The Higgs Hierarchy Problem: Should we care about it?

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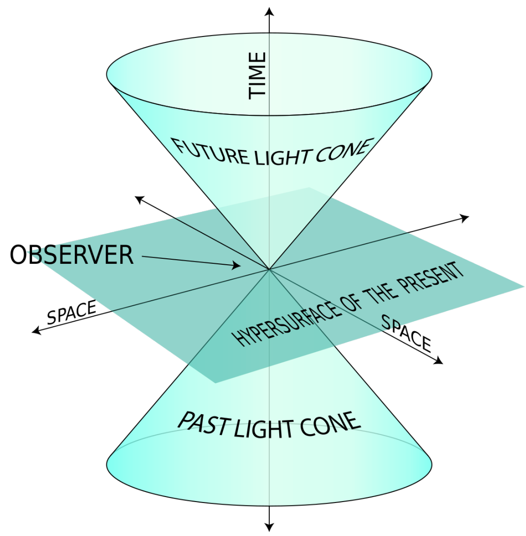
What do we *care* about?

The most recent BIG breakthroughs:

Discovered satisfactory notion of **causality:** Special Relativity

Understood that **particles do not have a position:**

Detectors have $\rightarrow$ **Field** Observables $\mathcal{O}(t, \vec{x})$



Microcausality Principle

Incorporates and supersedes QM and SR

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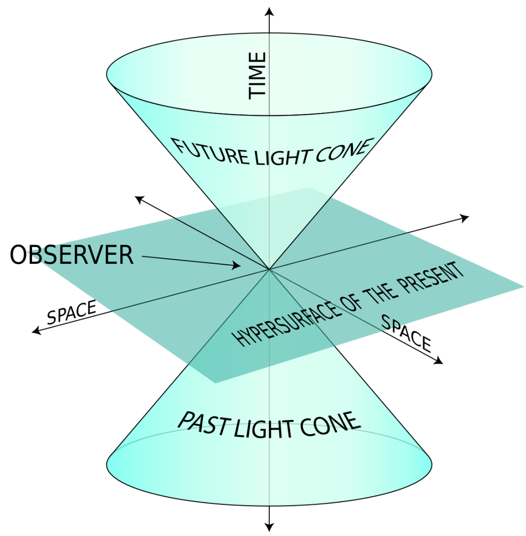

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Practical QFT and the Standard Model

Perturbative local QFT **implements** the Big Principles, does not follow from them.
Is surely incomplete (or, the Principles are) because it fails with Gravity.

The SM is one practical QFT that **accommodates** observed particles/fields. And not all of them (DM). Existence (or not) of BSM can only come from experiments.

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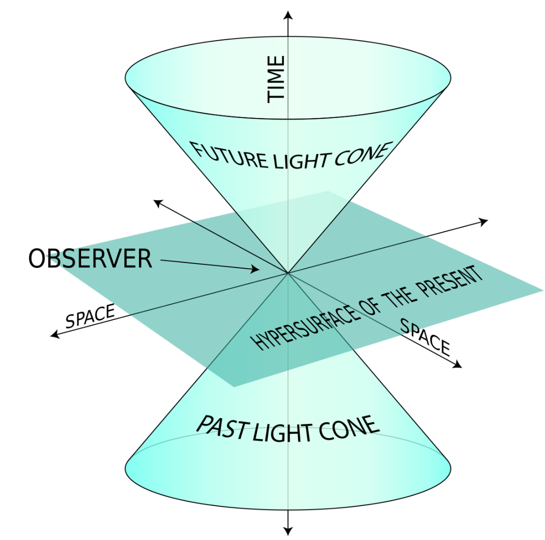

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[nor of course why the SM particles/fields/parameters]

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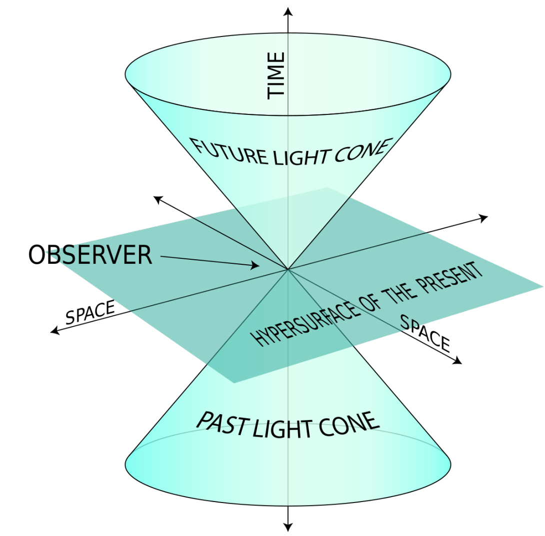
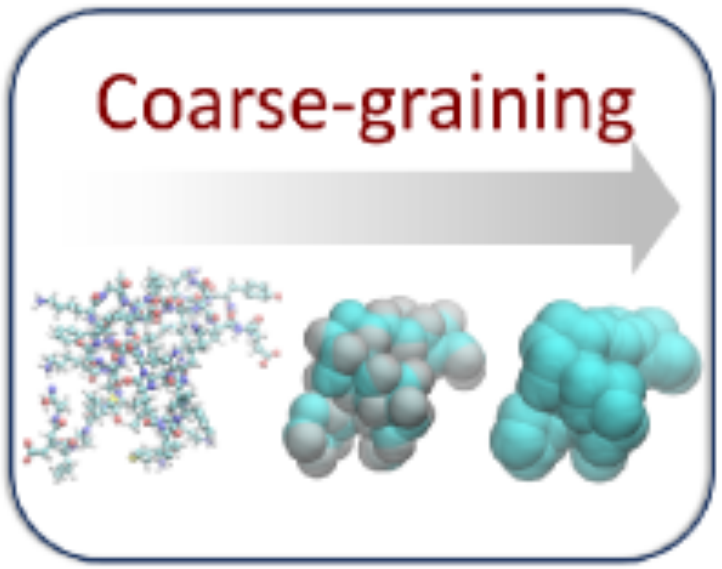


Microcausality Principle

The **Wilsonian Paradigm** could be (or *have been*?) the answer:

Symmetries&Selection Rules, and (generalised) dimensional analysis, are universally valid rules also beyond practical QFT



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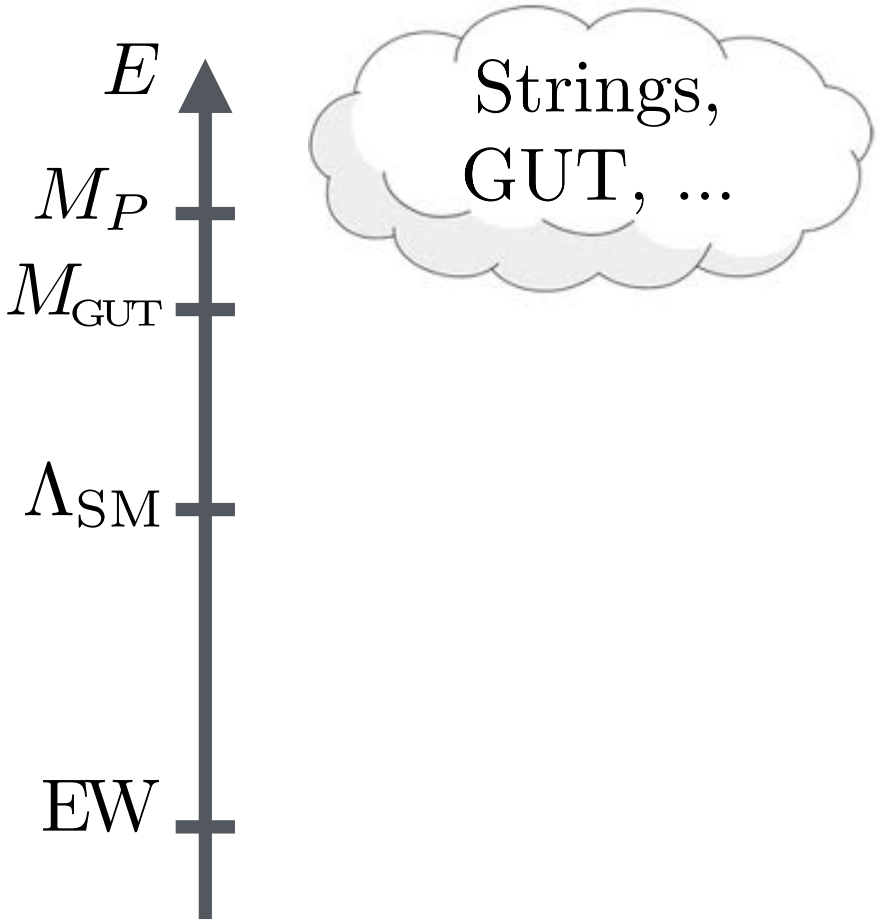
A tale from the 90's



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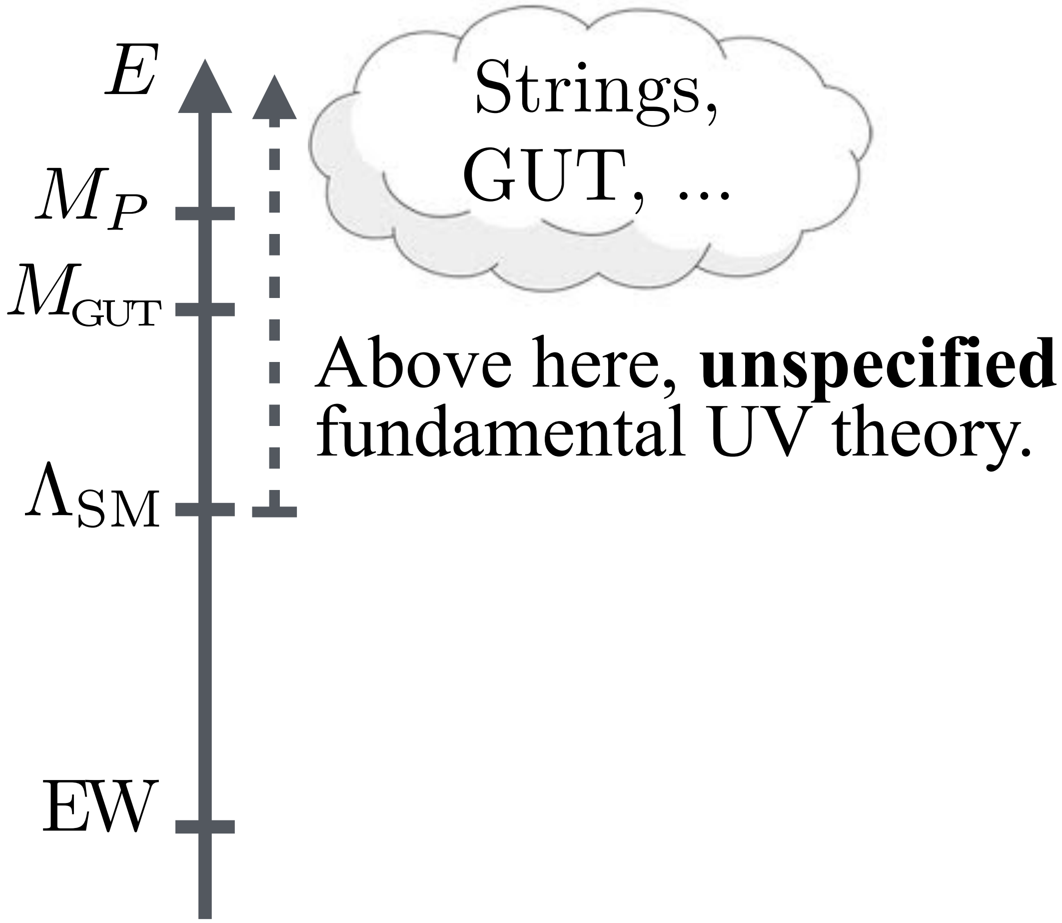

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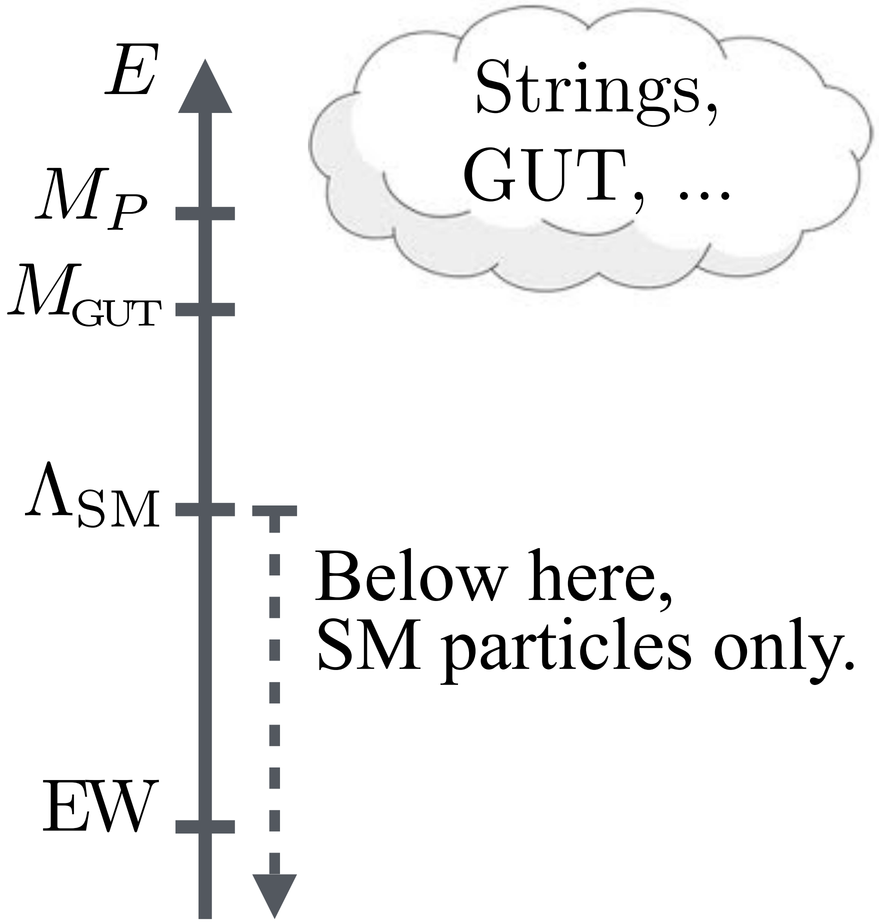

Assume UV theory engineers light SM particle content.
Heavy BSM particles start at the Λ_{SM} (SM cutoff) scale.

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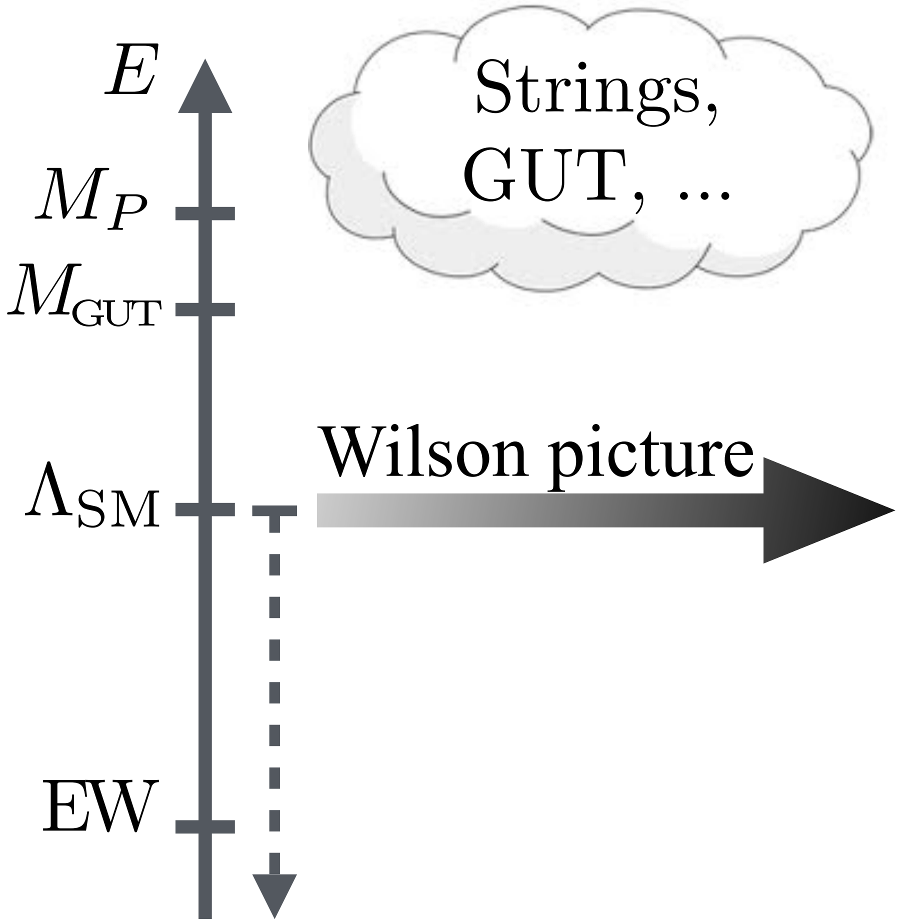

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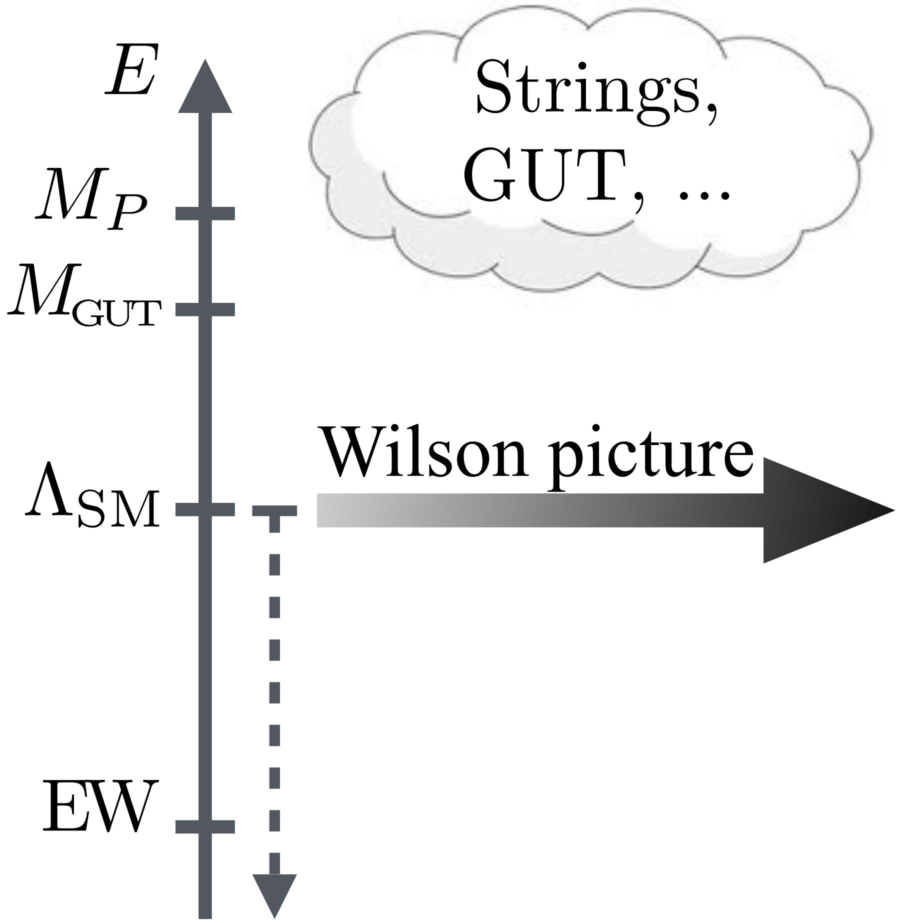

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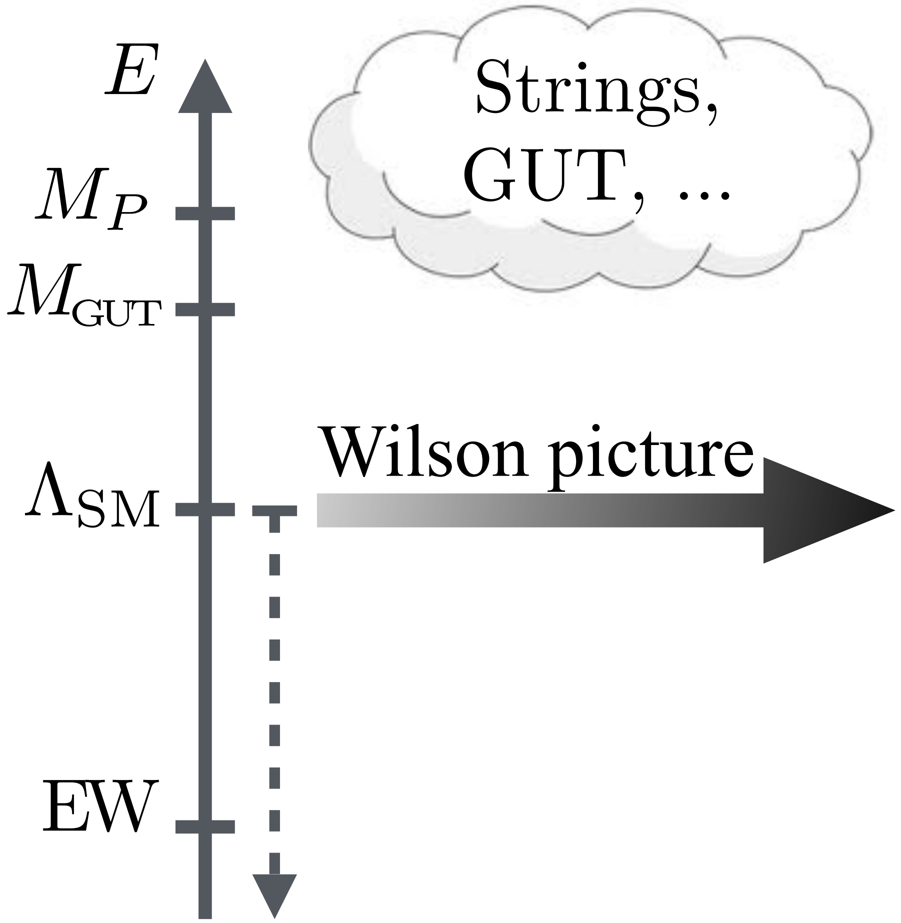

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If numerical coefficients are of order one, we say that UV theory is **generic**: no special request to String model-builders!

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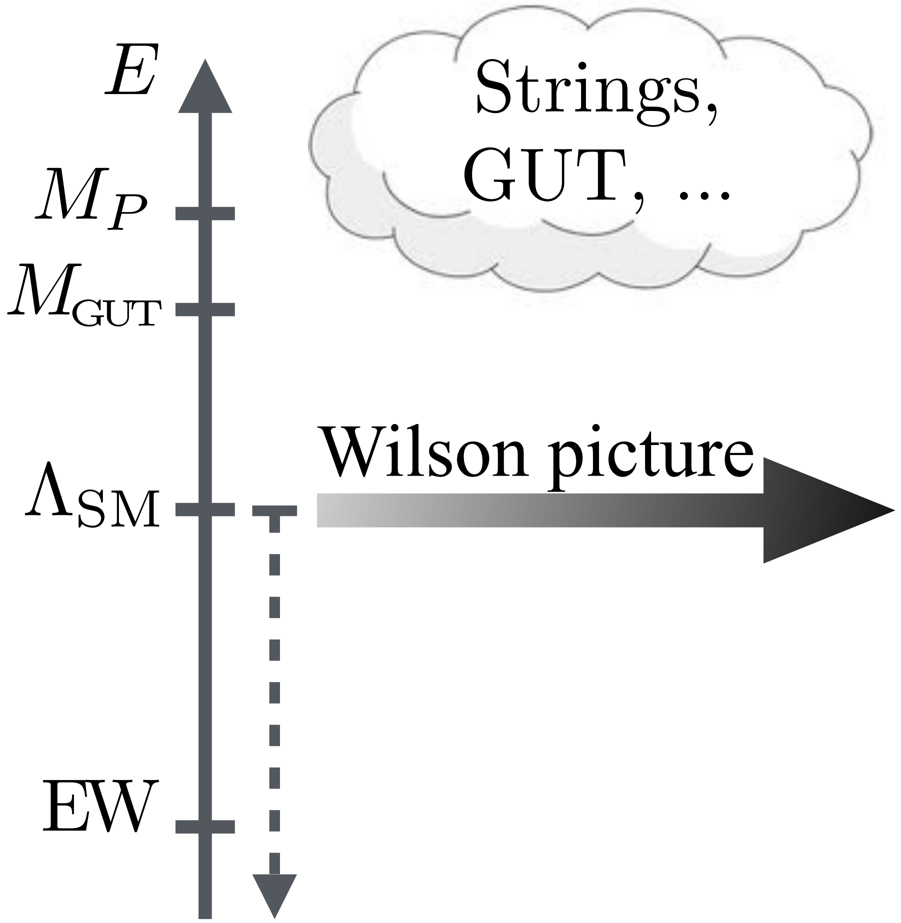

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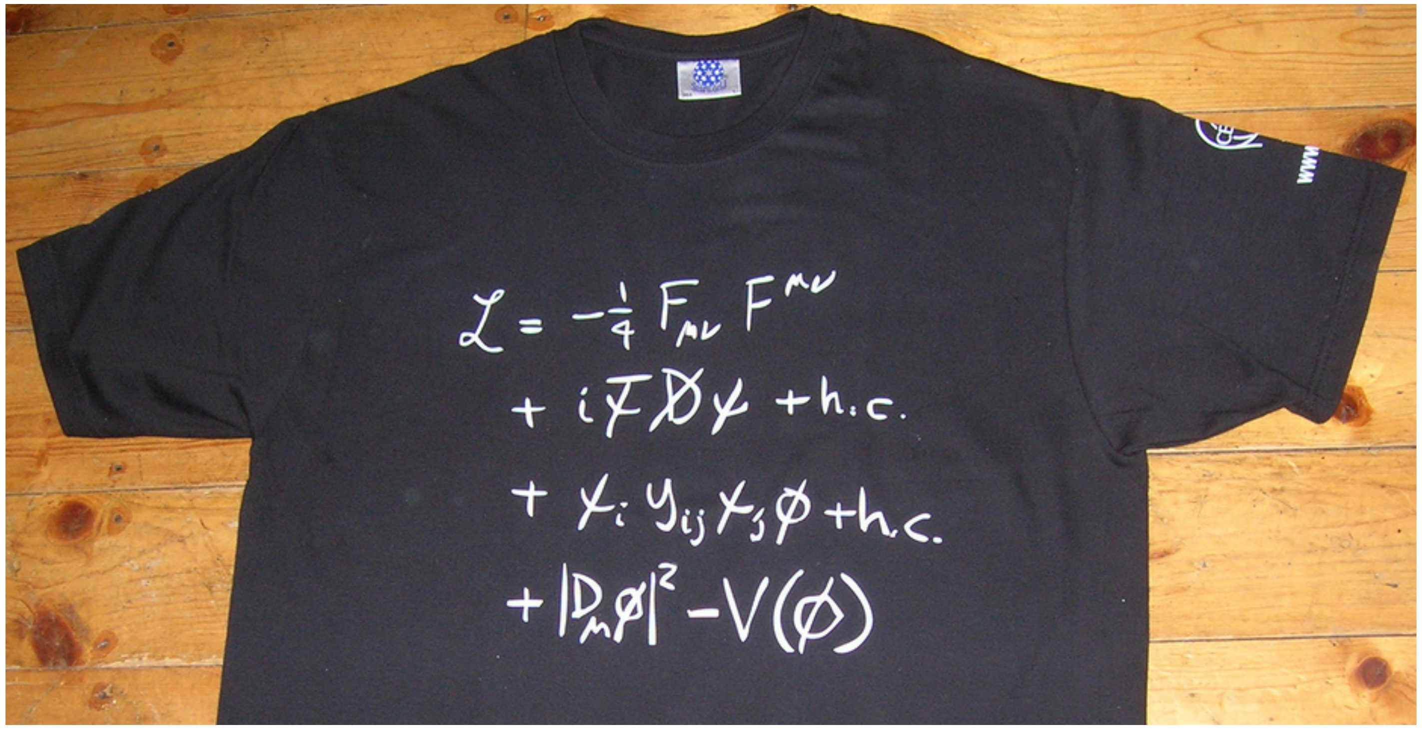
$\mathcal{L}^{(d=4)}$: The CERN T-shirt Lagrangian (almost)



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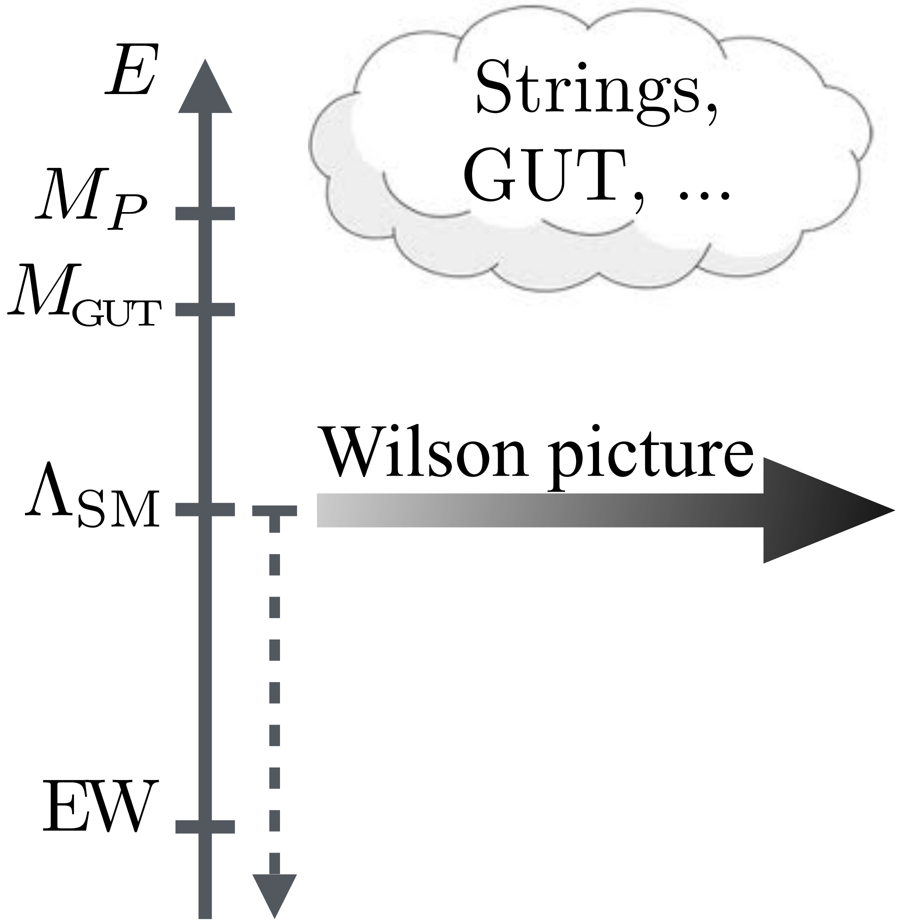

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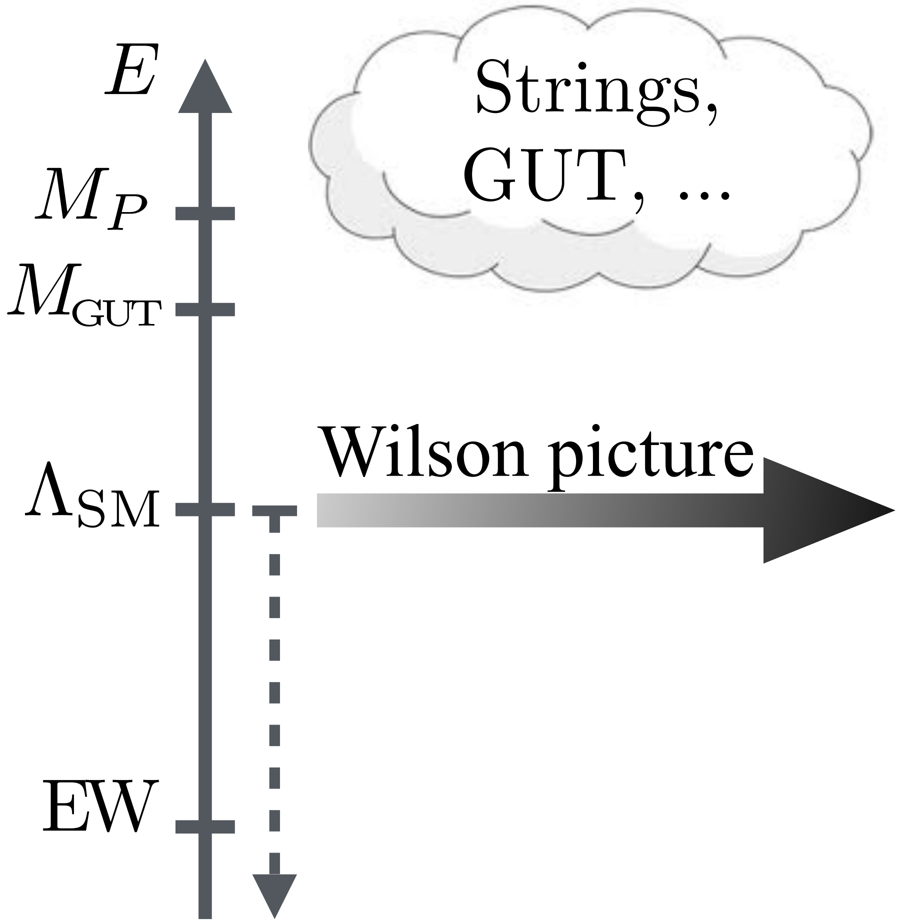

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$\mathcal{L}^{(d=4)}$: describes all what **we see** (almost)
… and what **we don't see**

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

${\rm BR}(\mu \to e\gamma)_{\rm exp} < 10^{-12}$ **!!** ⟷ ${\rm BR}(\mu \to e\gamma)_{(d=4)} = 0$
Accidental Lepton family symm.

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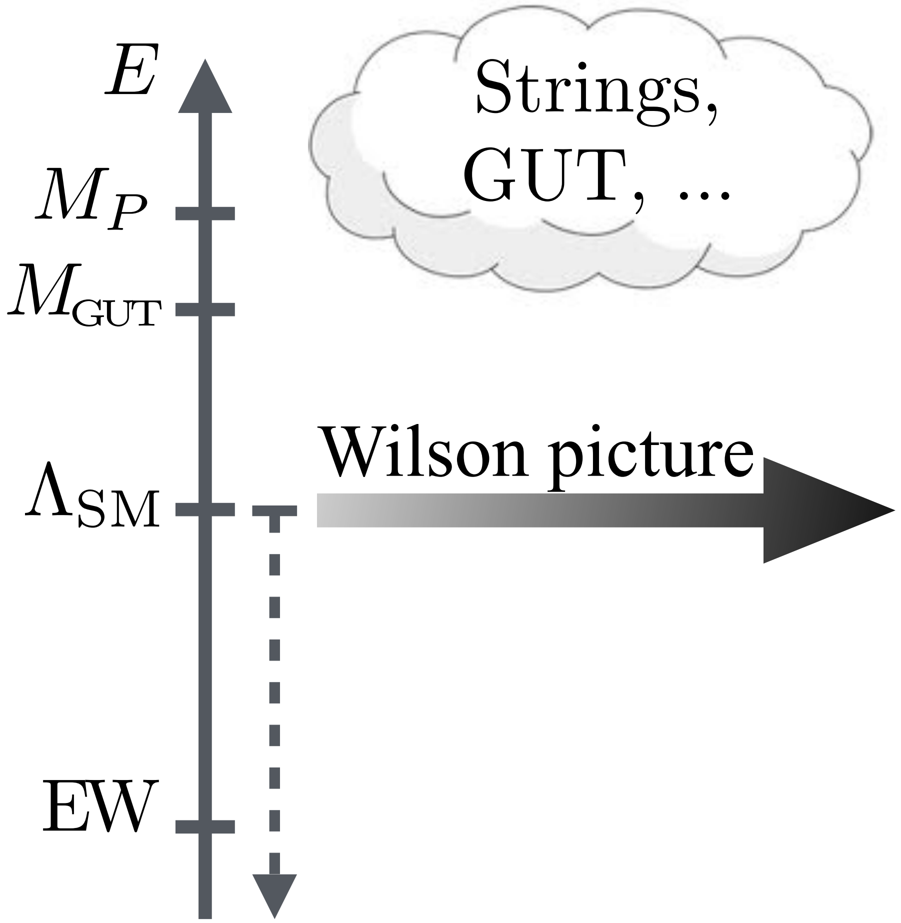

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$$\mathcal{L}^{(d=5)} = (\overline{L}_L H^c)(L_L^c H^c) \quad \longleftrightarrow \quad m_\nu \sim v^2/\Lambda_{\mathrm{SM}}$$

unique (Weinberg) operator — Majorana neutrino mass

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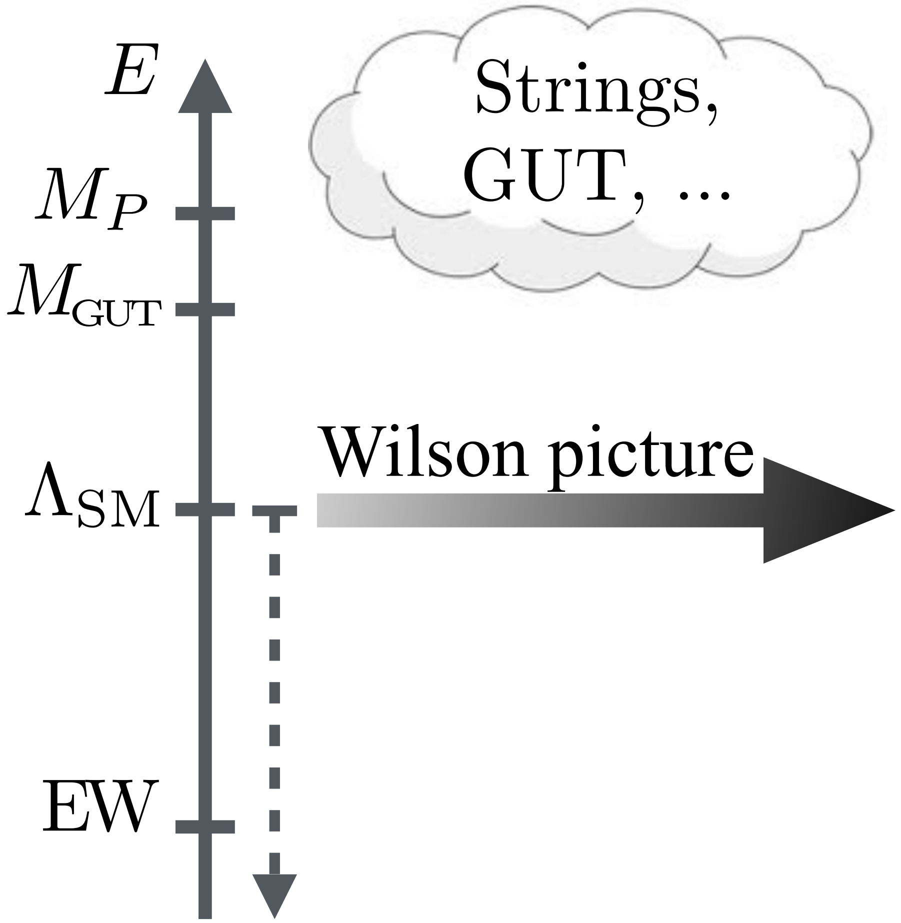

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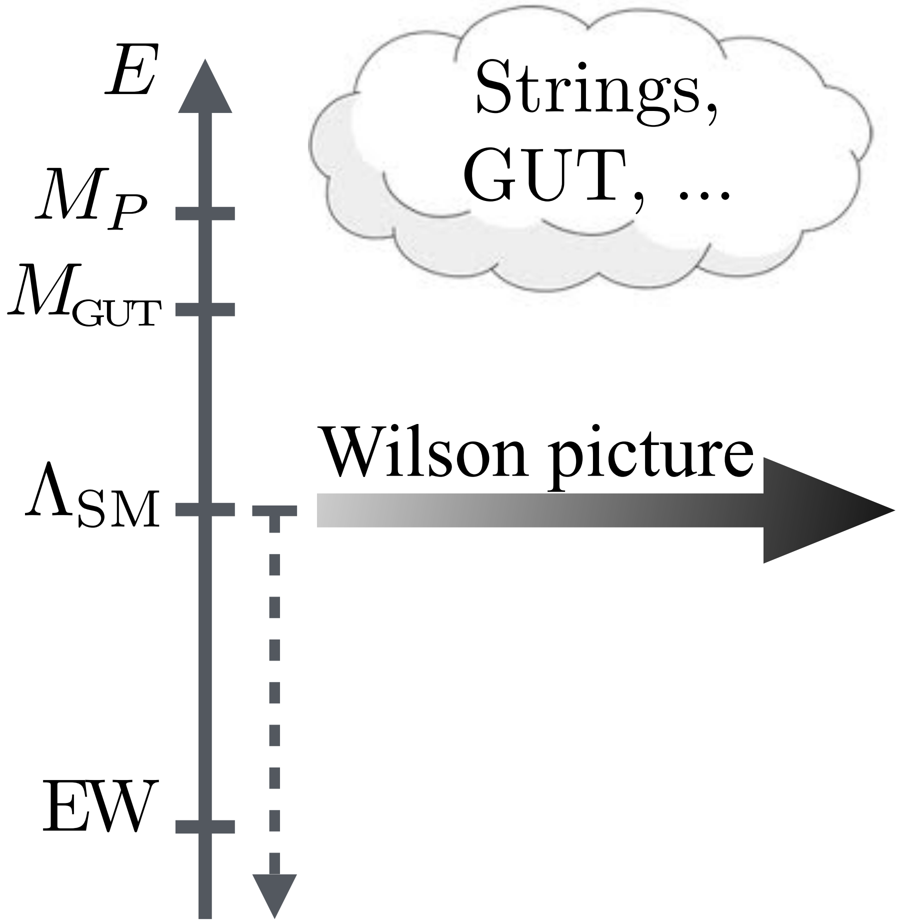

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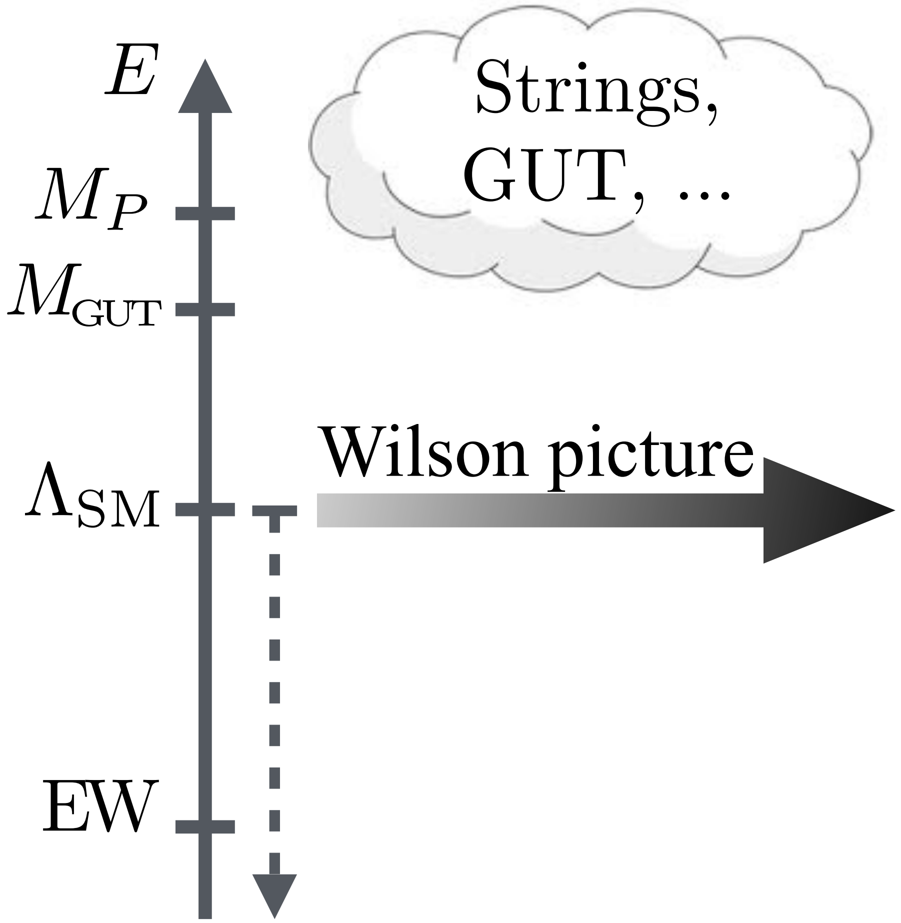

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If Wilson picture is right, $\Lambda_{\rm SM} \ggg$ TeV *explains* observations

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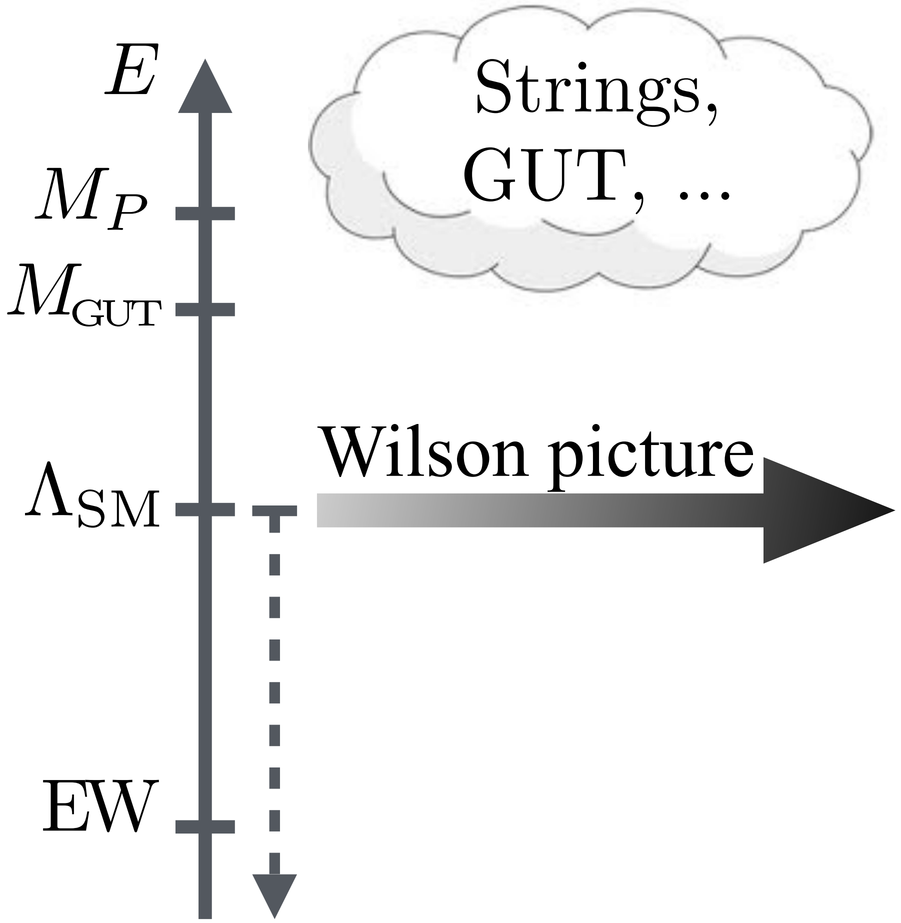

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Beyond dimensional analysis:

- Count powers of UV **coupling** g_*
  [the EFT from **generic UV** does not have all c’s ~1!]
- **Symmetries** of UV, and their breaking by **Spurions**
  [make UV less generic, but in controlled manner]

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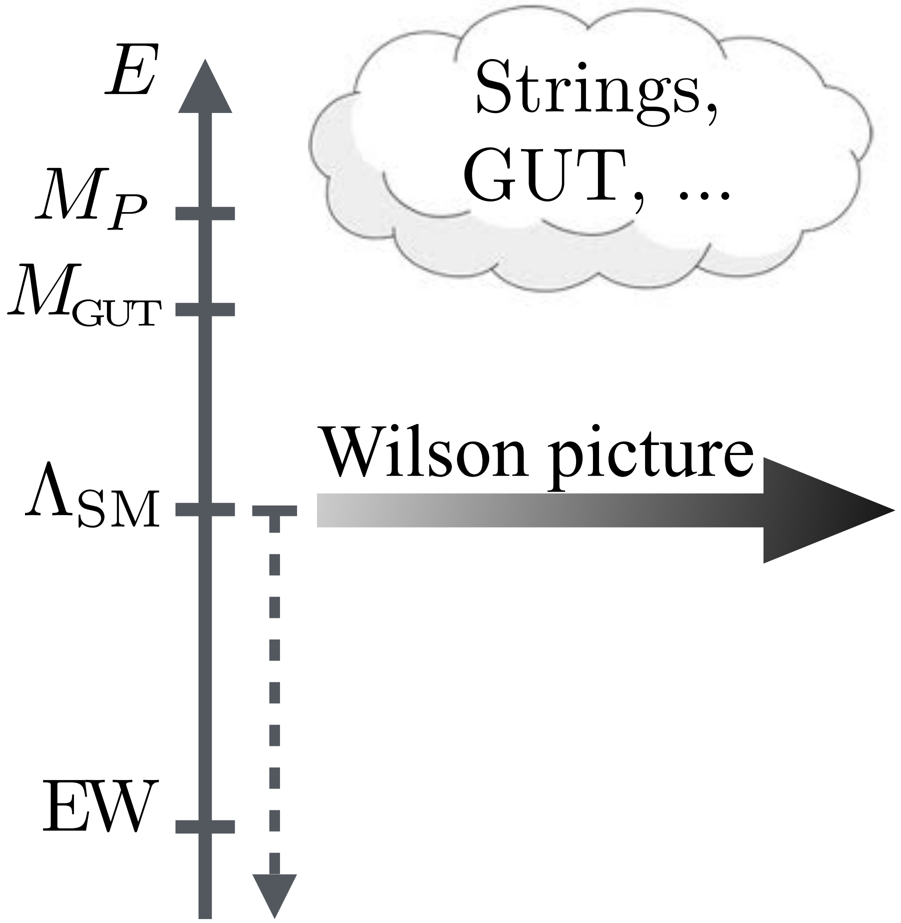

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Plenty of small SM parameters are "understood" in this way.

E.g., flavour pattern from UV symmetries/spurions at super-high Λ_{SM}

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Implications of the Wilsonian picture:

- Neutrinos are, obviously, Majorana particles
- Proton will decay, though is unclear when
- Flavour pattern explanation will emerge at high energy
- Dark Matter? Whatever, but Minimal DM sounds great
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$$\mathcal{L}_{H\text{-mass}} = \Lambda^2_{\rm SM}\mathcal{L}^{(d=2)} = \Lambda^2_{\rm SM} H^\dagger H$$

Instead: $$\mathcal{L}_{H\text{-mass}} = \frac{m_H^2}{2} H^\dagger H$$

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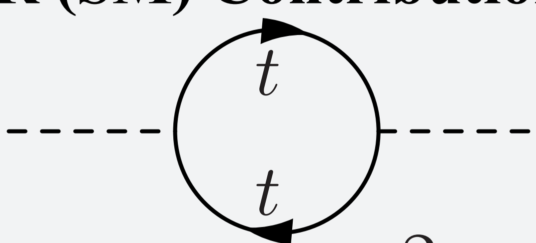
The **Naturalness Problem:**

Why $m_H \ll \Lambda_{\rm SM}$?

Naturalness Problem in practice

UV **explanation** of m_H (and Higgs) must enable to **predict** m_H.

IR (SM) Contribution



$$\delta_{\rm SM} m_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda_{\rm SM}^2$$

(NOT a quadratic divergence calculation!!)

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

$$= \int_0^{\lesssim \Lambda_{\rm SM}} dE(\ldots) + \int_{\lesssim \Lambda_{\rm SM}}^\infty dE(\ldots)$$

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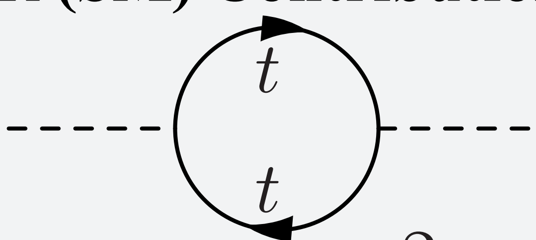

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UV (BSM) Contribution

$$\delta_{\rm BSM} m_H^2 = c\Lambda_{\rm SM}^2$$

Since the result must be $(125\ \text{GeV})^2$, the two terms are almost equal and opposite and cancel, by an amount

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\,\text{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,\text{GeV}}\right)^2$$

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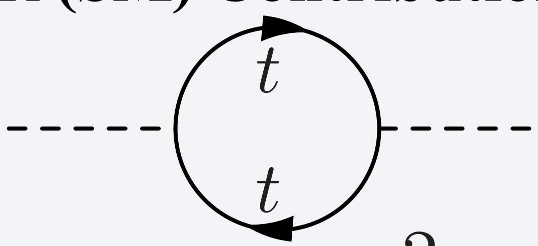

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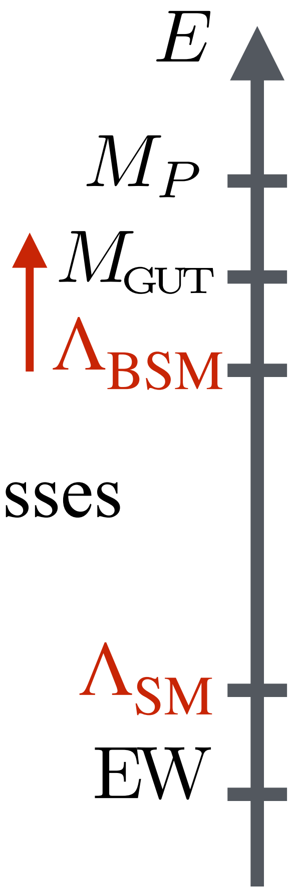
Fine-tuning: quantifies the “degree of Un-Naturalness”

Naturalness Problem implications

Three possibilities:

Option #1:

- Wilson paradigm is right.
- $\Lambda_{\text{SM}} \sim$ TeV.
- "Natural" BSM from Λ_{SM} to $\Lambda_{\text{BSM}} \ggg$ TeV.
  Duly engineered BSM to preserve Wilsonian SM successes



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Guidance for TeV and higher energy exploration:

- Useful BSM is Guidance, not "Motivation"!
- "Natural" BSM targets $\subset$ general direct or EFT exploration.
- Strengthen Un-Naturalness discovery by pushing fine-tuning bound up.
  Keep doing that until there is more energy/precision available.

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Option #2:

- Wilson paradigm is right.
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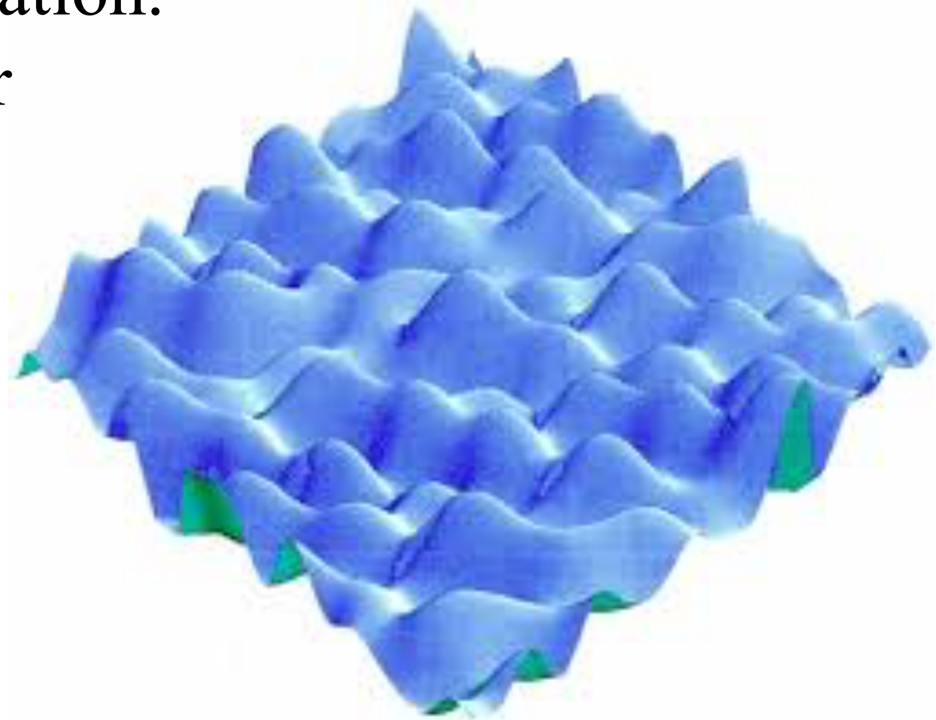

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Can this be the guidance to infer the underlying theory?

- Anthropic reason why we exist on Earth's surface rather than anywhere else in Galaxy is "clear", based on Chemistry/Biology/Astronomy.
- Still, we don't know how likely is that we exist (nor we know about aliens)
- Would have we learned Chemistry by studying this "fine-tuning" problem?
- Naturalness might **not be the "right" problem** by which we will advance

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Option #3:

- Wilson paradigm is wrong.
- Radically new principles or principles' implementation.
  Concrete ideas missing.
- Most groundbreaking and hence interesting option.

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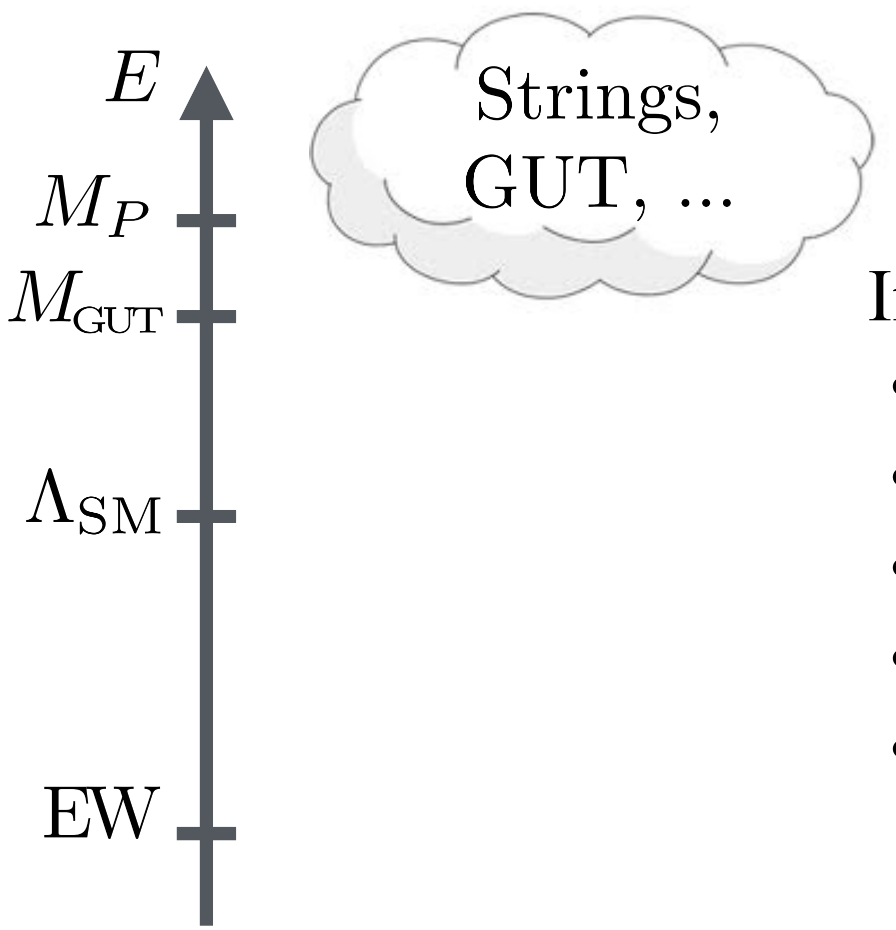
A non-possibility:

We don't understand m_H (and the c.c.), but all the rest "is fine".



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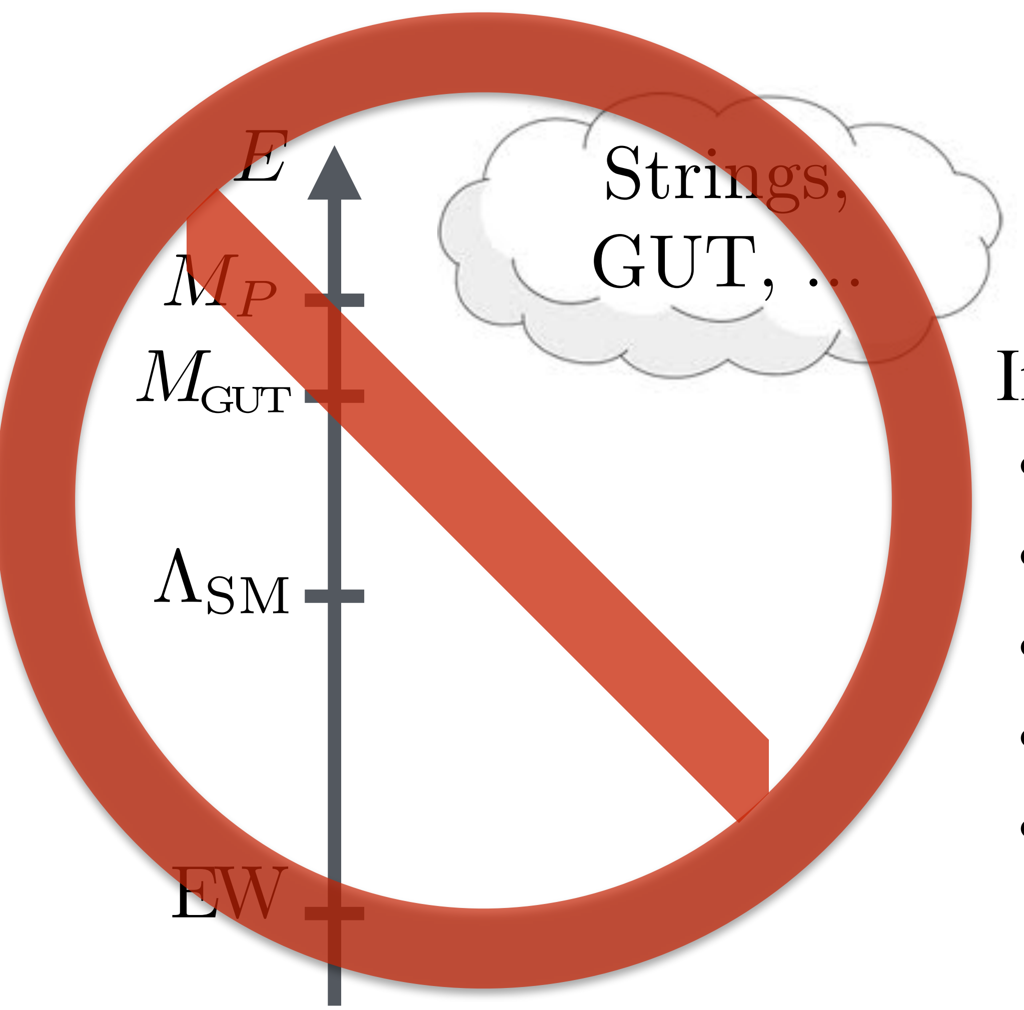
No! We cannot cherry-pick. If give up, give up everything!



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- Neutrinos are, obviously, Majorana particles
- Proton will decay, though is unclear when
- Flavour pattern explanation will emerge at high energy
- Dark Matter? Whatever, but Minimal DM sounds great
- No BSM particles at conceivably accessible energy

The Higgs physics case

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The Higgs is revolutionary!

One more direct experimental confirmation of the Practical QFT implementation of QM+SR principles (and indirectly of the principles).

The **first manifestation of** a new class of theories: **massive gauge theories**

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Higgs is not a superconductor
There is no Higgs "medium"

Spin-one relativistic particles and their high-energy description are as unique of hep as it sounds

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Testing new SM predictions is a prime target

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We must check!!

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Is it the Standard Model Higgs Particle?

- Single-Higgs couplings
- Trilinear Higgs coupling

What is it made of?

- Composite Higgs

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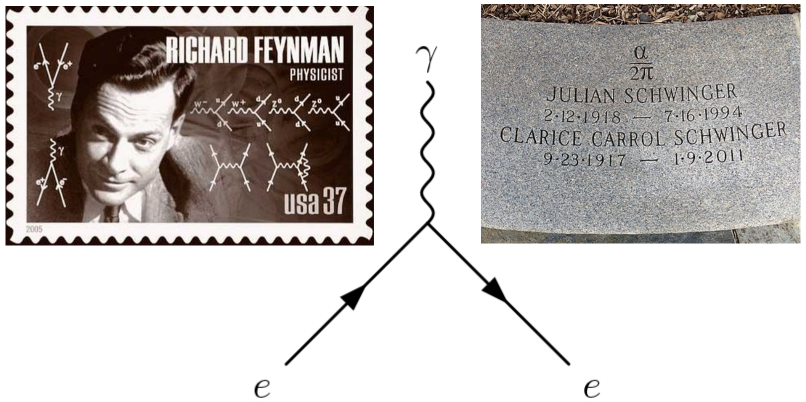
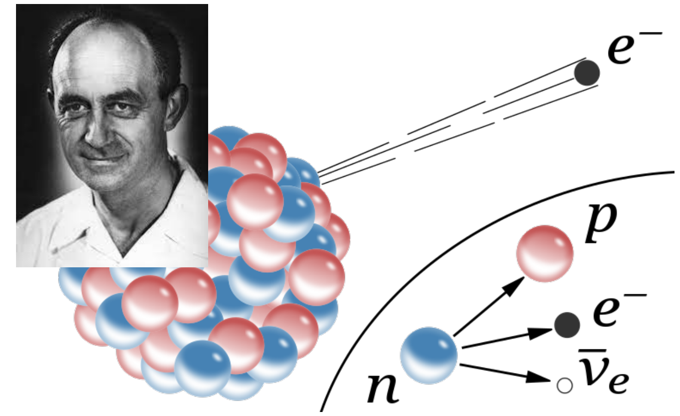
Is it the Standard Model Higgs Theory?

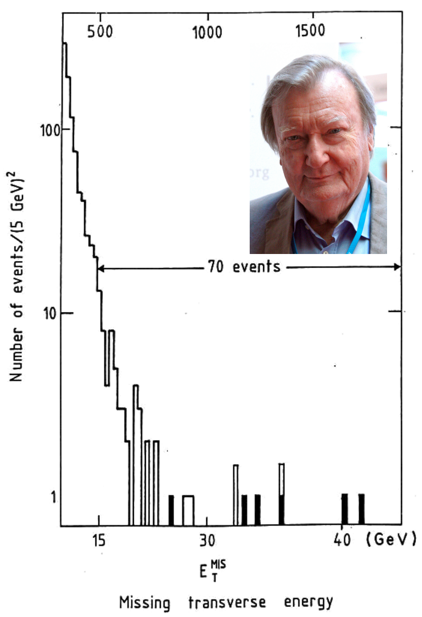
- High-energy EW (with Higgs) Physics

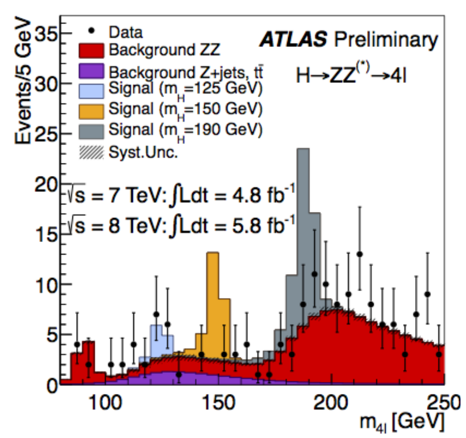
High-Energy EW+Higgs

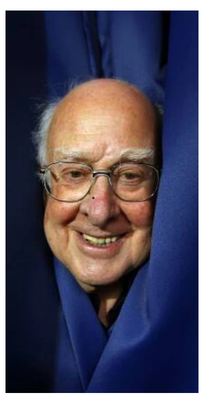


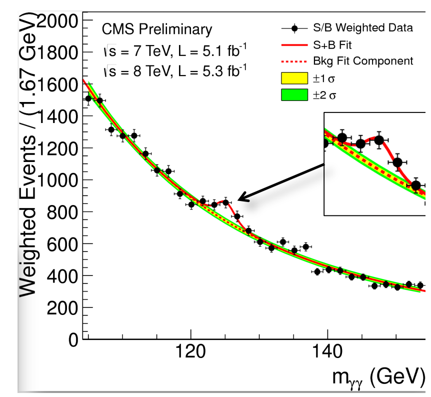


$E \ll m_W$









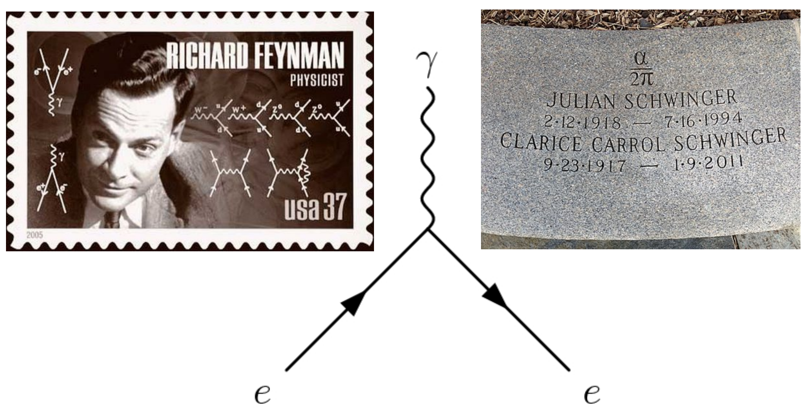
$E \gtrsim m_W$

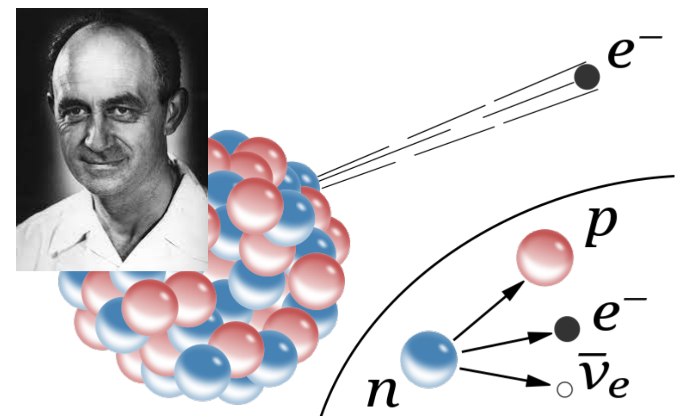
The Higgs particle shows up **here**

but theory needs it in order to go **there**

$E \gg m_W$

High-Energy EW+Higgs





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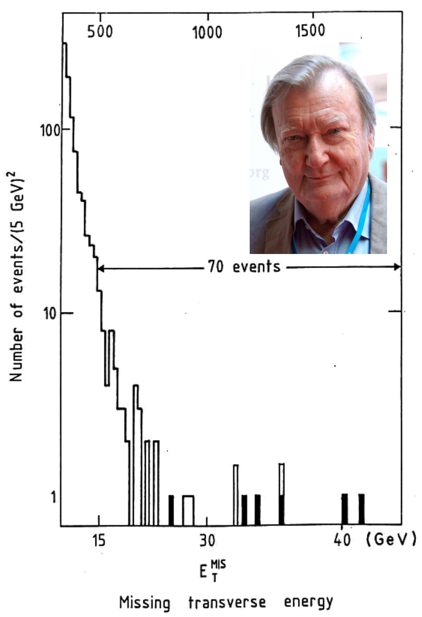
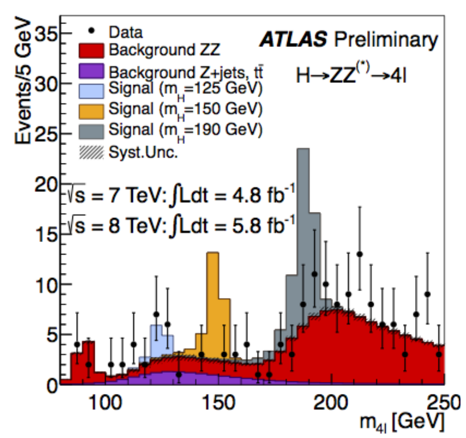
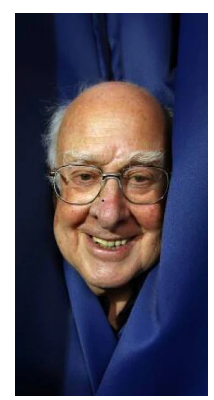
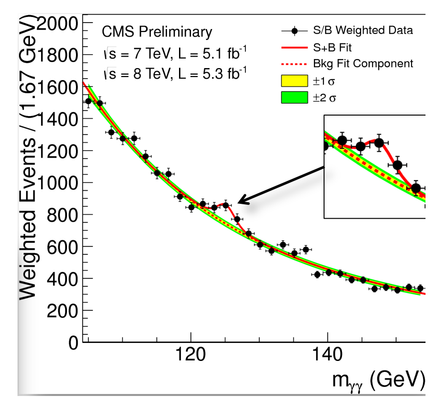








The Higgs particle shows up **here**

but theory needs it in order to go **there**

Most direct theory implications are at high En.

The role of the Higgs as part of the microscopic description of the EW force must be verified by **high energy** experiments

$E \gg m_W$

A **SM** physics case for future (muon!) colliders

The muon collider will **probe a new regime of EW (+H) force:**

$$\mathbf{E \gg m_W}$$

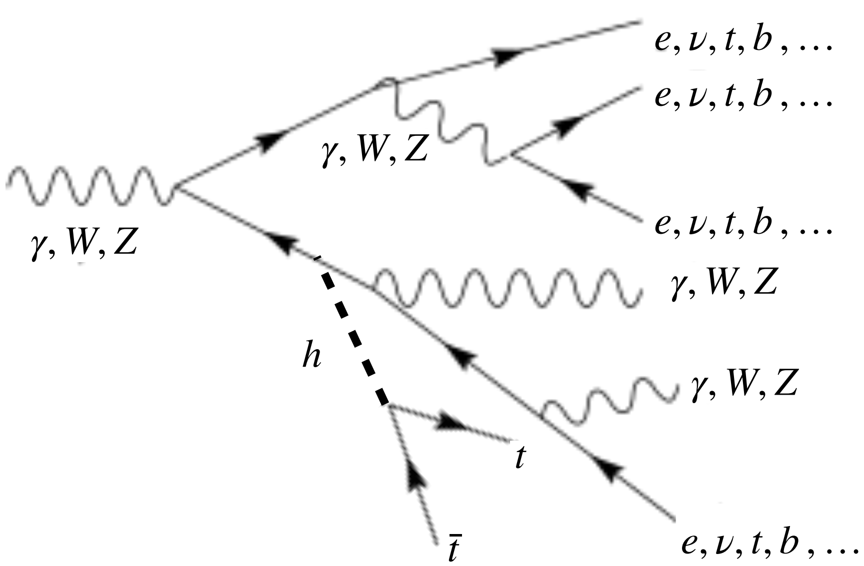
Plenty of cool things will happen:

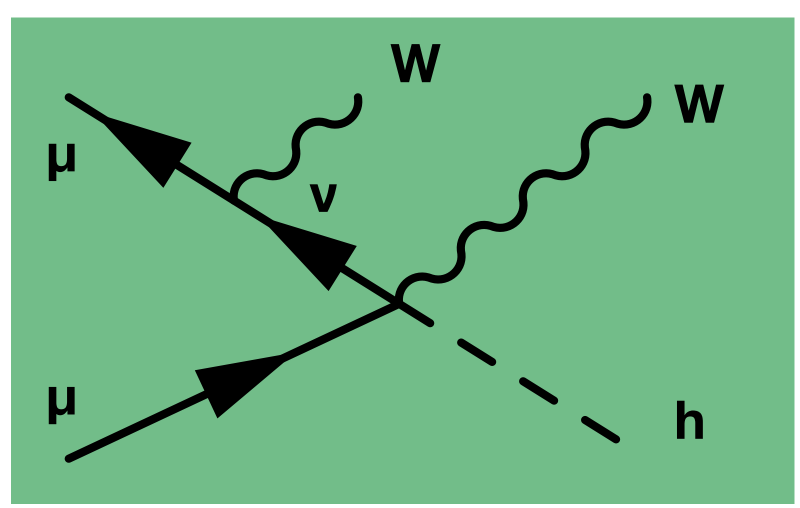
Electroweak Restoration. The $SU(2) \times U(1)$ group emerging, finally!

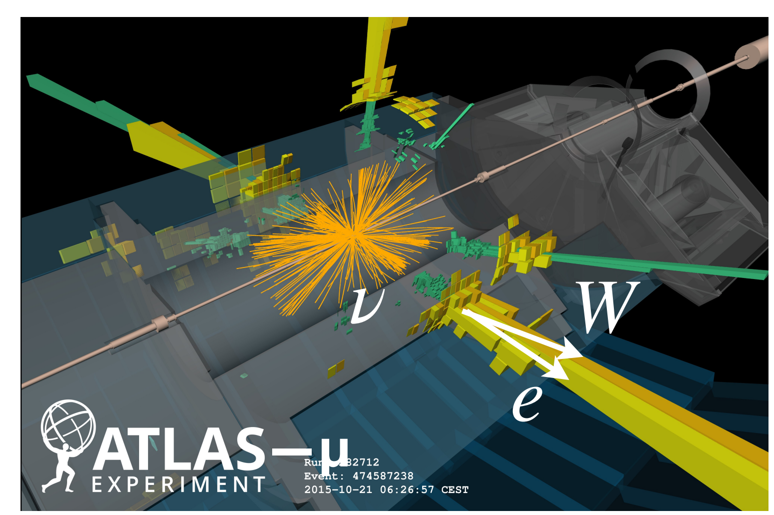
Electroweak Radiation in nearly massless broken gauge theory.
Never observed, never computed (and we don't know how!)

The **partonic content of the muon**: EW bosons, neutrinos, gluons, tops, …
Copious **scattering of 5 TeV neutrinos!**

The **particle content of partons:** e.g., find Higgs in tops, or in W's, etc
Neutrino jets will be observed, and many more cool things







Conclusions

Obviously we *care* about Naturalness

- The fundamental downside of the Wilson's "QFT=EFT" equation.
- **LHC disproved solutions, hence established the Problem!!**
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- Yes: useful organising principle for high-energy exploration.
- But, it might not be the right one.
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Higgs physics

- Too often reduced to a Naturalness search
- Instead, is the exploration of a new theory and a new regime of EW interactions
- Standard Model Higgs + EW physics is exciting!

Conclusions

Thank You !

Backup

Theory Challenges

EW theory is weakly coupled, but observables are not IR safe

$$E_{\text{cm}} \gg m_W$$

Large muon collider energy ← E_{cm} ; m_W → Small IR cutoff scale

Scale separation entails enhancement of Radiation effect.

Like QCD ($E \gg \Lambda_{\text{QCD}}$) and QED ($E \gg m_\gamma = 0$), **but:**

EW symmetry is broken:
- EW color is observable ($W \neq Z$).
- KLN Theorem non-applicable.
- (inclusive observables not safe)

→ **Practical need** of computing EW Radiation effects
- Enhanced by $\log^{(2)} E^2/m_{\text{EW}}^2$

EW theory is Weakly-Coupled
The IR cutoff is physical

→ **First-Principle** predictions **must** be possible
- For arbitrary multiplicity final state

Theory Challenges

EW theory is weakly coupled, but observables are not IR safe

$$E_{\rm cm} \gg m_W$$

Large muon collider energy

Small IR cutoff scale

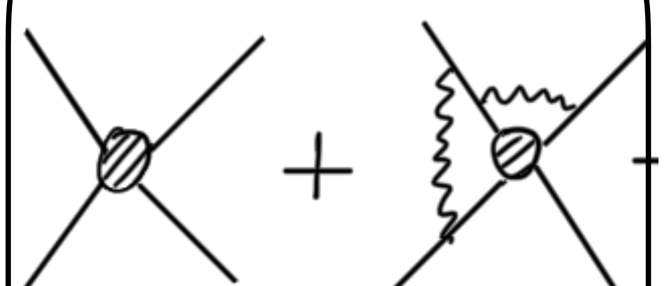
Scale separation entails enhancement of Radiation effect.

Quantitatively, resummation is needed.

10 TeV MuC

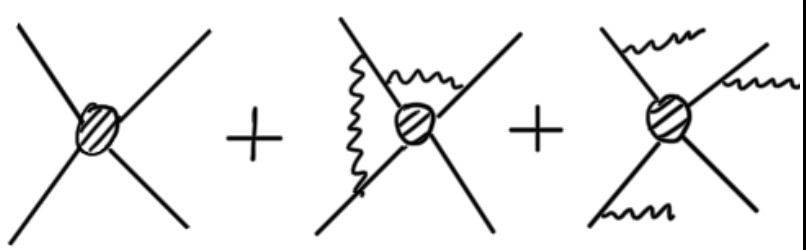
$$\exp\left[-g^2/16\pi^2 \log^2(E_{\rm cm}^2/m_{\rm w}^2)\times \text{Casimir}\right] \approx \exp[-1]$$

Exclusive X-S



Two hard bodies with **definite EW color**. Veto on EW bosons.

Semi-Inclusive X-S



Two hard bodies of **definite EW color**. EW bosons allowed.

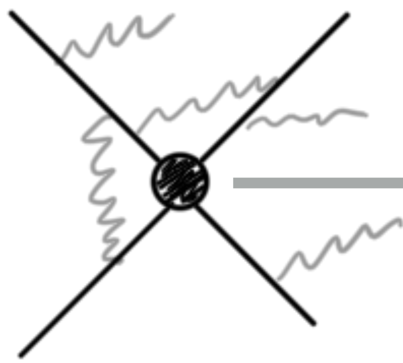
= charged

Process	N (Ex)	N (S-I)
e^+e^-	6794	9088
$e\nu_e$	—	2305
$\mu^+\mu^-$	206402	254388
$\mu\nu_\mu$	—	93010
$\tau^+\tau^-$	6794	9088
$\tau\nu_\tau$	—	2305
jj (Nt)	19205	25725
jj (Ch)	—	5653
$c\bar{c}$	9656	12775
cj	—	5653
$b\bar{b}$	4573	6273
$t\bar{t}$	9771	11891
bt	—	5713
Z_0h	680	858
$W_0^+W_0^-$	1200	1456
$W_{\rm T}^+W_{\rm T}^-$	2775	5027
$W^\pm h$	—	506
$W_0^\pm Z_0$	—	399
$W_{\rm T}^\pm Z_{\rm T}$	—	2345

Theory Challenges

Benchmark predictions we must learn how to make:

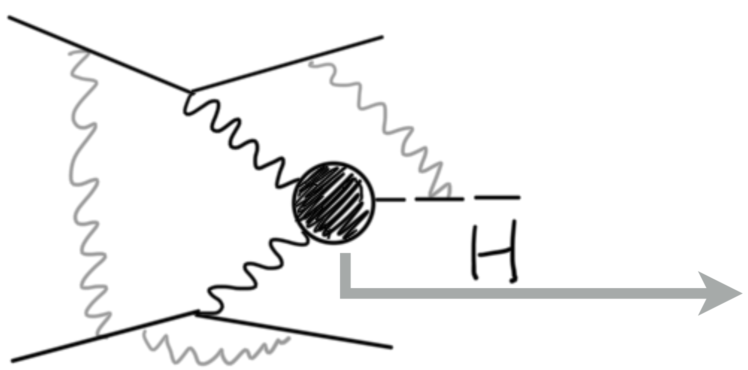
- Direct 2→2 annihilation:



$$\sqrt{\hat{s}} = E_{\rm cm} \gg m_{\rm w}$$

need X-S calculations and modelling of radiation (showering)

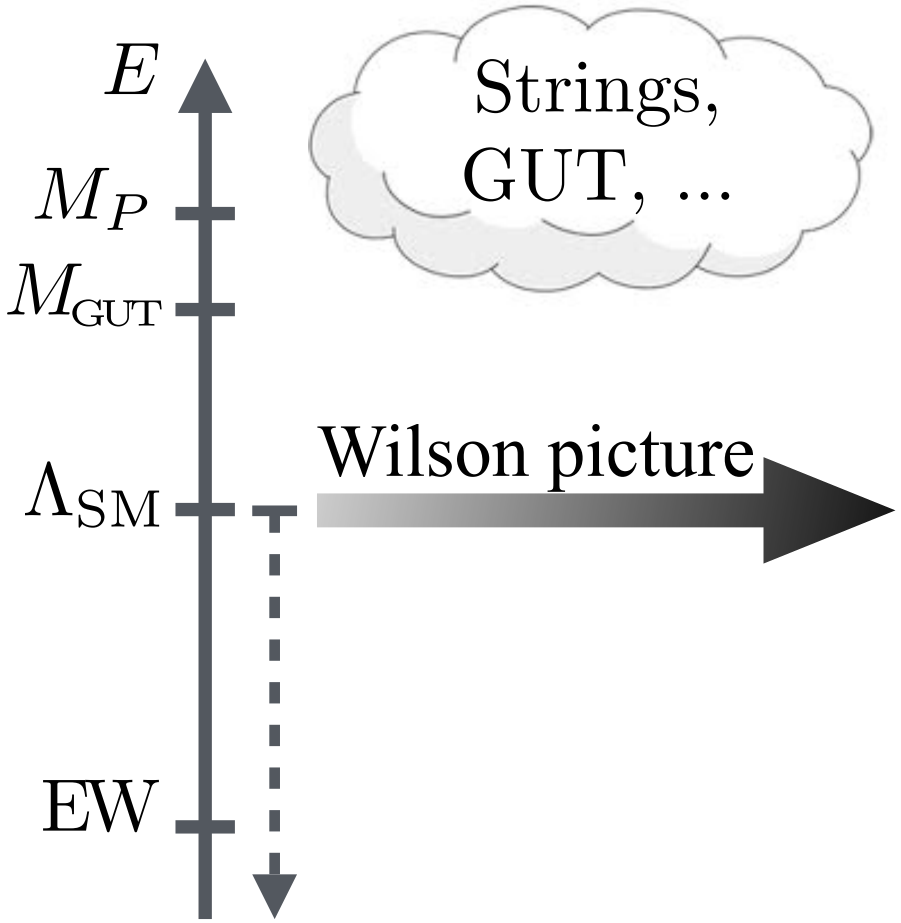
- EW-scale VBS: single Higgs production:



$$\sqrt{\hat{s}} = m_{\rm h} \simeq m_{\rm w}$$

same scale of radiation emission as of scattering

A tale from the 90's



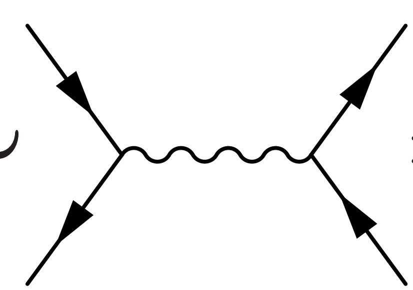
$\mathcal{L} =$ " sum of local operators made of SM fields and compatible with UV symmetries "

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\rm SM}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\rm SM}^2}\mathcal{L}^{(d=6)} + \ldots$$

dimensional analysis for coefficients

Beyond dimensional analysis:

- Count powers of UV **coupling** g_*
  [the EFT from **generic UV** does not have all c's ~1!]

Simplest (Fermi) EFT: $G_F \sim$  $= \dfrac{g_W^2}{4\sqrt{2}m_W^2}$