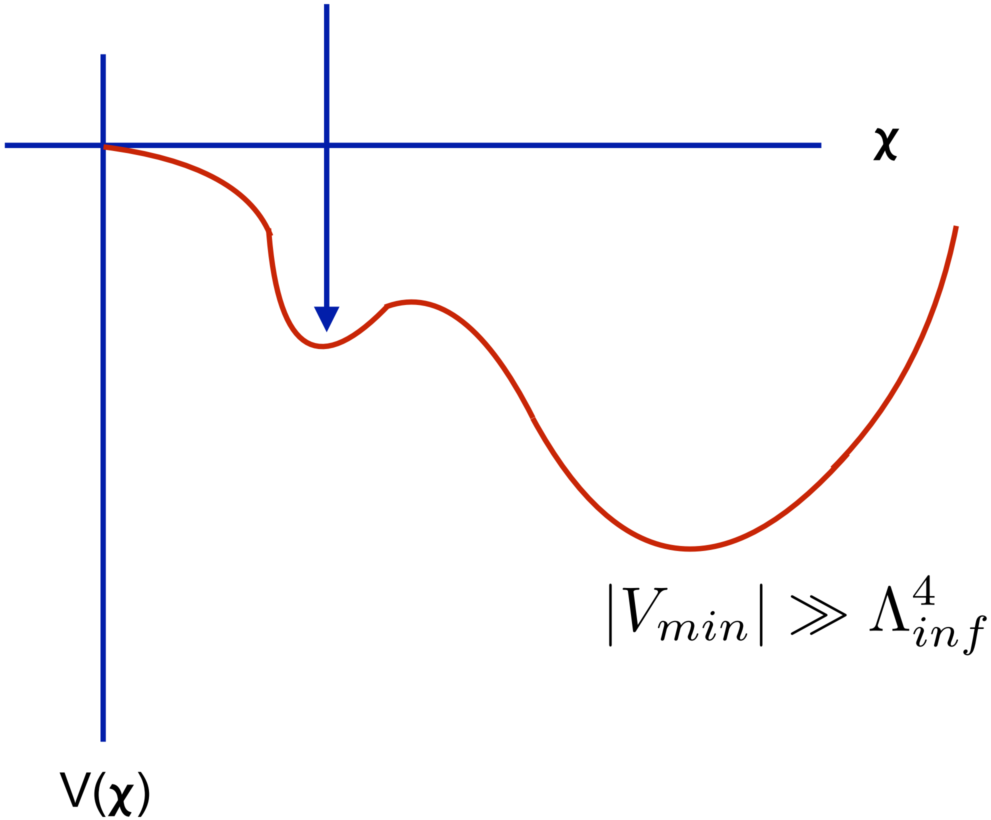
- If Higgs VEV non-zero < TeV - second metastable minimum of the dilaton potential appears at small vacuum energy

- Patches with large or vanishing Higgs VEV will quickly dynamically crunch, only patches with small Higgs VEVs will survive over a long period

- Patches with small Higgs VEV will dominate after long time (unlike anthropics)

Crunching solution to hierarchy problem

- New minimum of potential due to $\langle H \rangle \sim \text{TeV}$



- At new minimum CC should be smaller so that universe can undergo normal inflation and expansion

The RS/GW setup

- GW field **ϕ** in the bulk, with small mass **δ**

$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

$$\chi = \frac{1}{R'}$$

$$\phi_{GW}$$

$$k = 1/R$$

UV z=R

IR z=R’

- Effective dilaton potential after integrating out bulk

$$V_{\rm GW}(\chi) = -\lambda\chi^4 + \lambda_{\rm GW}\frac{\chi^{4+\delta}}{k^\delta}$$

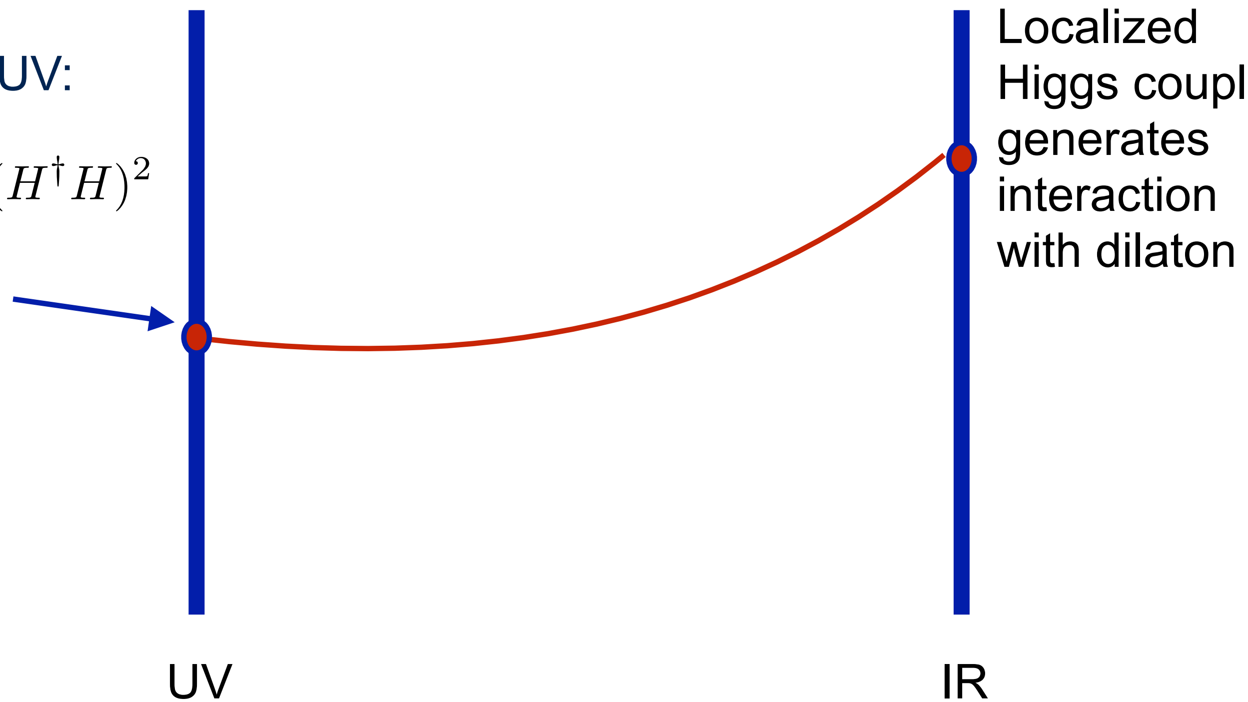
Effect of the Higgs

- Higgs also in the bulk (otherwise can not influence dilaton)

SM Higgs potential on UV:

$$V_H(H) = -m^2_{H,i} H^\dagger H + \lambda (H^\dagger H)^2$$

Acts as source for bulk



- Assume UV brane Higgs potential is varying in different patches and $m^2_{H,i}$ is $\mathcal{O}(\Lambda^2)$

Effect of the Higgs

- Assume bulk Higgs mass (Higgs approx. linear) $$\frac{m_b^2}{k^2} \approx -3 + \alpha$$

- General z-dependence ~ $$z^{2 \pm \sqrt{4 + m_b^2}}$$

- Effect of UV source on IR brane: $H_{\rm UV}\chi^{\sqrt{4+m_b^2}-2} = H_{\rm UV}\chi^{\frac{\alpha}{2}-1}$

- Adding IR localized Higgs terms will result in terms

$$|H|^2\chi^{2+\alpha} \qquad |H|^4\chi^{2\alpha} \qquad |H|^2\chi^{2+\alpha+\epsilon}$$

The CFT interpretation

- A CFT which is charged under SU(2). Turn on two operators:

- singlet $\mathcal{O}_\epsilon$ of dimension $4-\epsilon$

- doublet $\mathcal{O}_H$ of dimension $3+\alpha/2$.

- We couple the doublet operator to the Higgs in the UV:

$$\tilde{\lambda}_H \mathcal{O}_H^\dagger H + \tilde{\lambda}_\epsilon \mathcal{O}_\epsilon$$

- In the IR, we get the effective potential:

$$V_{eff} = a_0\chi^4 + a_1\tilde{\lambda}_H^2 H^2\chi^{2+\alpha} + a_2\tilde{\lambda}_H^4 H^4\chi^{2\alpha} + a_3\tilde{\lambda}_\epsilon\chi^{4+\epsilon} + a_4\tilde{\lambda}_\epsilon\tilde{\lambda}_H^2 H^2\chi^{2+\alpha+\epsilon} + \ldots$$

The full potential

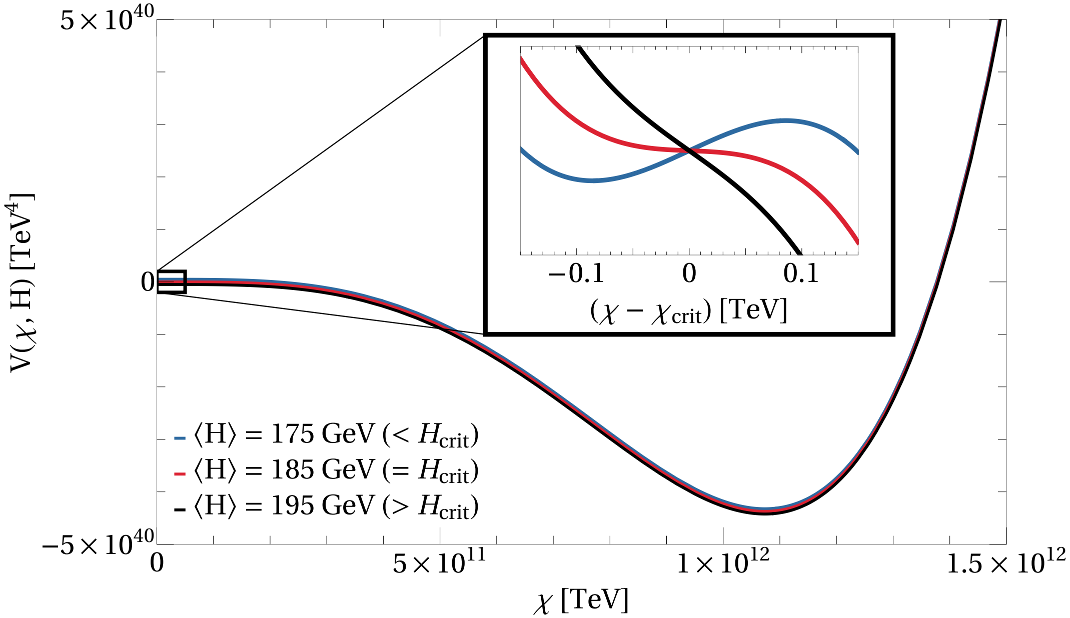
- The full potential: $V(\chi, H) = V_{\mathrm{GW}}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$.

$$V_H(H) = -m_{H,i}^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$V_{\mathrm{GW}}(\chi) = -\lambda \chi^4 + \lambda_{\mathrm{GW}} \frac{\chi^{4+\delta}}{k^\delta}$$

$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^\alpha} - \lambda_{H\epsilon} |H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$

- Second minimum (close to the origin) exists only if <H> is smaller than a critical value



Generating the hierarchies

- The scale of the Higgs VEV is set by

$$h_{crit} \sim k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \right)^{\frac{1}{\epsilon}}$$

- To get $h_{crit} \ll k$ need $\epsilon \ll 1$ and $\lambda_2 < \lambda_{H\epsilon}$

- Technically similar to the GW implementation of RS hierarchy (but here Higgses are elementary, totally different physics driving the hierarchy)

- In CFT language again need operators with small anomalous dimensions

Generating the hierarchies

- Since Higgs is in the bulk, we will also have SU(2) bulk gauge bosons and their KK modes. Those have to be > 3-4 TeV from LHC bounds.

- Implies little hierarchy $\frac{h}{\chi_{\rm min}} \simeq \frac{h_{\rm crit}}{\chi_{\rm min}} \lesssim 0.1$

- Since $\chi_{\rm min} \simeq \left(\frac{h^2}{k^\alpha} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}}$ need $\lambda_2, \lambda_{H\epsilon} < 10^{-2} \alpha \lambda_4$

- To avoid low Landau-pole $\lambda_4 \lesssim 3$, leading to $\lambda_2 \lesssim 10^{-2}$

- To ensure $V_{\chi H}$ dominates over $V_{\rm GW}$ at $\chi_{\rm crit}$ also need

$$\lambda \sim \lambda_{\rm GW} \lesssim \frac{\lambda_2^2}{\lambda_4} \qquad \lambda, \lambda_{\rm GW} \lesssim 10^{-5}$$

A light dilaton

- Consequence of little hierarchy: dilaton must be quite light and weakly coupled
- Mixing with Higgs: $\sin\theta \sim \frac{(\lambda_2 - \lambda_{H\epsilon})}{N}\frac{h\chi_{\rm min}}{m_h^2}$
- Dilaton mass $m_\chi \simeq m_h \sqrt{\frac{h}{\chi_{\rm min}}\frac{\pi\sin\theta}{\sqrt{6}N} - \frac{8\pi^2(\lambda - \lambda_{\rm GW})}{N^2}\frac{\chi_{\rm min}^2}{m_h^2}}$
- Mass bound: $0.2 m_h \gtrsim m_\chi \gtrsim 2\pi\frac{\chi_{\rm min}}{N}\sqrt{2(\lambda - \lambda_{\rm GW})}$
- Since $\chi_{\rm min} \simeq {\rm TeV},\ N \lesssim 40\ \text{and}\ \lambda, \lambda_{\rm GW} \gtrsim 10^{-6}$
- Numerically $0.1\ {\rm GeV} \lesssim m_\chi \lesssim 10\ {\rm GeV}$

A weakly coupled dilaton

- Dilaton will inherit Higgs interactions with SM matter from small mixing $\sin\theta \sim m_\chi^2/m_h^2$

- Numerically $10^{-7} \leq \sin\theta \leq 10^{-2}$

- Direct coupling to bulk gauge bosons via

$$\frac{\chi}{2\chi_{\min}\log\frac{R'}{R}}(F_{\mu\nu}^2 + Z_{\mu\nu}^2 + 2W_{\mu\nu}^2)$$

- Significant for photons $\frac{1}{4\Lambda_{\gamma\gamma}}\tilde{\chi}F_{\mu\nu}^2$, sub-leading for W,Z

Scan of parameter space

- Generated 10^5 points in region

  $k = 10^{11}$ GeV, $\delta = 0.01$, $N = 3$ and $\alpha = 0.05$, while uniformly sampling the other parameters from the ranges $\lambda_{\rm GW} \in (0.5, 1.5) \times 10^{-5}$, $\lambda_2 \in (0.5, 1.5) \times 10^{-2}$, $\lambda_{H\epsilon} \in (2, 4) \cdot \lambda_2$, $\lambda_4 \in (2, 3)$, and $\epsilon \in (0.03, 0.1)$. We also took $\lambda = 1.1\,\lambda_{\rm GW}$ and set the Higgs VEV $\langle H \rangle \simeq 174$ GeV.

- Requiring:
  - The metastable vacuum must exist and be located at $\chi_{\rm crit} > 1$ TeV.
  - $h_{\rm crit} \leq 2$ TeV so the Higgs VEV is natural.
  - The metastable vacuum reproduces the SM values of the Higgs mass and VEV and corresponds to a stable local minimum of the 2 dimensional potential.
  - The O(4) bounce action S_4 between the two potential minima is at least $\mathcal{O}(200)$ so that tunnelling is suppressed.

Scan of parameter space

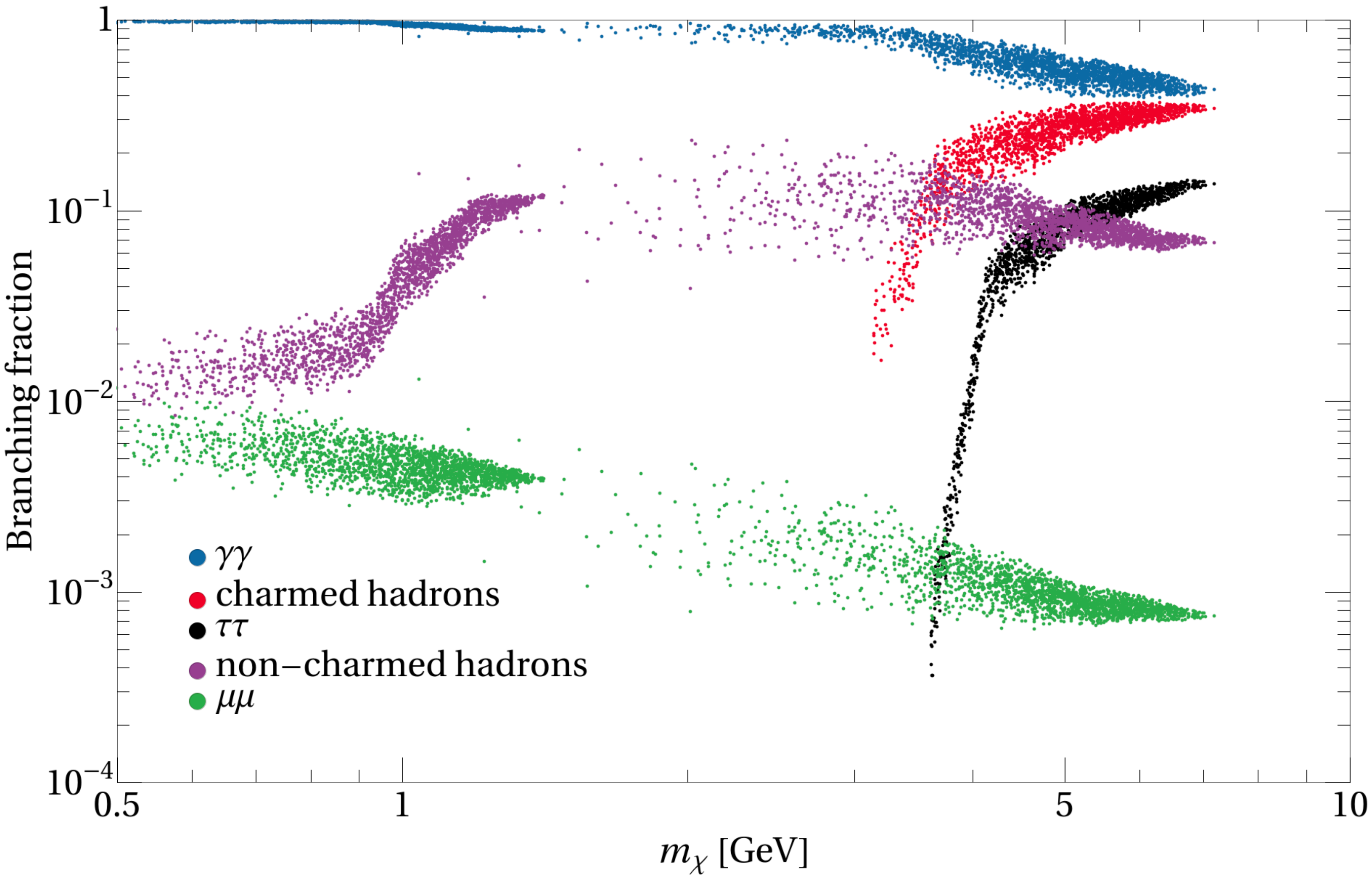
- Second scan $5\ 10^4$ points to test region with smaller dilaton masses

$$N = 8,\ \alpha = 0.1,\ \lambda_{\rm GW} = 2\times 10^{-6},$$

$$\lambda_2 \in (0.5, 1)\times 10^{-2},\ \text{and}\ \epsilon \in (0.05, 0.1)$$

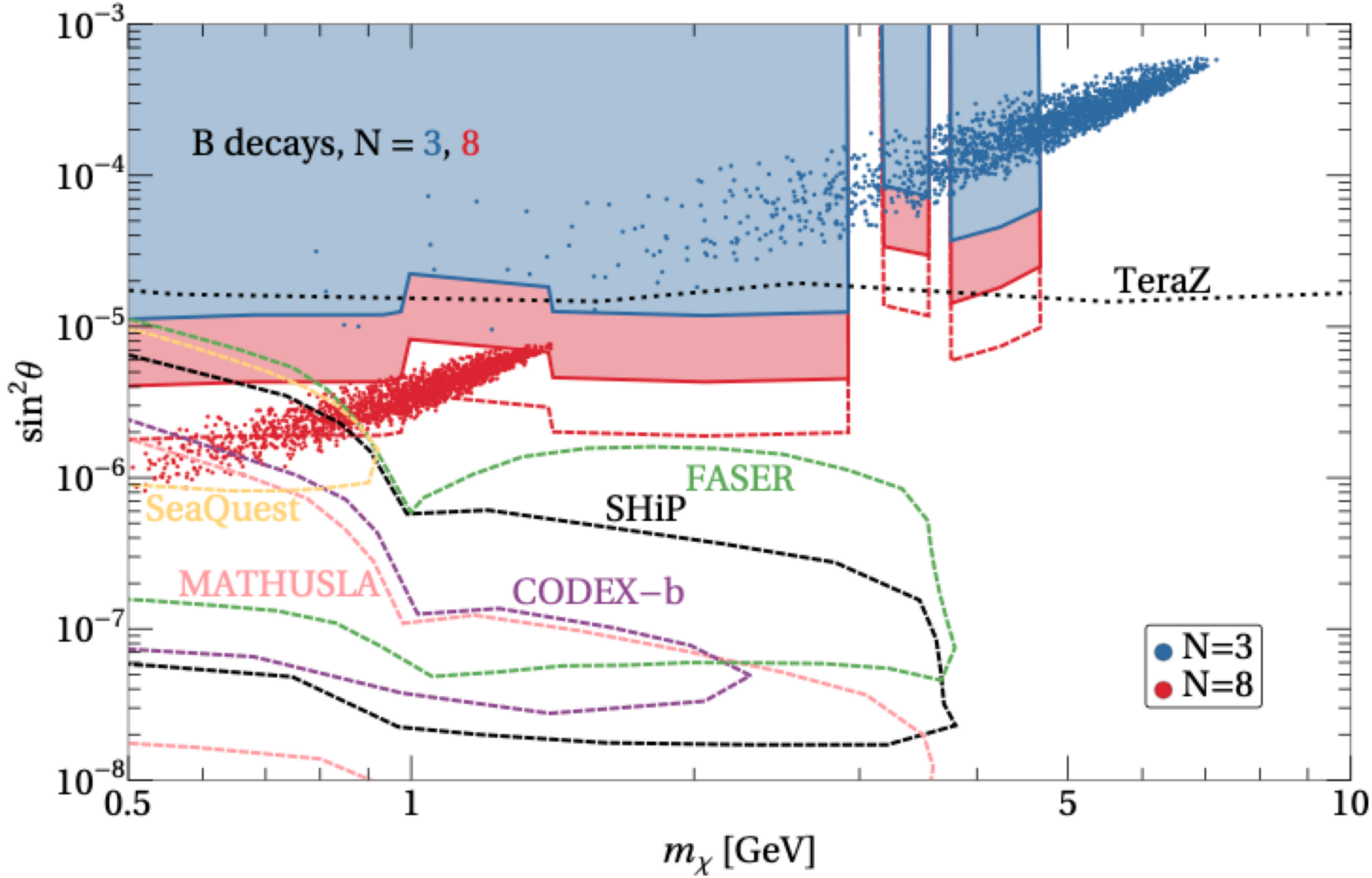
- And same requirements

Dilaton couplings



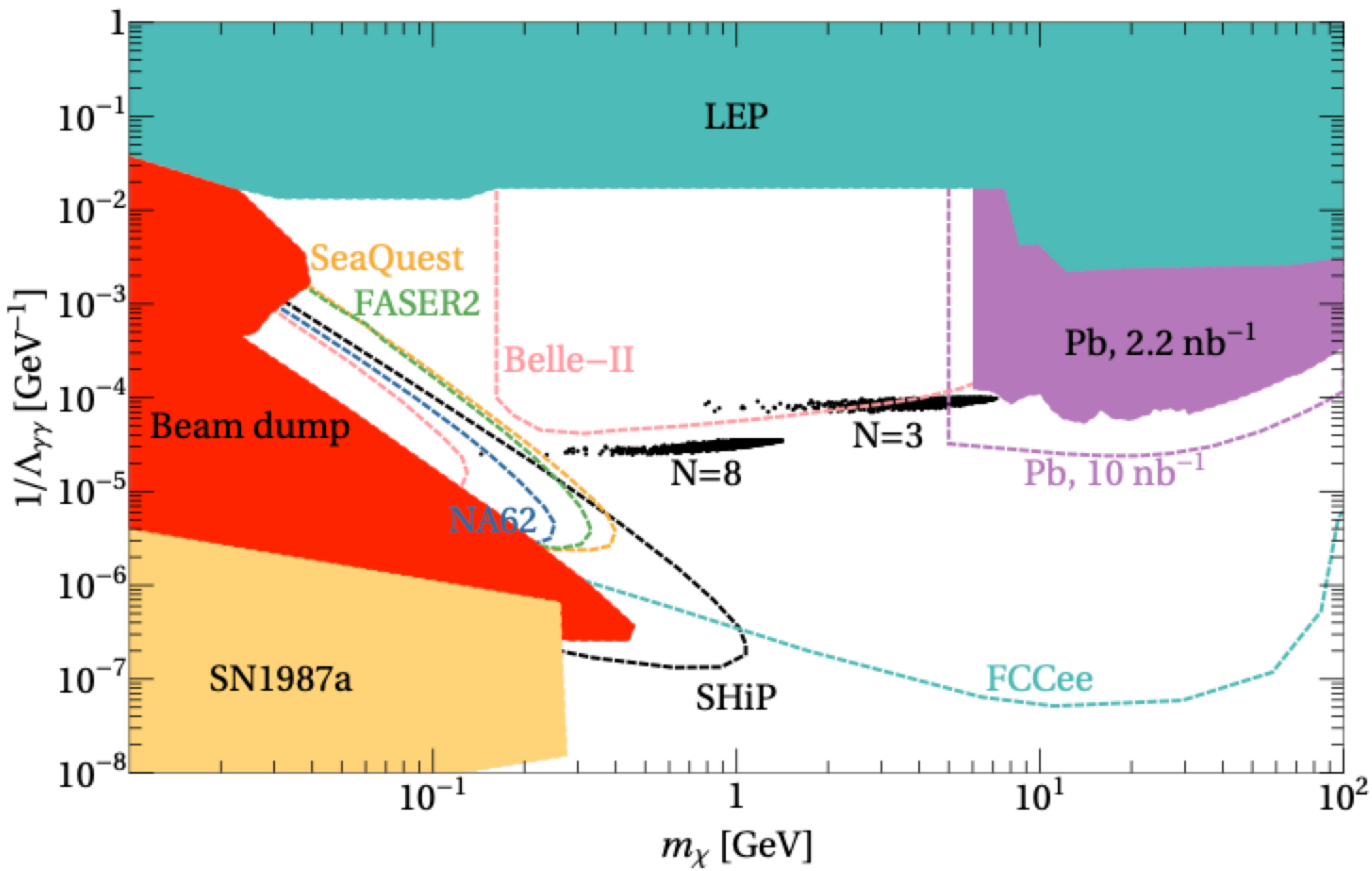
Constraints on dilaton

- Rare B-meson decays - LHCb and future LHCb projections
- $e^+e^- \to Z\chi$ at FCCee on the Z-pole
- Projections for searches for hidden light particles



Constraints on dilaton

- Direct photon coupling - tested at LEP from $e^+e^- \to \gamma\chi \to 3\gamma$
- FCCee will cover full region
- Future heavy ion collisions will also have some sensitivity



Experimental signals

- Light dilaton that can be observed (large regions already excluded)

- Also have W,Z KK modes - but these don't play a role in stabilizing hierarchy

- No top partners!

- While the construction is based on RS model, the Higgs is elementary here

- Physics (and signals) are completely different from holographic composite Higgs/MCHM-type constructions

Cosmological constraints

- During inflation Hubble scale should be below EW so that dilaton potential sensitive to Higgs VEV

$$M_I < \sqrt{M_W M_{\rm Pl}} \simeq 10^7 \ \text{TeV}$$

- Cutoff should be below this $\Lambda < M_I < 10^7 \ \text{TeV}$

- Energy density in true vacuum really negative

$$\lambda \chi_{GW}^4 > M_I^4 \longrightarrow k \gtrsim 17 M_I \ \text{for} \ \lambda \simeq 10^{-5}$$

- If CC problem solved by anthropics - maximal CC should not overwhelm negative CC at GW minimum: $\Lambda_{max} < \lambda \chi_{GW}^4$

Avoiding Eternal Inflation

- Ensure that patch actually crunches for VEV's with small or large <H>

- Field should roll down to true minimum, not get stuck eternally inflating. To ensure: quantum diffusion never dominates over classical evolution

- At large Higgs VEVs second derivative of potential at least $O(v^2)$ - and Hubble already required to be smaller

- At zero Higgs VEV situation more subtle - only have χ^4 term very small. Need to add new gauge group in bulk - a la Servant/von Harling

Summary

- New approach to the hierarchy problem

- Regions in space with large (or 0) Higgs VEV dynamically crunch

- Implementation via RS/GW construction

- Predicts light dilaton, can be measured

- No top partners, but W,Z KK modes

- Can also find a similar ``solution" to the CC problem (but didn't fit on the margins)

Backup slides

Properties of the potential

- Find critical value of h by neglecting GW piece

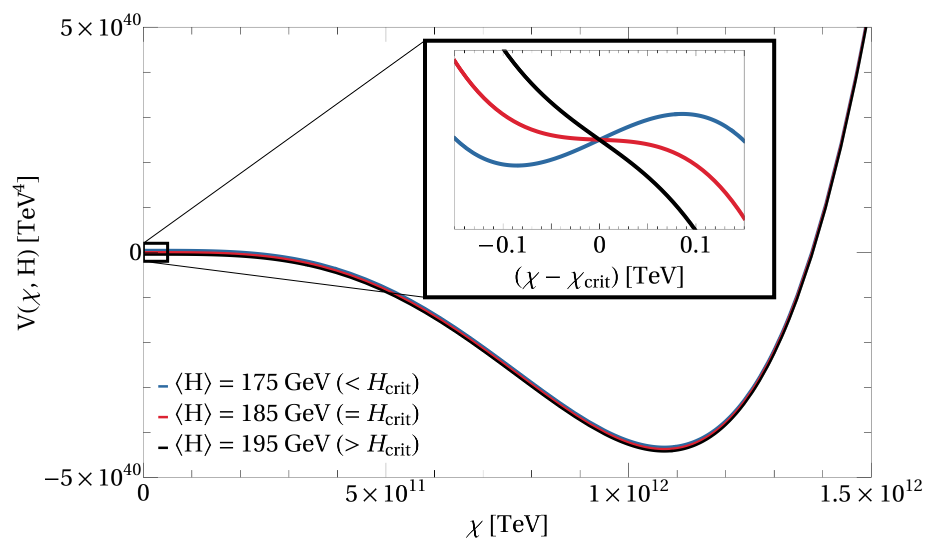
$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^\alpha} - \lambda_{H\epsilon} |H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$

$$h_{crit} \sim k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \right)^{\frac{1}{\epsilon}}$$

- Value of χ at inflection point: $\chi_{\rm crit} = k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \frac{4-\alpha^2}{(2+\epsilon)^2 - \alpha^2} \right)^{1/\epsilon}$

- The minimum:

$$\chi_{\rm min} \simeq \left(\frac{h^2}{k^\alpha} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}}$$



The small χ region

- To ensure we don't get stuck at small χ need to add additional piece to dilaton potential $\lambda_\gamma \chi^\gamma \tilde{\Lambda}^{4-\gamma}$

- Effect of additional small explicit breaking of scale invariance at scale $\tilde{\Lambda} \ll k$.

- Until scale $\chi_* \sim \tilde{\Lambda} \lambda_\gamma^{\frac{1}{4-\gamma}}$ effect negligible, but below description in terms of dilaton breaks down. Effectively as if negative mass of order χ_*^2

- Can get this by putting another gauge group in the bulk (for example QCD itself)

$$\frac{1}{g^2(Q,\chi)} = \frac{\log \frac{k}{\chi}}{k g_5^2} - \frac{b_{\rm UV}}{8\pi^2} \log \frac{k}{Q} - \frac{b_{\rm IR}}{8\pi^2} \log \frac{\chi}{Q} + \tau$$

The small χ region

- The dynamical scale of the bulk gauge group:

$$\tilde{\Lambda}(\chi) = \left(k^{b_{\rm UV}} \chi^{b_{\rm IR}} e^{-8\pi^2\tau} \left(\frac{\chi}{k}\right)^{-b_{\rm CFT}} \right)^{\frac{1}{b_{\rm UV}+b_{\rm IR}}} = \Lambda_0 \left(\frac{\chi}{\chi_{\rm min}}\right)^n$$

- For QCD and benchmark point $\chi_{\rm min} \simeq 1 \text{ TeV and } \langle H \rangle = 0$ we get $\tilde{\Lambda}(\chi_{\rm min}) \sim \Lambda_{\rm QCD} \sim 100 \text{ MeV}$ and $\chi_* \sim$

$10 - 100 \text{ MeV} \sim \Lambda_{\rm QCD}$

- This will ensure no eternal inflation as long as

$$\Lambda < \sqrt{\chi_* M_{\rm Pl}} \lesssim 10^5 \text{ TeV}$$

- With other bulk gauge groups can push Λ to 10^7 TeV

- This will also give $h_{\rm min} \sim 0.1 \chi_*$