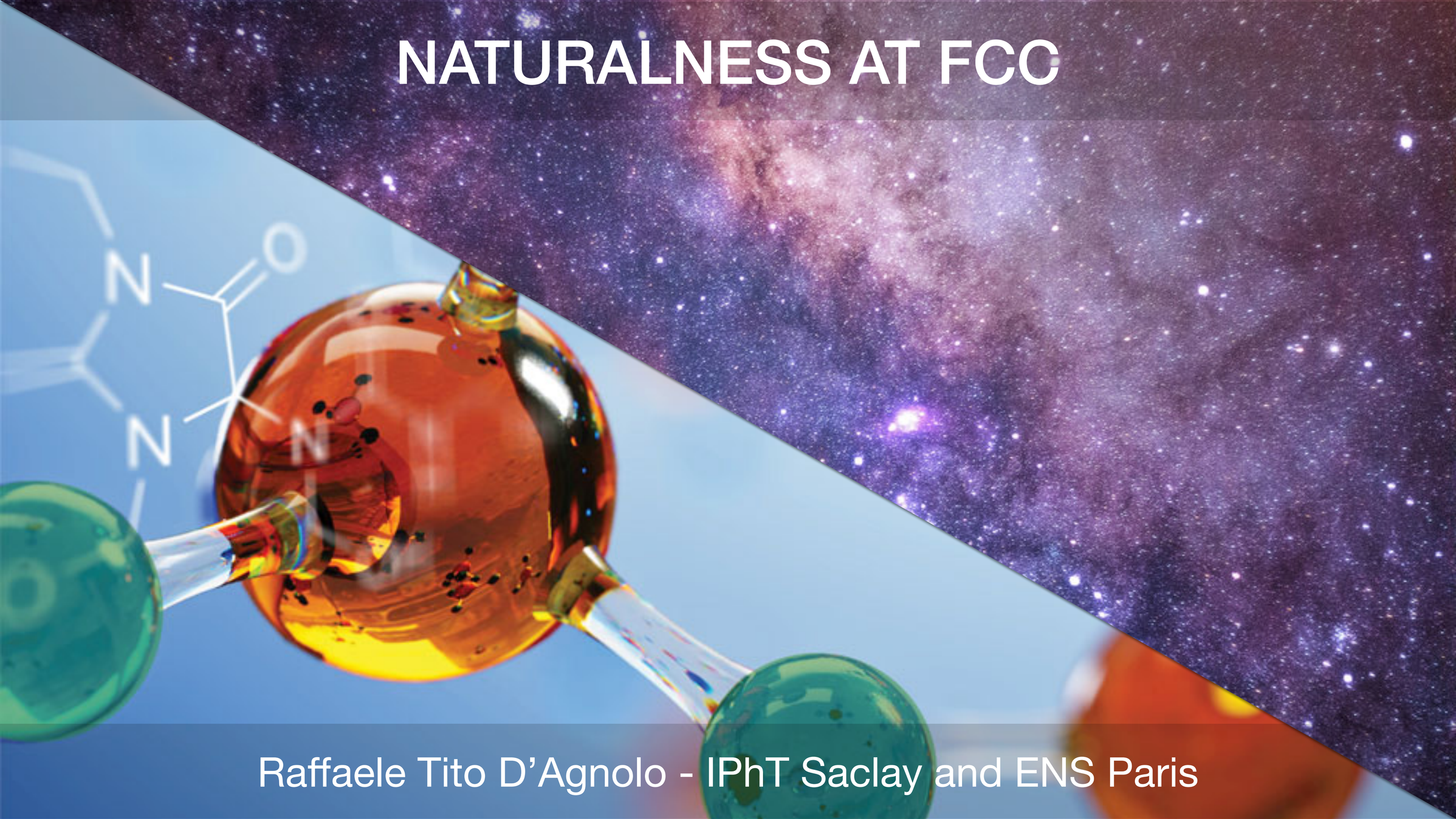
NATURALNESS AT FCC



Raffaele Tito D’Agnolo - IPhT Saclay and ENS Paris

Higgs Mass Squared

$$m_h^2 |H|^2$$

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

SYMMETRY-BASED ESTIMATE

$$m_h^2 \sim \frac{y_t^2 M_{\rm Pl}^2}{16\pi^2}$$

Symmetry~10^{34} Experiment

$$m_h^2 = 0$$

Special

———— Planck

———— New Symmetry

———— SM

$$m_h^2 \sim \frac{y_t^2 M_S^2}{16\pi^2}$$

M_S

——— Planck

——— New Symmetry

——— SM

Planck

Supersymmetry or Scale Invariance

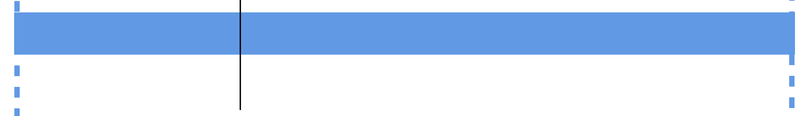
New Symmetry

SM

$$\left(m_h^2 |H|^2 \right)$$

We have been looking for answers at energies close to the Higgs mass for more than 40 years

Higgs Boson

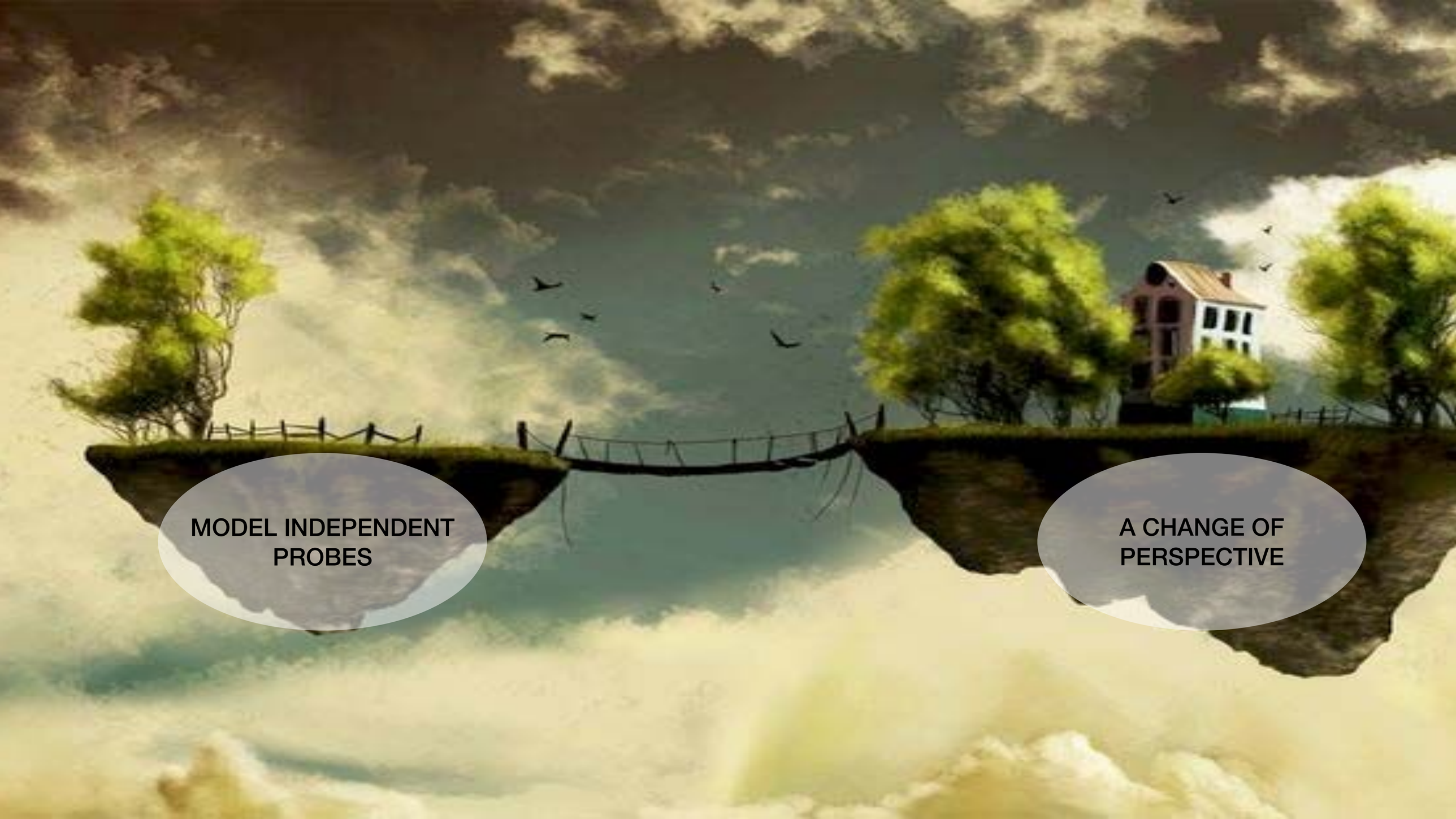


and we have not found them

It doesn’t work at all for the cosmological constant

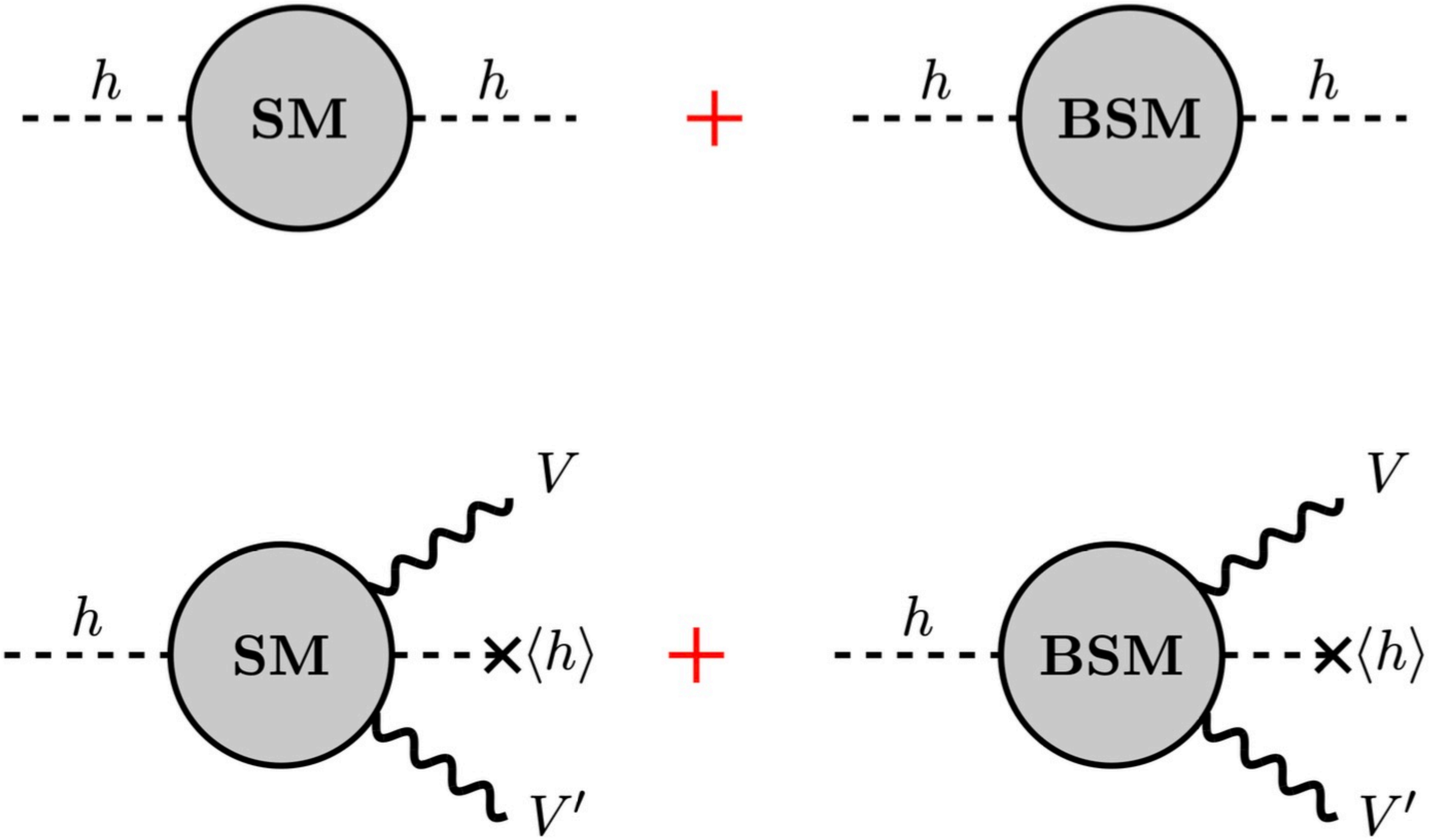
$$\Lambda \simeq (0.1\ \mathrm{meV})^4$$


WHAT NOW?


MODEL INDEPENDENT PROBES
A CHANGE OF PERSPECTIVE


MODEL INDEPENDENT
PROBES


h
SM
h
+
h
BSM
h


h
SM
h
+
h
BSM
h
V
h
SM
⟨h⟩
V'
+
V
h
BSM
⟨h⟩
V'

If you observe a deviation in Higgs couplings you can set an upper bound on the scale where **new bosons** must appear

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F. Nortier, G. Rigo, P. Sesma ’24

RTD, F. Nortier, G. Rigo, P. Sesma ’23

K. Blum, RTD, J. Fan ’15

N. Arkani-Hamed, K. Blum, RTD, J. Fan ‘12

If you observe a deviation in Higgs couplings you can set an upper bound on the scale where **new bosons** must appear

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Imagine that you observed a deviation in hWW and have then discovered the fermions that generate it

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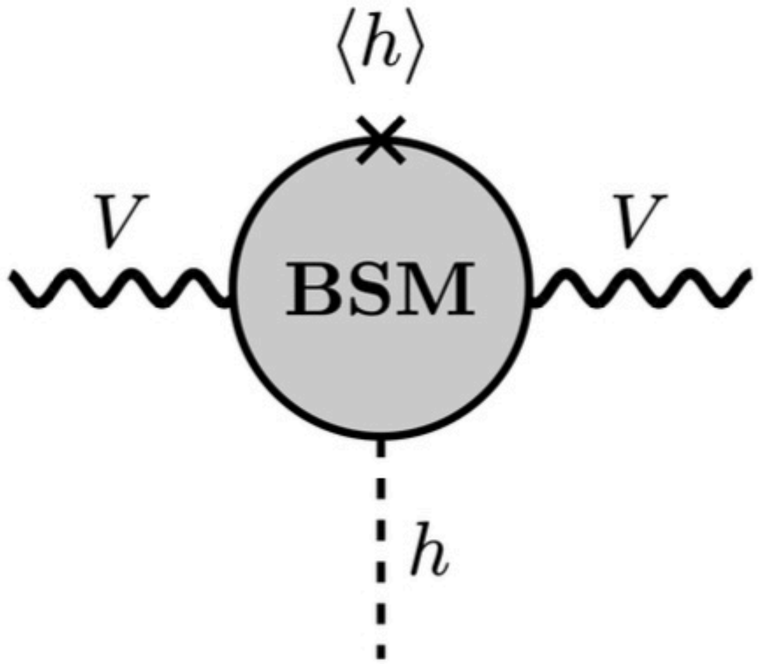

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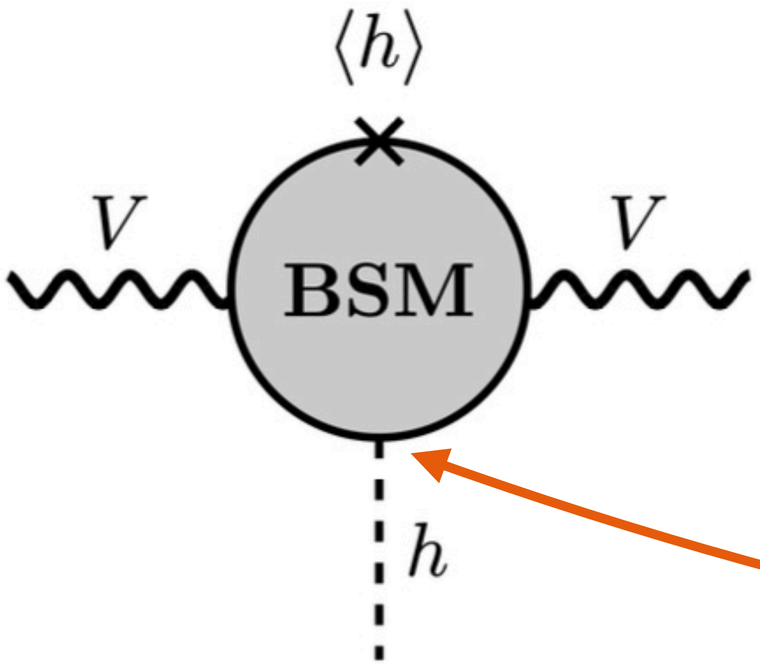
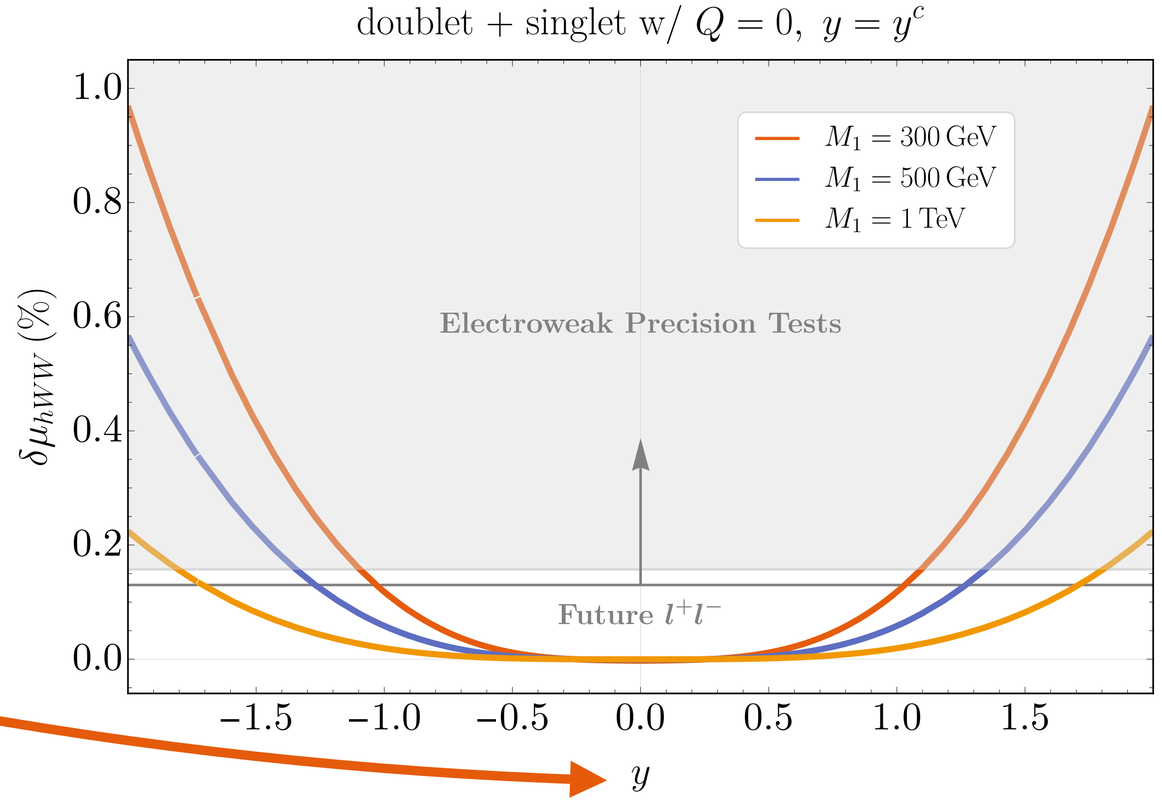


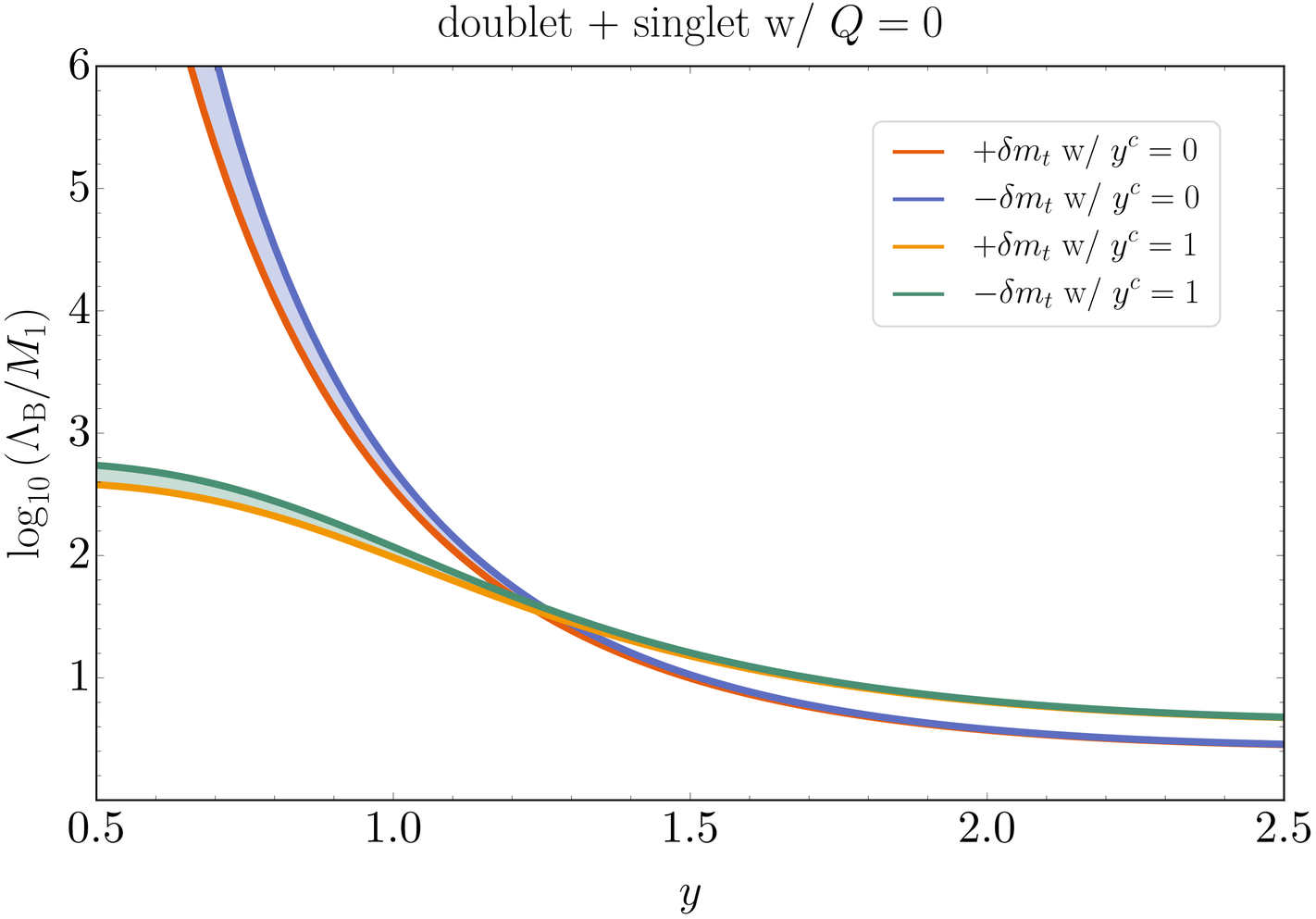


Large Yukawa couplings are “bad”

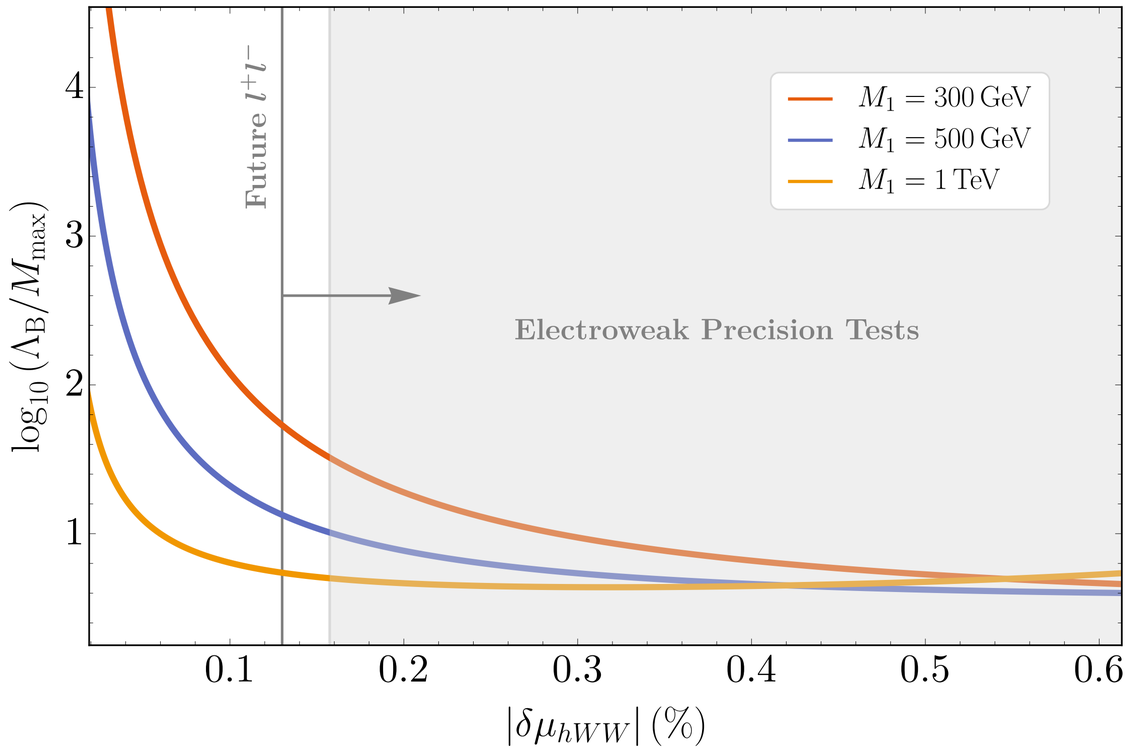
$$\frac{d\lambda}{d\log E} \sim -\frac{y^4}{16\pi^2}$$

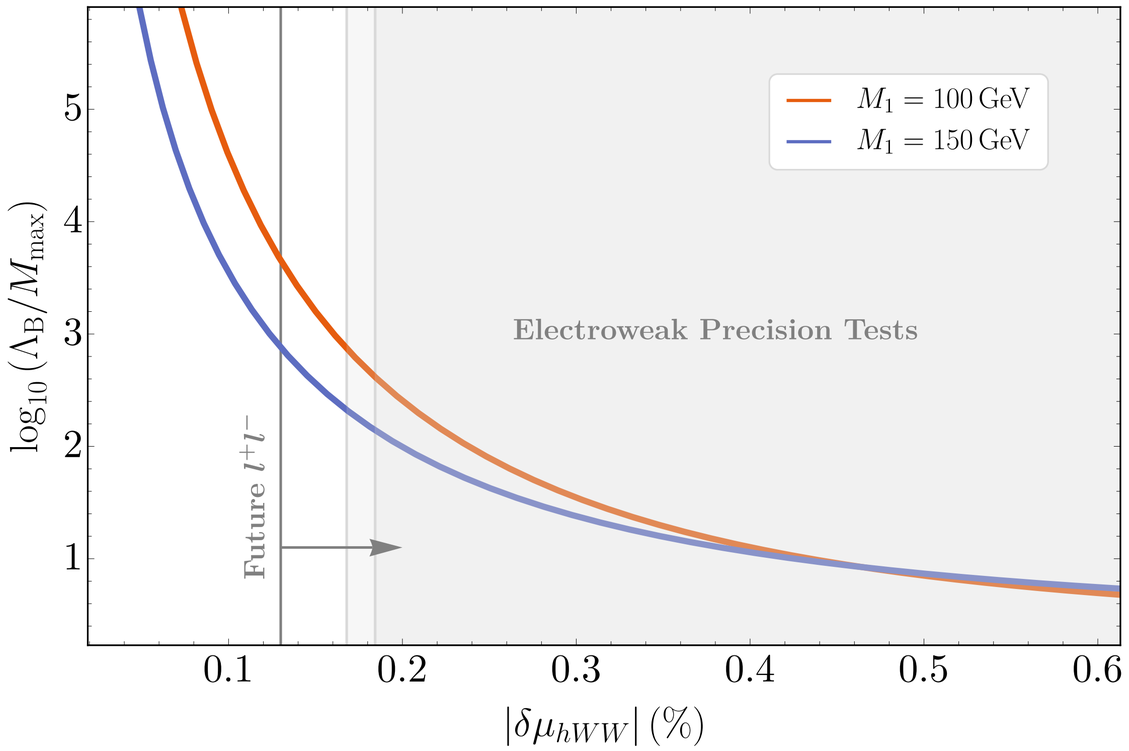
$$\frac{dy}{d\log E} \sim \frac{y^3}{16\pi^2}$$

Large Yukawa couplings are “bad”

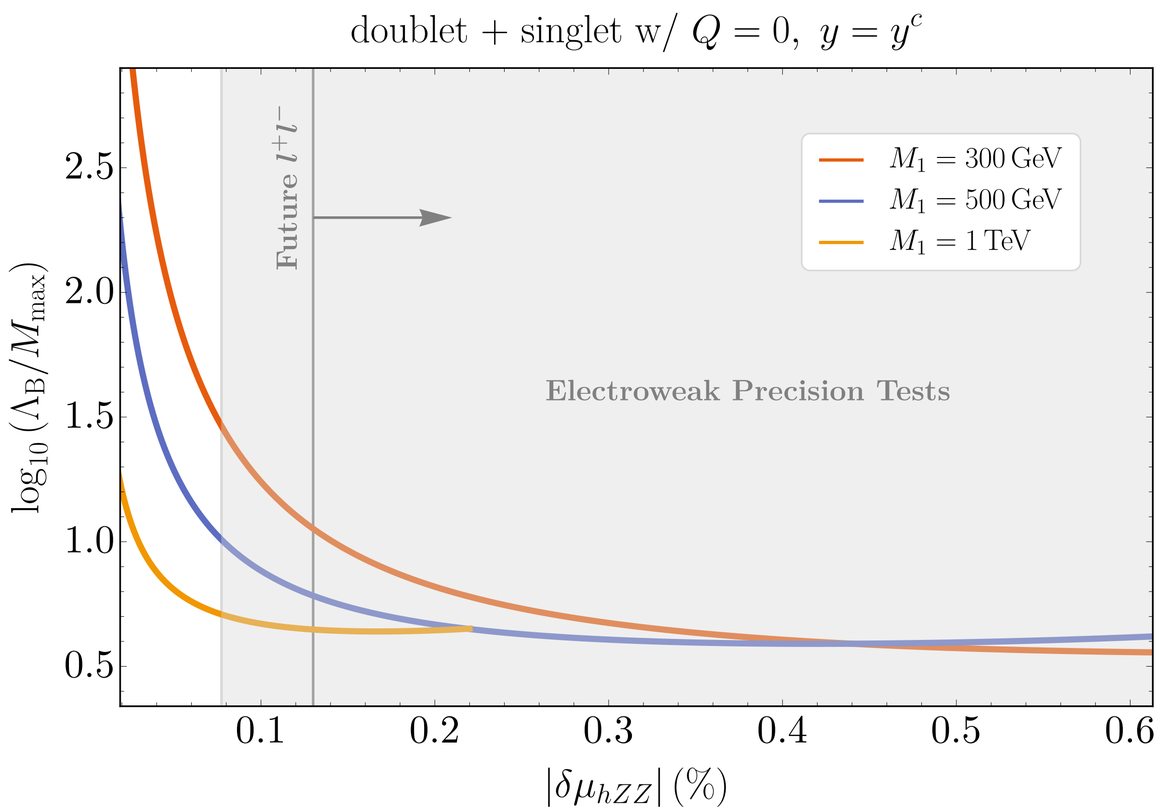


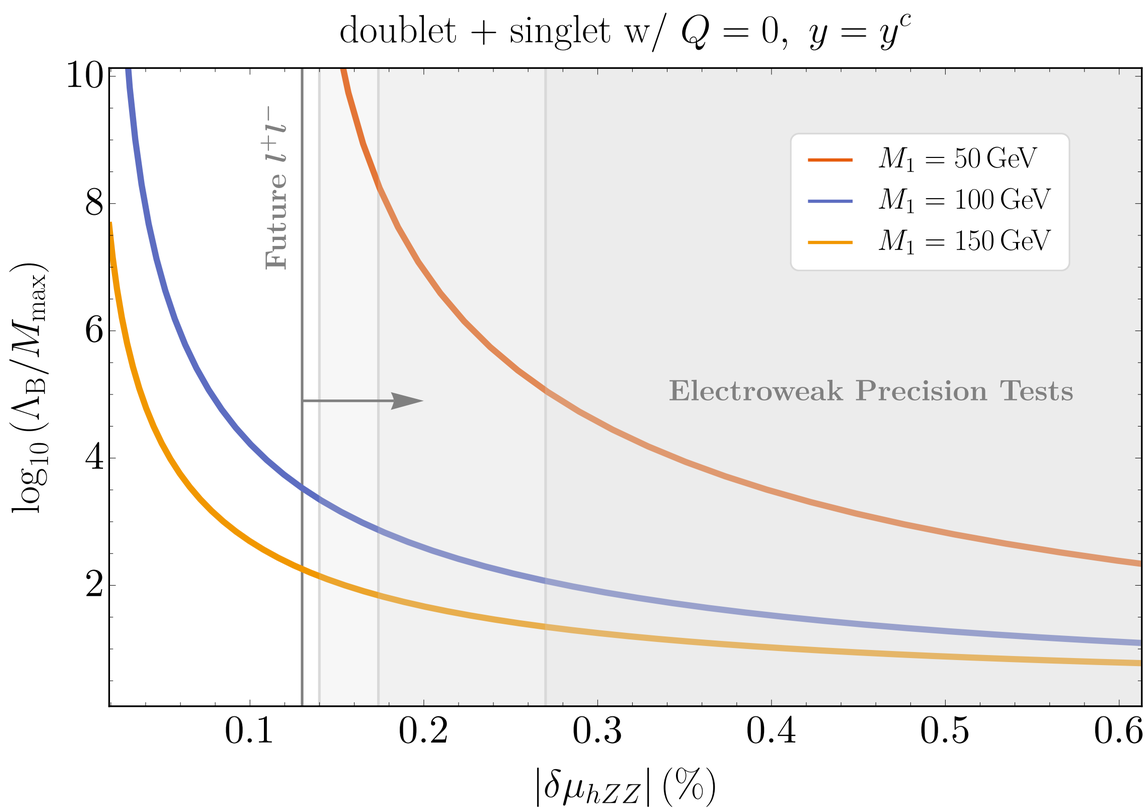
hWW


doublet + singlet w/ $Q = 0,\ y = y^c$
$M_1 = 300\,\mathrm{GeV}$
$M_1 = 500\,\mathrm{GeV}$
$M_1 = 1\,\mathrm{TeV}$
Future l^+l^-
Electroweak Precision Tests
$\log_{10}(\Lambda_B/M_{\max})$
$|\delta\mu_{hWW}|\,(\%)$


doublet + singlet w/ $Q = 0,\ y = y^c$
$M_1 = 100\,\mathrm{GeV}$
$M_1 = 150\,\mathrm{GeV}$
Future l^+l^-
Electroweak Precision Tests
$\log_{10}(\Lambda_B/M_{\max})$
$|\delta\mu_{hWW}|\,(\%)$

hZZ


doublet + singlet w/ $Q = 0,\ y = y^c$
Future l^+l^-
Electroweak Precision Tests
$M_1 = 300\,\mathrm{GeV}$
$M_1 = 500\,\mathrm{GeV}$
$M_1 = 1\,\mathrm{TeV}$
$\log_{10}(\Lambda_B/M_{\max})$
$|\delta\mu_{hZZ}|\,(\%)$


doublet + singlet w/ $Q = 0,\ y = y^c$
Future l^+l^-
Electroweak Precision Tests
$M_1 = 50\,\mathrm{GeV}$
$M_1 = 100\,\mathrm{GeV}$
$M_1 = 150\,\mathrm{GeV}$
$\log_{10}(\Lambda_B/M_{\max})$
$|\delta\mu_{hZZ}|\,(\%)$

ROUGH SUMMARY

If you see a deviation in hWW or hZZ at HL-LHC or FCC-ee
you will detect new bosons at FCC-hh (at the latest)

RTD, F. Nortier, G. Rigo, P. Sesma ’23


A CHANGE OF
PERSPECTIVE

1. We tune

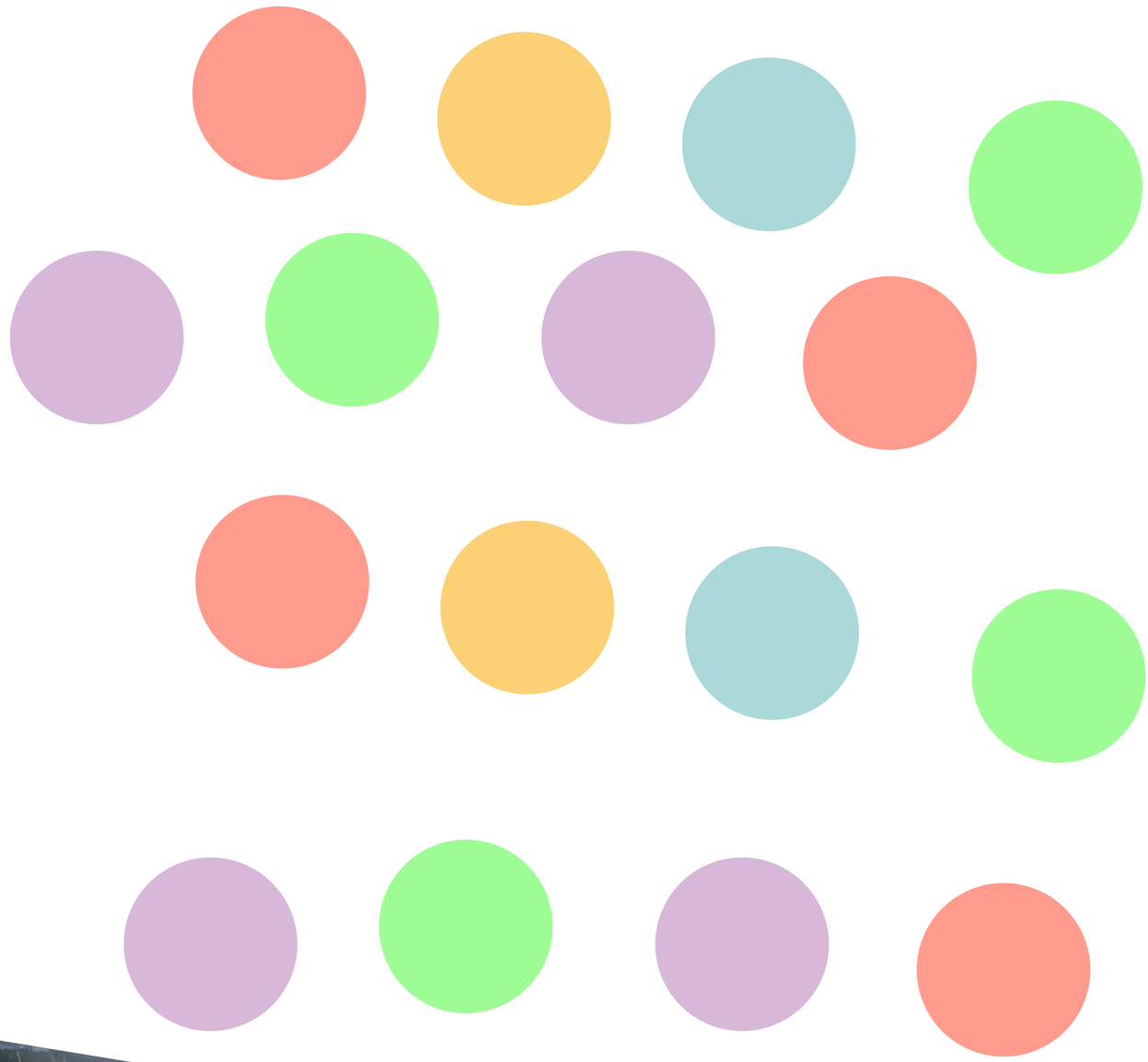
2. There is no mass scale beyond the SM [1305.6939]

3. The Higgs mass and the CC are inputs

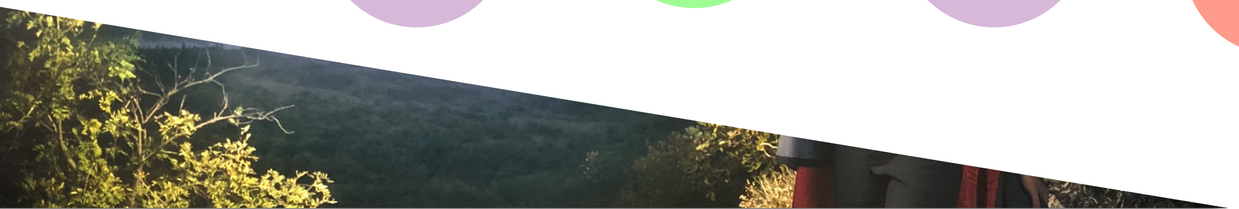
4. UV/IR Mixing [1909.01365]

5. Swampland on steroids

1. We tune
2. In 4D you get GR with ghosts
3. We don't know any theory of QG that does it
4. Possible, but we don't have any idea how to write a theory that works
5.
6. **There is a landscape**



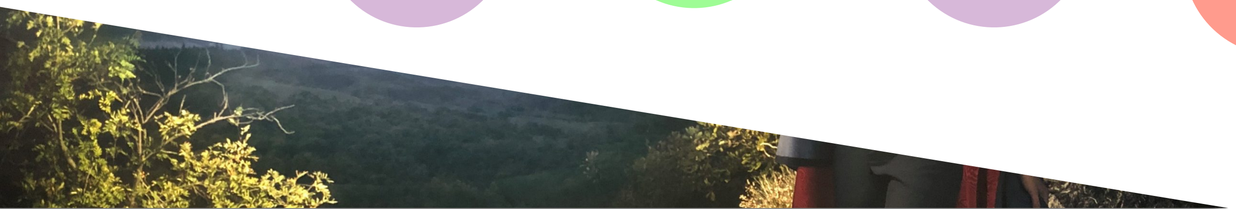
Causally Disconnected Universes with different values of the Standard Model parameters, populated by inflation



1. One day it can be tested experimentally

2. Currently our most concrete explanation for the cosmological constant

3. It probably exists independently of the problem



ONE EXAMPLE

C.Csaki, RTD, M. Geller, A. Ismail ‘21

Landscape of Higgs Masses populated by inflation

$$-\Lambda_{\rm H}^2 \leq m_H^2 \leq \Lambda_{\rm H}^2$$

$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

ONE EXAMPLE

After a time

$$t_c < M_{\rm Pl}/\Lambda_{\rm H}^2$$

All patches where the Higgs vev

$\langle H^0 \rangle \simeq v$

$$\langle H^0 \rangle \equiv h$$

Is outside of a certain range

$\langle H^0 \rangle \simeq v$

$$h_{\rm min} \lesssim h \leq h_{\rm crit}$$

crunch

$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

ONE EXAMPLE

Only universes with the observed value of the weak scale can live longer than a Planck time and inflate. **Today the multiverse looks like**:

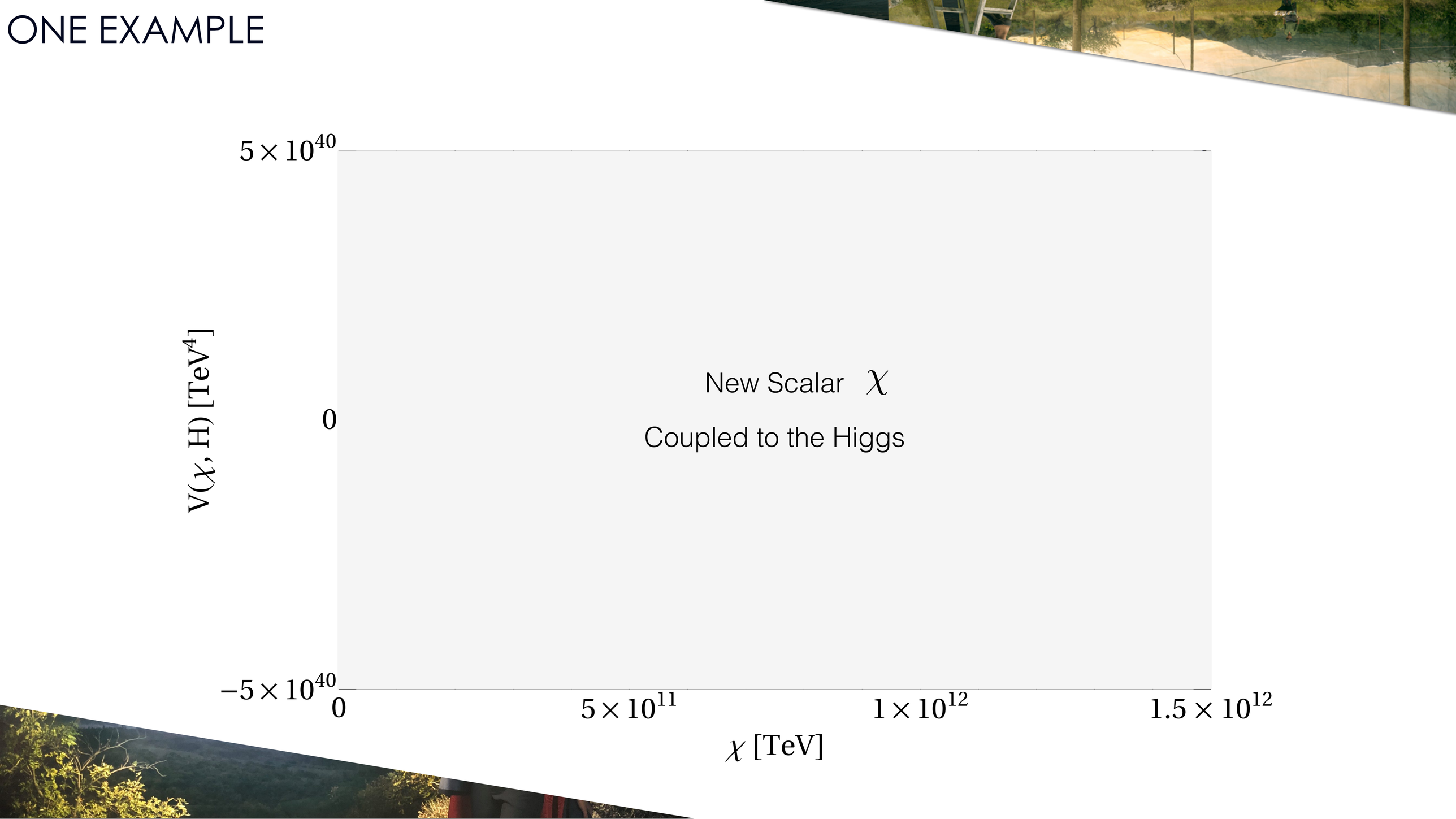
$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

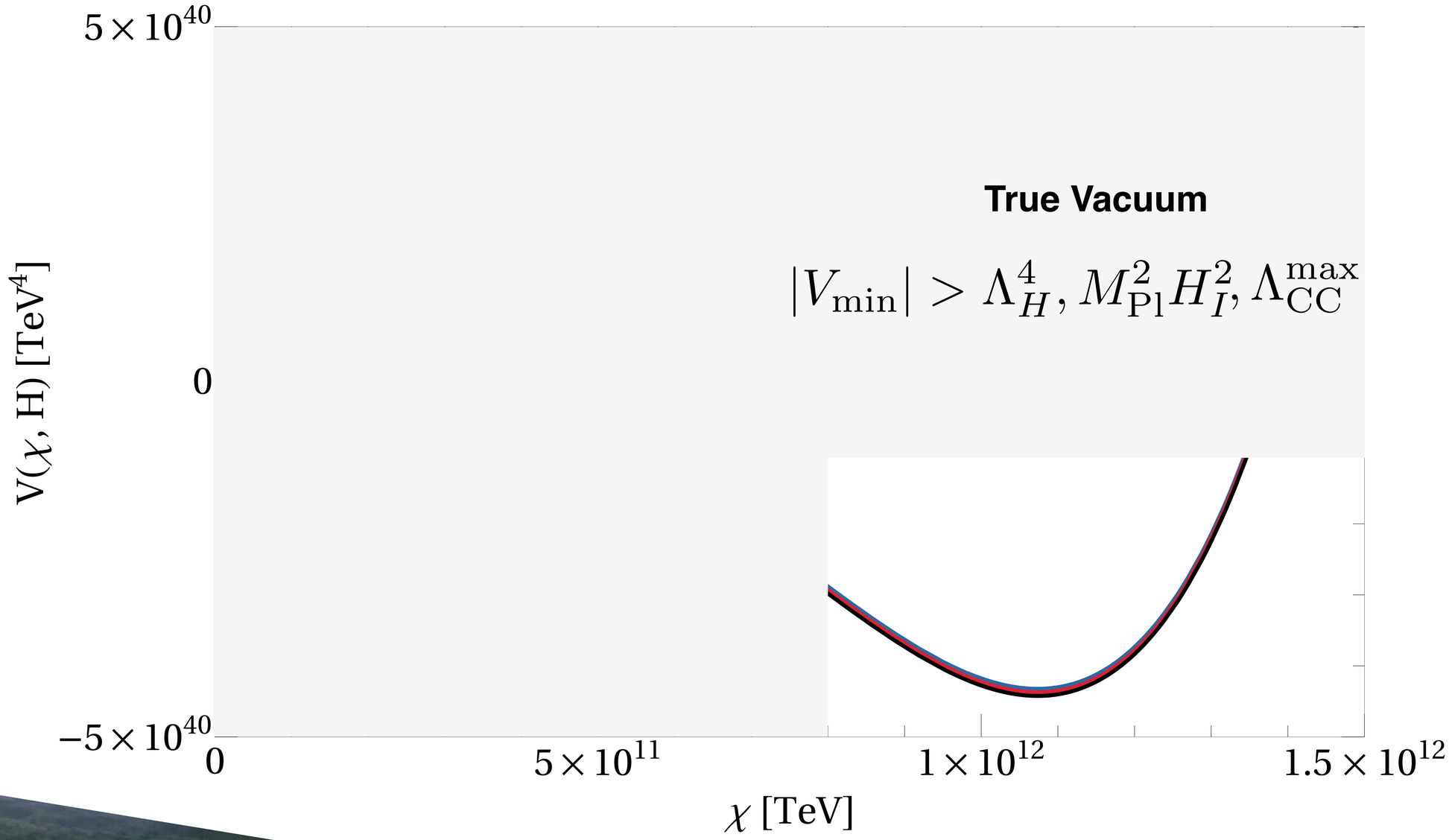
$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

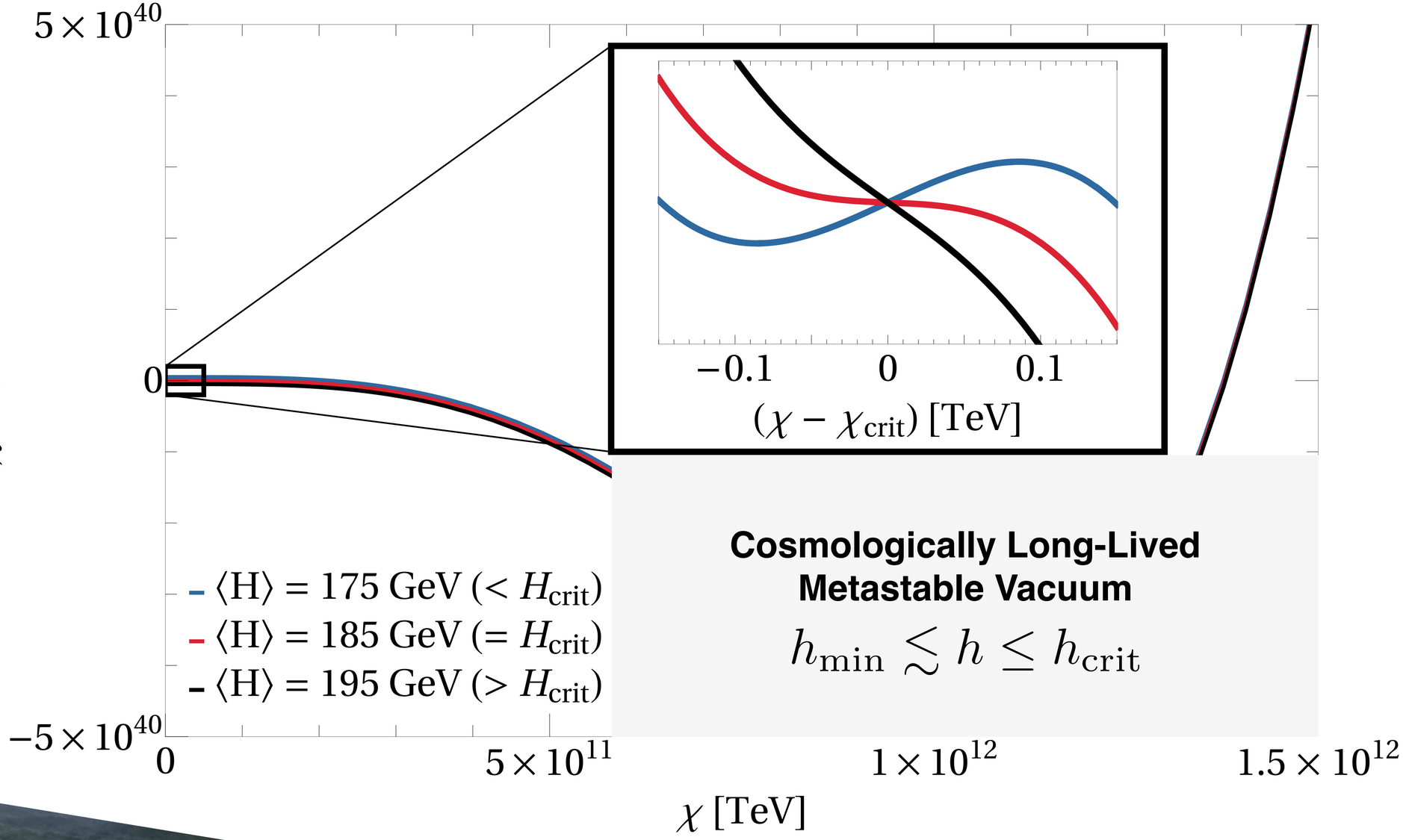
ONE EXAMPLE


5×10^{40}
0
-5×10^{40}
$V(\chi, H)$ [TeV^4]
New Scalar χ
Coupled to the Higgs
0
5×10^{11}
1×10^{12}
1.5×10^{12}
χ [TeV]

ONE EXAMPLE


True Vacuum
$|V_{\rm min}| > \Lambda_H^4, M_{\rm Pl}^2 H_I^2, \Lambda_{\rm CC}^{\rm max}$
5×10^{40}
0
-5×10^{40}
V(χ, H) [TeV⁴]
0
5×10^{11}
1×10^{12}
1.5×10^{12}
χ [TeV]

ONE EXAMPLE

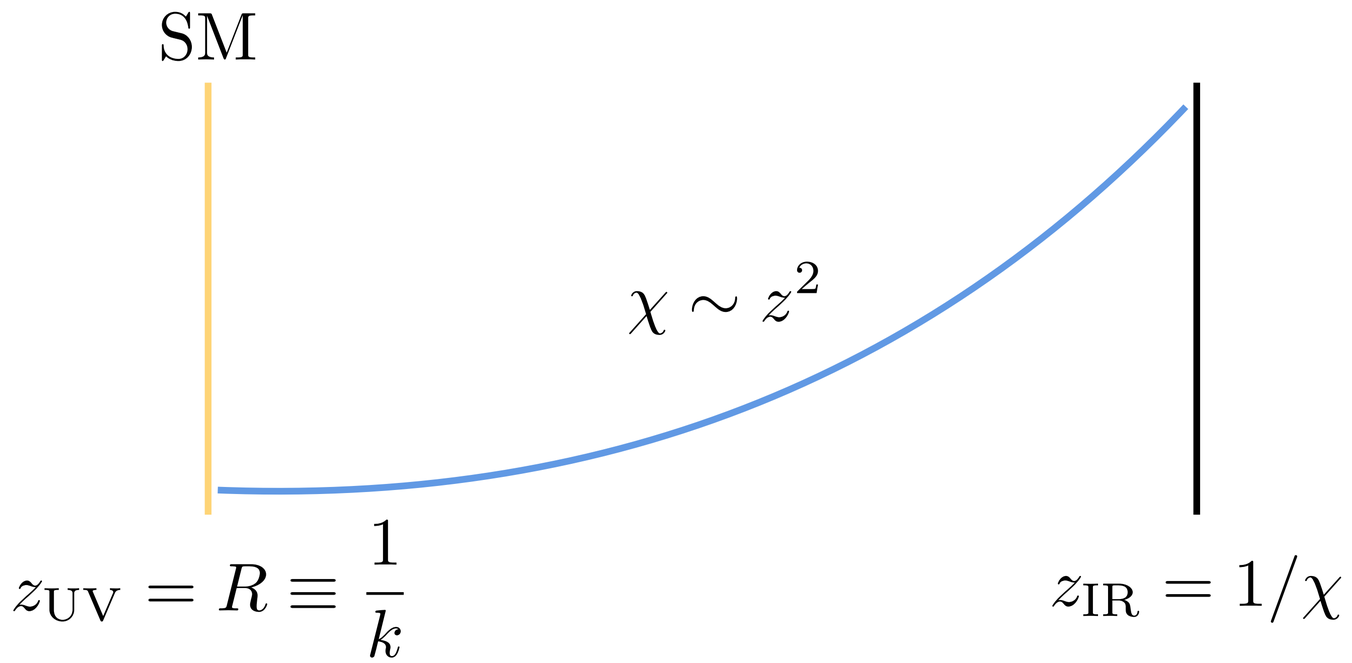


Cosmologically Long-Lived Metastable Vacuum

$$h_{min} \lesssim h \leq h_{crit}$$

CRUNCHING FROM SCALE INVARIANCE

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



CRUNCHING FROM SCALE INVARIANCE

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

SM

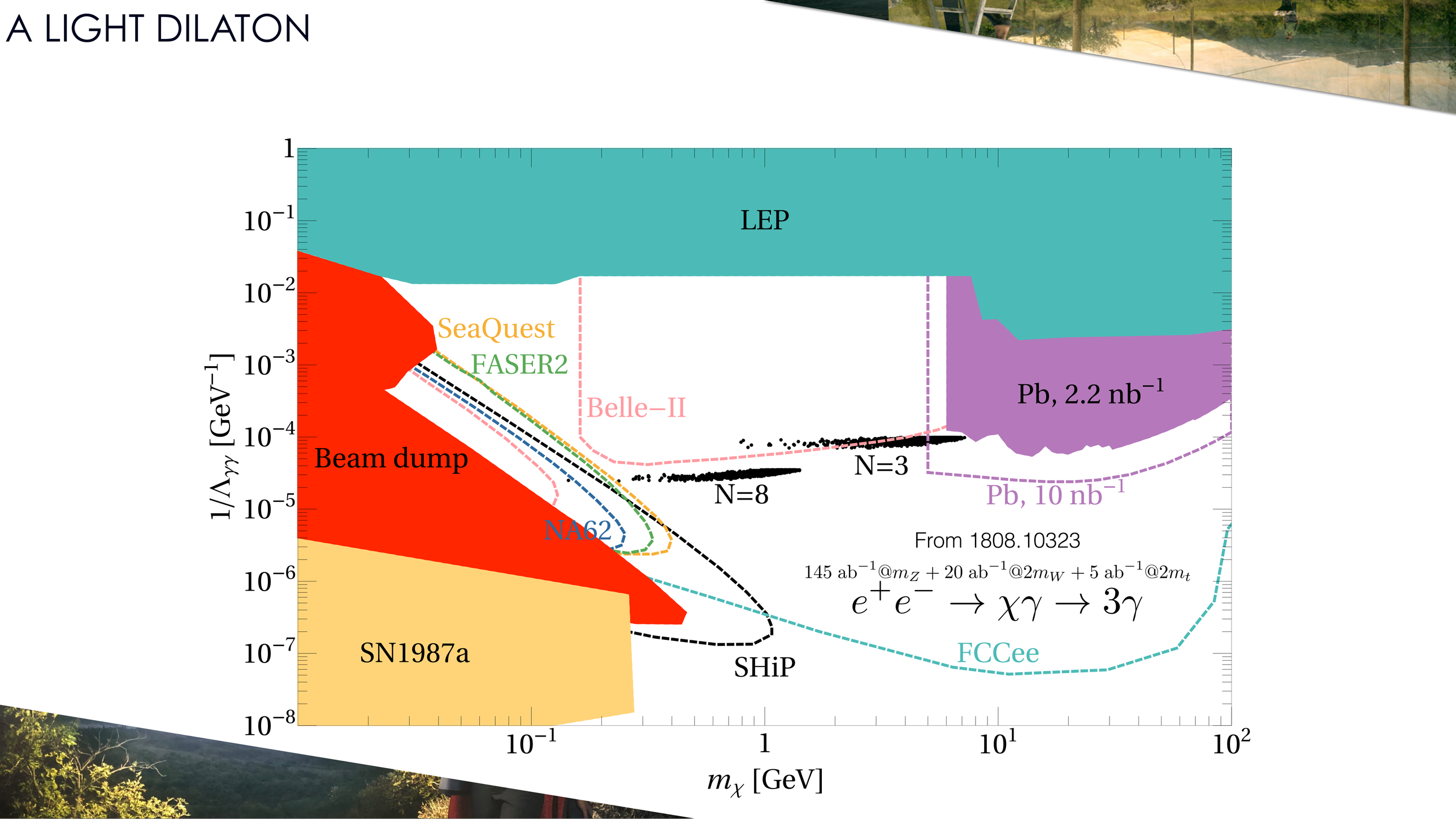
H, W, Z, γ

$\phi_{\rm GW}$

$z_{\rm UV} = R \equiv \frac{1}{k}$

$z_{\rm IR} = 1/\chi$

A LIGHT DILATON

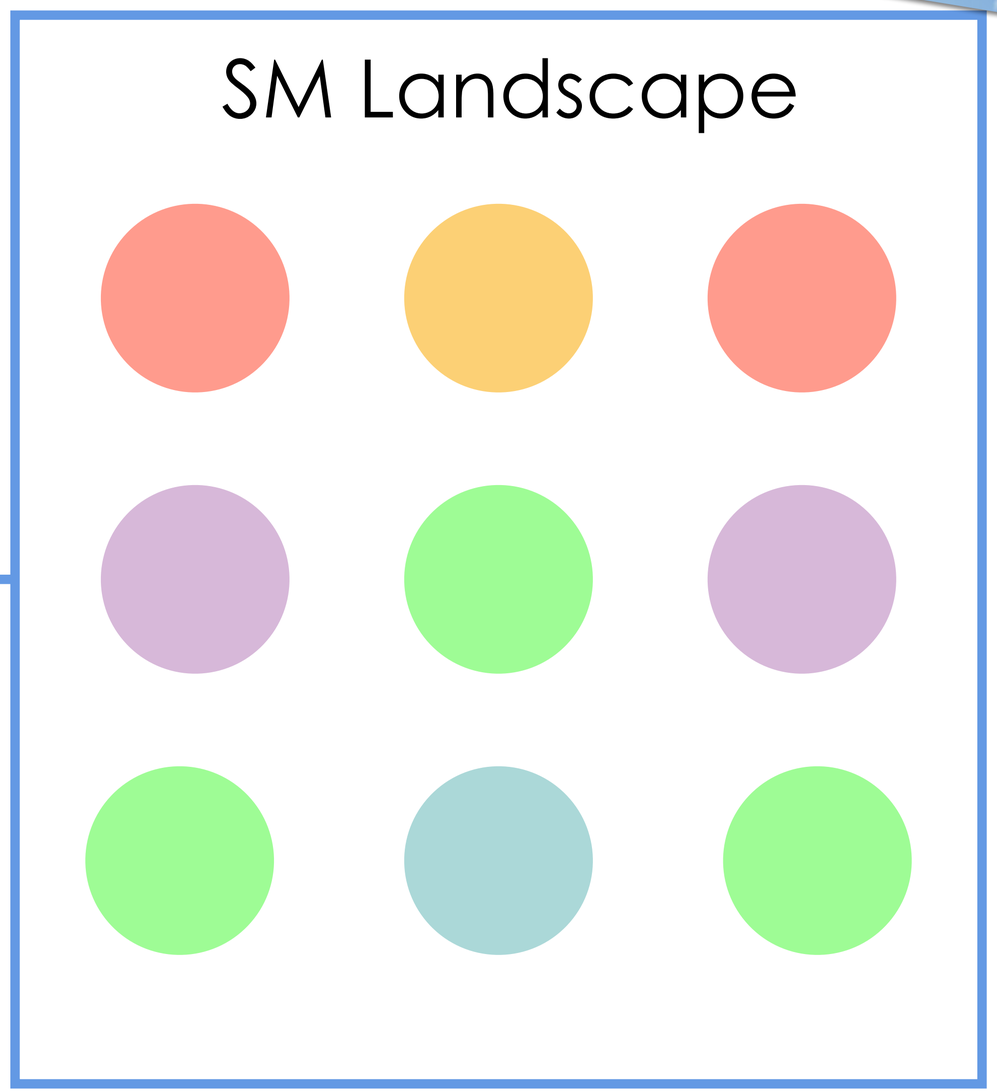


A GENERAL LESSON

GENERAL STRUCTURE

Symmetric Sector

$$M_S \ll M_{\rm Pl}$$



Symmetric Sector

$$M_S \ll M_{\rm Pl}$$

SM Landscape

An event triggered by the symmetric sector selects the observed

$$m_h^2$$

Symmetric Sector

$$\Lambda_S \ll M_{\rm Pl}$$

Sensitive to the Higgs mass

SM Landscape

$G\widetilde{G}$

ALPs

$F\widetilde{F} + yLHE^c$

$m \lesssim v \simeq 174\ \mathrm{GeV}$

HL-LHC and FCC-ee

$H_1 H_2$

$m \lesssim v \simeq 174\ \mathrm{GeV}$

HL-LHC and FCC-ee