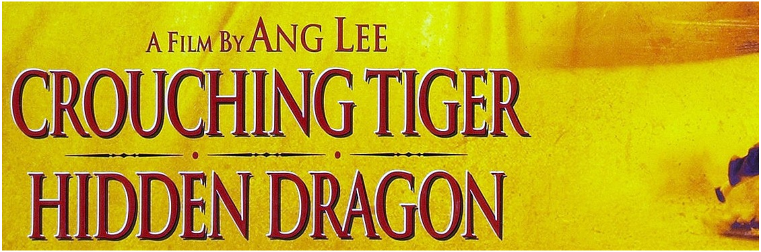


LEPP theory seminar, 3 September 2020

(a new approach to the hierarchy problem)

arXiv:2007.14396

in collaboration with C. Csáki, R. T. D'Agnolo, and M. Geller

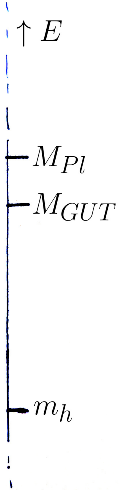
LEPP theory seminar, 3 September 2020

The hierarchy problem

Sensitivity of m_H^2 to the scale of new physics

Traditional approaches typically predict new particles at the TeV scale

Do we *need* top partners?



Other approaches

Cosmological dynamics can select a small Higgs VEV (relaxion, *N*naturalness, etc.)

Large corrections to m_H^2 are unsuppressed

See also: anthropic solutions


Cosmological Relaxation of the Electroweak Scale

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] and Surjeet Rajendran[3]

[1]Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305
[2]Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218
Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720
[4]Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan
(Dated: June 24, 2015)

The Selfish Higgs

G.F. Giudice,[a] A. Kehagias,[b] A. Riotto[a,c]

[a]CERN, Theoretical Physics Department, Geneva, Switzerland.
[b]Physics Division, National Technical University of Athens 15780 Zografou Campus, Athens, Greece.
[c]Department of Theoretical Physics and Center for Astroparticle Physics (CAP) 24 quai E. Ansermet, CH-1211 Geneva 4, Switzerland.

E-mail: gian.giudice@cern.ch, kehagias@central.ntua.gr, antonio.riotto@unige.ch

*N*naturalness

*N*ima Arkani-Hamed,[1] Timothy Cohe*N*,[2] Raffaele Tito D'Ag*N*olo,[1] A*N*son Hook,[3] Hyu*N*g Do Kim,[4] and David Pi*N*ner[5]

[1]School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA
[2]Institute of Theoretical Science, University of Oregon, Eugene, OR 97403, USA
[3]Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305, USA
[4]Department of Physics and Astronomy and Center for Theoretical Physics, Seoul National University, Seoul 151-747, Korea
[5]Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA

Mass Hierarchy and Vacuum Energy

Clifford Cheung[a] and Prashant Saraswat[b]

Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125

Inflating to the Weak Scale

Michael Geller[1,2], Yonit Hochberg[3], and Eric Kuflik[3]

[1]Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742, USA
[2]Department of Physics, Tel Aviv University, Tel Aviv, Israel and
Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel

Our approach

Landscape of m_H^2 values up to a cutoff Λ:

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

Patches crunch unless $h \equiv \langle H^0 \rangle$ satisfies

$$H_I \lesssim \boxed{h_{\mathrm{min}}} \lesssim \boxed{h < h_{\mathrm{crit}} \sim \mathcal{O}(\mathrm{TeV})}$$

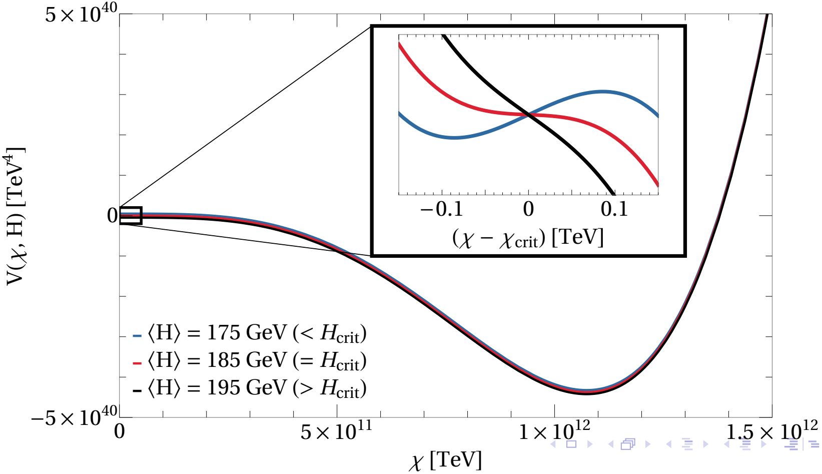
Hubble during inflation

Many ways to get this; not the main focus

Our mechanism!

Our approach

Higgs couples to dilaton of a spontaneously broken CFT sector w/ large, negative vacuum energy



The CliffsNotes

$h < h_{\text{crit}} \to$ long-lived metastable vacuum $\to$ standard cosmological history

$h > h_{\text{crit}} \to$ roll down to true vacuum $\to$ crunch!

Main predictions:

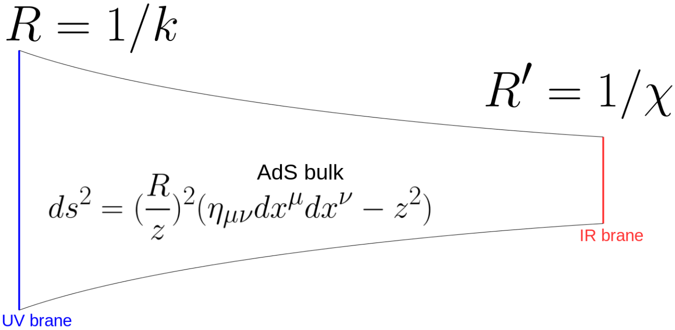
- light (0.1–10 GeV) dilaton
- KK electroweak gauge bosons*
- **no** top partners

*which have NOTHING to do with resolving the hierarchy problem

RS model

Standard 5D warped description of CFT with Goldberger-Wise stabilization

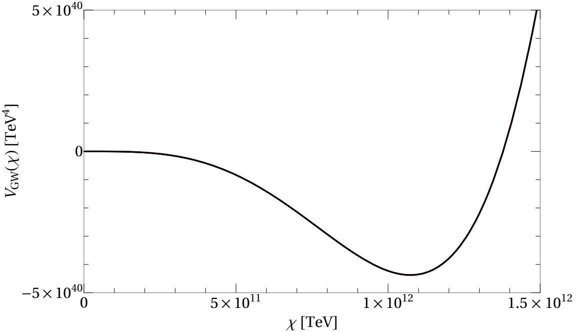
Dilaton χ identified with IR brane location



GW potential

GW field yields potential $V_{GW}(\chi) = -\lambda\chi^4 + \lambda_{GW}\chi^{4+\delta}$

Small explicit breaking of scale invariance (δ) by GW bulk mass



$$\chi_{GW} \sim k\left(\frac{\lambda}{\lambda_{GW}}\right)^{1/\delta}$$

Brane-localized terms

Higgs field sourced on UV brane; VEV scales as $z^{2\pm\sqrt{4+m_b^2}}$

Can show UV source scales on IR brane as
$H_{\mathrm{UV}}\chi^{\sqrt{4+m_b^2}-2} \equiv H_{\mathrm{UV}}\chi^{\alpha/2-1}$; $\alpha = 2\sqrt{4+m_b^2}-2$

Brane-localized quadratic term $\rightarrow |H|^2\,\chi^{2+\alpha}$

Brane-localized quartic term $\rightarrow |H|^4\,\chi^{2\alpha}$

Allow terms including GW scalar $\sim z^{\epsilon}$ (or any other nearly marginal field) $\rightarrow |H|^2\,\chi^{2+\alpha+\epsilon}$

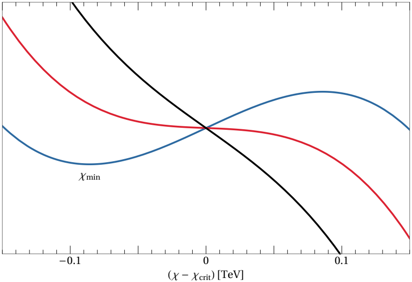
Brane-localized terms

Putting this all together:

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

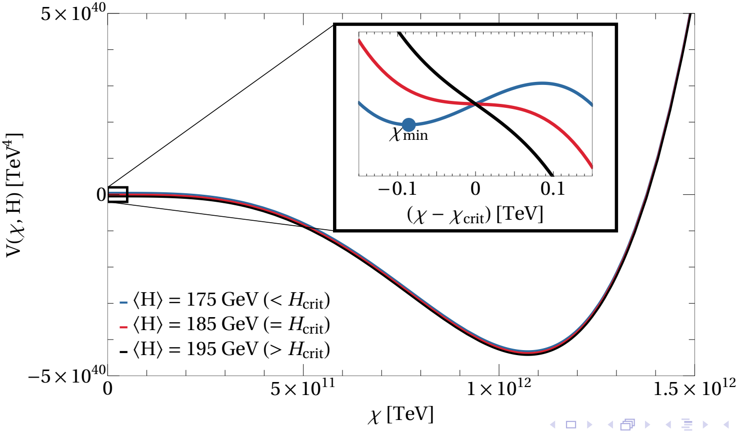
For small $h < h_{\rm crit}$, $V_{H\chi}$ has a local minimum in χ!

Minimum disappears for $h \geq h_{\rm crit}$



The full potential

$$V(\chi, H) = V_{\mathrm{GW}}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$



Analytical estimates

Neglecting V_{GW} around metastable minimum, estimate:

- $$h_{\rm crit} = k\left(\frac{\lambda_2}{\lambda_{H\epsilon}}\frac{4-\alpha^2}{(2+\epsilon)^2-\alpha^2}\right)^{\frac{1-\alpha/2}{\epsilon}}\sqrt{\frac{\lambda_2}{\lambda_4}\frac{\epsilon(2+\alpha)}{2\alpha(2-\alpha+\epsilon)}}$$
- $$\chi_{\rm crit} = k\left(\frac{\lambda_2}{\lambda_{H\epsilon}}\frac{4-\alpha^2}{(2+\epsilon)^2-\alpha^2}\right)^{1/\epsilon}$$
- $$\chi_{\rm min} \simeq \left(\frac{h^2}{k^\alpha}\frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2}\right)^{\frac{1}{2-\alpha}}$$

Large separation of scales $h_{\rm crit}, \chi_{\rm crit}, \chi_{\rm min} \ll k$ from small ϵ

Analytical estimates

Neglecting V_{GW}—is this okay?

Require V_{GW} to be dominated by $V_{H\chi}$ around $\chi_{\rm crit}$
$\rightarrow \lambda \sim \lambda_{GW} \lesssim \dfrac{\lambda_2^2}{\lambda_4}$

Larger λ, λ_{GW} washes out the metastable minimum

The little hierarchy

Little hierarchy: $\dfrac{h}{\chi_{\rm min}} \lesssim 0.1$

Implies $\lambda_2 \lesssim 10^{-2}$; $\lambda, \lambda_{GW} \lesssim 10^{-5}$

And a light dilaton:

Dilaton mass and mixing

$$m_\chi \simeq m_h \sqrt{\frac{h}{\chi_{\rm min}} \frac{\pi \sin\theta}{\sqrt{6}N} - \frac{8\pi^2(\lambda - \lambda_{\rm GW})}{N^2} \frac{\chi^2_{\rm min}}{m_h^2}}$$

$$\sin\theta \sim \frac{(\lambda_2 - \lambda_{H\epsilon})}{N} \frac{h\chi_{\rm min}}{m_h^2}$$

Phenomenology

Reminder: no top partners!

Bulk Higgs $\rightarrow$ KK electroweak gauge bosons

No KK gluons (*but we *may* want bulk QCD; more on this later)

Dilaton inherits SM Higgs couplings, suppressed by $\sin\theta$

Additional direct coupling to EW gauge bosons:

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

Important!

Not important!

Parameter scans

Take $k = 10^8$ TeV, $h \simeq 174 = 246/\sqrt{2}$ GeV

	Parameter	Scan 1 range	Scan 2 range
V_{GW}	λ	$1.1\lambda_{GW}$	$1.1\lambda_{GW}$
	λ_{GW}	$(0.5, 1.5) \times 10^{-5}$	$\mathbf{2 \times 10^{-6}}$
	δ	0.01	0.01
$V_{H\chi}$	λ_2	$(0.5, 1.5) \times 10^{-2}$	$\mathbf{(0.5, 1) \times 10^{-2}}$
	$\lambda_{H\epsilon}$	$(2, 4) \times \lambda_2$	$(2, 4) \times \lambda_2$
	λ_4	$(2, 3)$	$(2, 3)$
	α	0.05	$\mathbf{0.1}$
	ϵ	$(0.03, 0.1)$	$\mathbf{(0.05, 0.01)}$
	N	3	$\mathbf{8}$

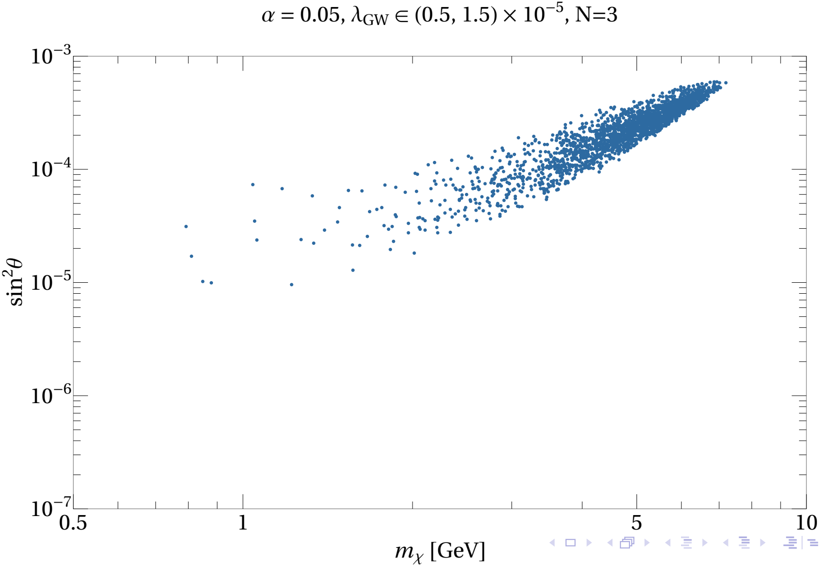
Scan 2 probes lower masses (differences in **bold**)

Selection criteria

Randomly generate 10^5 points, retain those that satisfy:

- Existence of second potential minimum at $\chi_{\rm min} > 1$ TeV
- $h_{\rm crit} \leq 2$ TeV for naturalness
- Minimum of 2D potential, reproduces SM Higgs mass
- Metastable vacuum cosmologically long-lived ($S_4 \gtrsim 200$)

Higher mass scan



Bounds

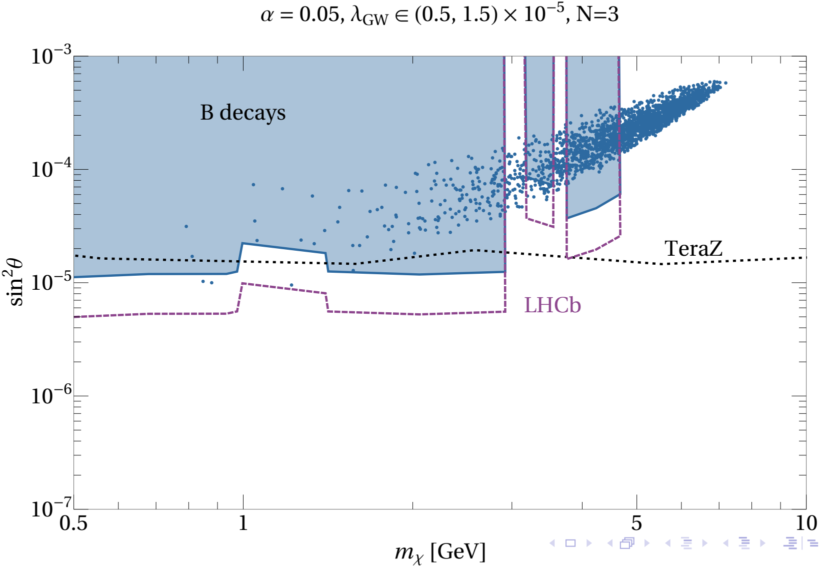
Rare B meson decays:

- $B^{\pm} \to K^{\pm}\chi \to K^{\pm}\mu^{+}\mu^{-}$
- $B^{0} \to K^{*0}\chi \to K^{*0}\mu^{+}\mu^{-}$

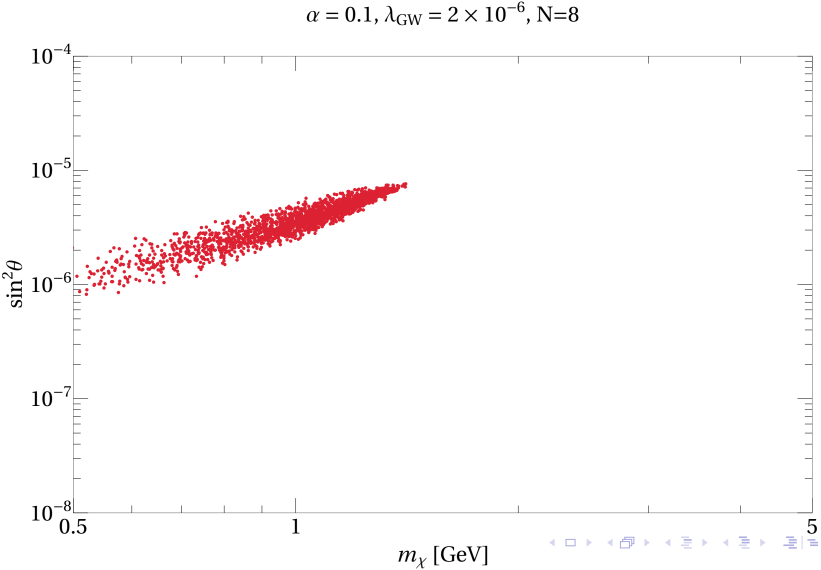
Future $e^{+}e^{-}$ collider running on Z pole ("TeraZ"), via

$$e^{+}e^{-} \to Z \to Z^{*}\chi$$

Higher mass scan



Lower mass scan



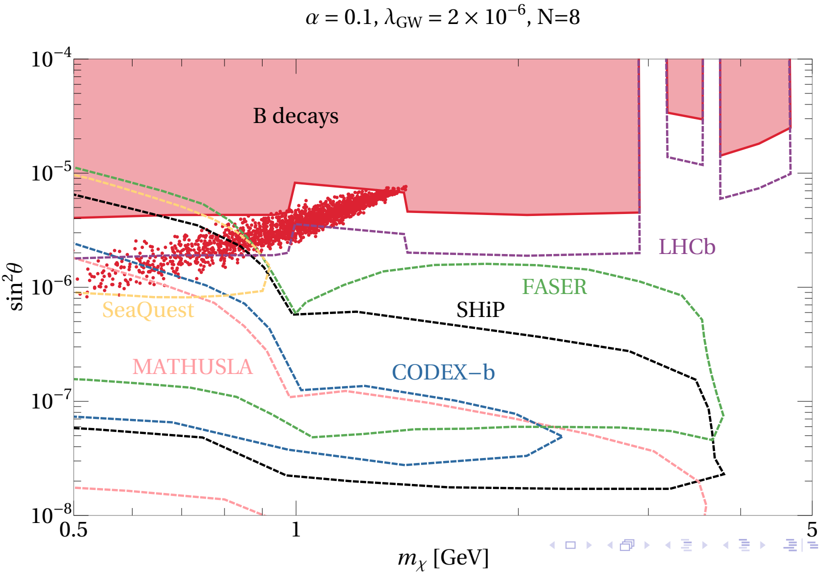
Some more bounds

LHCb B decay bounds still apply

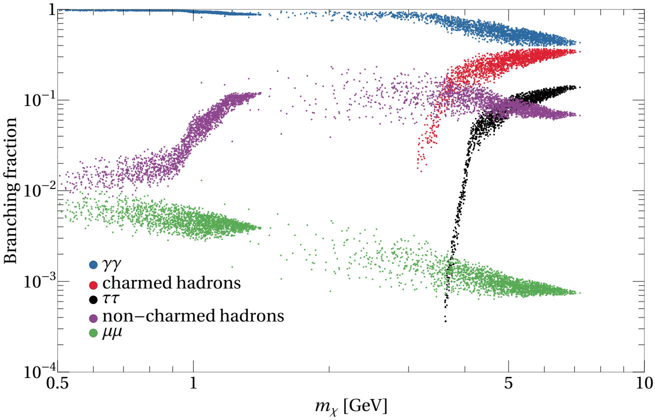
Searches for light, weakly-coupled particles, also through B decays:

- Proton beam dumps (SeaQuest and SHiP)
- FASER
- MATHUSLA
- CODEX-b

Lower mass scan



χ decays mainly to photons

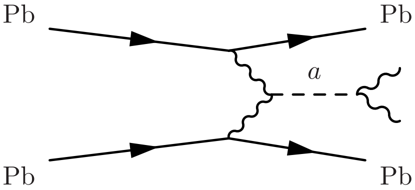


So how can we probe the photon coupling?

The photon coupling

e^+e^- colliders: $e^+e^- \to \gamma\chi \to 3\gamma$

Peripheral heavy ion collisions (Z^4 enhancement!):



Knapen, Lin, Lou, Melia 1607.06083

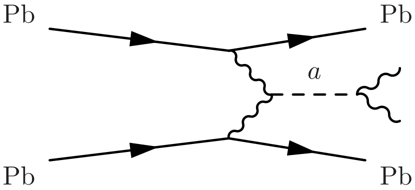
Electron beam dumps

Supernovae

The photon coupling

e^+e^- colliders: $e^+e^- \to \gamma\chi \to 3\gamma$

Peripheral heavy ion collisions (Z^4 enhancement!):

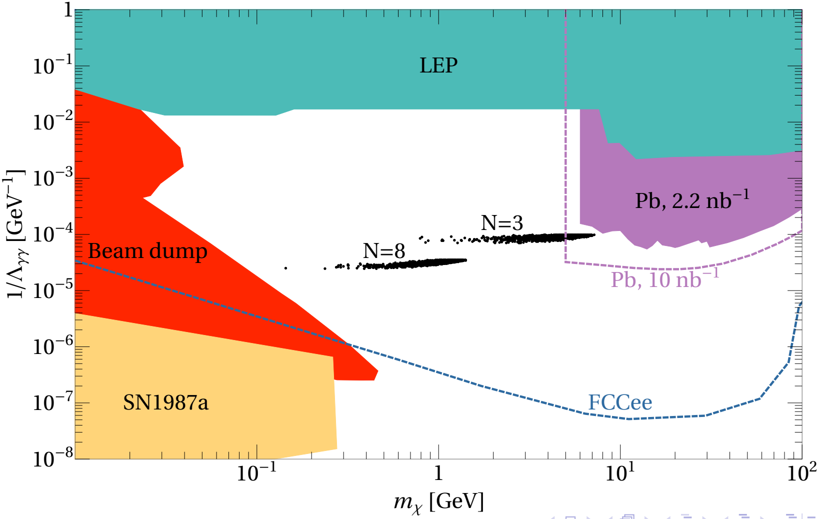


Knapen, Lin, Lou, Melia 1607.06083

Electron beam dumps

Supernovae

The photon coupling



Pheno summary

Parameter space mainly probed by rare B decays

Regions free of bounds around 0.5–1.5 GeV and 5–7 GeV

Will be further probed by:

- more B decay data at LHCb
- searches for weakly-coupled, light particles (FASER, SeaQuest, etc.)
- future lepton colliders (FCCee, CepC, etc.)

the first two of these within the next decade!

Some further considerations

Tuning: recall $\lambda_2 \lesssim 10^{-2}$; $\lambda, \lambda_{GW} \lesssim 10^{-5}$

UV completion?

Cosmological constraints

Generating a minimum VEV $h_{\min}$

Some further considerations

Tuning: recall $\lambda_2 \lesssim 10^{-2}$; $\lambda, \lambda_{GW} \lesssim 10^{-5}$

UV completion?

Cosmological constraints

Generating a minimum VEV h_{min}

Parameter bounds

Little hierarchy:

$$\frac{\chi_{\min}}{h_{\rm crit}} \simeq \left(\frac{h^\alpha}{k^\alpha} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}} \sim \mathcal{O}(1) \times \sqrt{\frac{\lambda_4}{\lambda_2}} \gtrsim 10$$

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

V_{GW} destroys second minimum unless $\lambda, \lambda_{GW} \lesssim \lambda_2^2/\lambda_4 \sim 10^{-5}$

NDA

$\lambda_2 |H|^2 \chi^{2+\alpha}/k^\alpha$: brane-localized mass term, quadratically divergent

Expect

$$\lambda_2 \sim \frac{1}{16\pi^2}\frac{\Lambda^2}{\chi^2}$$

GW quartic $\lambda\chi^4$:

$$\lambda \sim \frac{1}{16\pi^2}\frac{\Lambda^4}{\chi^4}$$

Bellazzini *et al.* 1209.3299

So we need a low cutoff $\Lambda \lesssim \chi$!

Can we get $\Lambda \lesssim \chi$?

Depends on particular UV completion—interesting direction for further work

e.g. SUSY bulk, broken on UV brane and spont. broken on IR brane

High breaking scale on UV $\rightarrow$ very heavy sfermions

$\mathcal{O}(\text{few} \times 100)$ GeV electroweakinos, so fully natural λ's!

Some further considerations

Tuning: recall $\lambda_2 \lesssim 10^{-2}$; $\lambda, \lambda_{GW} \lesssim 10^{-5}$

UV completion?

Cosmological constraints

Generating a minimum VEV $h_{\rm min}$

Some further considerations

Tuning: recall $\lambda_2 \lesssim 10^{-2}$; $\lambda, \lambda_{GW} \lesssim 10^{-5}$

UV completion?

Cosmological constraints

Generating a minimum VEV $h_{\min}$

The scale of inflation

Require $H_I < M_W$ so dilaton is sensitive to EW-scale Higgs VEVs

Leads to $M_I \lesssim \sqrt{M_W M_{Pl}} \sim 10^7$ TeV

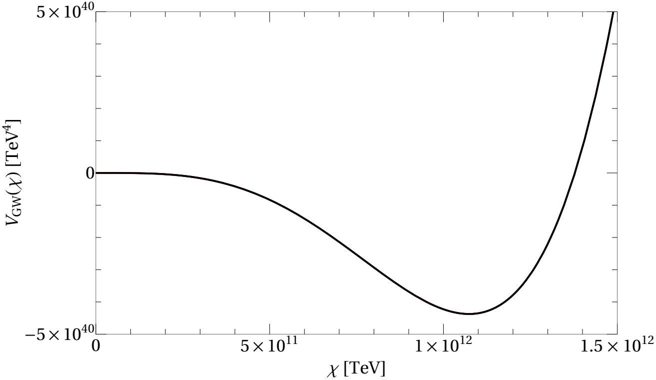
Vacuum energy density must be negative:

$$\underbrace{\boxed{\Lambda < M_I}}_{\text{UV completion of Higgs sector}} \; ; \; \underbrace{\boxed{\lambda \chi_{GW}^4 > M_I^4}}_{\text{Energy density in GW vacuum}} \to k \gtrsim 17 M_I$$

Small Higgs VEVs

As $h \to 0$ we worry about eternal inflation

Nearly flat potential near $\chi = 0$



A solution

von Harling & Servant 1711.11554

Baratella, Pomarol, Rompineve 1812.06996

Add to potential $\lambda_\gamma \chi^\gamma \tilde{\Lambda}^{4-\gamma}$, with $\tilde{\Lambda} \ll k$

Defines scale $\chi_* = \tilde{\Lambda} \lambda_\gamma^{\frac{1}{4-\gamma}}$

In the IR $\chi \lesssim \chi_*$:

- Explicit breaking of scale invariance dominates
- Description in terms of dilaton breaks down
- Effectively generates $\mathcal{O}(\chi_*^2)$ mass term

Bulk gauge group

Generate new term by any relevant operator with a coupling that grows in the IR

How about bulk QCD? Can show

$$\chi_* \sim \tilde{\Lambda} \sim \Lambda_{\mathrm{QCD}}$$

for $\chi_{\min} \sim 1$ TeV, $h = 0$

Dark gauge group also works!

Need highest Hubble constant in landscape $< \chi_*$ for no eternal inflation

Yields minimal Higgs VEV $h_{\min} \sim 0.1\chi_*$

Cosmological constant

Compatibility with anthropic solution—ensure patches in GW minimum really crunch

Leads to $\Lambda_{\max} \lesssim \lambda \chi_{GW}^4$

Recall max Hubble given by χ_*; assume sets scale of CC landscape

Then $\Lambda_{\max} \sim \sqrt{\chi_* M_{Pl}} \sim 10^5$ TeV for bulk QCD

Can push up to 10^7 TeV depending on confining scale of gauge group

Summary

Higgs VEV tied to cosmological stability

Predicts light dilaton (0.1–10 GeV), probed in

- rare B decays,
- searches for light, weakly-coupled particles,
- at a future e^+e^- collider

Electroweak KK states at TeV scale—and possibly superpartners?
UV completion left to future work, could lead to observable signals

Thank you!


A talk By ~~Ang Lee~~ Ameen Ismail
CRUNCHING DILATON
HIDDEN NATURALNESS

What happened to the $\pm$ sign?

Generically we can expand

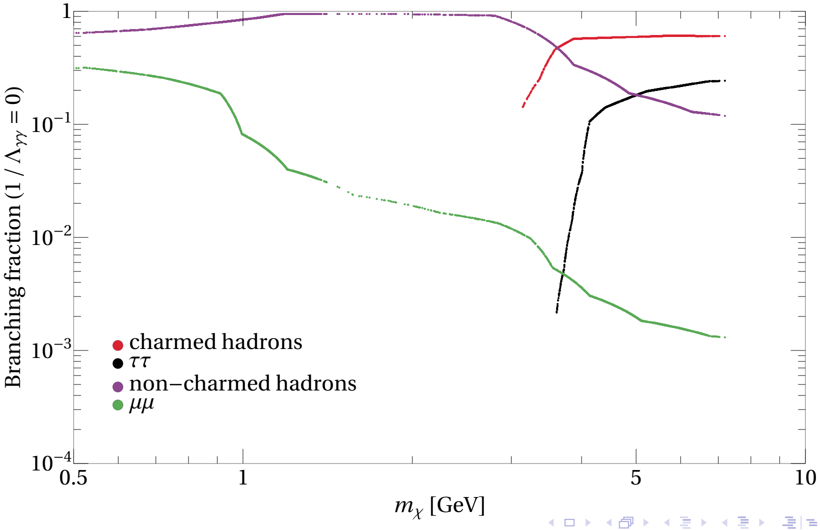
$$\phi = \phi_+ (\frac{z}{R})^{2+\sqrt{4+m_b^2}} + \phi_- (\frac{z}{R})^{2-\sqrt{4+m_b^2}}$$

Impose B.C.'s $\phi = \phi_0$ @ $z = R$, $\partial\phi = 0$ @ $z = R'$

Solve for ϕ_+, ϕ_-, and find $\phi \sim R^{2-\sqrt{4+m_b^2}} \sim \chi^{\sqrt{4+m_b^2}-2}$

i.e. both terms scale the same way

Dilaton branching ratios



Relevant experiments

SeaQuest and SHiP: proton beam dumps at Fermilab and SPS, respectively

FASER: far-forward detector planned for Run 3

MATHUSLA: proposed surface detector at HL-LHC

CODEX-b: LLP detector at LHCb interaction point

RGE for bulk QCD

Evolution of gauge coupling for bulk QCD at scale Q:

$$\frac{1}{g^2(Q,\chi)} = \frac{\log\frac{k}{\chi}}{kg_5^2} - \frac{b_{\rm UV}}{8\pi^2}\log\frac{k}{Q} - \frac{b_{\rm IR}}{8\pi^2}\log\frac{\chi}{Q} + \tau$$

Dynamical scale

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

Then $\tilde{\Lambda}(\mathrm{TeV}) \sim 100$ MeV
and $n \gtrsim 0.1 \to \chi_* \sim$ 10–100 MeV