Before, Behind and Beyond the Standard Model

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CERN

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Plan of the lecture

- **Before the SM**
  - No-Lose Theorems
  - Why the Higgs is Revolutionary
- **Behind the SM**
  - The “SM-only” option
  - The Naturalness Argument
  - “Microscopic” Naturalness (and the LHC)
  - What if Un-Natural?
- **Beyond the SM**
  - What could be there …
  - … that we can probe

No-Lose Theorems

A number of **guaranteed** discoveries in the history of HEP

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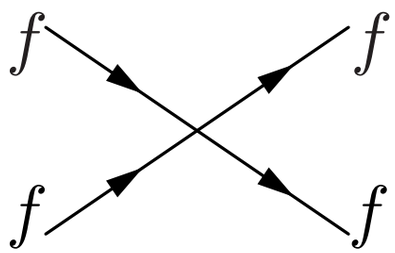

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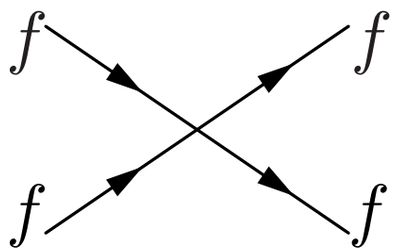

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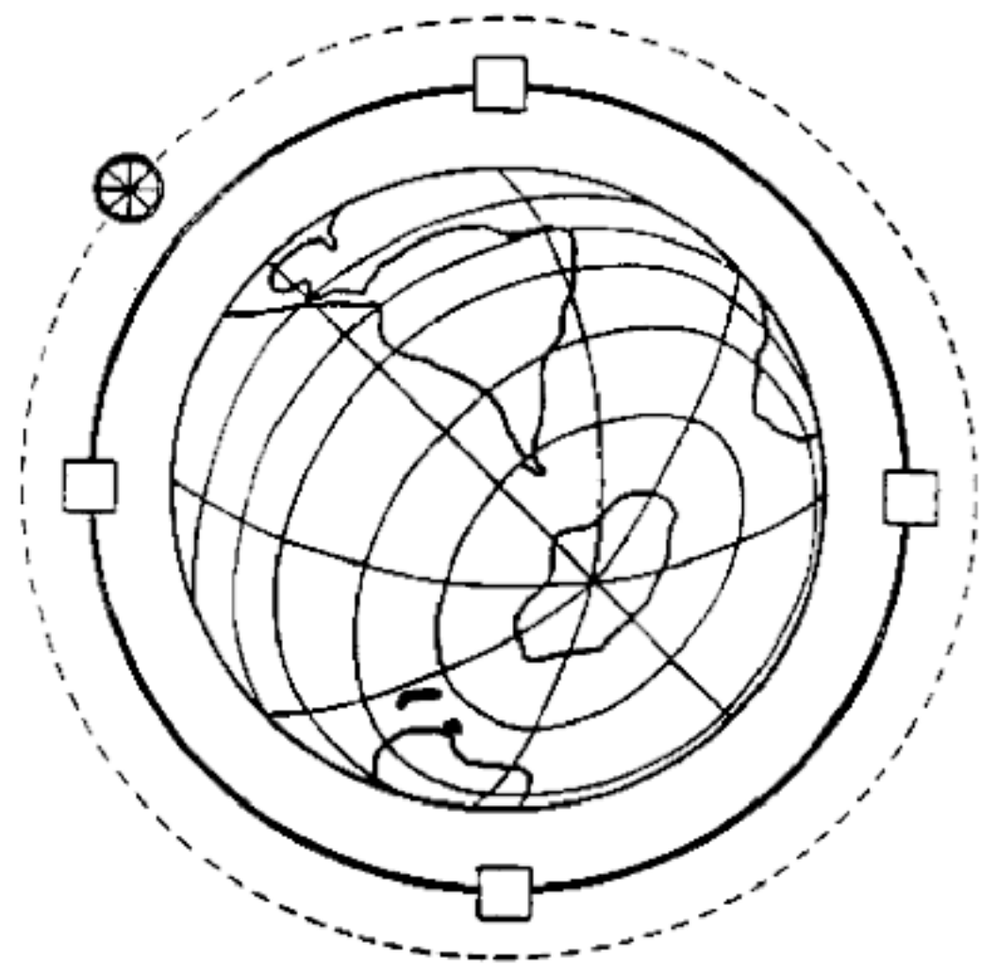
Fermi was aware of the Fermi Theory No-Lose Theorem!

Fermi's **Ultimate Accelerator:**

$$E_B = 5000\,\mathrm{TeV}$$

$$\sqrt{s} = \sqrt{2\,m_P\,E_B} = 3\,\mathrm{TeV}$$

Fermi could not predict 2-beams collisions, nor improved magnets



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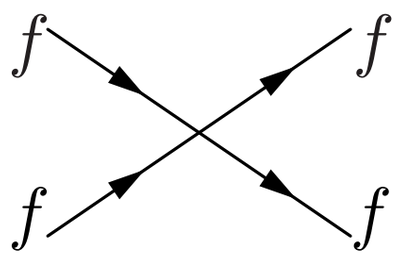

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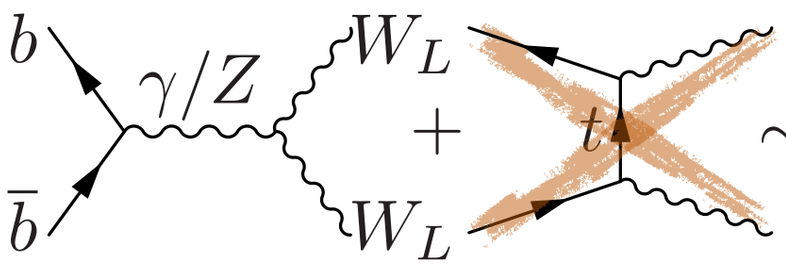

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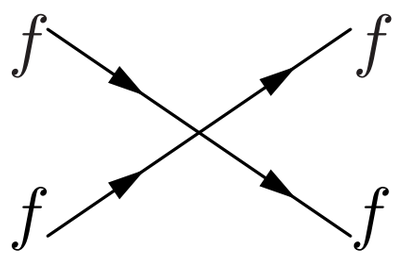

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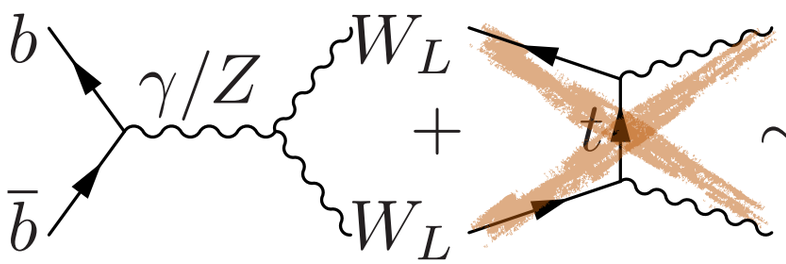

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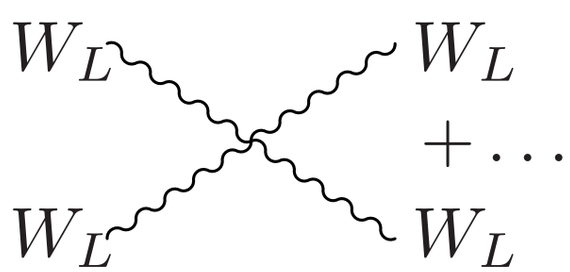
Beyond the (Higgsless) EW Theory:



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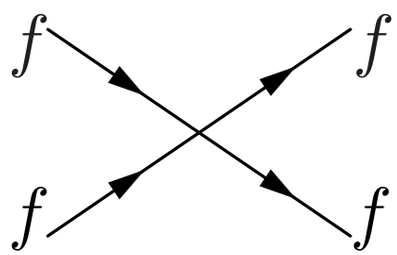

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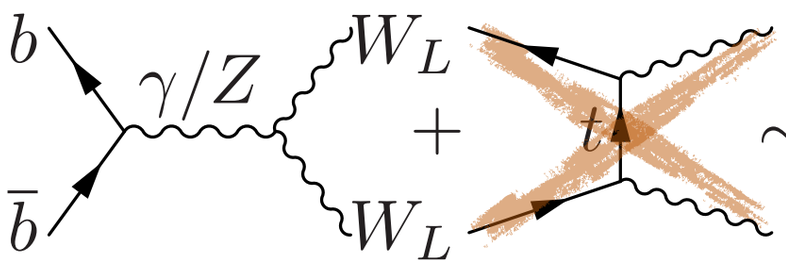

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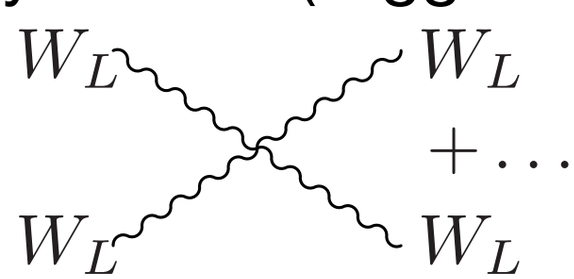

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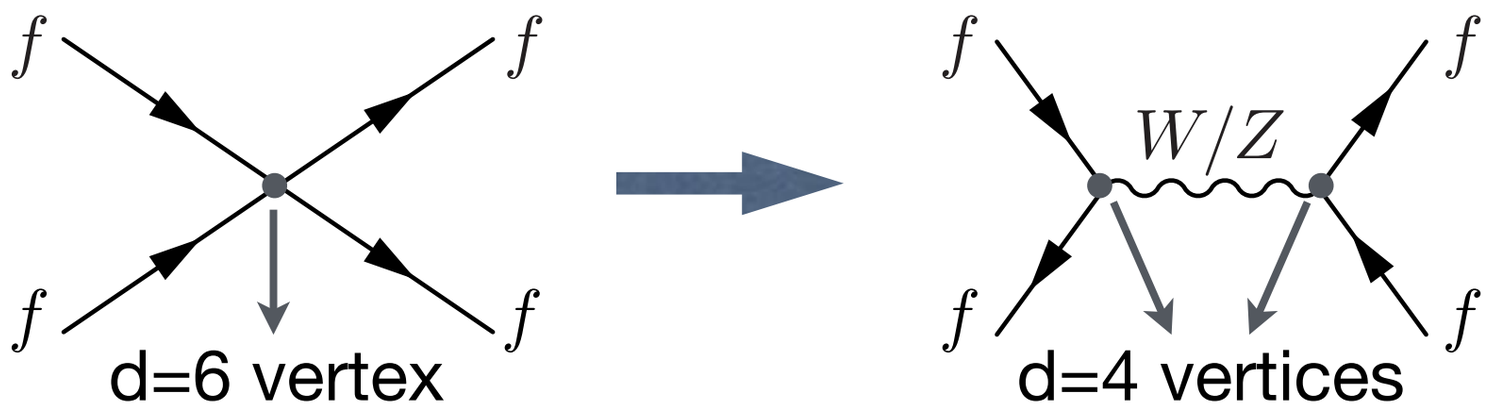
Each secretly due to d=6 non-renormalizable operators, signalling nearby new physics.

No-Lose Theorems

Each time we exploit one No-Lose Theorem, we get rid of one d=6 operator …

e.g.



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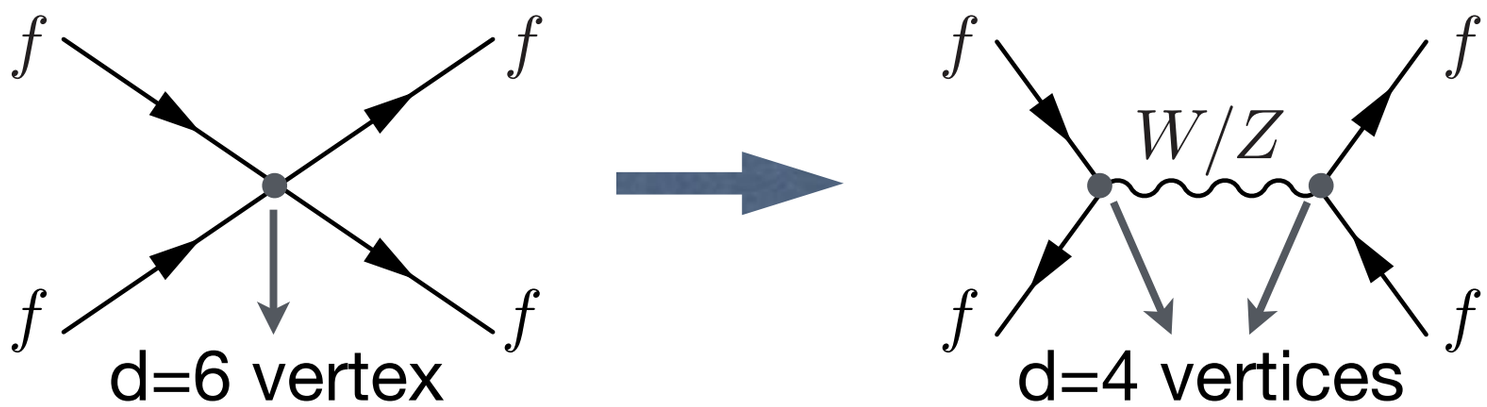
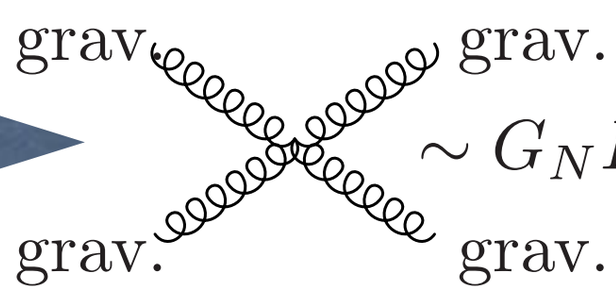


… and only one is left after Higgs discovery …

$$\frac{1}{G_N}\sqrt{g}R \longrightarrow$$



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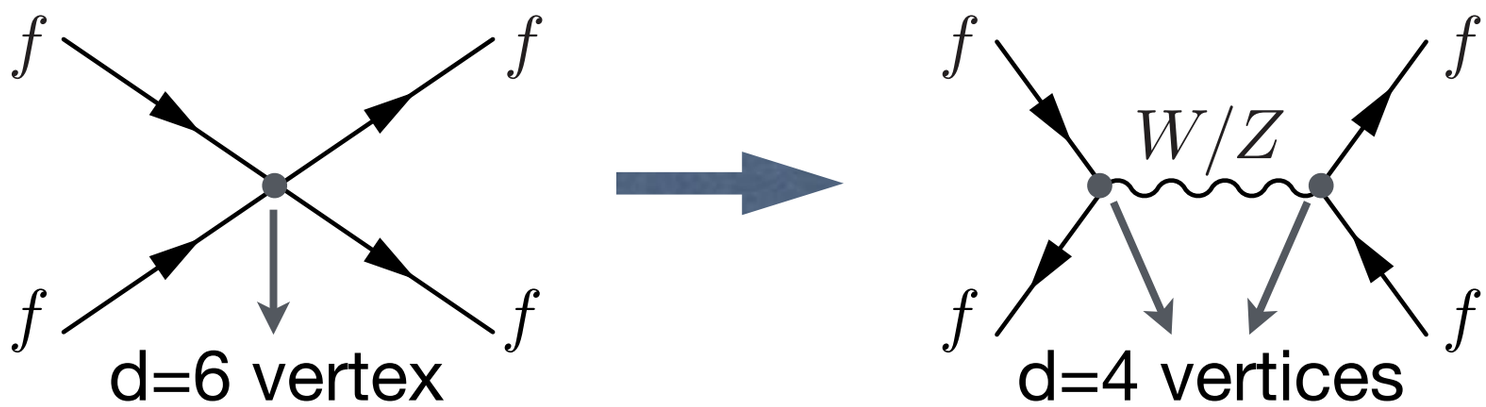

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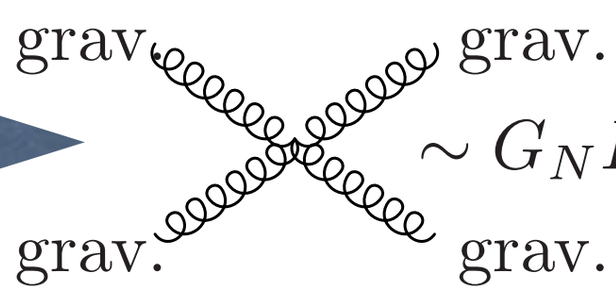

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… the last, impractical, No-Lose Theorem is Q.G. at M_P !

No-Lose Theorems

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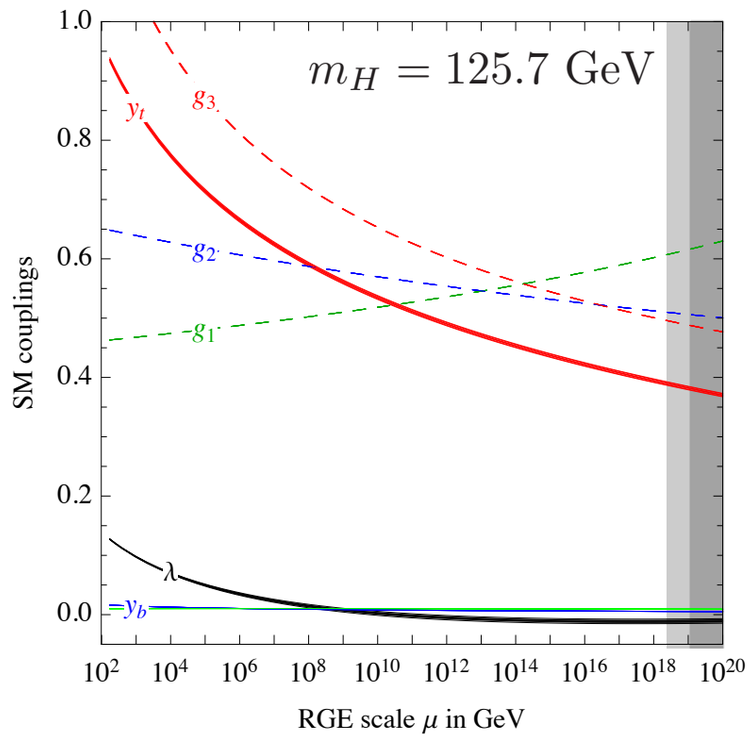

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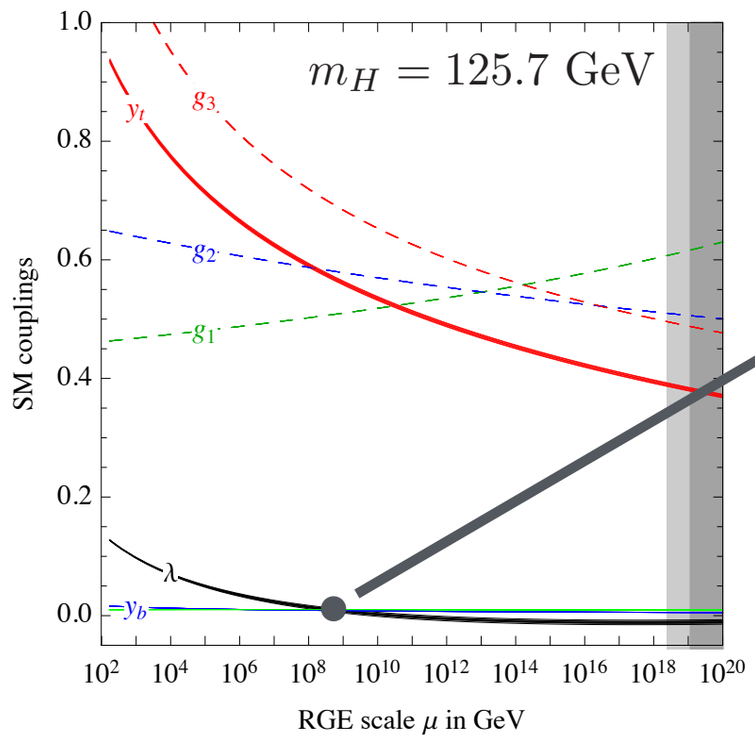

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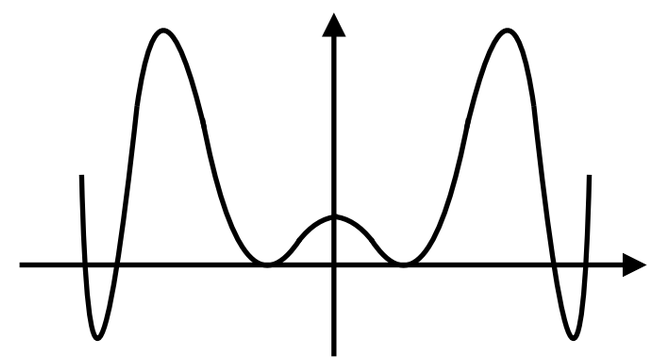

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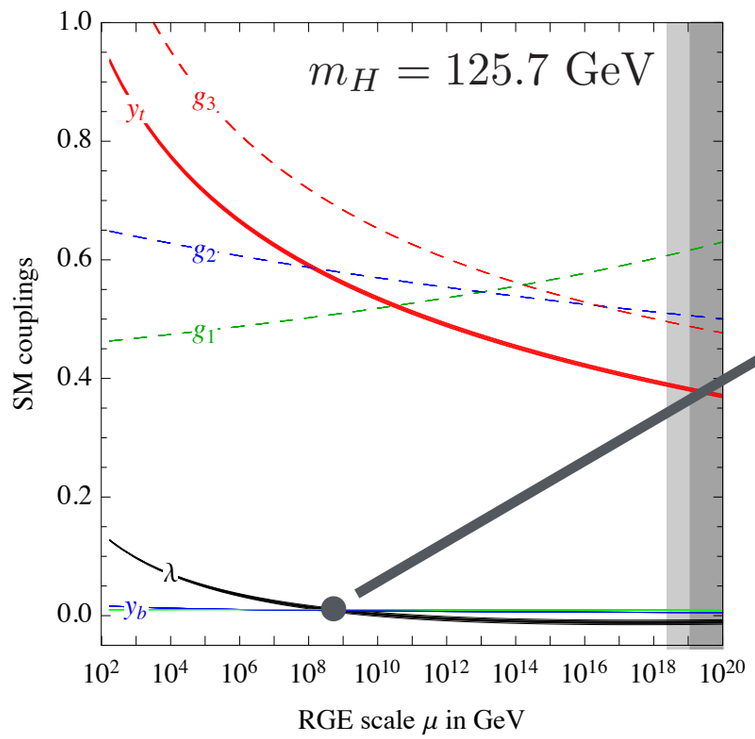

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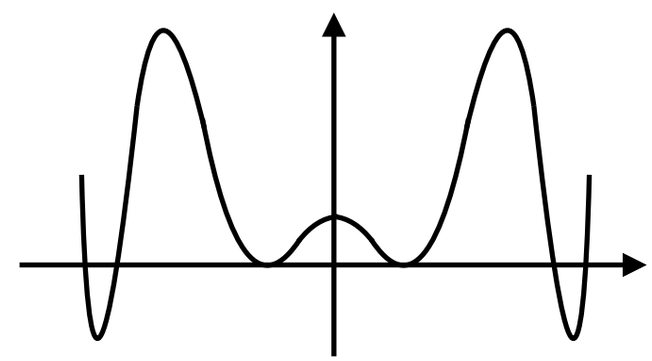
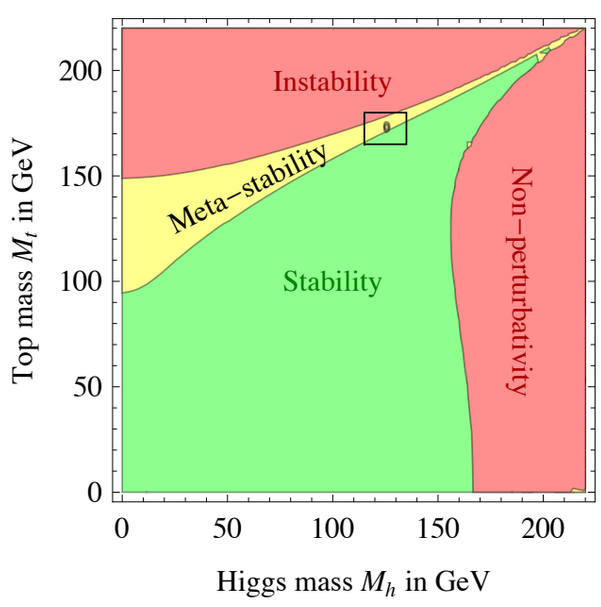
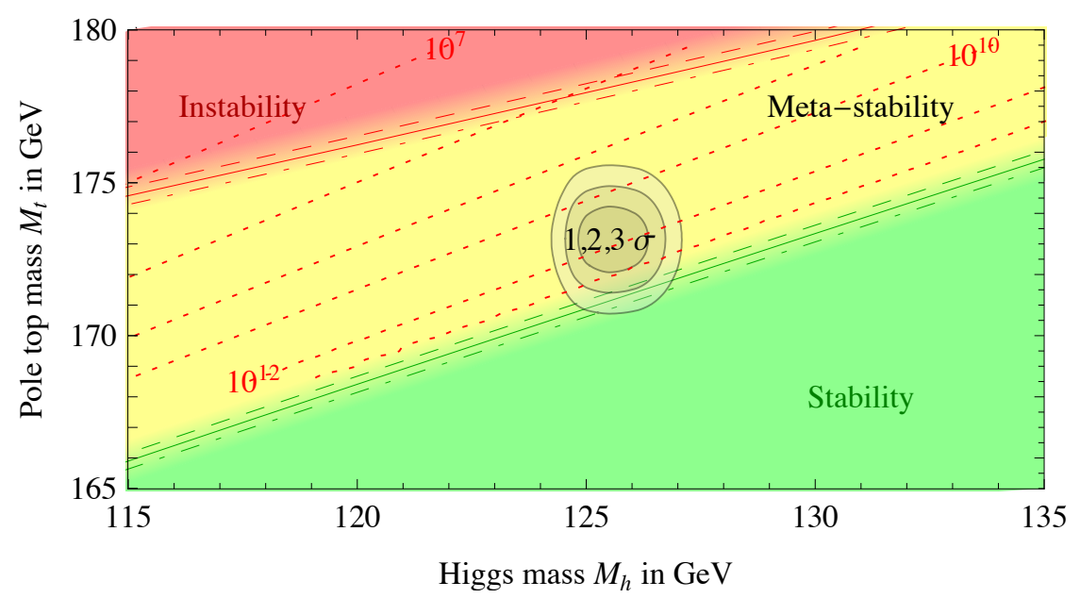


But no need of N.P.

Non trivial result. Depends on Higgs and Top mass:





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HEP before the Higgs

HEP after the Higgs

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories**

Behind the SM

Physics is the continuous effort towards a deeper understanding of the laws of Nature.

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BSM $\neq$ **Beyond** the SM

(goal is not ``new physics" per se)

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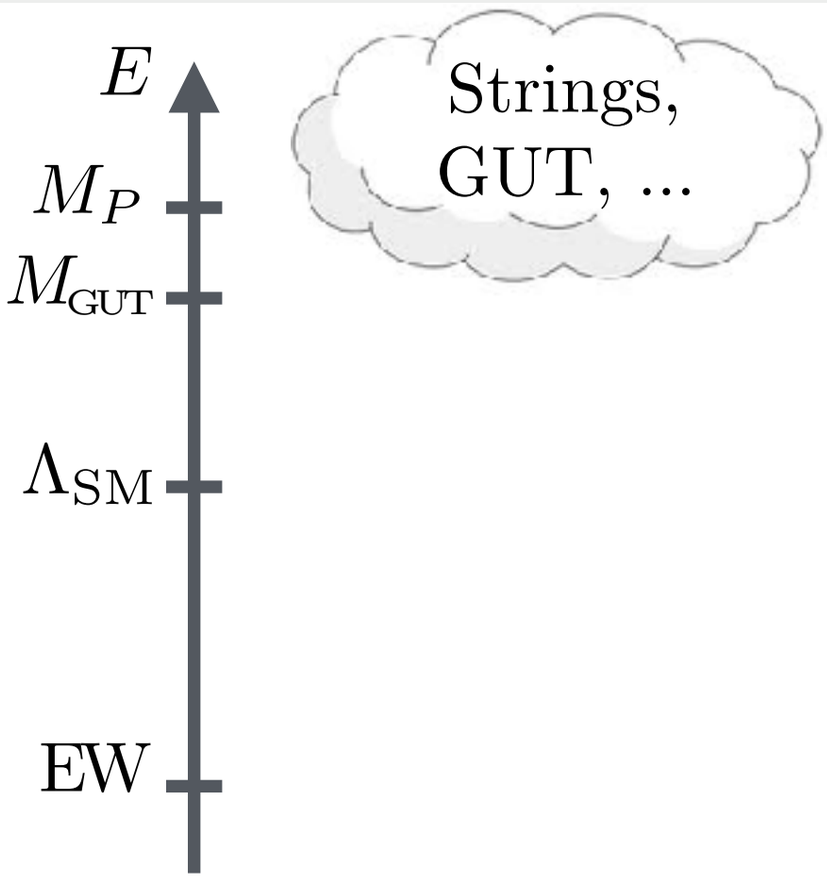
BSM $=$ **Behind** the SM

(goal is explain SM mysteries)

The “SM-only” Option



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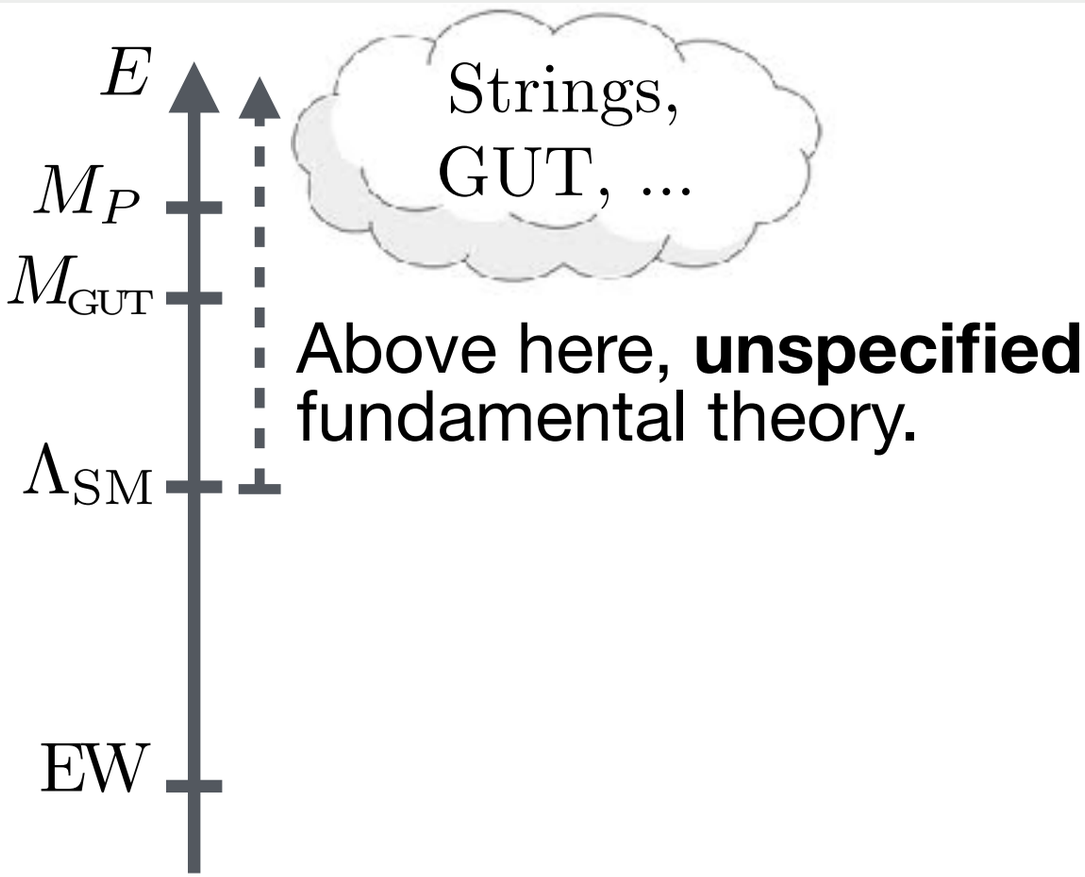

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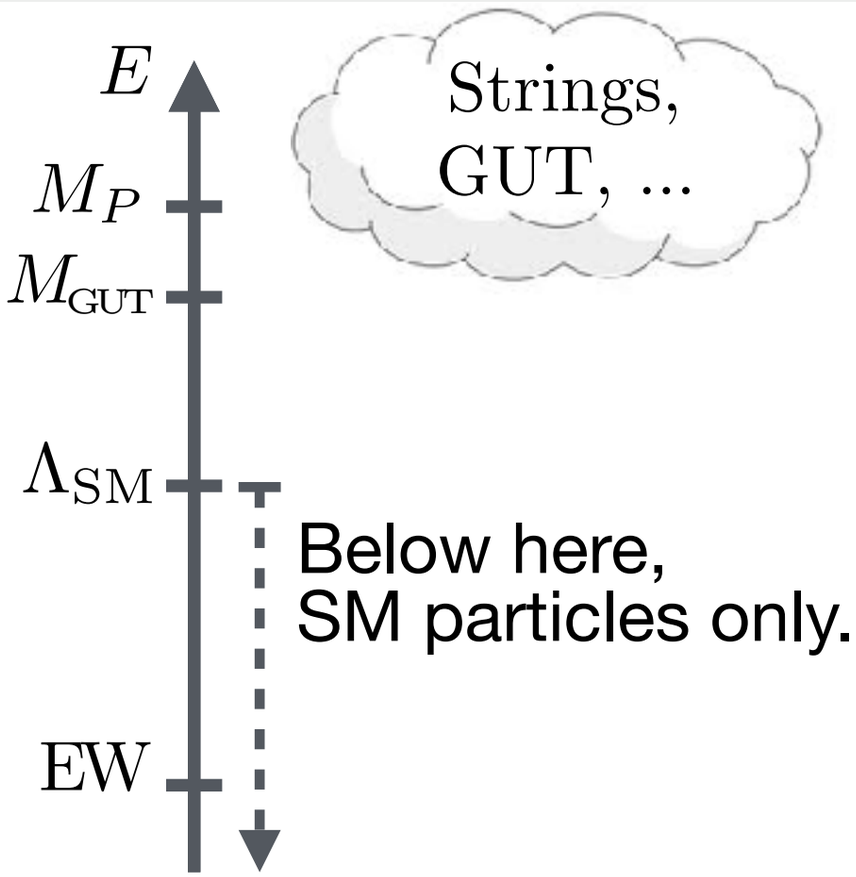

Below $\Lambda_{\rm SM}$, fundamental theory reduces to SM fields and SM (Lorentz+gauge) symmetries.

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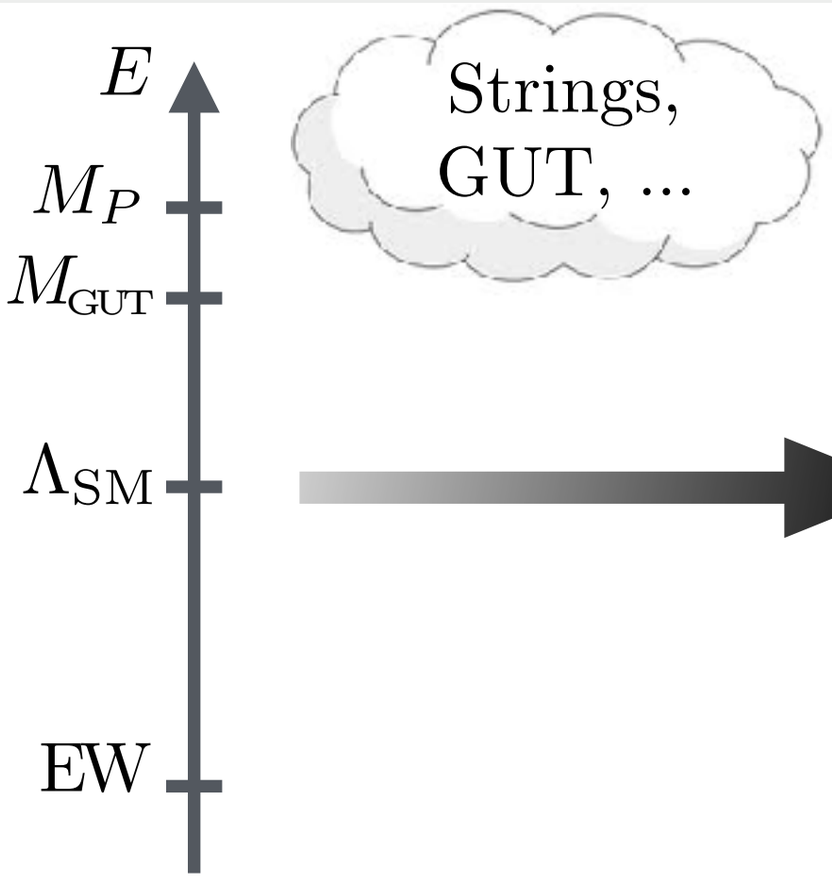

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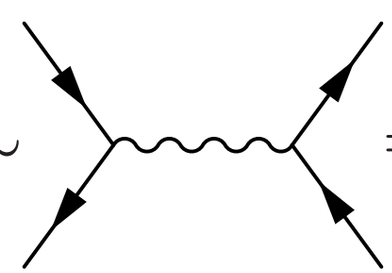
One day, effective SM Lagrangian and parameters will be **derived from the fundamental theory**.

Fermi theory analogy: $G_F \sim$  $= \dfrac{g_W^2}{4\sqrt{2}m_W^2}$

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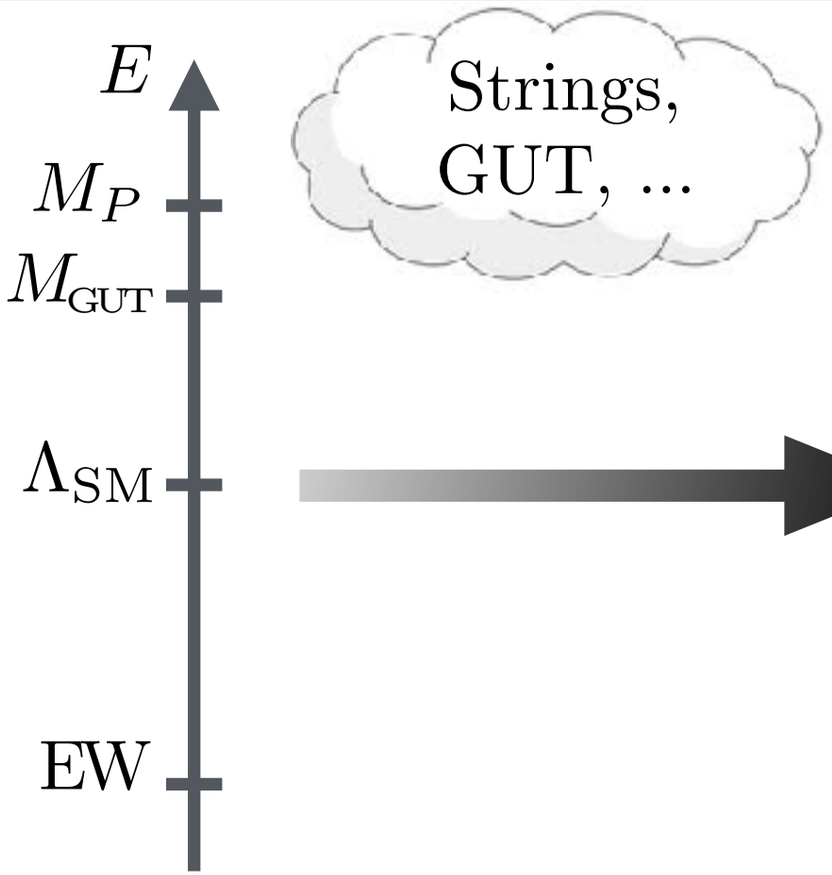

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dimensional analysis for coefficients

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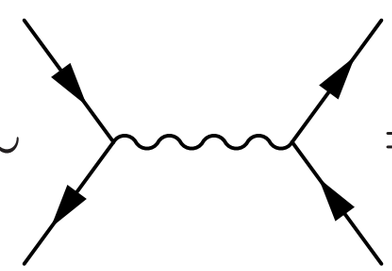

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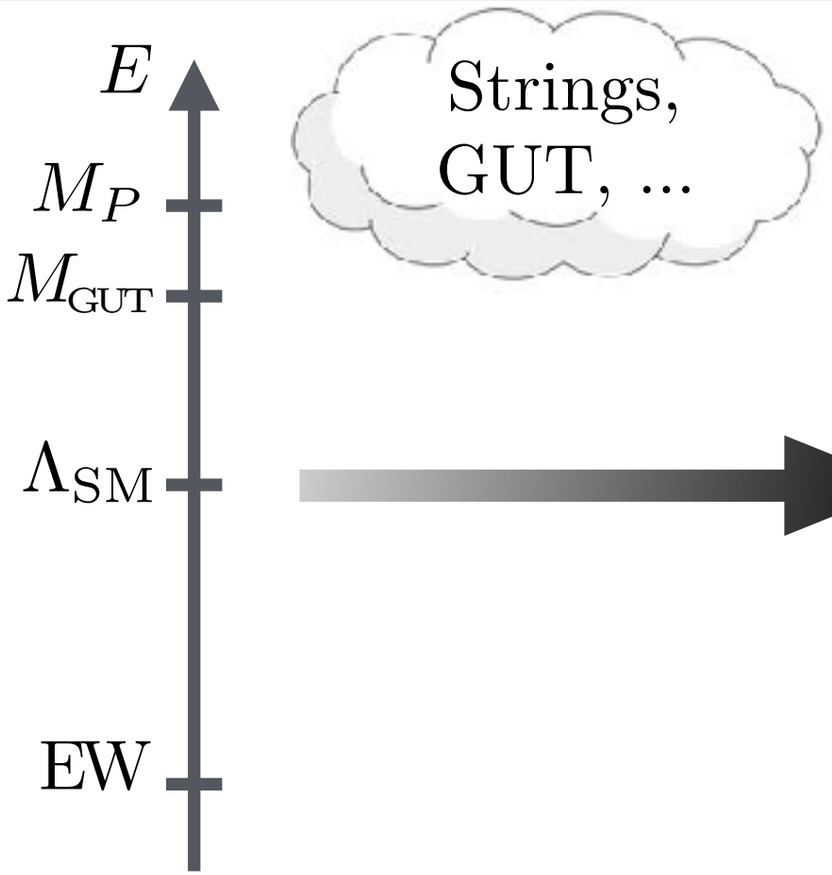

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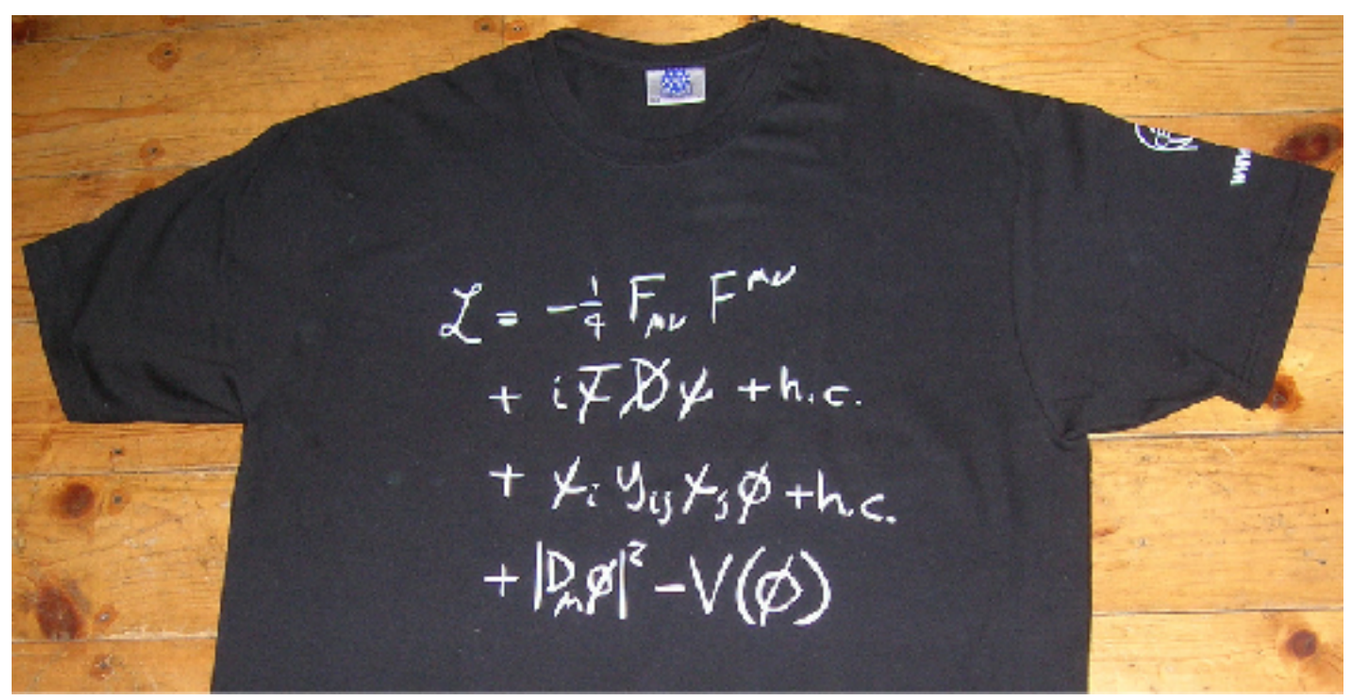
$\mathcal{L}^{(d=4)}$: the CERN T-shirt Lagrangian (almost)



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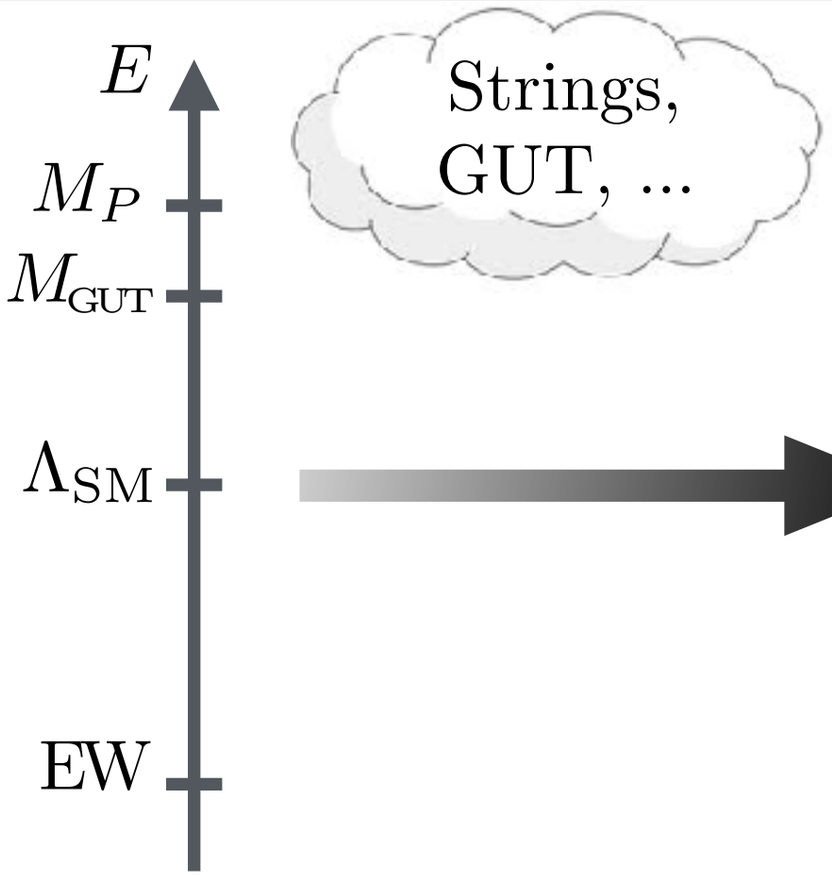

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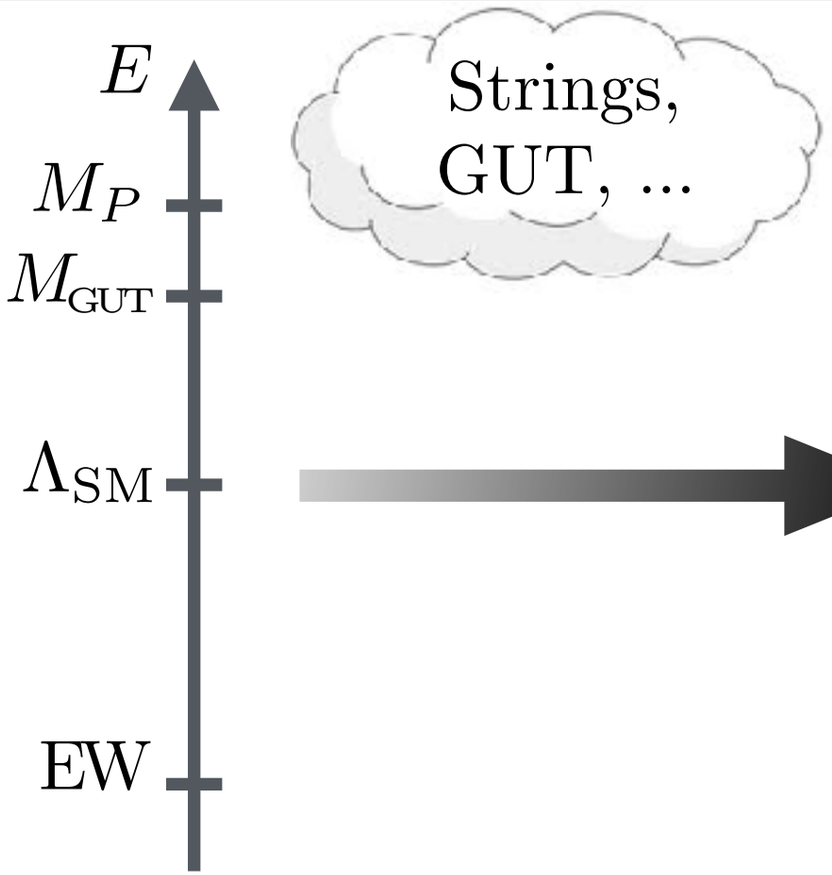

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$\mathcal{L}^{(d=4)}$: describes all what **we see** (almost) …
… and what **we don’t see.**

$(\Gamma_{\rm proton}/m_{\rm proton})_{\rm exp.} < 10^{-64}$ **!!** $\longleftrightarrow$ $(\Gamma_{\rm proton}/m_{\rm proton})_{(d=4)} = 0$

accidental Baryon num. symm.

$\mathrm{BR}(\mu \to e\gamma)_{\rm exp} < 10^{-12}$**!!** $\longleftrightarrow$ $\mathrm{BR}(\mu \to e\gamma)_{(d=4)} = 0$

accidental Lepton family symm.

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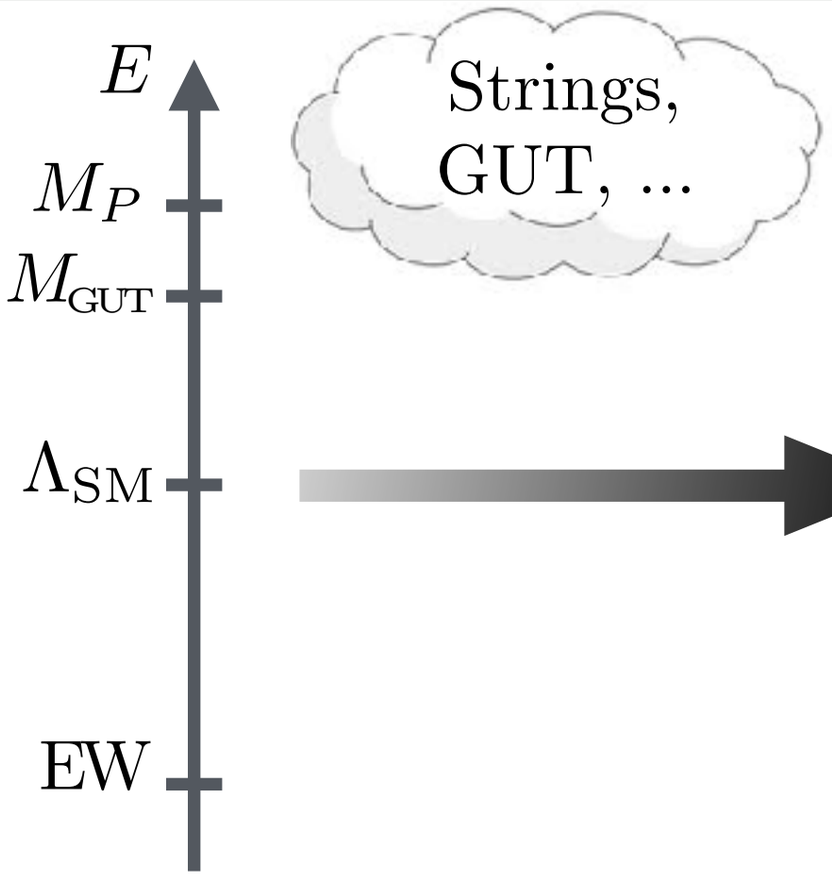

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$\mathcal{L}^{(d=5)}$: can describe what **we see small**

$$\mathcal{L}^{(d=5)} = (\overline{L}_L H^c)(L_L^c H^c)$$

unique (Weinberg) operator

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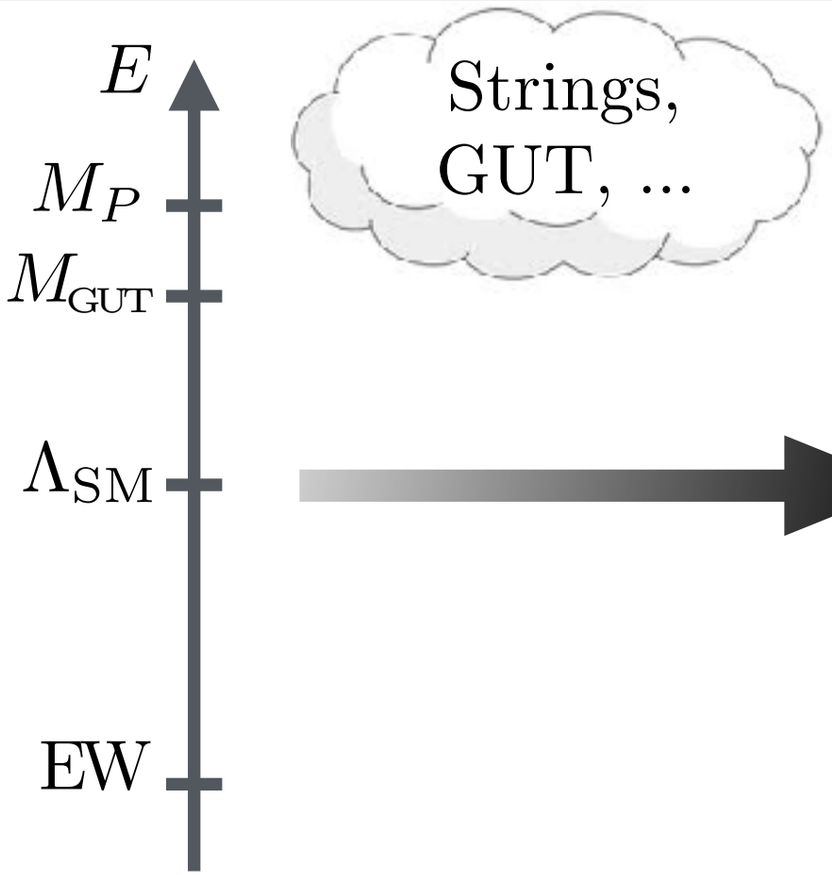

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unique (Weinberg) operator ⟷ Majorana neutrino mass-matrix

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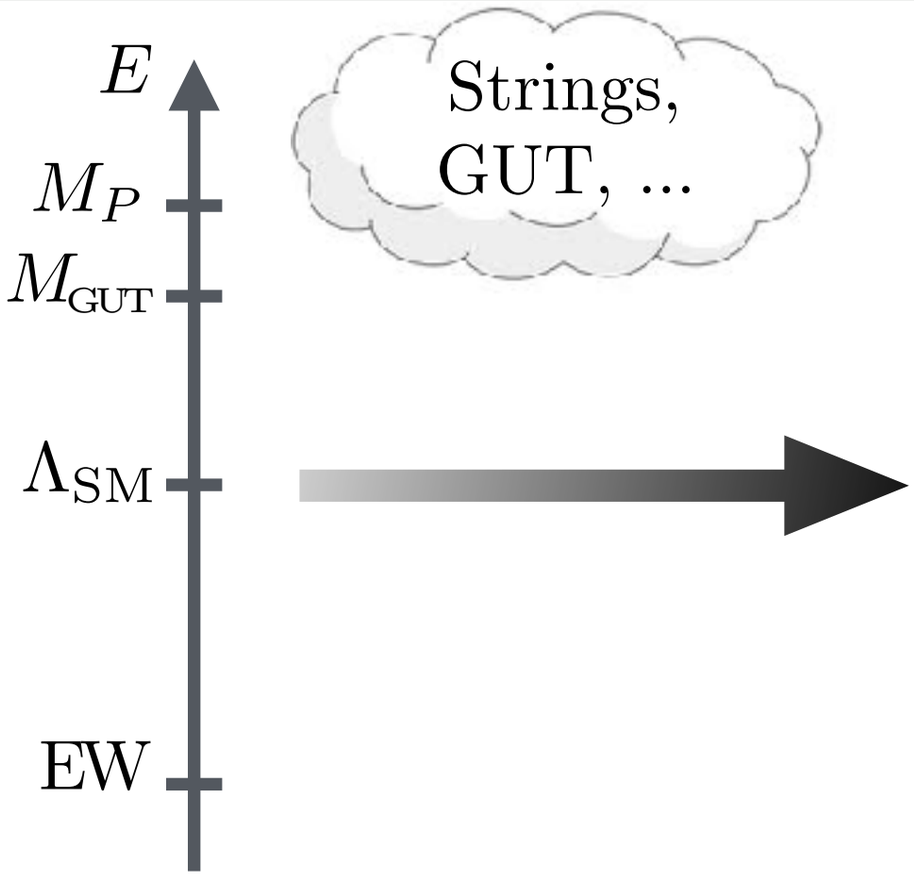

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right ν mass size if $\Lambda_{\rm SM} \sim 10^{14}{\rm GeV} \sim M_{\rm GUT}$!!

$\mathcal{L}^{(d=5)} = (\overline{L}_L H^c)(L_L^c H^c)$ ⟷ $m_\nu \sim v^2/\Lambda_{\rm SM}$

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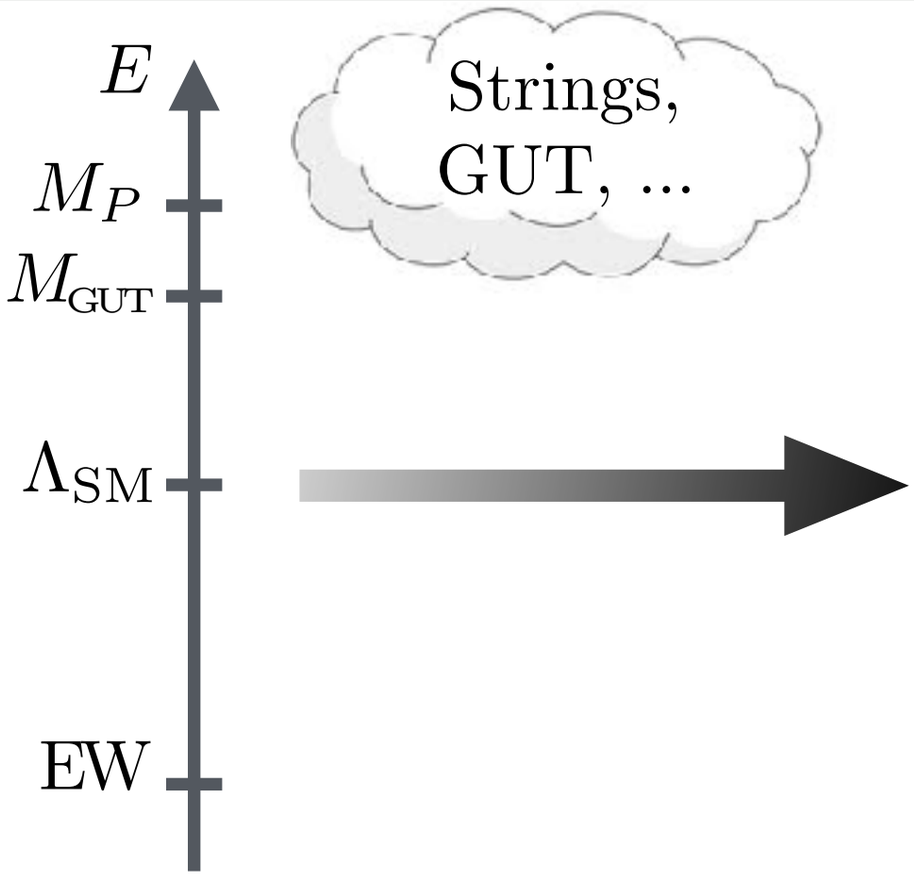

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dimensional analysis for coefficients

$\mathcal{L}^{(d=4)}$: describes all what **we see** (almost) …
… and what **we don’t see.**

$\mathcal{L}^{(d=5)}$: can describe what **we see small**
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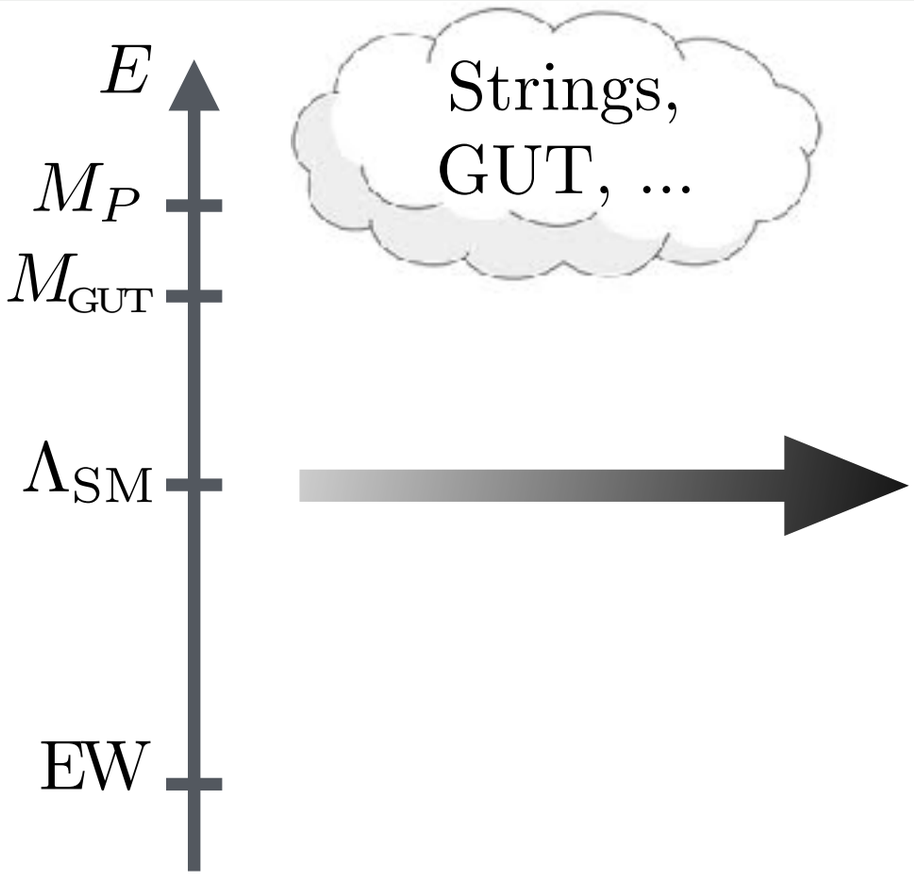
The “SM-only” Option



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Majorana ν’s and p-decay would be indications of SM-only

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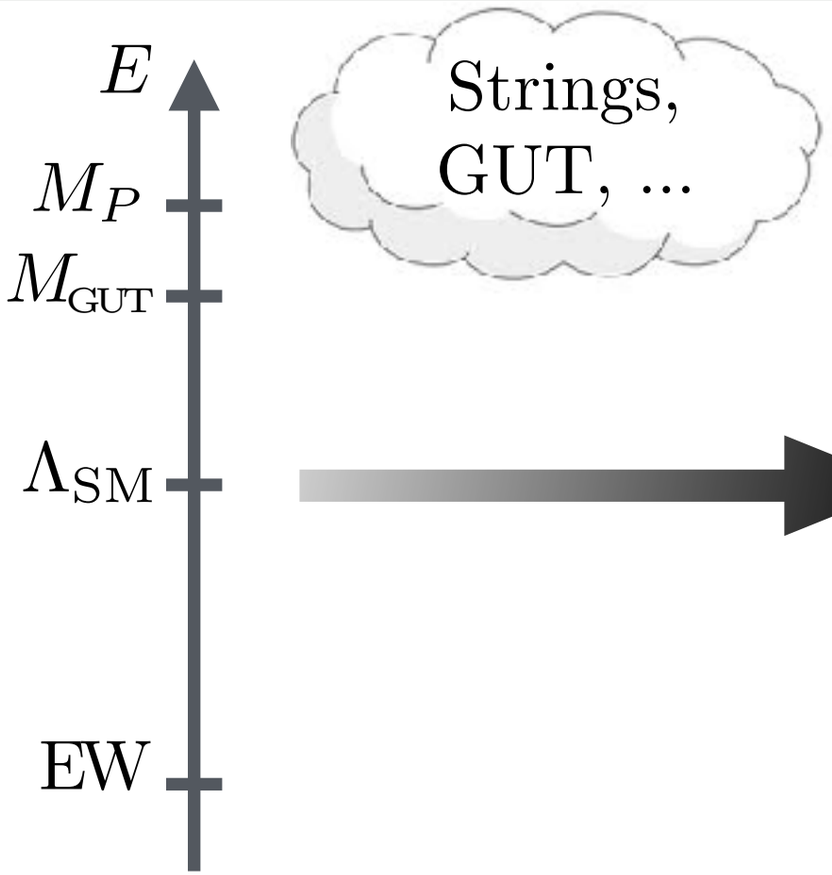

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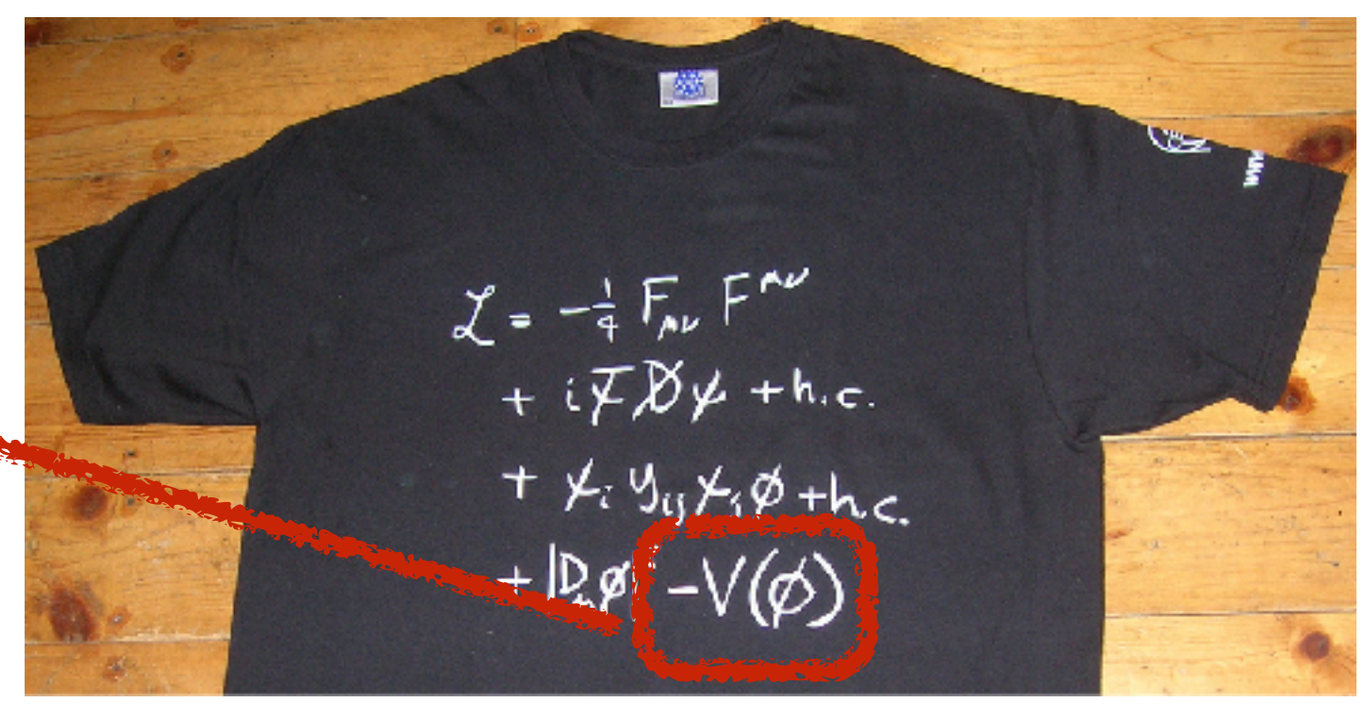

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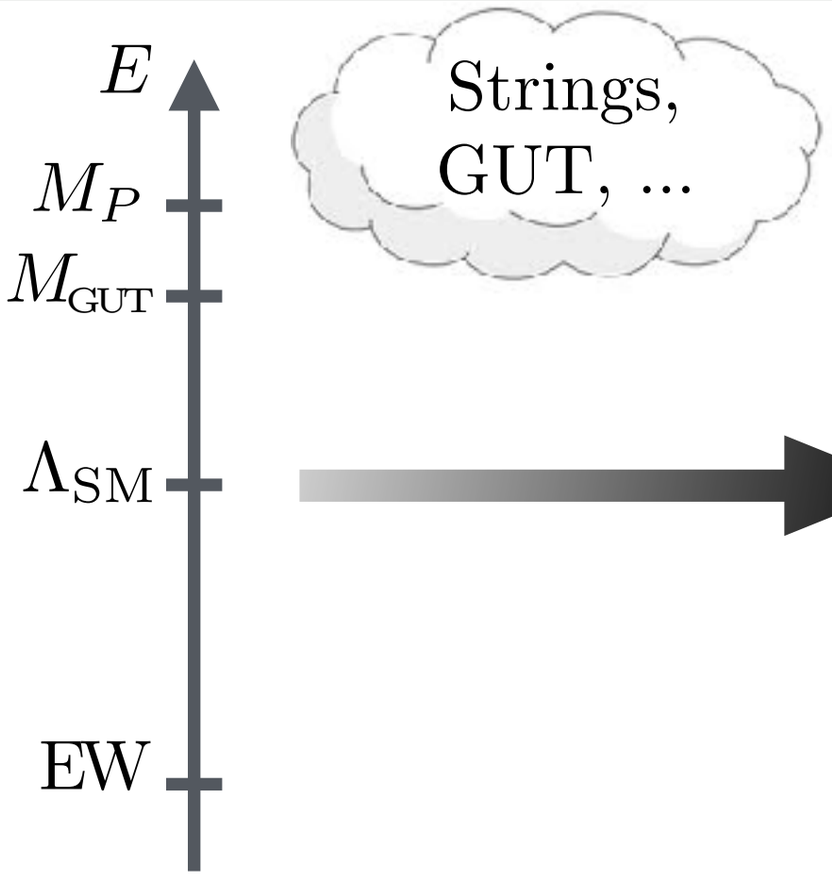

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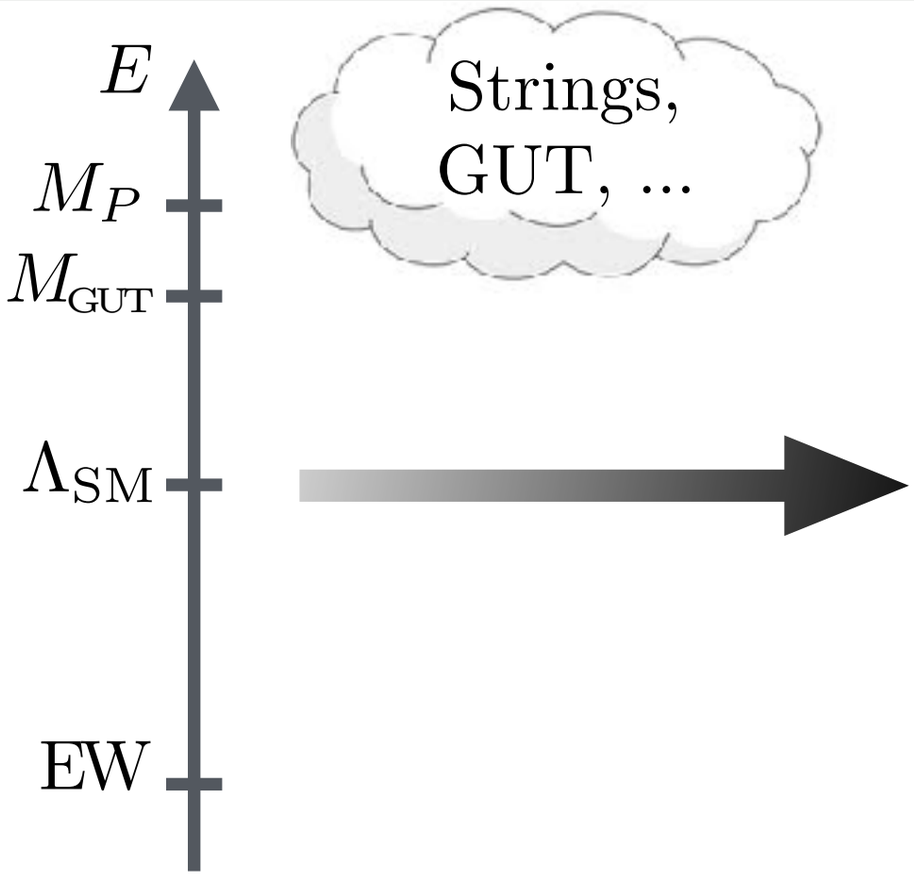

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The **Naturalness Problem**: Why $m_H \ll \Lambda_{\rm SM}$?

(or, why dim. analysis works for d>4 and not for d<4?)

The Naturalness Argument
(not a Theorem)

To understand Naturalness, think to the “Final Theory” formula that **predicts** m_H. It will look like this:

$$m_H^2 = \int_0^\infty dE \frac{dm_H^2}{dE}(E; p_{\mathrm{FT}})$$

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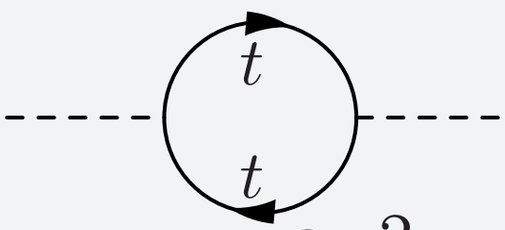

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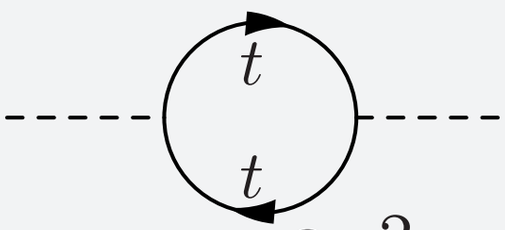

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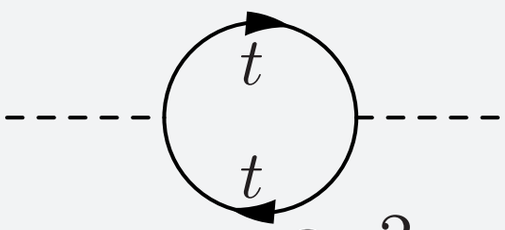

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Fine-tuning: quantifies the "degree of Un-Naturalness"

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"Is m_H Natural?" $=$ "Is m_H Predictable?"

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G.Galilei

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Where to stop?

$\Delta \sim 10$ definitely **OK**

$\Delta \sim 1000$ probably **not OK**

Microscopic Naturalness

Half a century of thoughts led to only **two mechanisms** that provide a Natural microscopic origin for Higgs mass

Compositeness **Supersymmetry**

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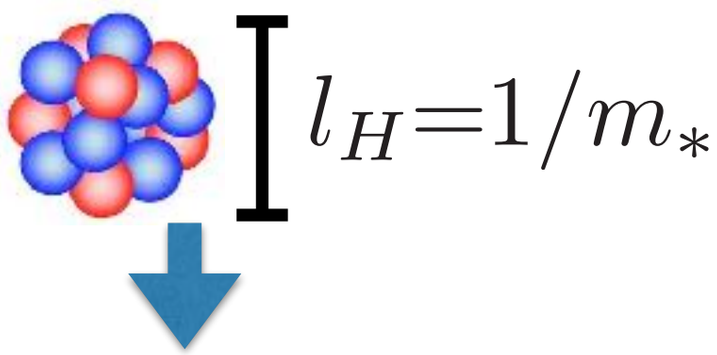
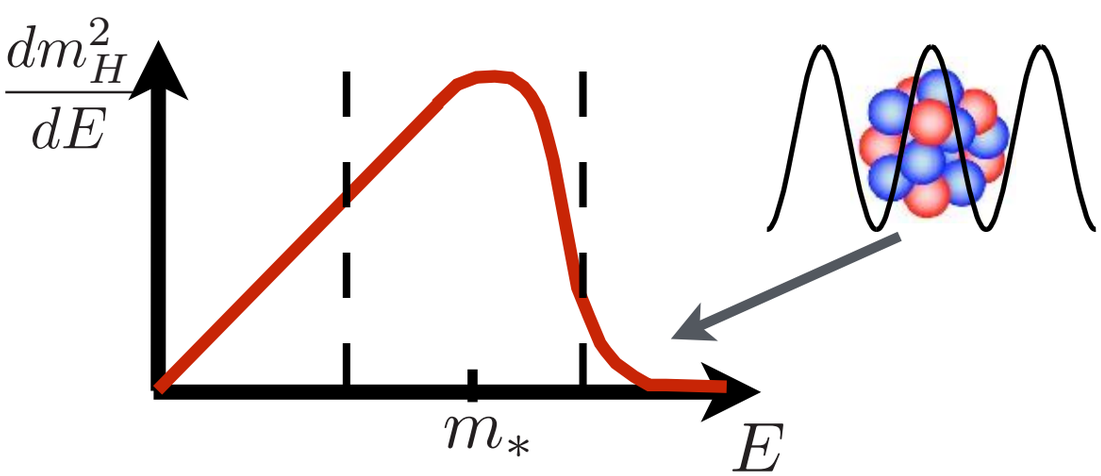
Higgs = 

Higgs is **transparent** to HE modes



m_H generation **localised** at m_*

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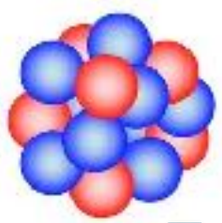
Higgs =  $l_H = 1/m_*$

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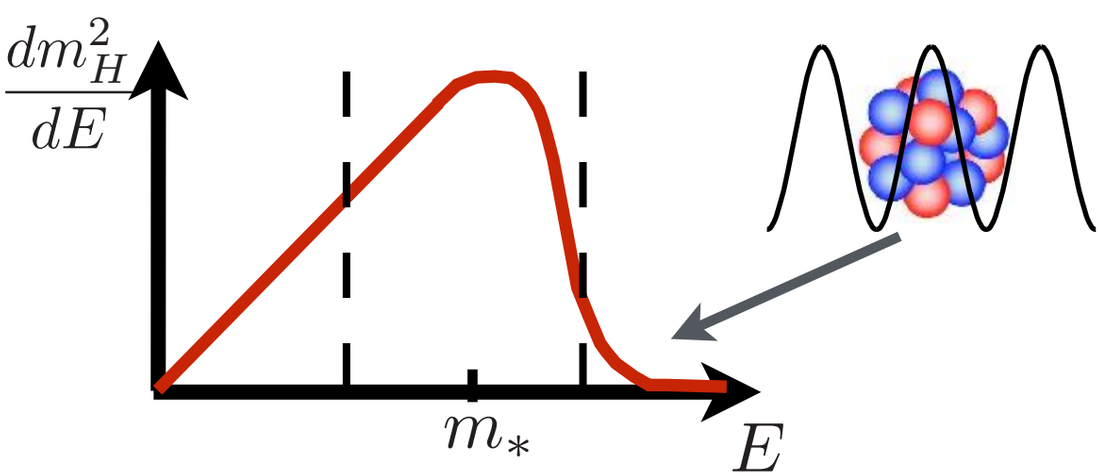

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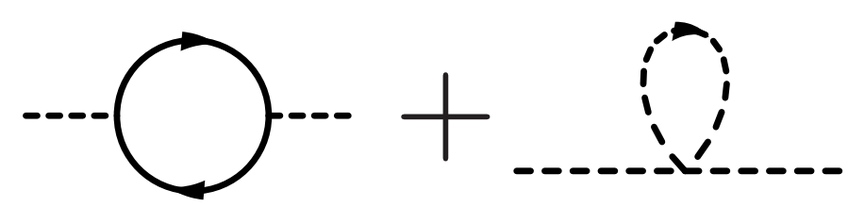
Supersymmetry

Higgs protected by fermionic superpartner chiral symmetry.

With soft breaking, produces famous top/stop cancellation:



$$\delta_{\rm IR} m_H^2 \simeq \frac{3}{8\pi^2}\Lambda^2[y_t^2 - \tilde{y}_t^2] + \frac{3y_t^2}{8\pi^2} M_{\tilde{t}}^2 \log(\Lambda/M_{\rm EW})$$

The Composite Higgs Picture

Composite Sector

Higgs

Elementary Sector

SM **gauge fields:** $W_\mu^\alpha,\ B_\mu$**.**

SM **fermions:**$\{t_L, b_L\},\ t_R, \ldots$

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"Minimal" breaking: $\mathrm{SO}(5) \to \mathrm{SO}(4)$

Delivers one Higgs doublet only in the spectrum

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Also notice that:

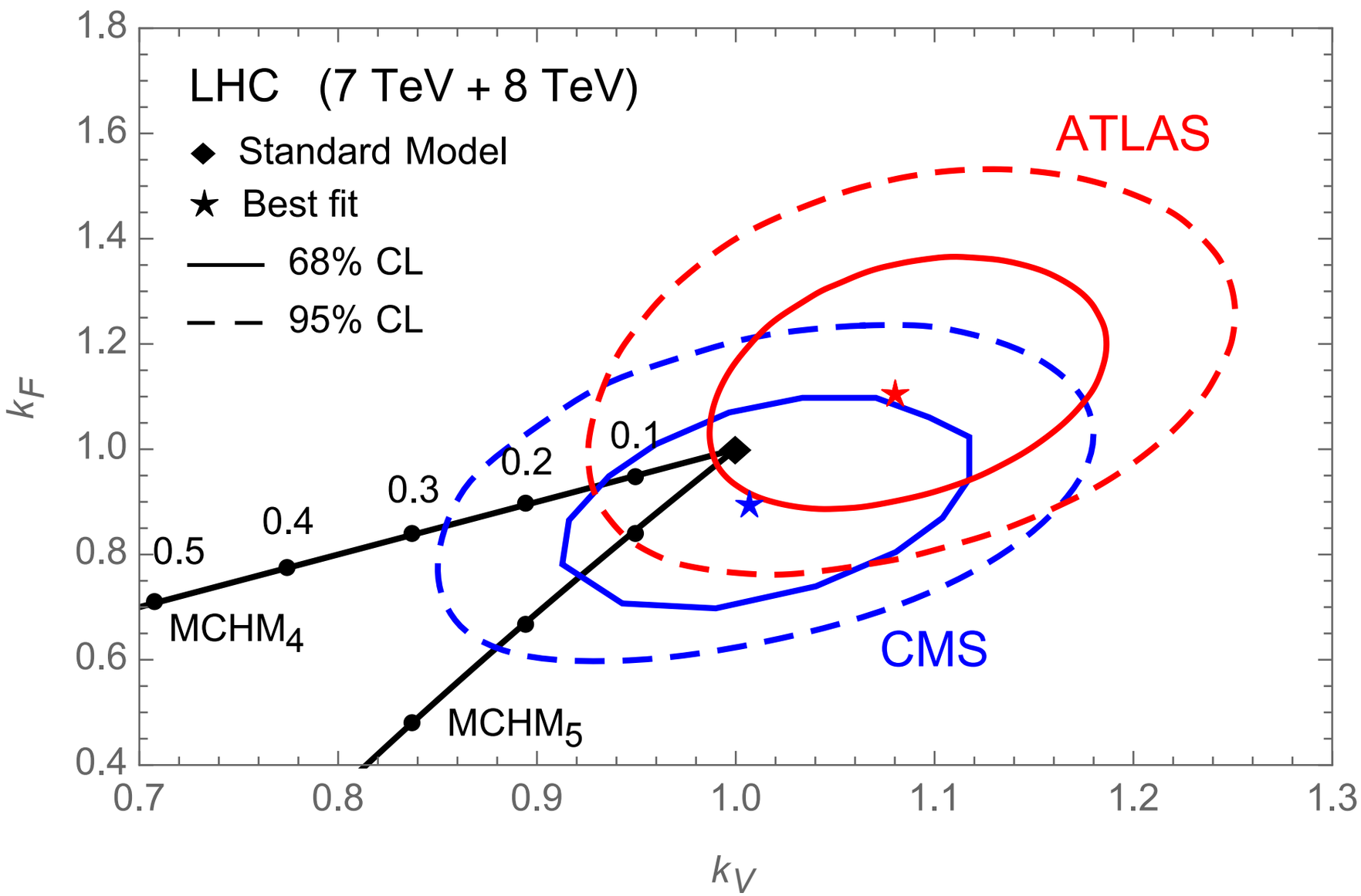
Scaling dimension ~ 5/2 required for top Operator. UV-feasible or not?

Phenomenology built on assumed symmetry patterns and dim. analysis.

UV model believed unnecessary for LHC viability assessment of the scenario

Composite Higgs Signatures

Higgs couplings: robustly predicted by Goldstone symm.
Departures from SM ~ $\xi = v^2/f^2$, and $1/\xi$ is irreducible source of **fine-tuning.**



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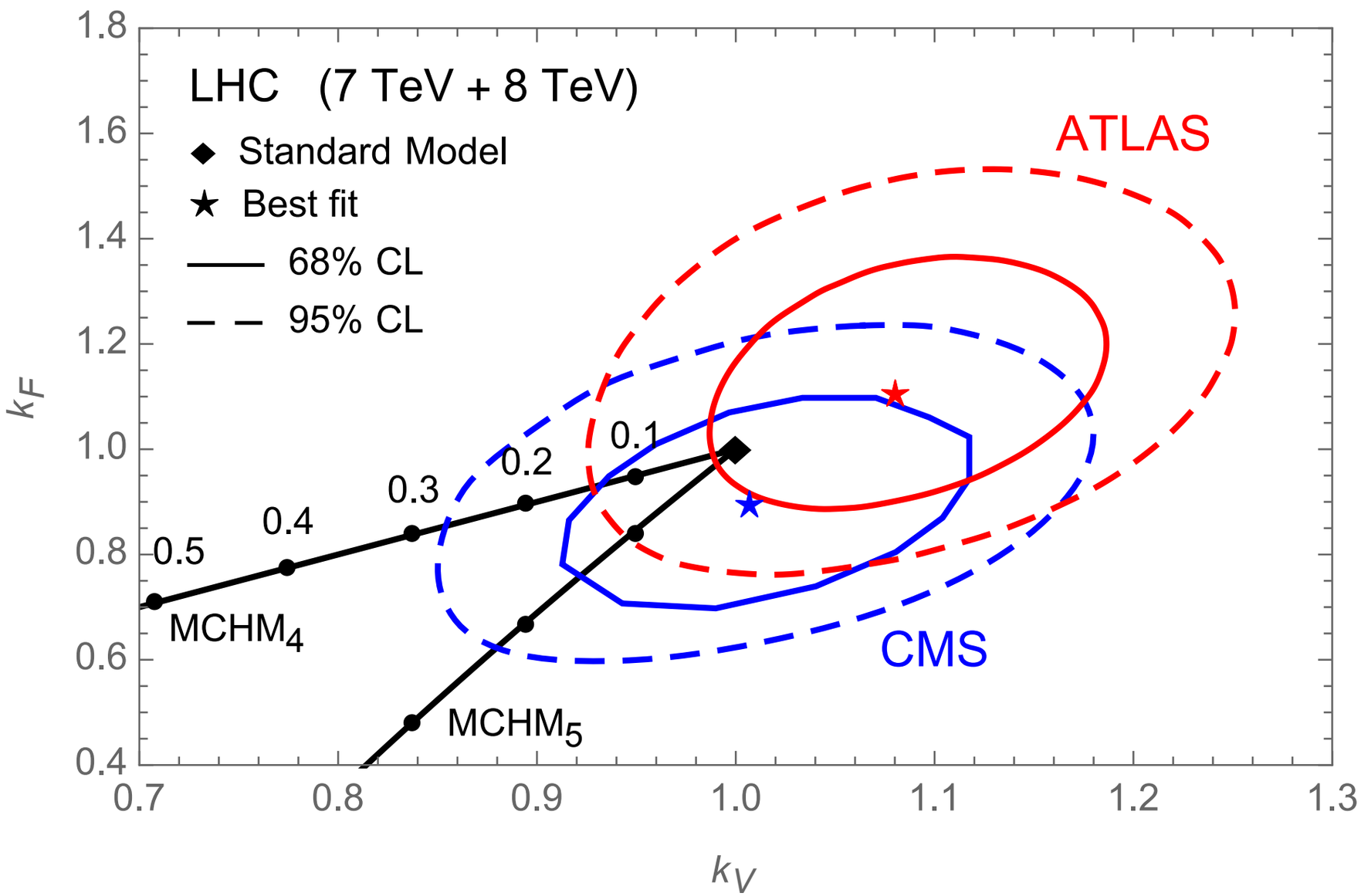
More will come from future LHC precision program in Higgs and EW sector.



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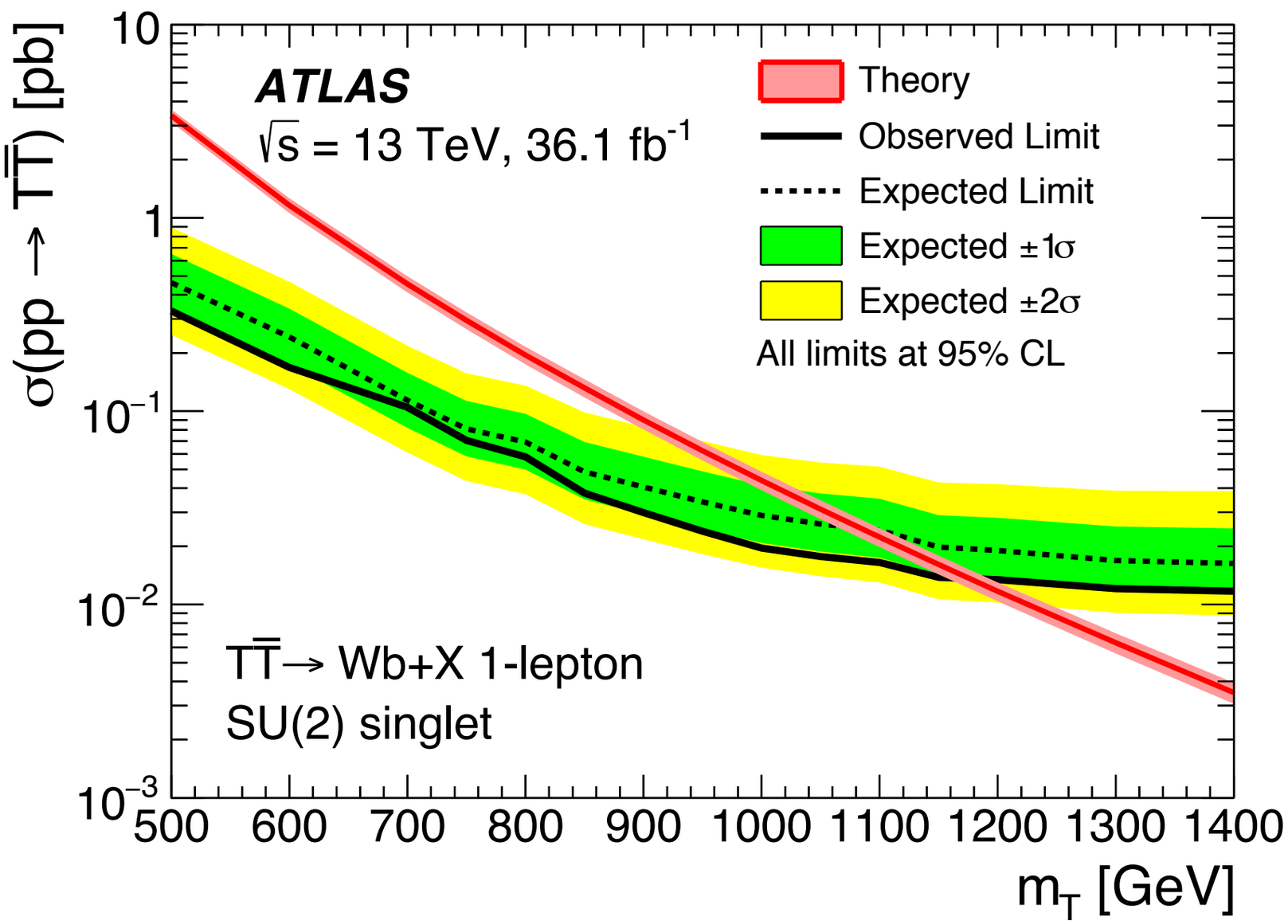
Composite Higgs Signatures

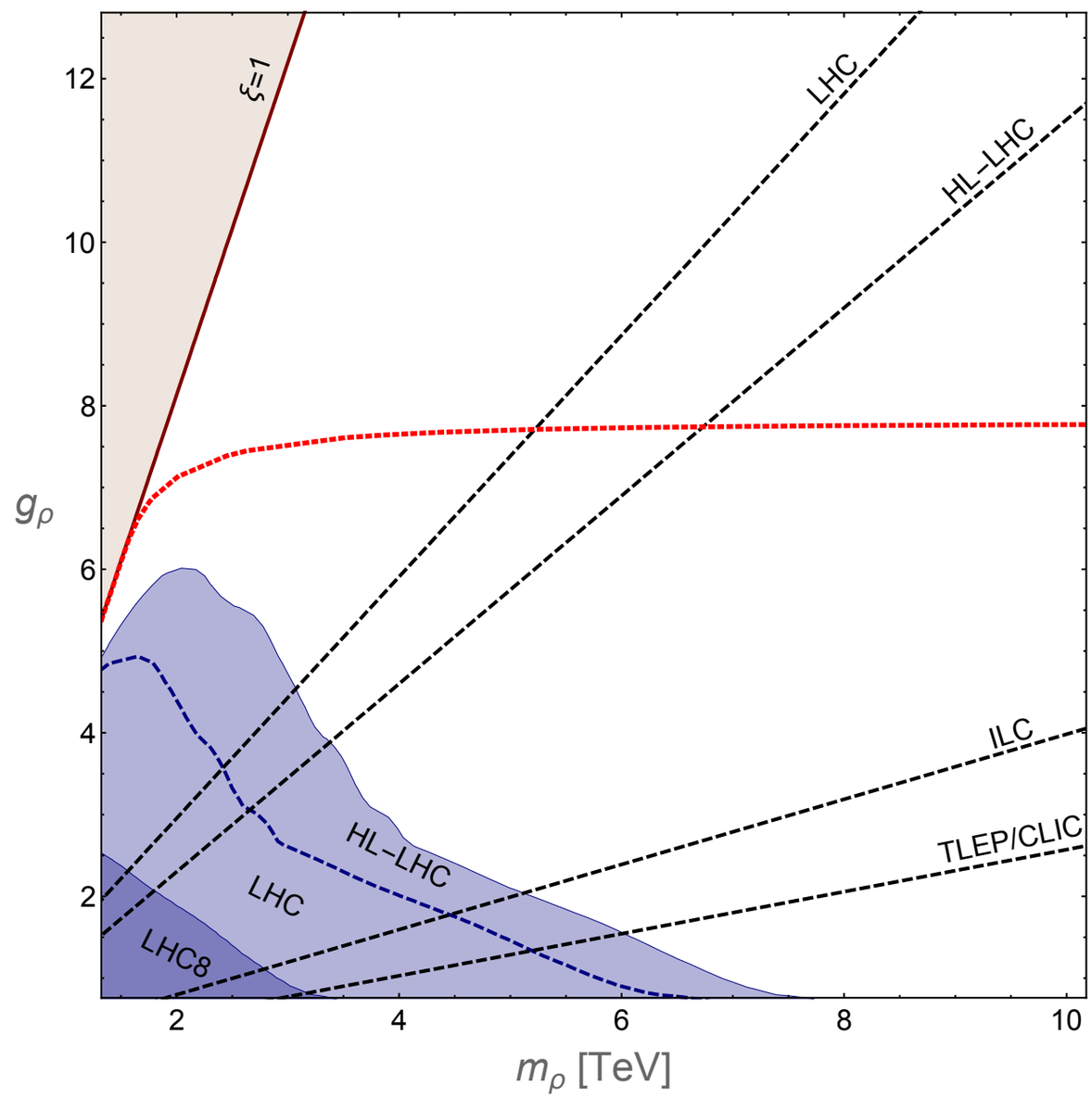
Fermionic top partners: must be light, or cost extra tuning, given m_H.

Current bounds at ~ 1.2 TeV. Final LHC reach of ~ 1.5 or 2 (model-dependent)



Composite Higgs Signatures

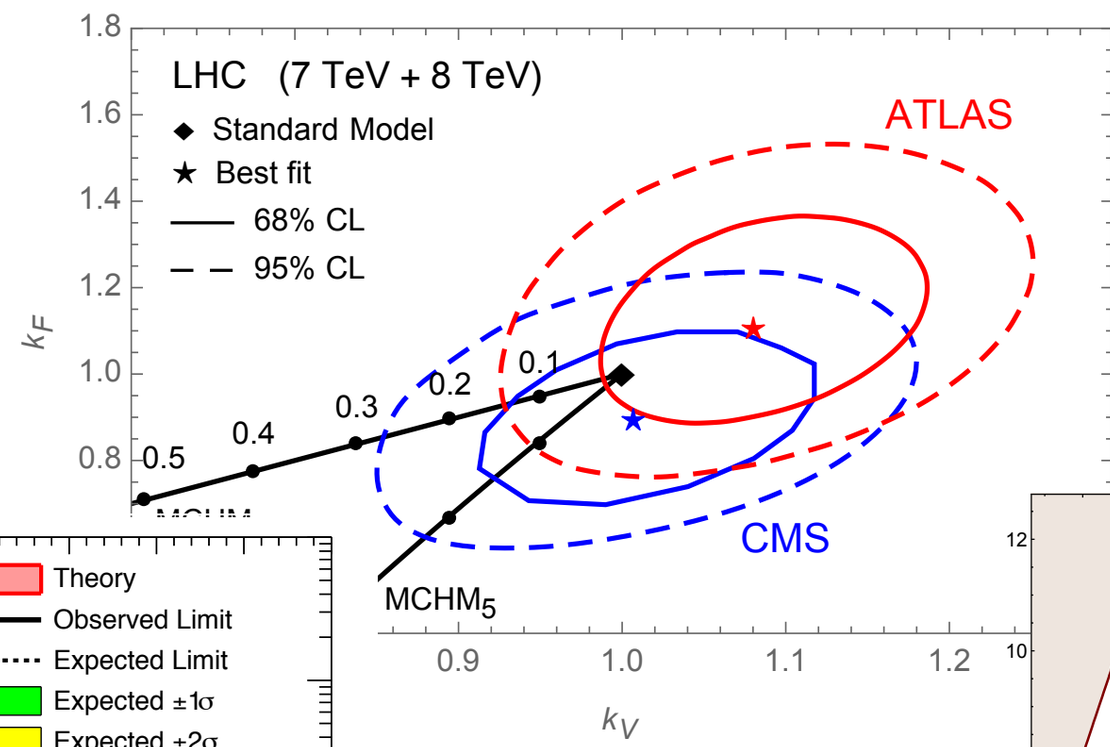
Heavy Vectors: the most robust direct signature

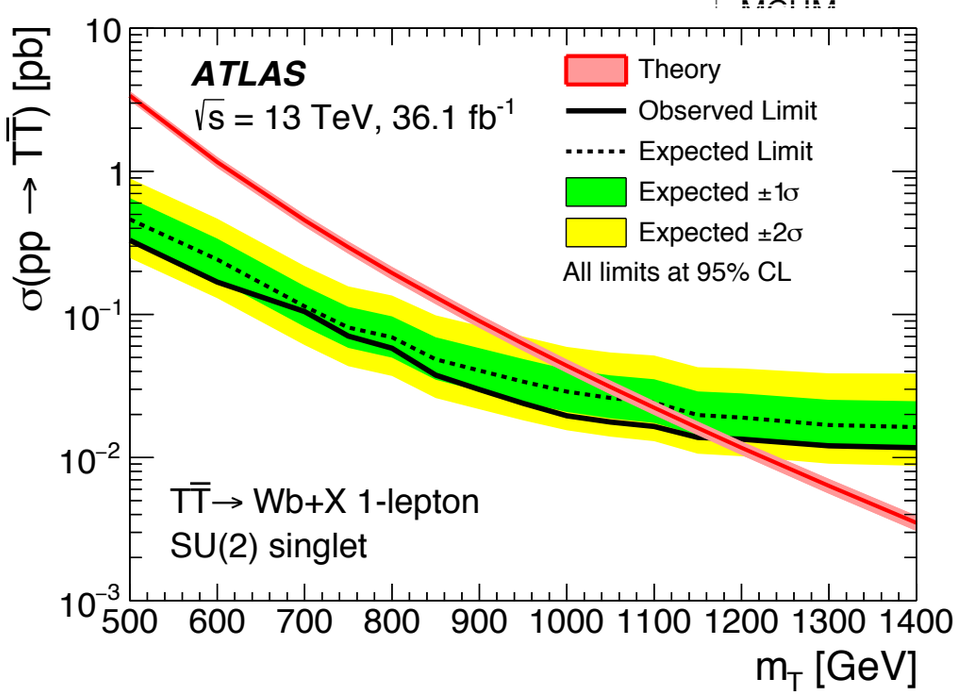


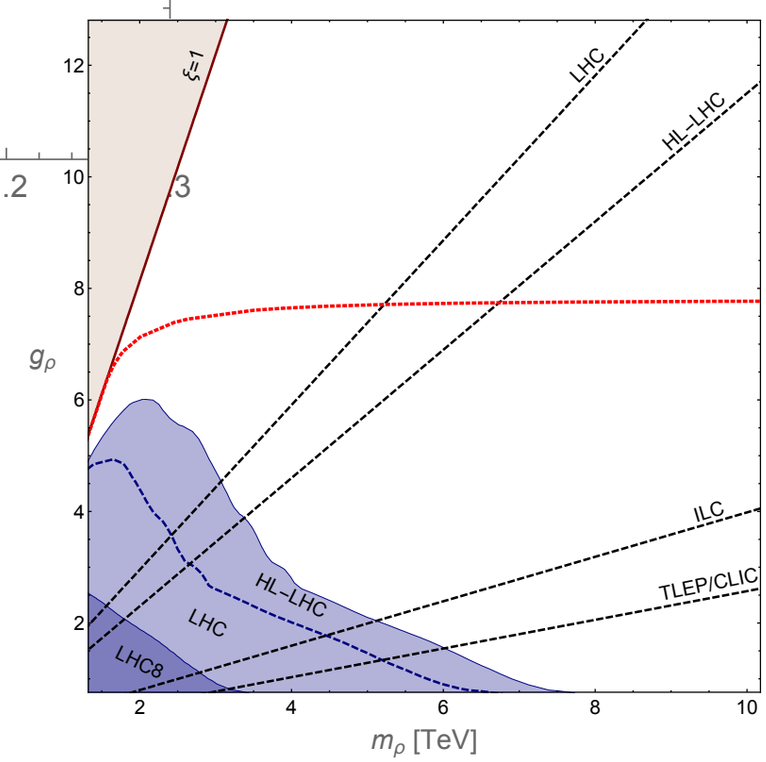
Composite Higgs Signatures

The LHC can robustly **exclude** CH up to one-digit tuning

Very limited **discovery** (and characterisation) prospects







Supersymmetry: A Tale from the 80’

In 89, **any sensible physicist** would have believed in SUSY.

- Natural theory
- Truly minimal viable model (MSSM)
- Dark Matter Candidate
- Easily comes from string theory

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  LHC is telling us
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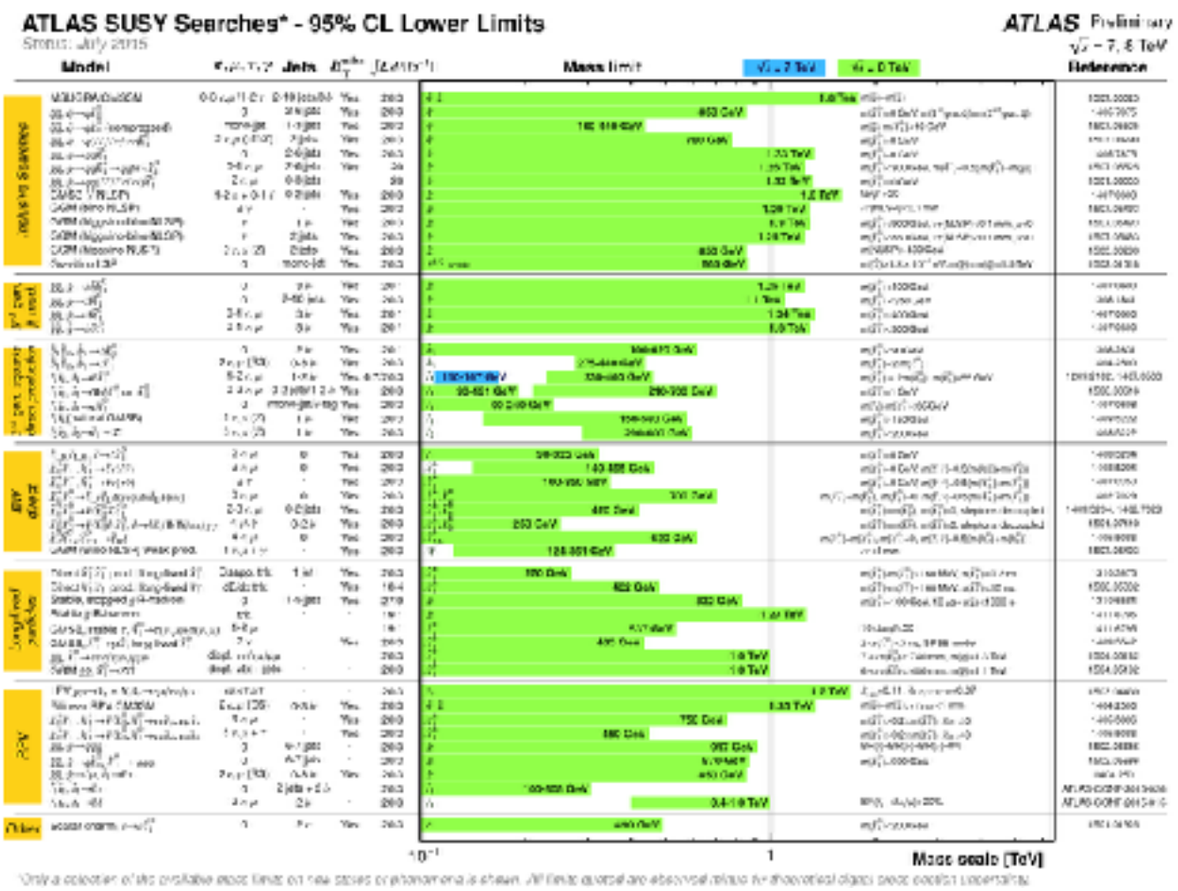
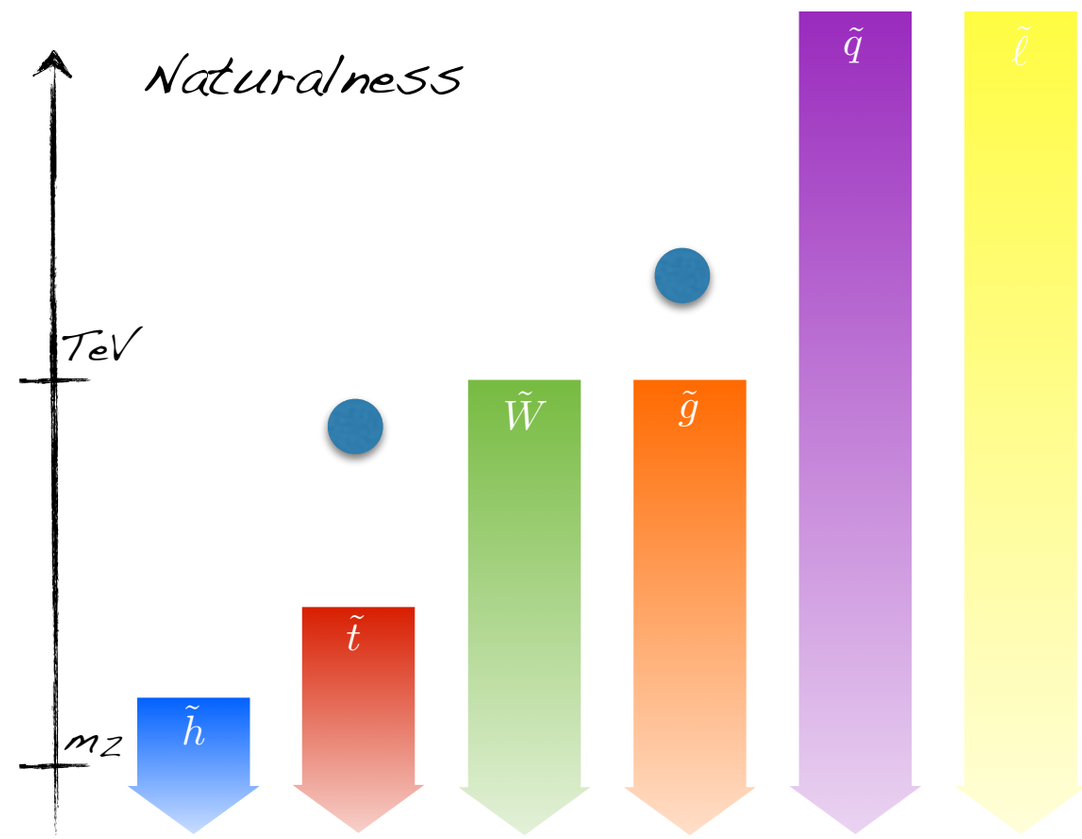
LHC SUSY Searches

Quantitative illustration



Qualitative illustration



from arXiv:1309.0528

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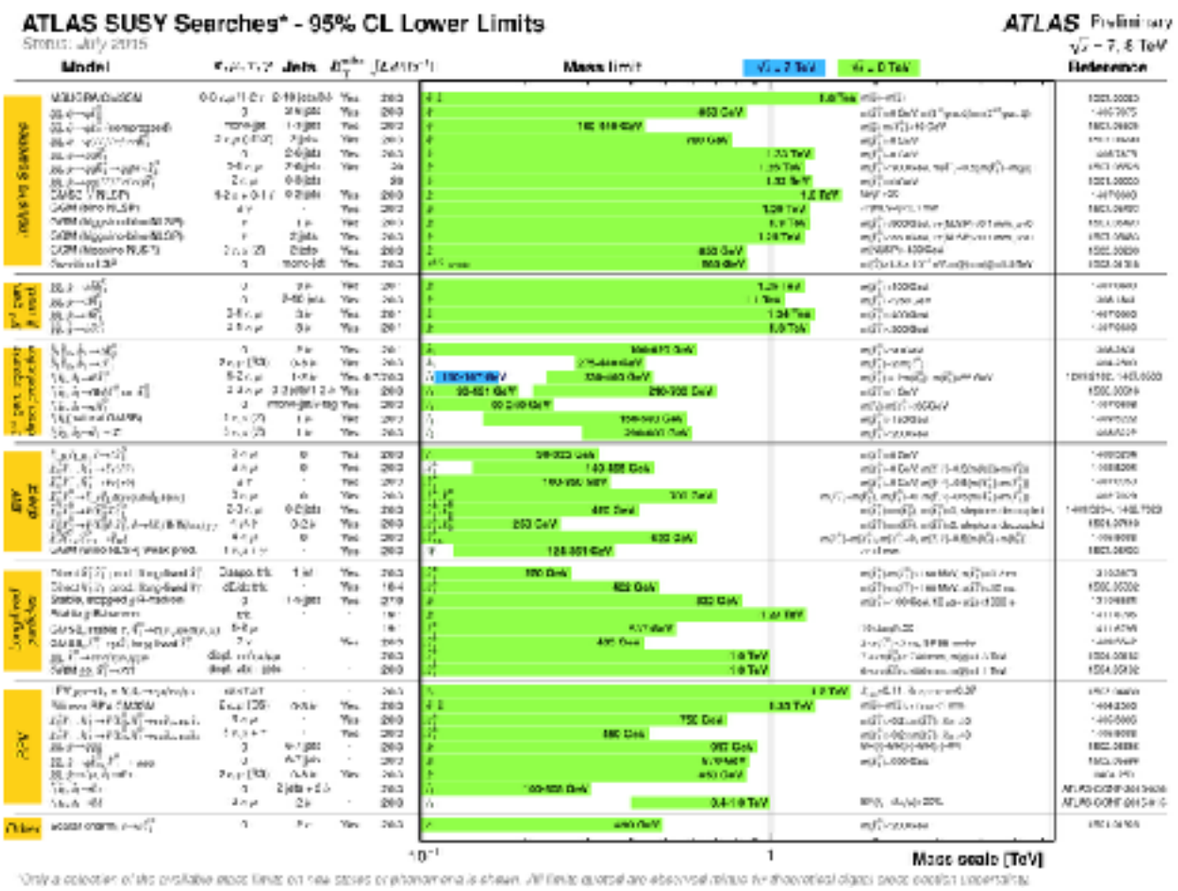

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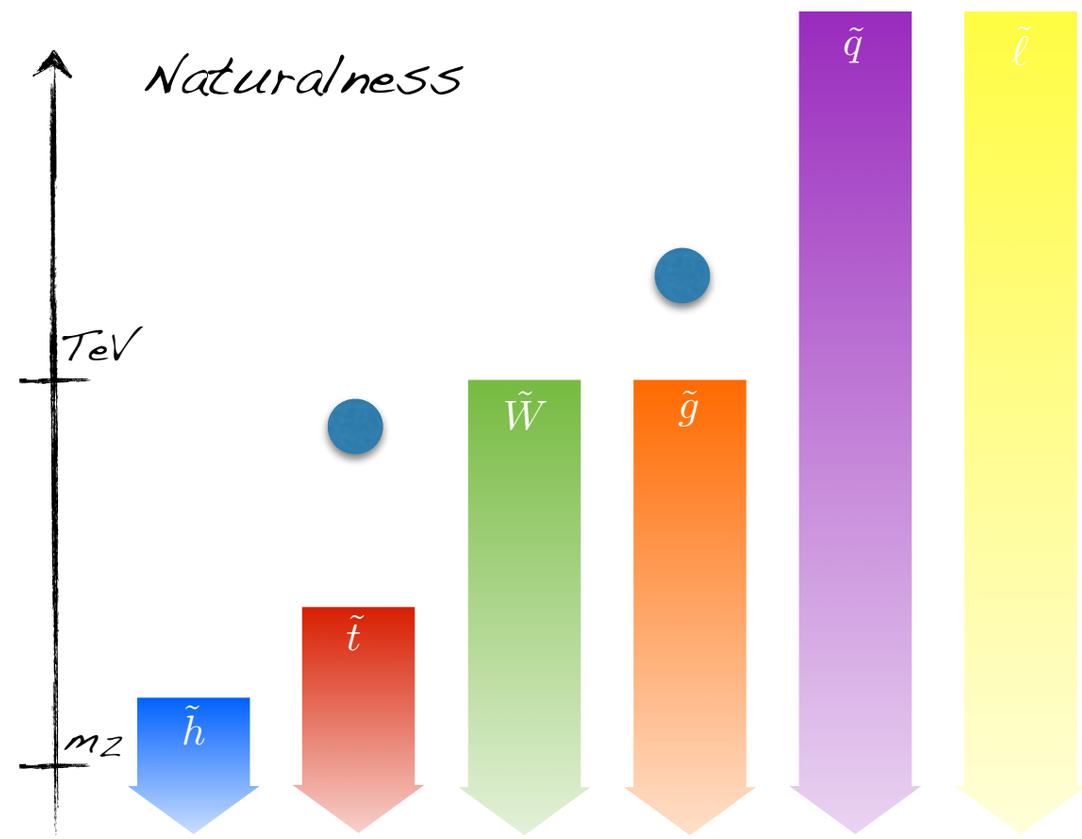

from arXiv:1309.0528

Higgs couplings also relevant in non-minimal scenarios

LHC SUSY Searches

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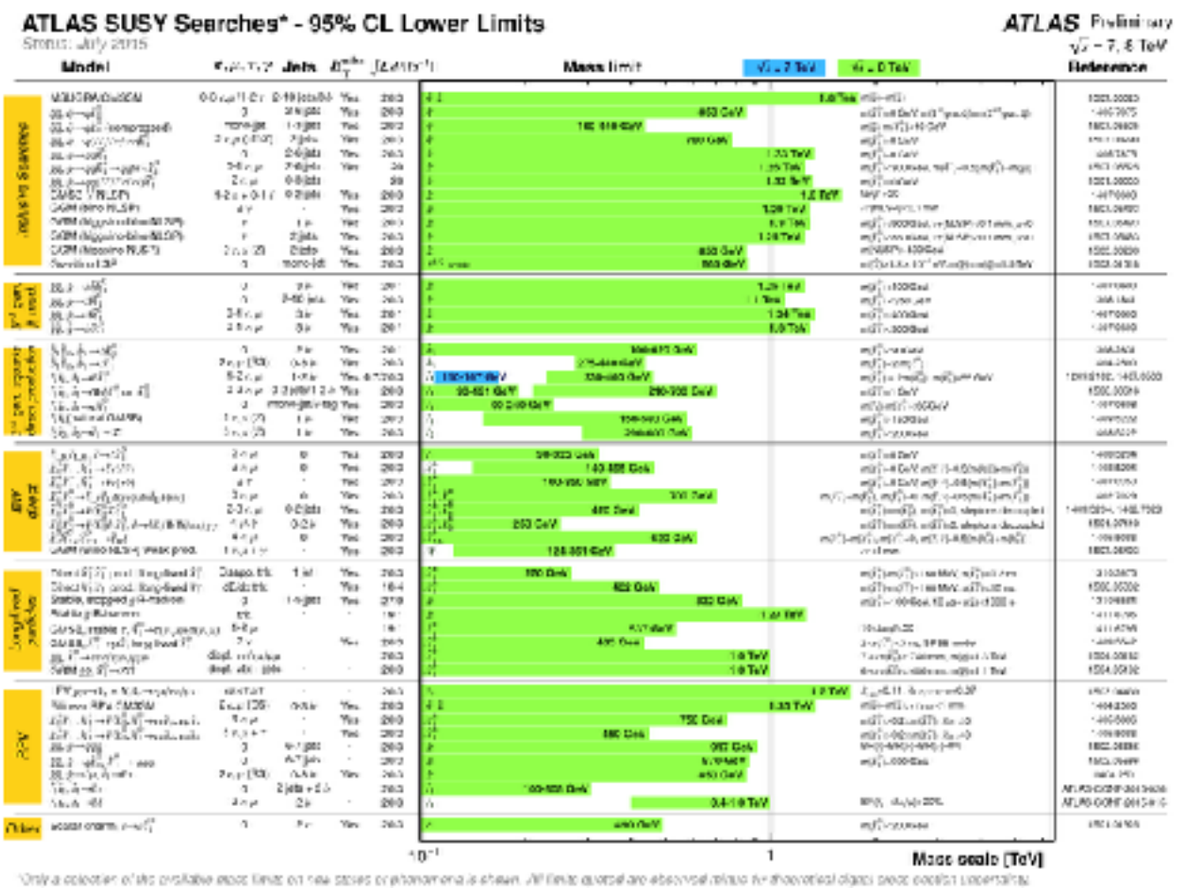

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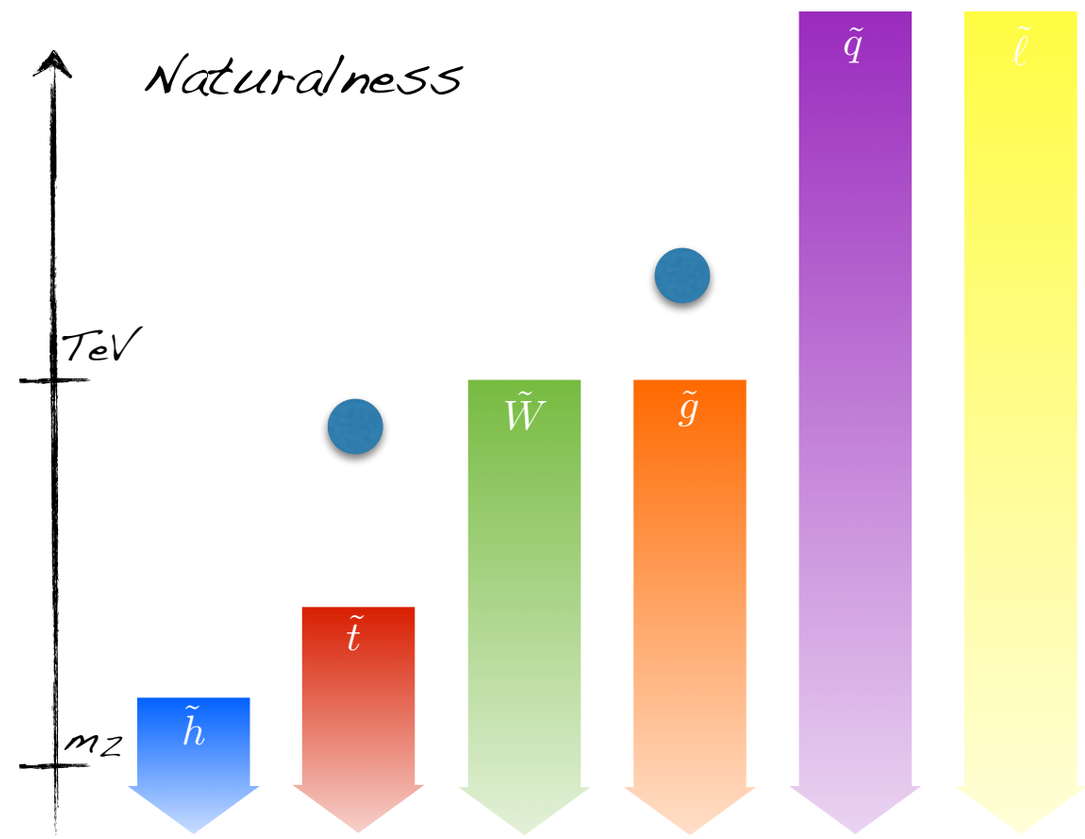

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Higgs couplings also relevant in non-minimal scenarios

Like CH, 1-digit tuning or more generically unavoidable

What if Un-Natural?

(Un-)Naturalness **discovery** has **profound implications**

- **Crucial** to make our best with LHC phenomenology and model building.
- Any **loophole?** [Twin Higgs, Folded SUSY, compressed spectra …]

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If Un-Natural, m_H has no **microscopic** origin (e.g. $\neq G_F$).

It could:

- be a fundamental input par. of the Final Theory
- have **environmental anthropic** origin
- have **dynamical** (set by time evolution) origin

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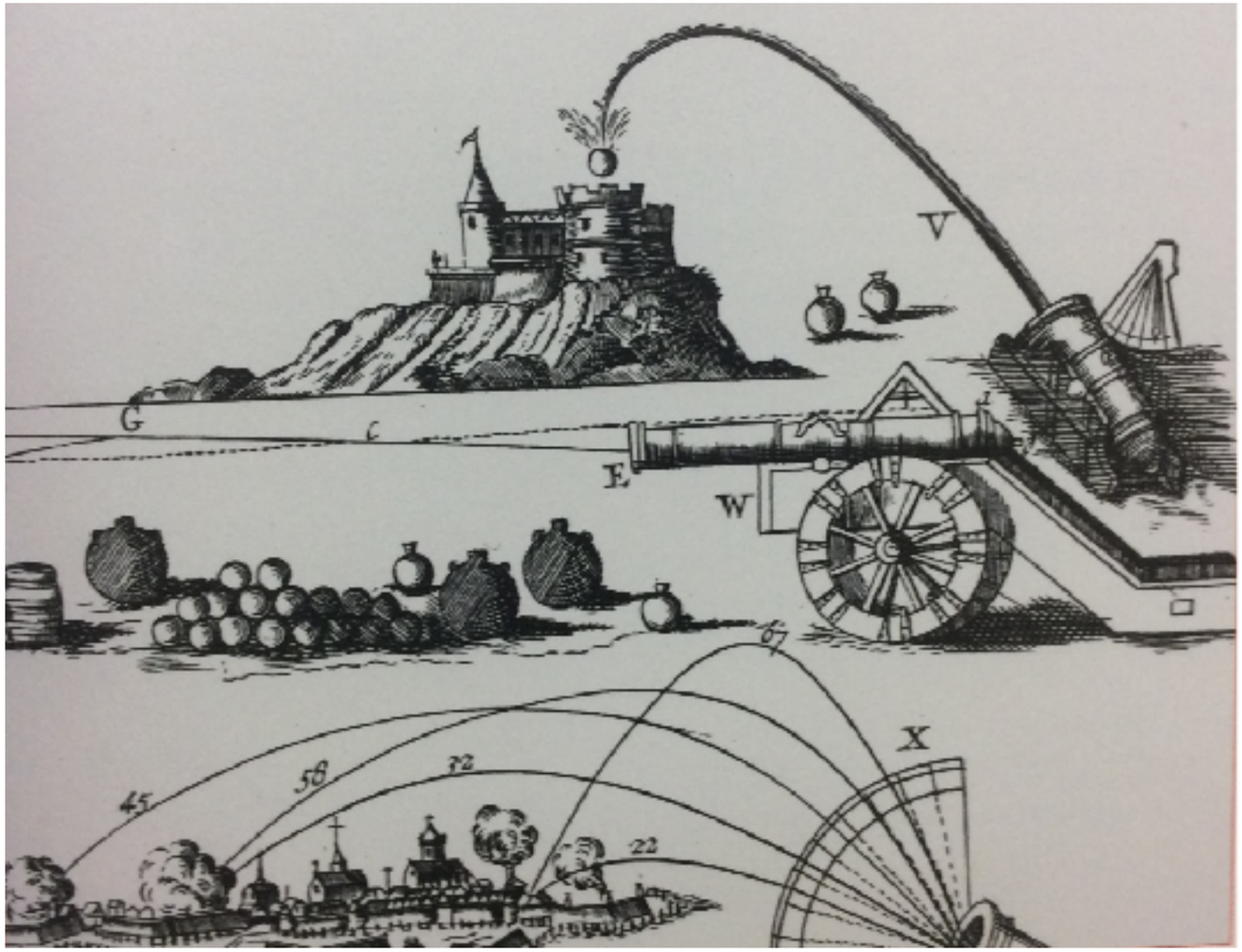

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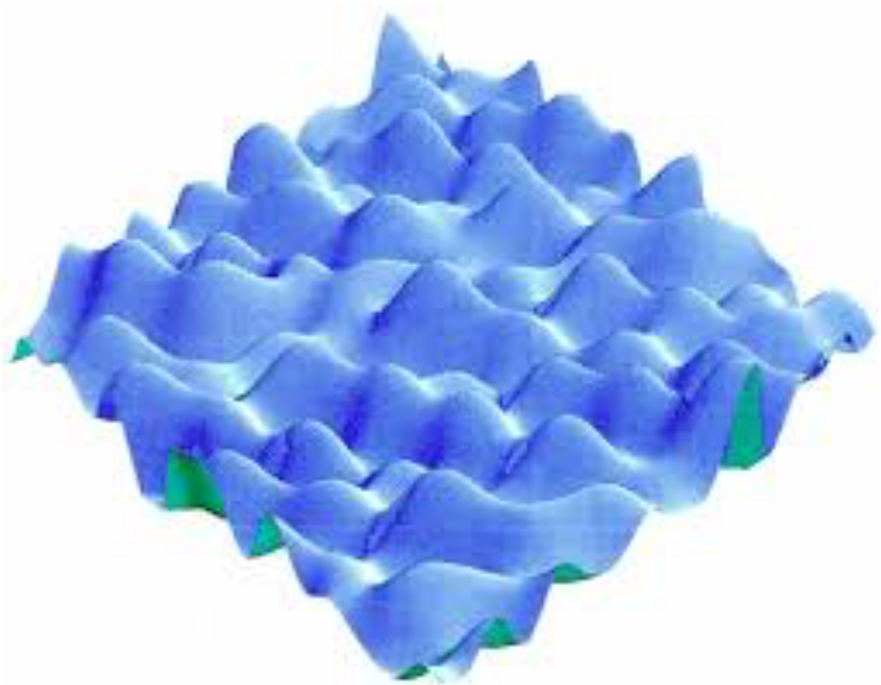

Landscape of vacua

Higgs mass depends on the vacuum where we live.

Not quite like g. Vacua are **causally disconnected**. Cannot go there and check.

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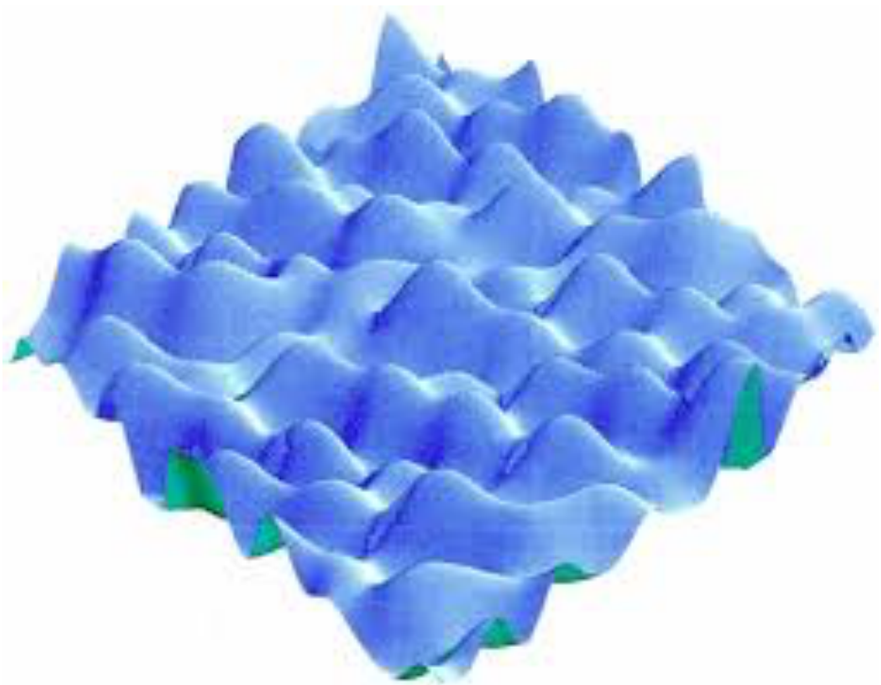
Environment in itself **not a solution:** why $m_H \ll \Lambda_{\rm SM}$?



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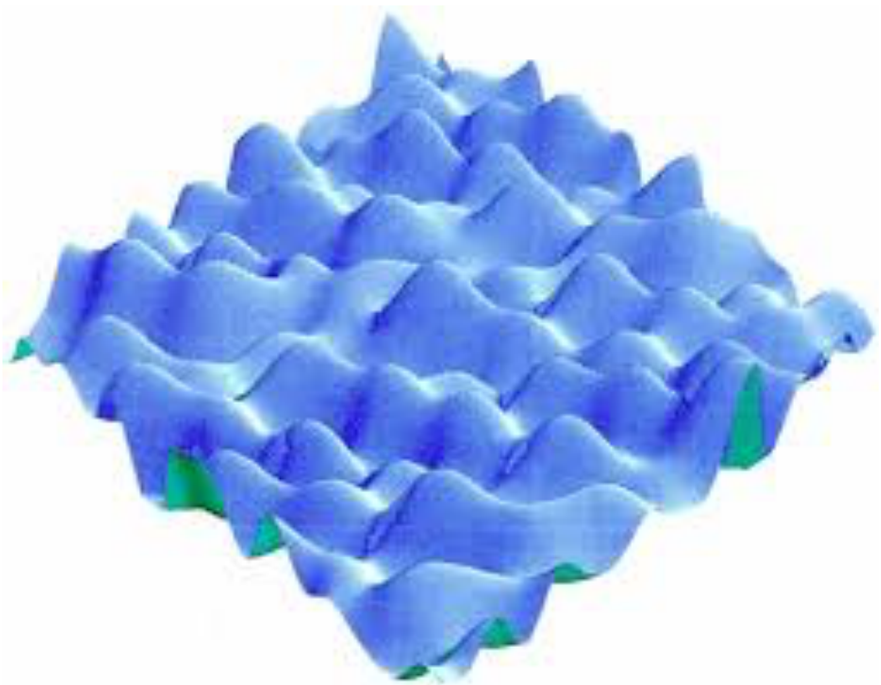
E.g., why 15°C is the average temperature of earth?



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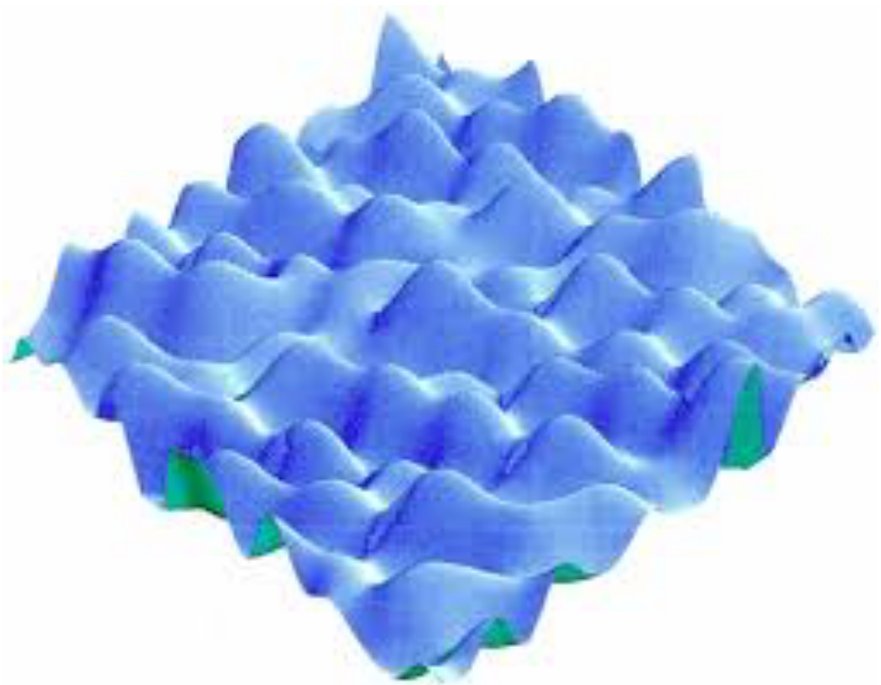

Landscape of vacua

We live where we can. There might be **upper bound** on m_H for us to exist.

Landscape distribution peaks at Λ_{SM}, but has a tail. Likely to live **close to the upper bound**.

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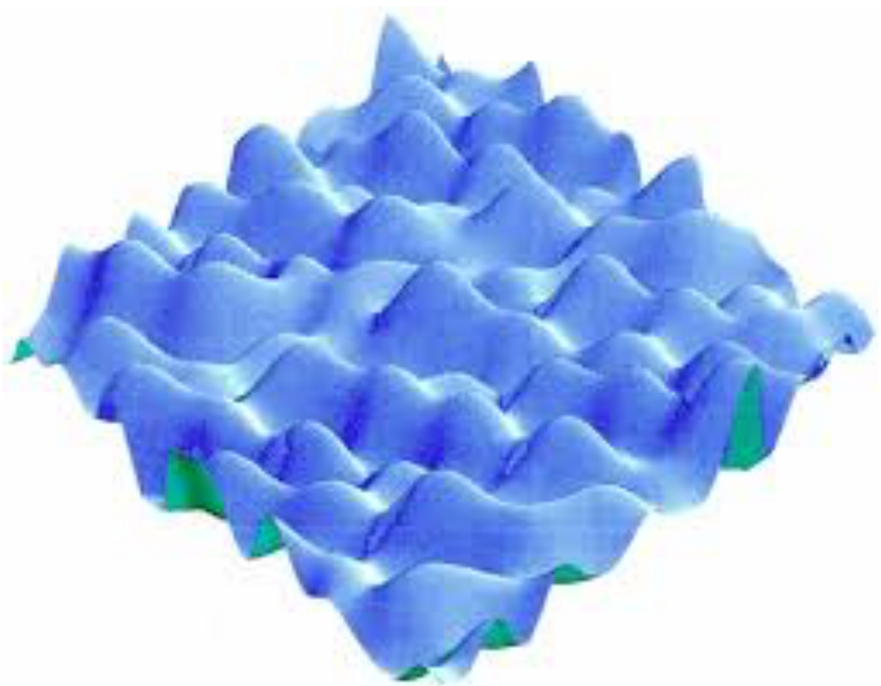

Landscape of vacua

Successful Weinberg prediction of the Cosmological Constant:

For galaxies to form, it must be:

$$\Lambda_{\rm c.c.} \lesssim ({\rm few} \cdot 10^{-3}{\rm eV})^4 \sim 10^{-120} M_P^4$$

Observed value:

$$\Lambda_{\rm c.c.} \simeq (2 \cdot 10^{-3}{\rm eV})^4$$

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[Graham, Kaplan, Rajendran, 2015]

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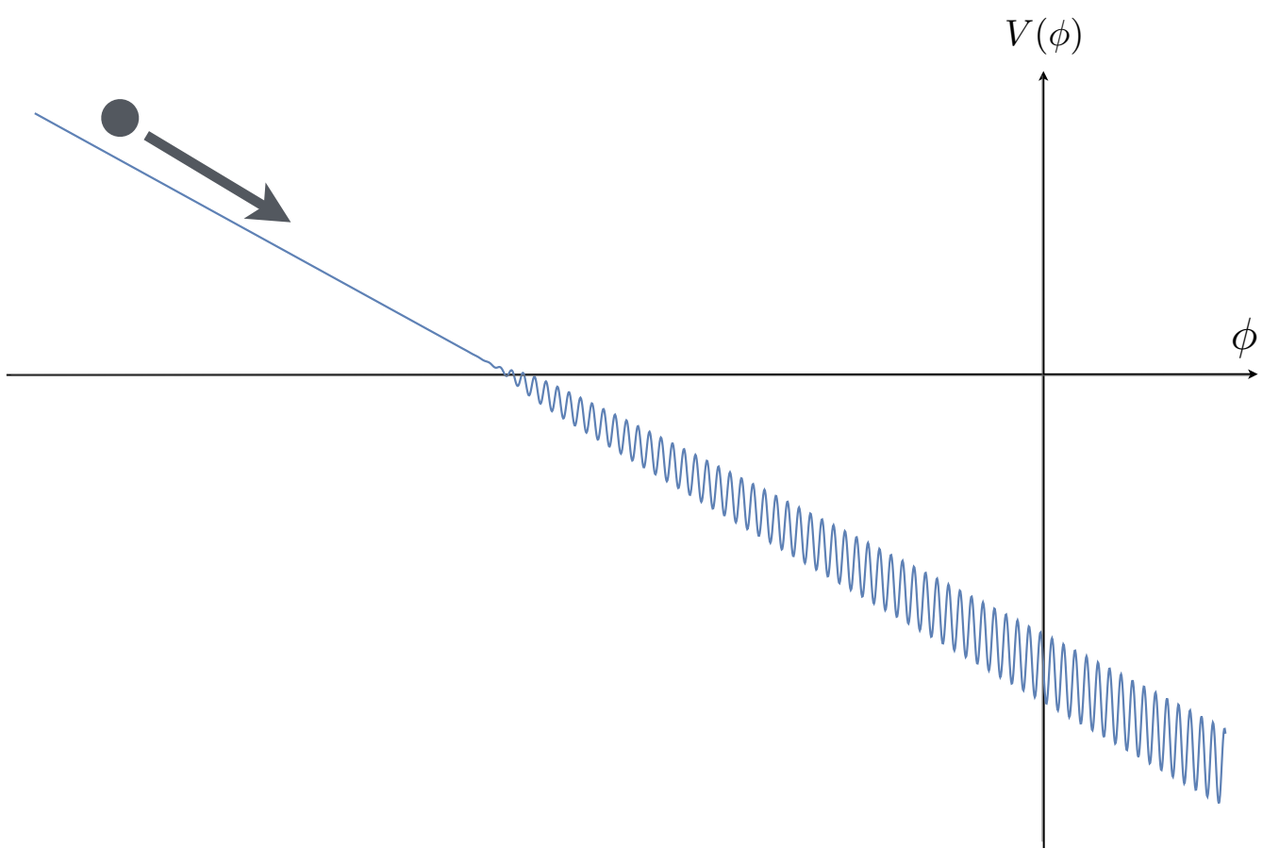
Recent proposal: **Relaxion**

Field-dependent Higgs mass **Proportional to Higgs VEV**

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$



Field rolls during Inflation.

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Because of the cos term.

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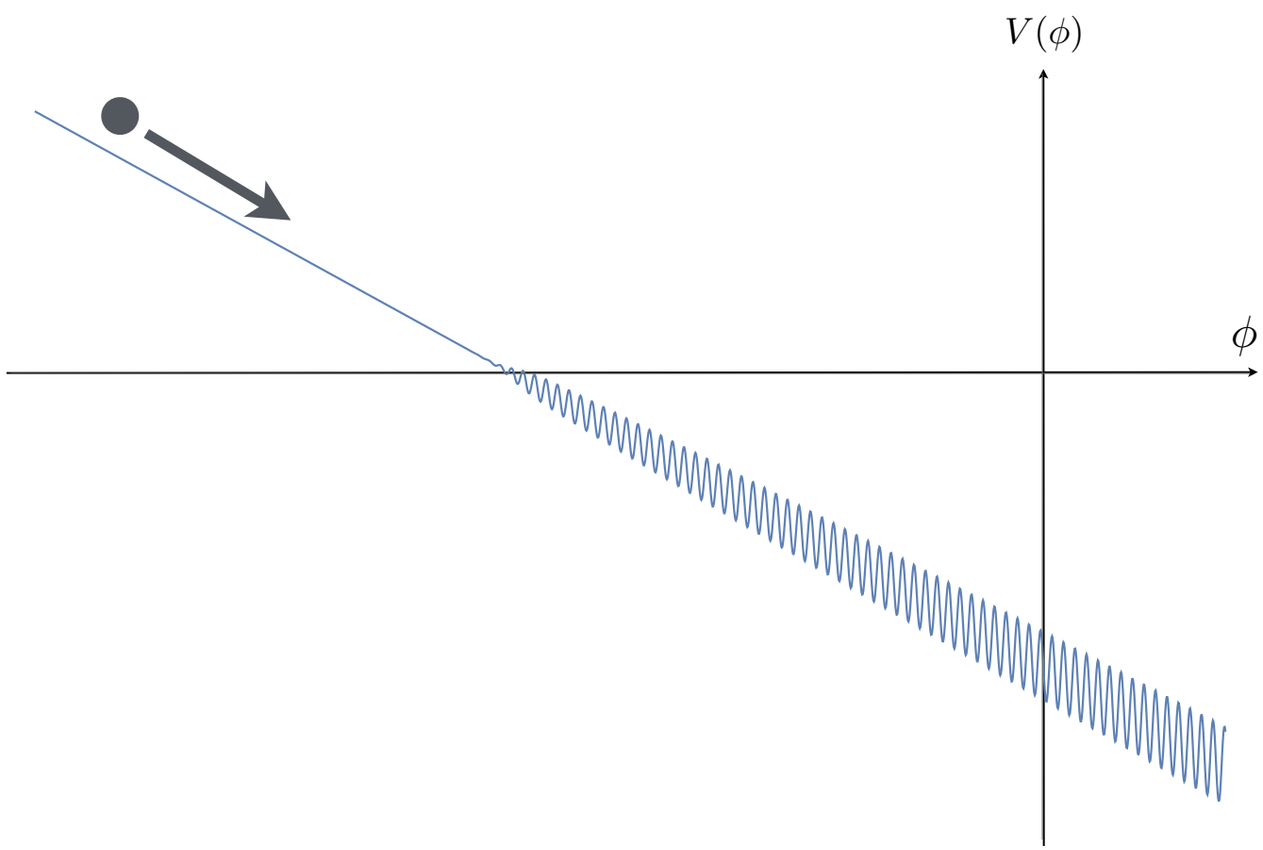

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Viability of large field excursion requires ad hoc mechanism like **Clockwork** [Kaplan, Rattazzi & Choi, Kim, Yun]

What if Un-Natural?

One can like/believe these radical speculations or not.

One can argue that they involve too much complexity to produce a concrete BSM scenario.

One can hope in UV physics “obeying different rules”, nullifying Naturalness problem, but concretely what?

All this shows the **dramatic impact** Un-Naturalness discovery is having on our field.

Beyond the SM

What could be there …

- Light DM
- Very Light DM
- Axions
- Portals (ν_R ,γ_D, ..)

} The Coupling Frontier
[not as easy to characterise as the Energy one]

- DM as primordial Black Holes? [**direct** GW probe?]
- What to do with LIGO/Virgo? [on top of g/γ speed?]

Beyond the SM

… that we can probe

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Direct Detection

DM-e scattering/absorption,
on SC, graphene …

conversion in γ [e.g. ADMX], or
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Lab Production

Dedicated:
beam dump [e.g. SHIP]
missing momentum [e.g. LDMX]
detection [e.g. BDX]

Parasitical:
e.g. Mathusla/CODEX-b

Summary

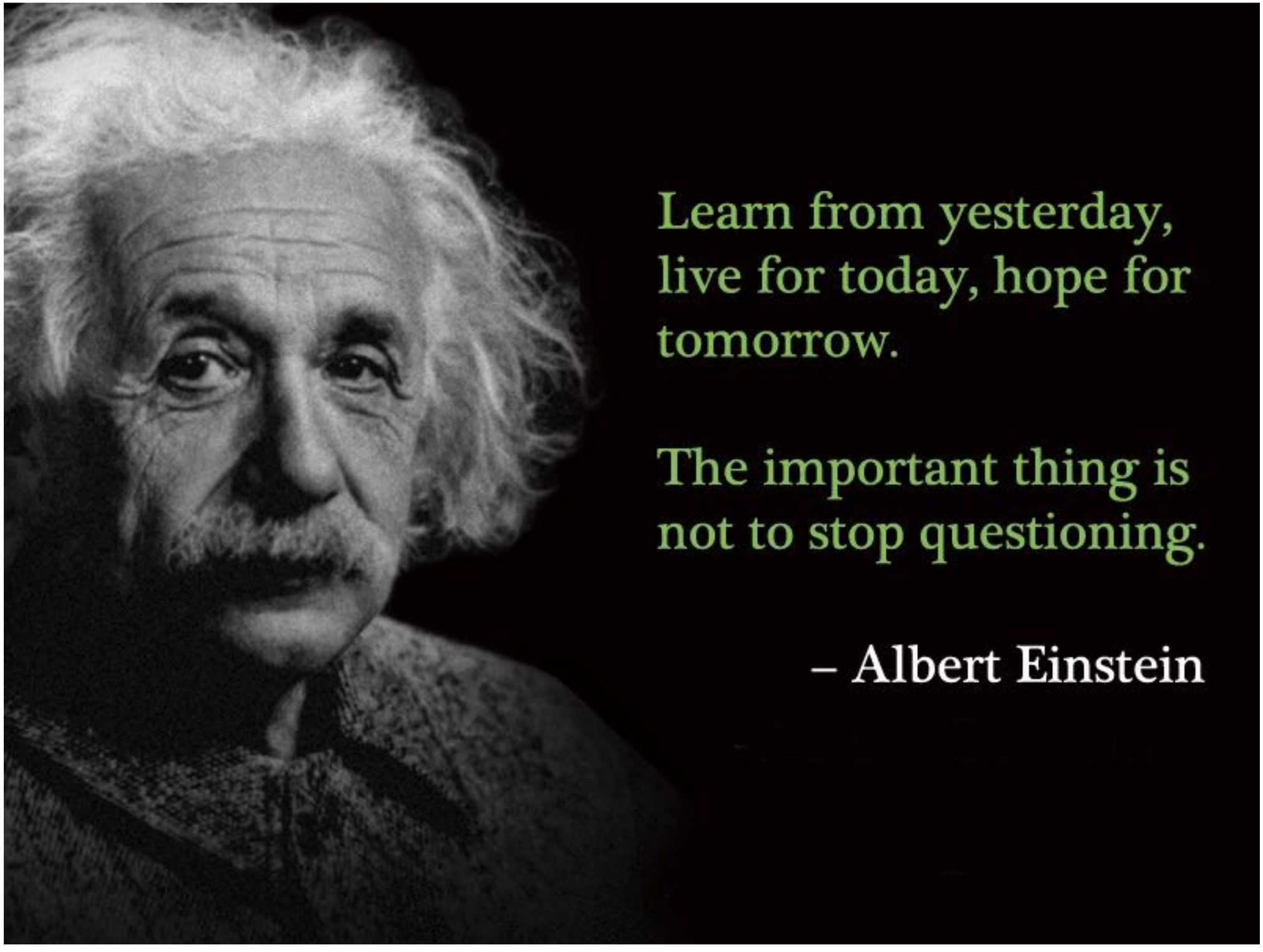
After the Higgs, no **discovery guarantee** in HEP, nor in other areas of fundamental interactions physics

LHC entering a mature stage is opportunity for great phenomenology. Conclusive TeV-scale exploration?

Exploring new ideas on “Un-Naturalness” implications

Physics **Besides** (≠Beyond) Colliders is a flourishing field. Interesting interplay with experimental/technological developments in other fields.

Summary


Learn from yesterday, live for today, hope for tomorrow.
The important thing is not to stop questioning.
– Albert Einstein