Un-natural vs Natural Theories of the TeV Scale

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thanks to Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Kiel Howe, Isabel Garcia Garcia

Hierarchy Problem

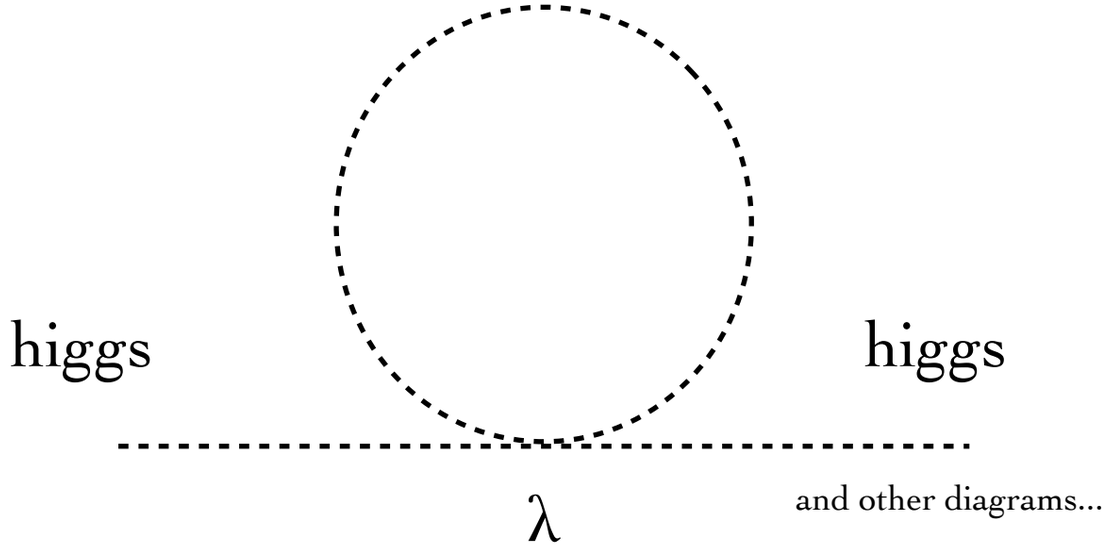
- Discovery of Higgs with properties consistent with elementary scalar dof makes hierarchy problem even more pressing

$$\langle h \rangle = 247\,\mathrm{GeV} \lll M_{\mathrm{Planck}}$$

- Often stated that in absence of SUSY or compositeness

$$\delta m^2 \simeq \frac{\lambda}{16\pi^2}\Lambda^2$$

must be < EW scale if higgs vev is to be natural



- Misleading: SM renormalizable theory and divergencies do not appear in renormalized pert'n theory. Have to interpret meaning of cutoff correctly

Hierarchy Problem

- Quadratic cutoff correction is proxy for possible dependence of higgs mass parameter on physical but unknown UV mass thresholds. Not reliably calculable in IR theory. (eg, dim reg only gives IR-saturated log terms)

- From UV perspective can discuss hierarchy problem directly in terms of Wilsonian RG flow of finite quantities

eg, for non-SUSY GUT theory just below GUT scale...

$$\mathcal{L} = \mathcal{L}_{321} + m^2 H^2 + \sum \frac{O}{M_{GUT}^{(d-4)}}$$

relevant term generated by interactions with GUT-scale particles

Hierarchy Problem

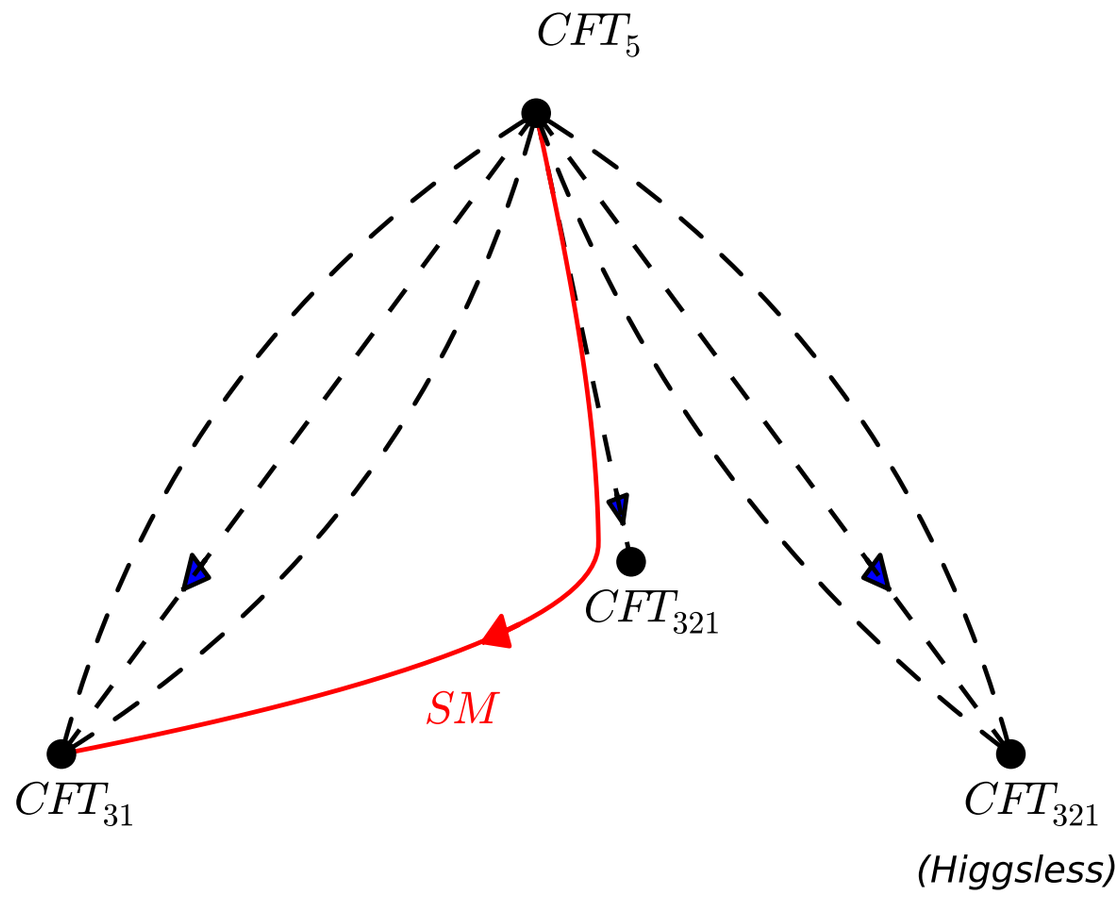


fig from Sergei Dubovsky

- Mystery: SM trajectory very closely approaches vanishing IR Higgs mass parameter when trajectory in UV isn't special (no enhanced symmetry) and large corrections present
- *cf.* tuning of a phase transition to 2nd-order point - there is nothing *a-priori* special about 374.4C and 217.7atm for water
- Hierarchy problem is sharpest for theories where Higgs properties (EWSB and mass) are calculable

Hierarchy Problem & "Physical Naturalness"?

Bardeen, Foot, Shaposhnikov, Lykken, Strumia, Dubovsky

- Keep scale of gravity at Planck mass
- In principle gravity might be UV completed with no new particles so not affecting the Higgs mass (this not true of string constructions as far as we know)
- Additionally suppose there are no other too heavy particles materially coupling to Higgs

Is this a successful "no-tuning" solution to hierarchy problem (with no low-energy consequences)?

Consequences of Physical Naturalness

- All BSM states carrying SM gauge quantum numbers must be below a few TeV (so no high scale GUT)

- Yukawa coupled particles can be heavier, $M_{\nu R} < 10^7$ GeV

- Gravitationally coupled particles less than 10^{12} GeV? (requires a 3 loop calculation not yet performed)

Arvanitaki

Challenges for Physical Naturalness

- Must do all physics with previous constraints:

  Charge quantization

  Family quantum numbers

  Dark matter

  Neutrino masses

  Baryogenesis

  Inflation (high scale if BICEP2 interpretation correct)

  Flavour

  $\sin^2\theta_w$...

- AND avoid ALL Landau Poles in a controllable way

Model Building Physical Naturalness

Arvanitaki, Dimopoulos, Dubovsky, Strumia, Villadoro

- Must expand gauge group at TeV scale (SU(4)xSU(2)xSU(2), $SU(3)^3$ ...) to avoid U(1) Landau pole
- And add states to avoid Higgs quartic Landau pole...
- And do all rest of physics satisfying physical naturalness bounds...
- And still have mysteries of a) how gravity manages to be UV completed, and b) what sets weak-to-Planck scale ratio (remember this is supposed to be distinct from an anthropic solution)...

Looks very tough: attempts so far failed even at first stages, but worth more study

Hierarchy problem remains real and serious!

Given the importance of this for future theory and experiment useful to look at other cases of small numbers in physics...

Naturalness - Dynamics

Problem	Solution
Hydrogen Binding Energy	$E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2} m_e$
Deuteron Binding Energy Nuclear Binding Energy	$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$
π^+ - π^o mass difference	Symmetry/Dynamics
$K - \bar{K}$ mixing	Flavour Symmetry
QCD scale	Dimensional Transmutation
Electron Mass	Chiral Symmetry

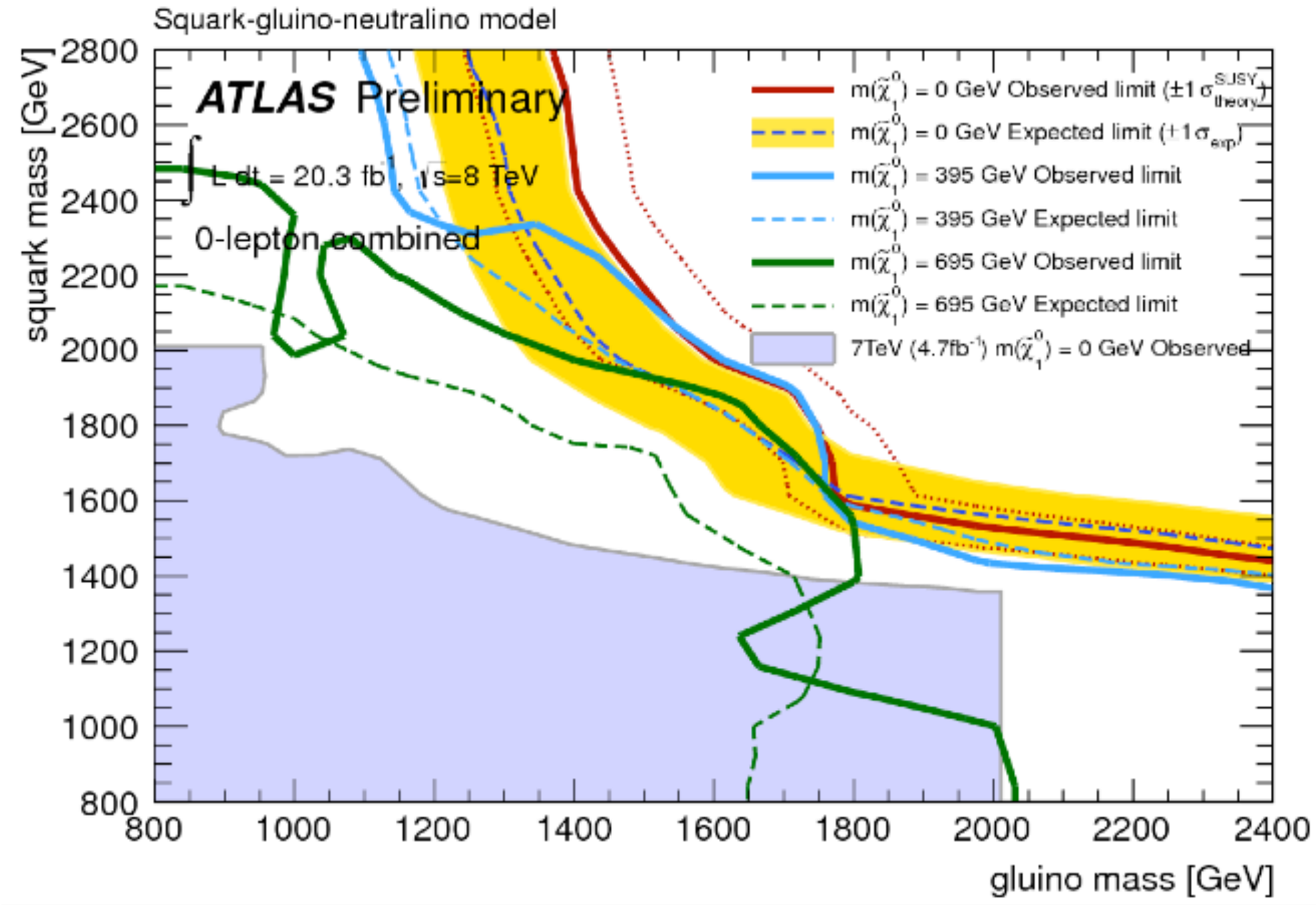
Something else…

Problem	Solution
Earth-Sun Distance	Anthropic Selection 10^{22} suns
Cosmological Constant	Anthropic Selection 10^{500} universes???
7 eV line of ^{229}Th nucleus	"Look-elsewhere" effect
Solar Eclipse & moon's size	Plain luck!

Anthropic's major flaw: we know nothing about distribution of stable vacua, which parameters scan and how, and what properties we should select for. Once accept <1% tuning why not 0.001% or 0.0000000001%?? No principle at all in my opinion

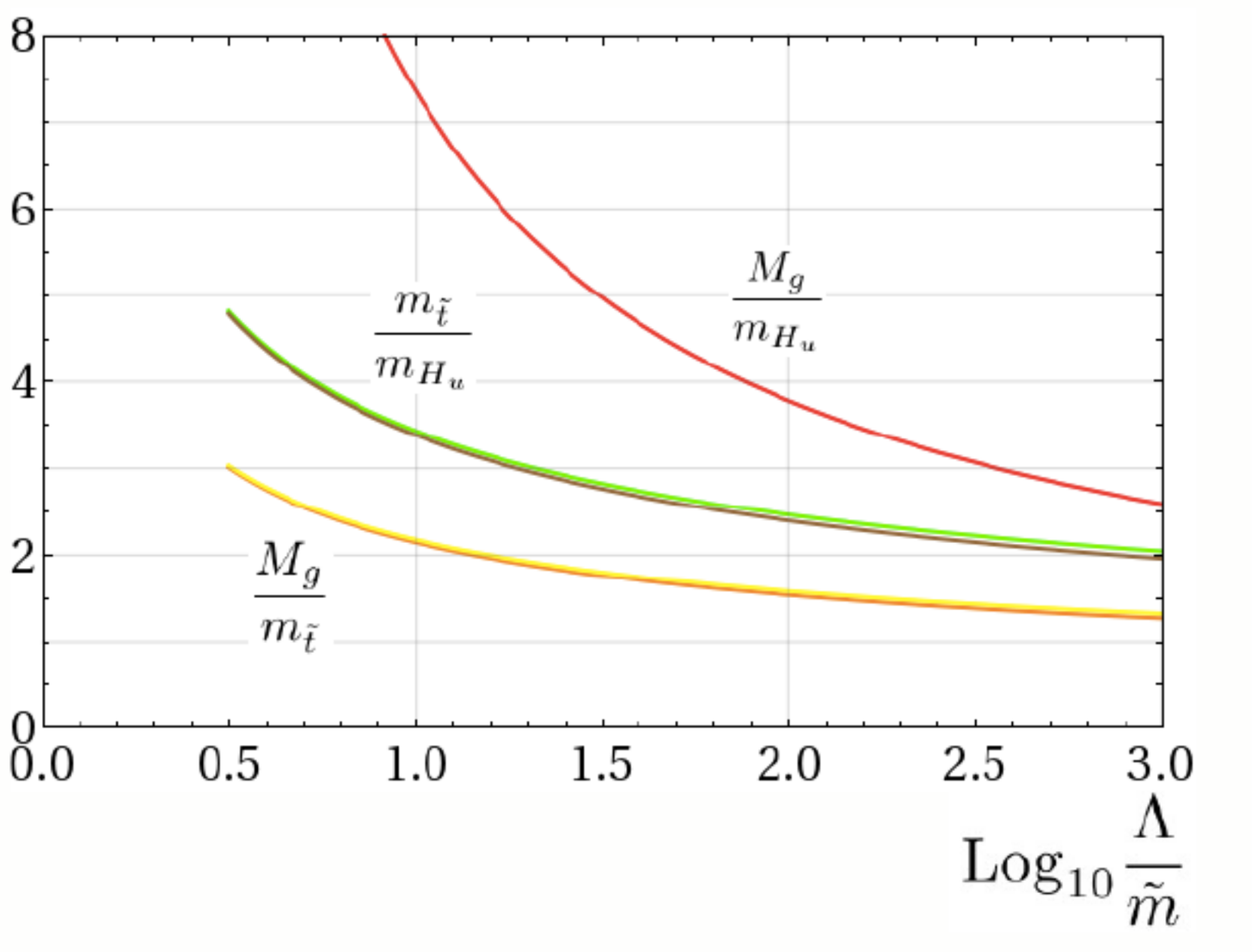
No one is going to believe an anthropic EW 'solution' until every possibility of symmetry & dynamics is exhausted

The Missing Superpartner Problem



The Gluino Sucks Problem

Log RG evolution quickly pulls up stop mass, and thus EW scale, to gluino mass

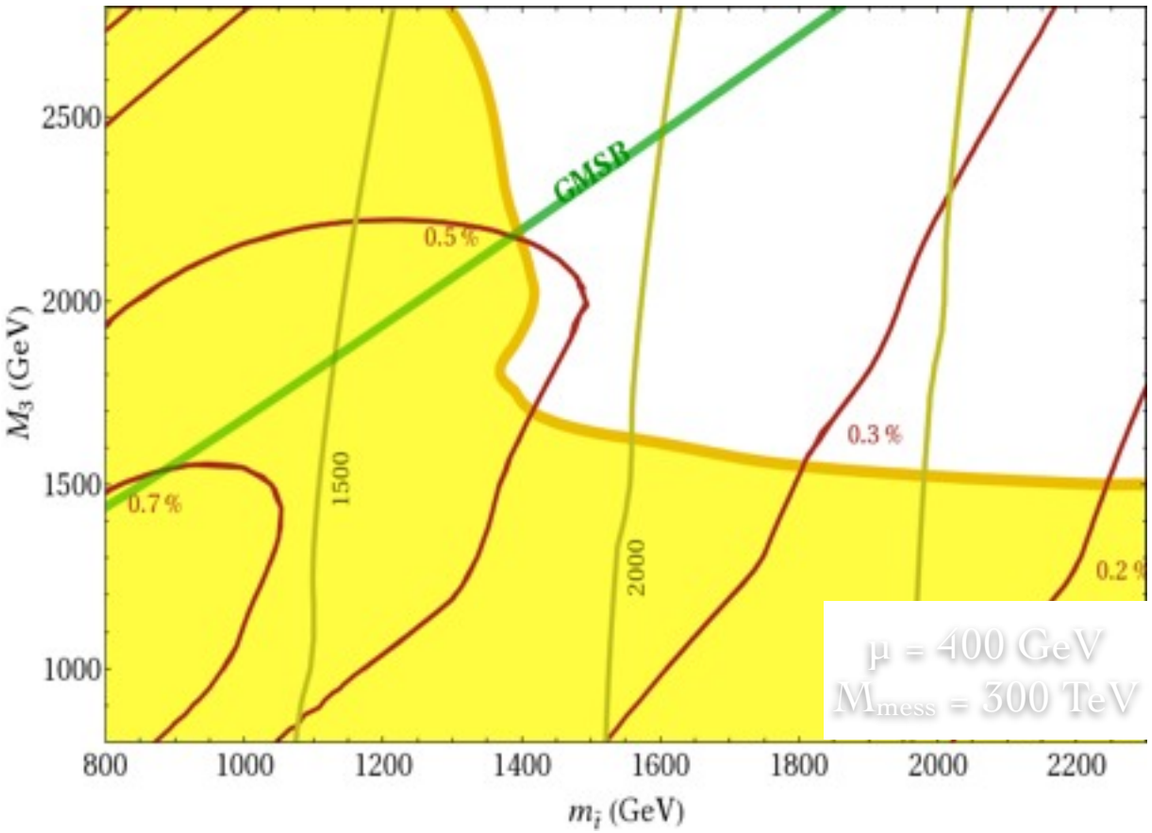


Gluino bounds constrain all MSSM-like scenarios...

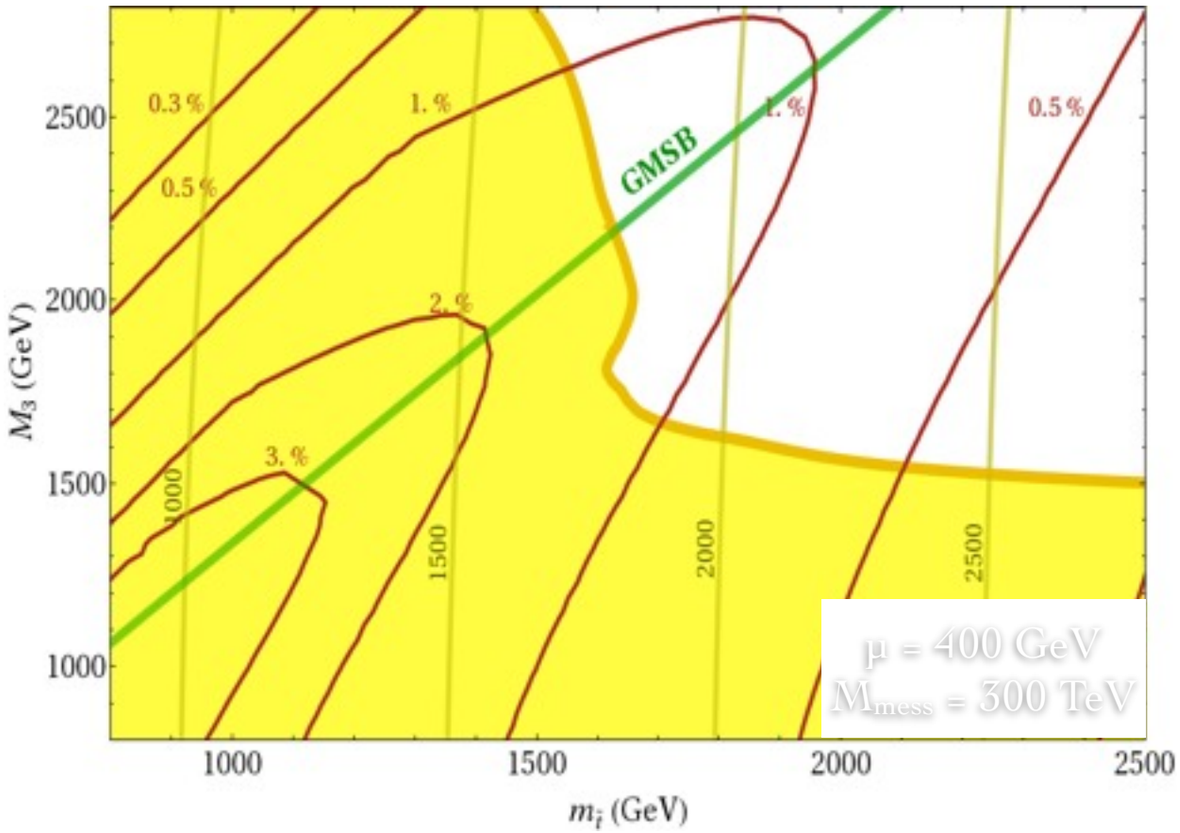
Status of Naturalness in MSSM-like SUSY

- In the MSSM: Tuning dominated by achieving the Higgs Mass
- In any model that fixes the Higgs mass: Tuning dominated by LHC bounds

MSSM with A-terms



NMSSM
or any model that "fixes" the Higgs mass



Arvanitaki et. al. (2013)

LHC pushes the bounds on Naturalness for MSSM-like models

Last Vestiges of Naturalness?
(*traditional* MSSM-like SUSY)

- Natural SUSY (1st/2nd gen sfermions heavy)
- R-Parity breaking: B violation (hide via hadrons)
- Hide and Seek models ("just-so" spectra and decays)

Natural SUSY and RPV: Gluino bounds already imply ~1% tuning

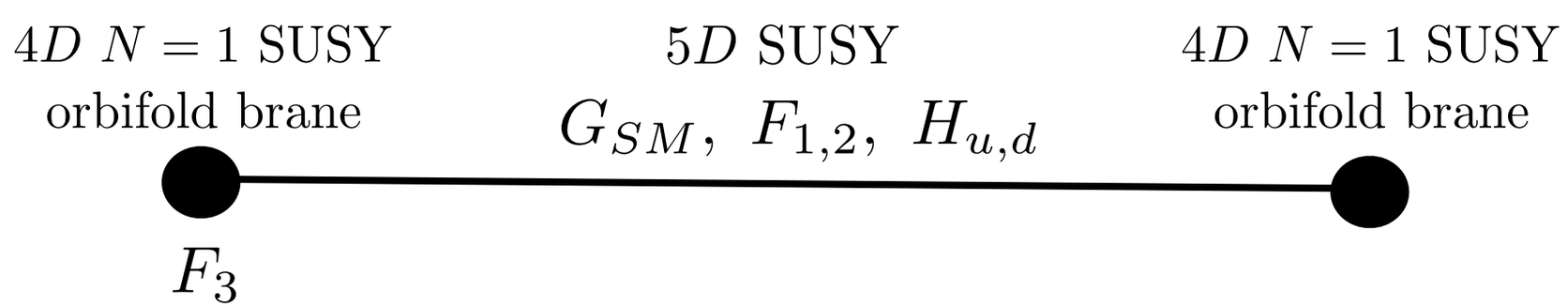
Hide & Seek: Many `coincidences' needed so still highly tuned

A natural theory requires abandoning MSSM structure

Maximally Natural SUSY

Savas Dimopoulos, Kiel Howe, JMR
arXiv:1404.7554 & papers in preparation +
SD, Isabel Garcia Garcia, KH, JMR

Consider 4D theories arising from 5D SUSY with maximal Scherk-Schwarz SUSY breaking (SSSB) at a KK scale 1/R of several TeV



Never well approximated by a 4D softly-broken N=1 SUSY limit

Higgsinos, gauginos, and 1st/2nd family sfermions get (mainly Dirac) SSSB masses of size 1/2R by SUSY-breaking bc

ONLY $\langle H_u \rangle \neq 0$. Down-like quark and lepton masses from Kahler couplings to $H_u^\dagger$

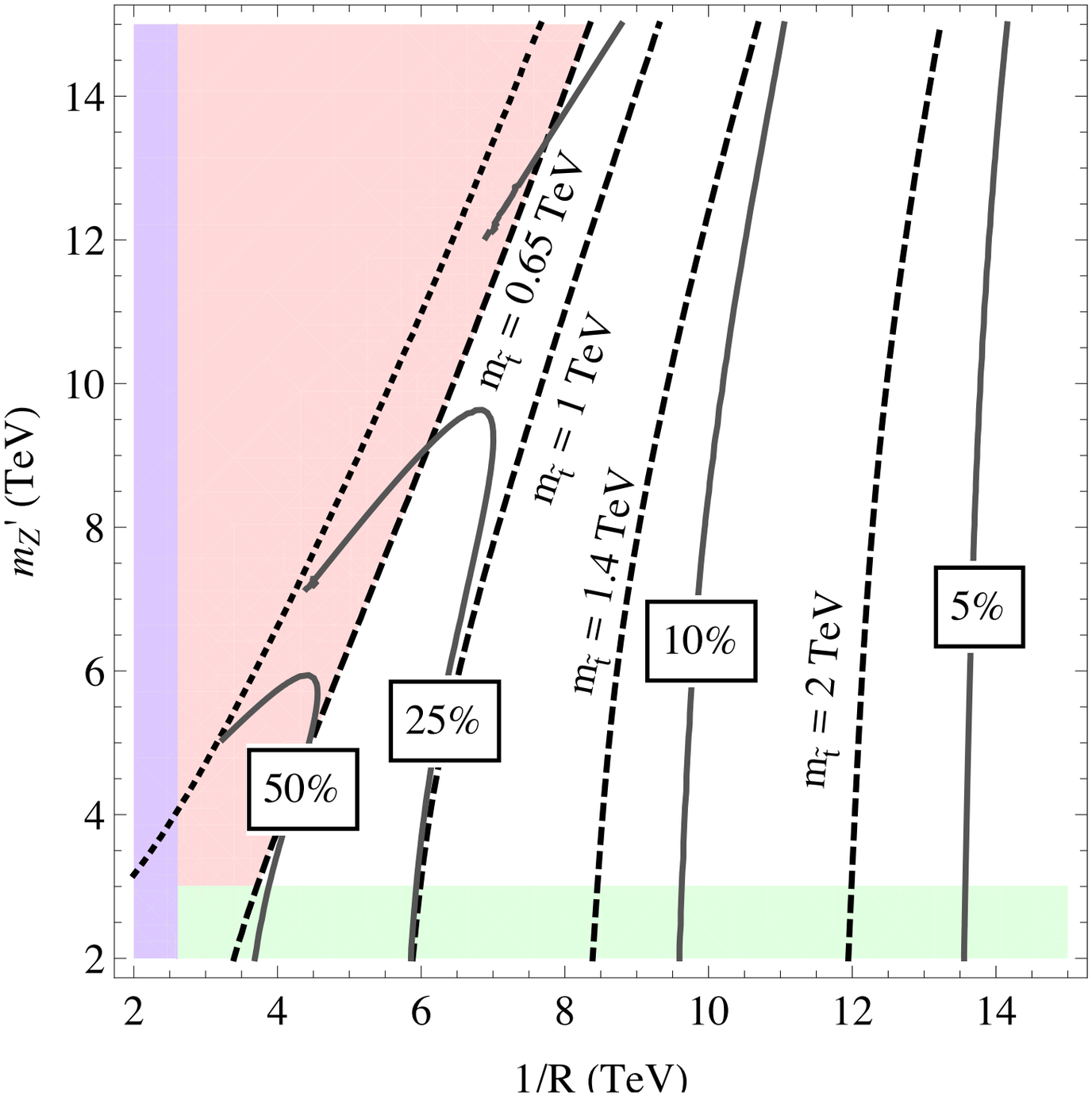
R. Davies, JMR, M. McCullough, arXiv1103.1647

NO $\tan\beta,\ B_\mu,\ \mu$

(Physical Higgs is automatically SM-like up to loop-level effects)

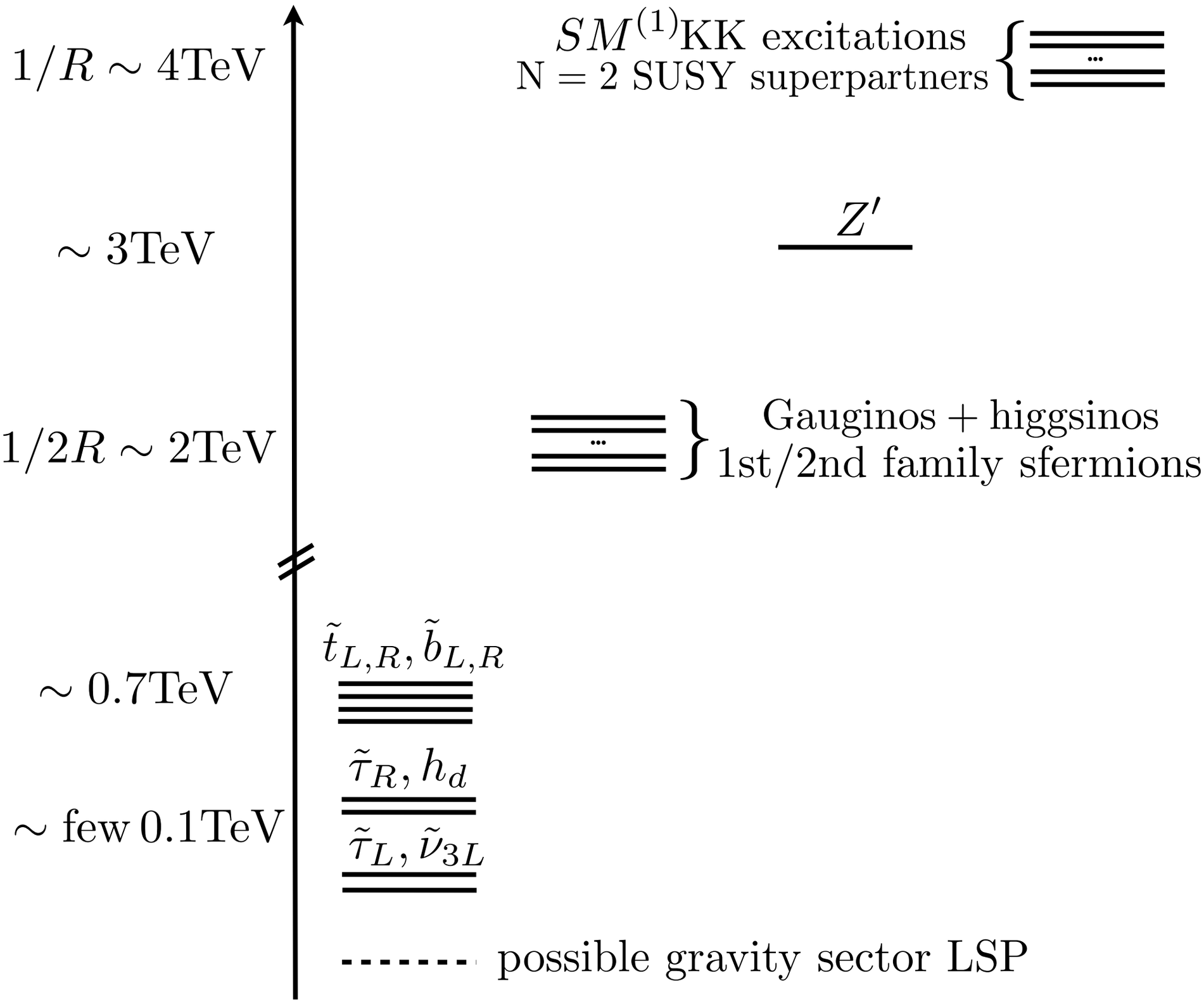
Maximally Natural SUSY

Apart from 3rd generation sfermions SM-charged SUSY spectrum is remarkably heavy, with only ~ 50% tuning at a gluino mass of ~2 TeV, stop mass ~650 GeV, and KK ~4 TeV



For minimal tuning must introduce Z' with non-decoupling D-term to get 126 GeV Higgs

Maximally Natural SUSY

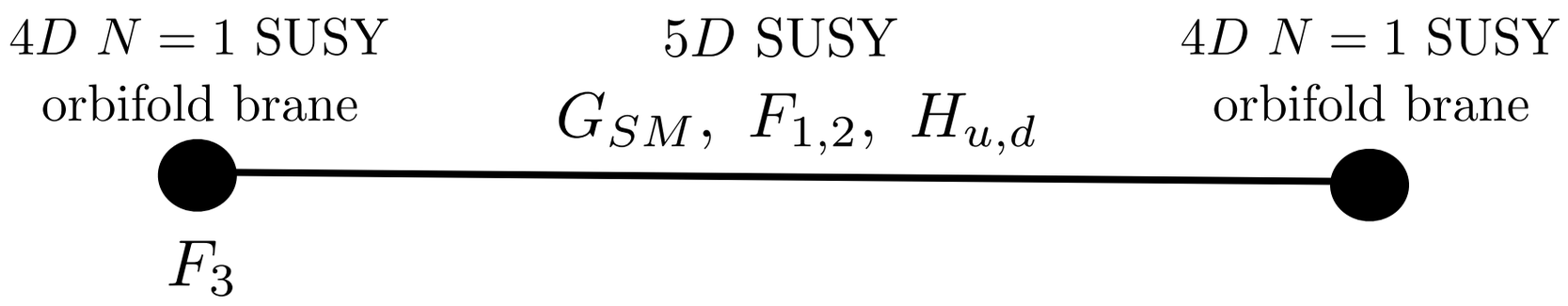


Maximally Natural SUSY

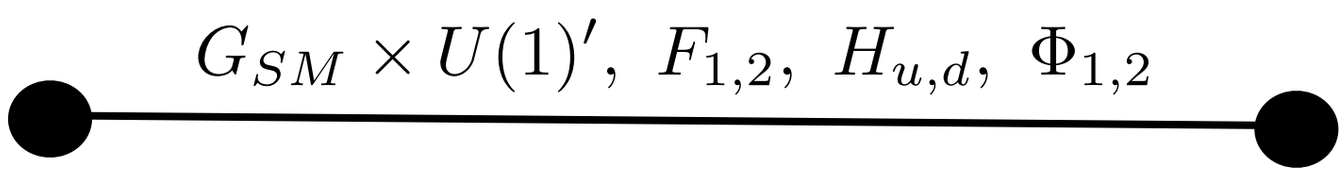
Why so much less tuned than usual?

- No tree-level tuning as no μ
- SUSY breaking directly communicated to Higgsinos, gauginos, and 1st/2nd family sfermions. 3rd family protected from tree SUSY breaking
- SSSB is super-soft as it is a non-local (in 5d) breaking of SUSY. No logs, so suppresses the gluino sucks problem
- A natural SUSY spectrum is trivial to obtain via localization of the 3rd family on a 4D brane (also vital for successful EWSB)
- There is an approximate $U(1)_R$ symmetry

Maximally Natural SUSY

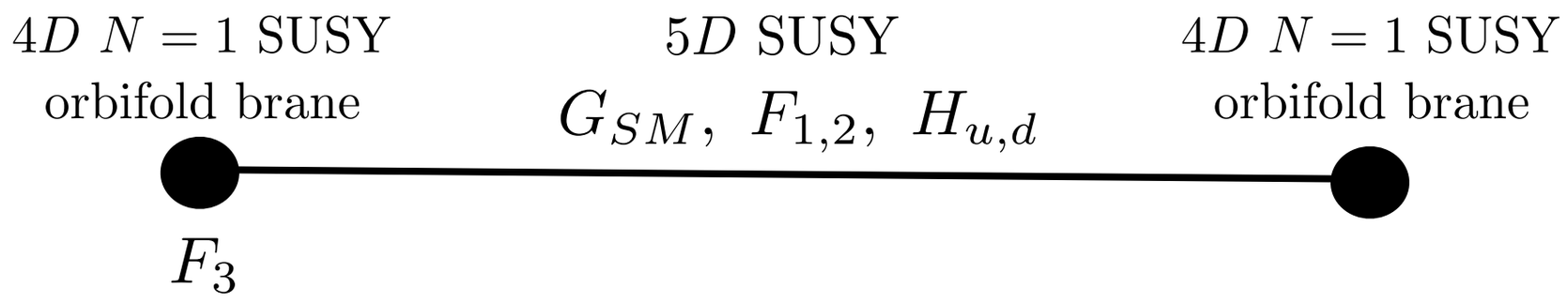


For *minimal* tuning more structure - a U(1)' -
needed to get 126 GeV Higgs mass

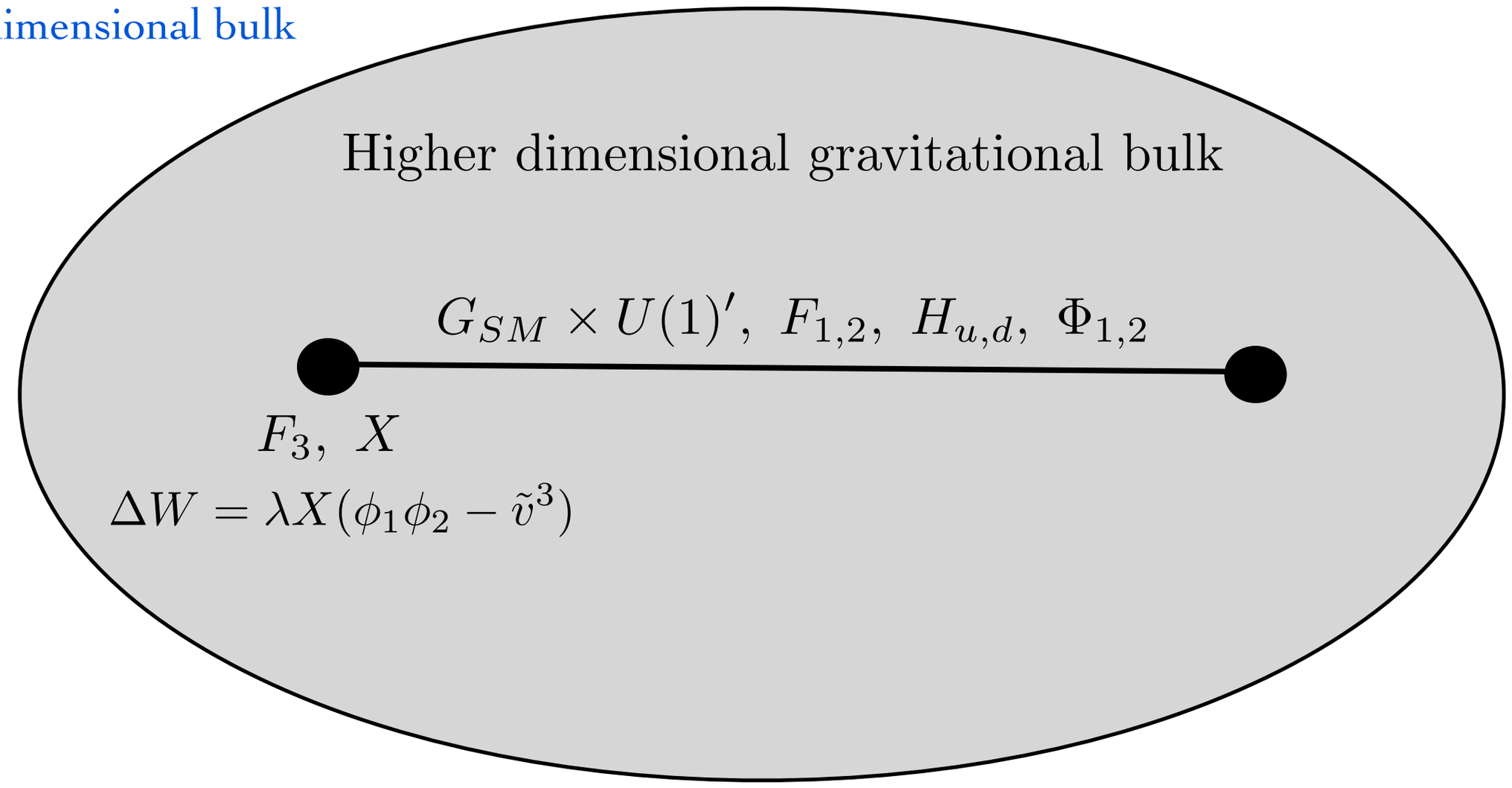


$$\Delta W = \lambda X(\phi_1\phi_2 - \tilde{v}^3)$$

Maximally Natural SUSY

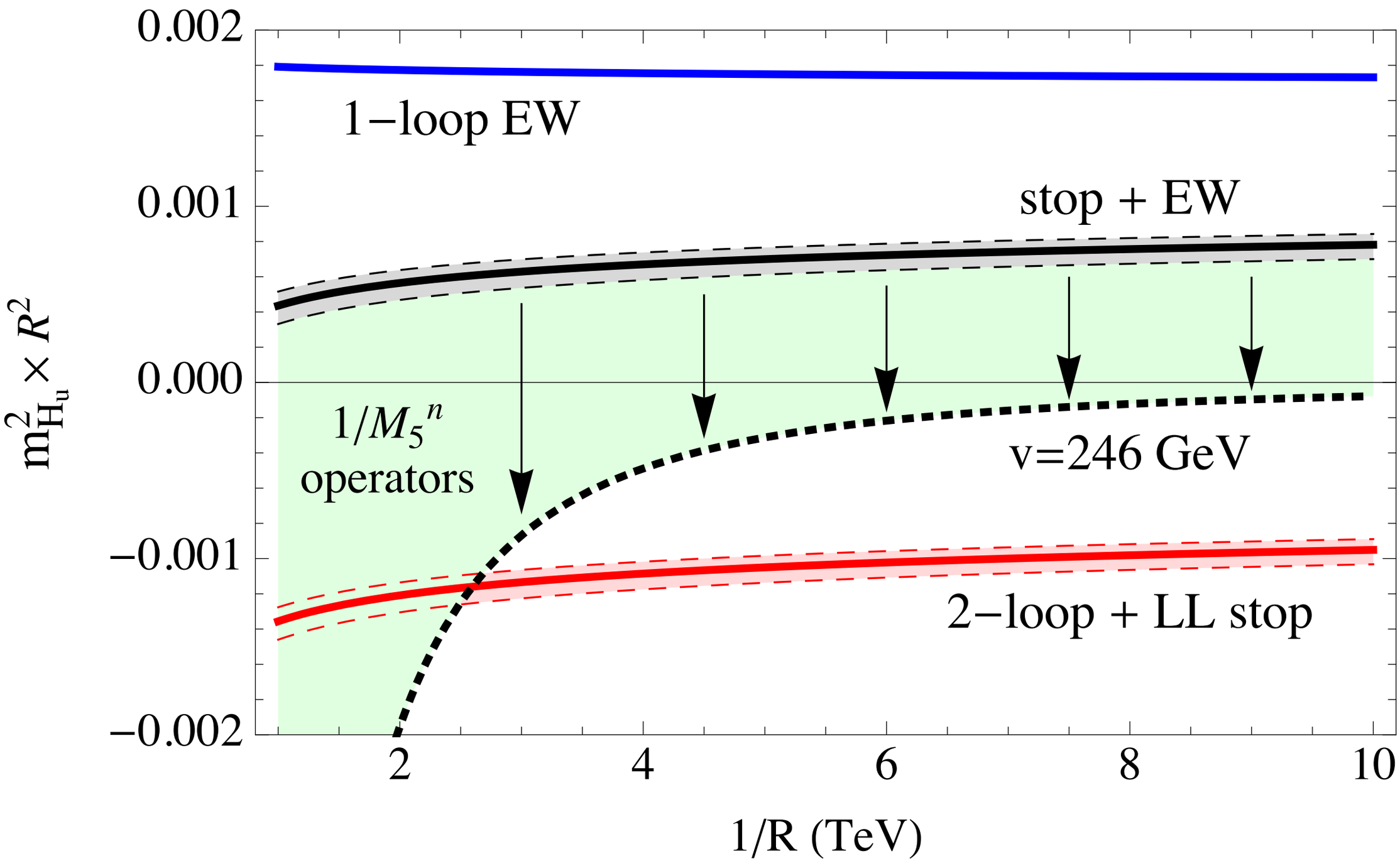


And of course to get G_N must embed in higher-dimensional bulk

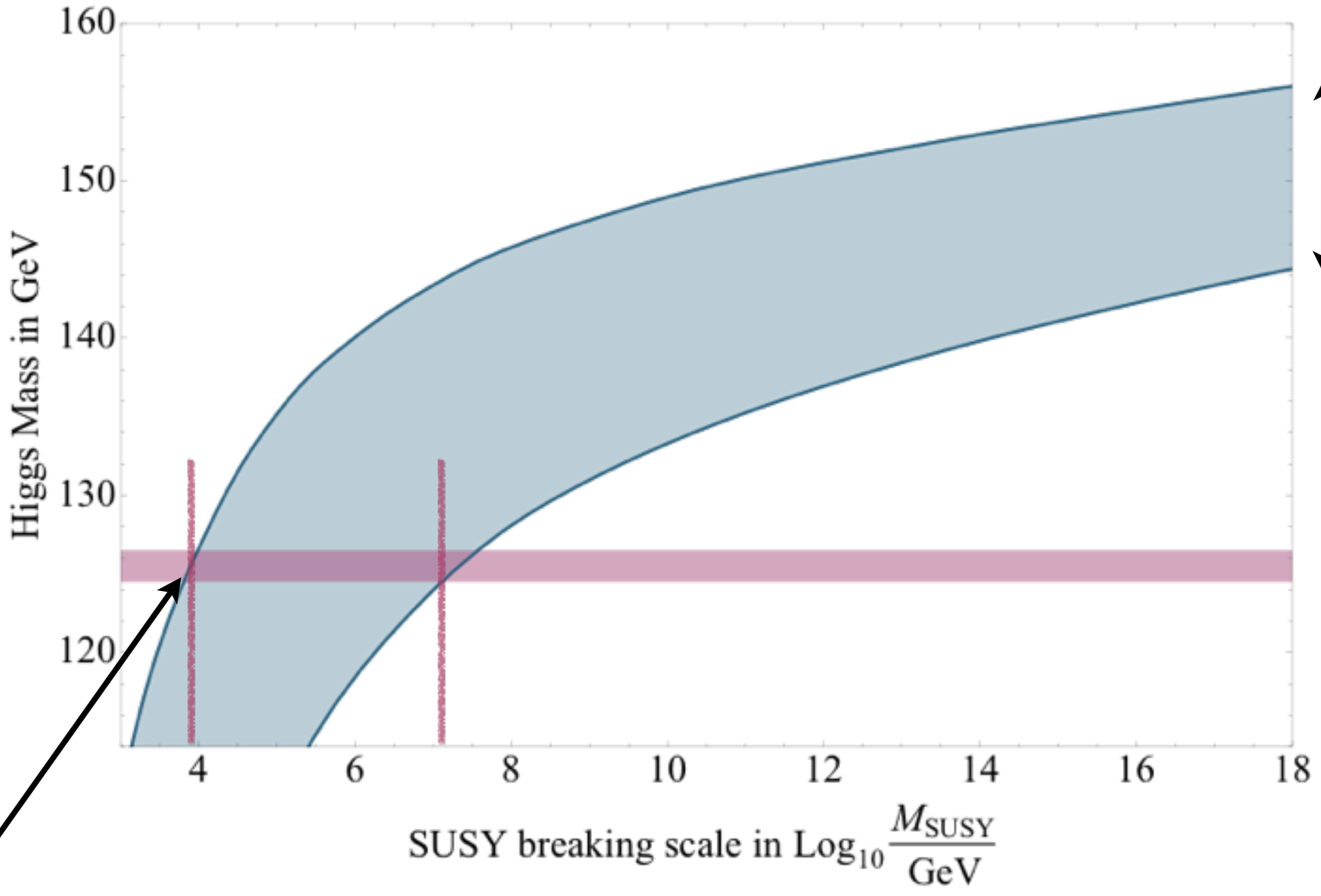


Maximally Natural SUSY

How EWSB works: (magnitude of EW scale^2 1-EW-loop effect from EW-ino masses)



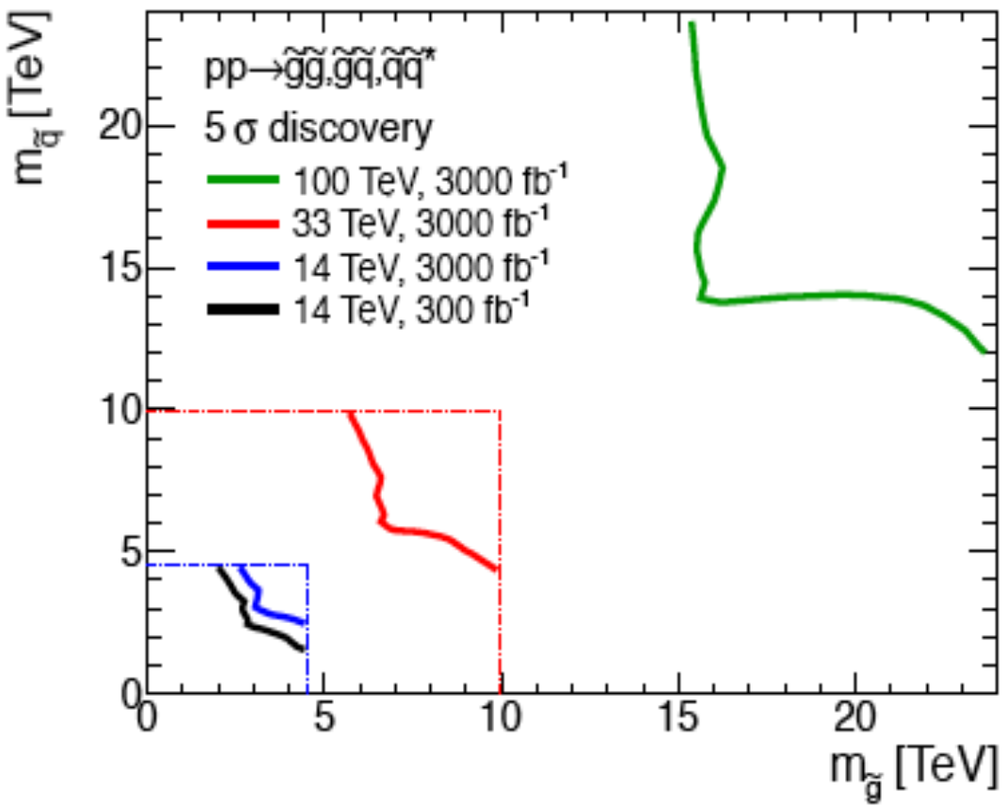
Amusing Possibility for 126 GeV Higgs



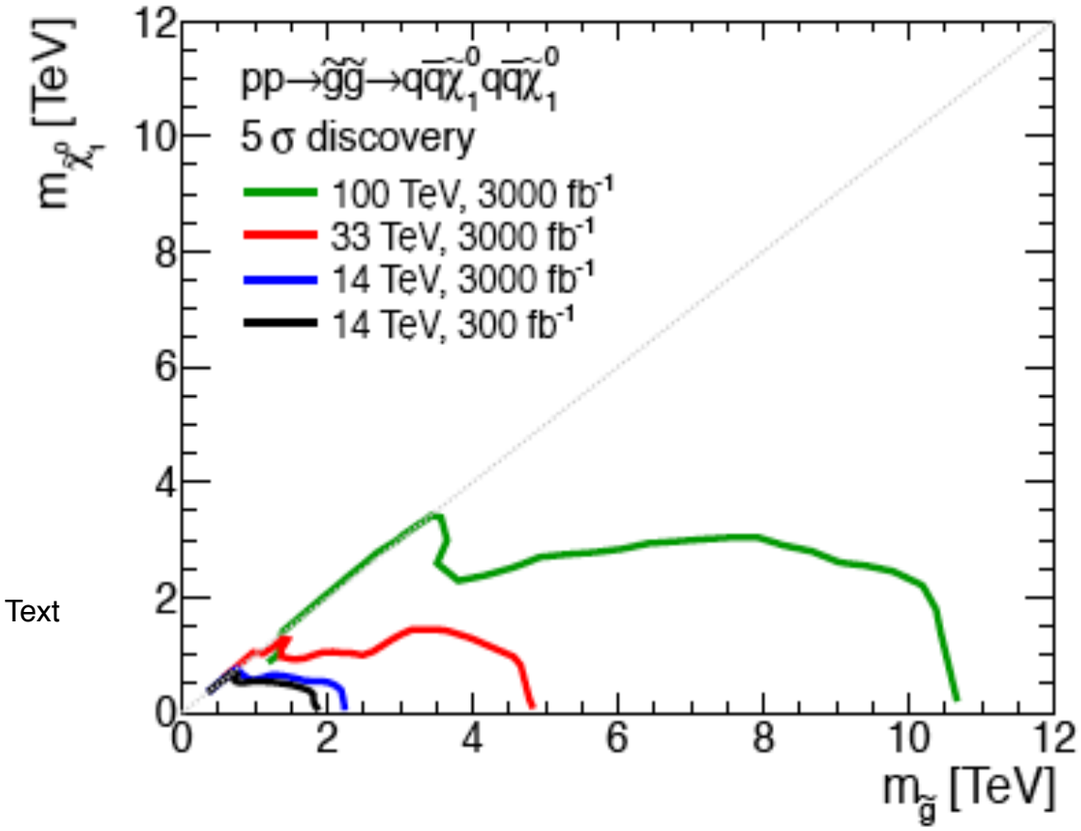
For stop mass ~3TeV & 10TeV gluino (~ 3% tuning) successful Higgs mass without need of U(1)' sector as model automatically realises $\tan\beta \to \infty$ limit without flavour problems

Discovery Reach of 100 TeV

squark-gluino



LSP-gluino



Text

Cohen et. al. (2013)

LHC 14: Probing MSSM-like theories much worse than 1% tuned, and Max Natural SUSY in dominant region of parameter space

100 TeV Collider: Probes MSSM-like theories at 0.01% level, and can discover simplest Max Natural SUSY in regime giving 126GeV higgs at ~3% tune