Why is the Higgs So Important?

Particle Physics

|| ?

Study of Building Blocks of Matter

Particle Physics

≠ [At least not merely]

Study of Building Blocks of Matter

Particle Physics

||

Study of Fundamental Laws of Nature,

governed by still-mysterious union of

Space-Time + Quantum Mechanics

New Physics ? New Particles

New Physics ≠ New Particles

New Physics = New Phenomena

New Physics = New Principles

17'th → 20'th Century Physics

March of REDUCTIONISM

March of SYMMETRIES

Whatever the Ultimate Theory

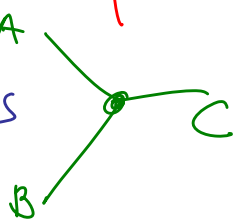
Relativity

Quantum Mechanics

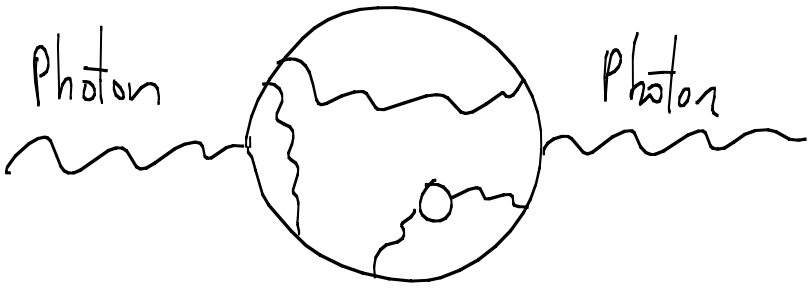
Symmetries

Reductionism

↳ Massless particles interacting as



with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. ← unique, "gravity"



Massless: 2 d.o.f
Massive 3 d.o.f

Power of QM + Spacetime symmetries.
Also why "photons", "chiral fermions" can+do emerge from condensed matter systems

The Higgs is the critical bridge between massive, low-E + massless high-E worlds.

[NOT SYMMETRY BREAKING, BUT SYMMETRY-ENHANCING!]

Belief in Principles Paid Off

$$0, \frac{1}{2}, 1, \frac{3}{2}, 2$$

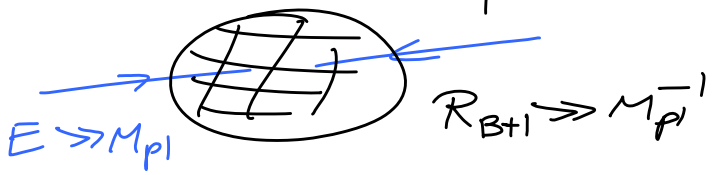
Higgs is first "really new" particle we've seen!

21st Century Revolutions

* Doom of Spacetime, end of Reductionism
* Why is the Universe Big?
* REALLY NEW IDEAS NEEDED, beyond paradigms of SPACETIME + INTERNAL SYMMETRIES.

UV/IR

* Because of Gravity,



Deep UV = Deep IR

Reductionism / Wilsonian Paradigm False

THE FUNDAMENTAL LAWS ARE NOTHING LIKE THOSE OF CONDENSED MATTER:

FAR DEEPER + MORE RADICAL

$$\left(\frac{E}{V}\right) = \int d^3k \; \frac{1}{2}\sqrt{k^2 + m_B^2} - \frac{1}{2}\sqrt{k^2 + m_F^2}$$

$m_B^2 \to g^2|h|^2$, $m_F^2 \to \lambda^2|h|^2$

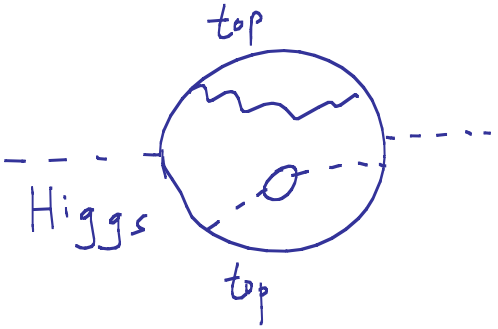
$$= \Lambda_{UV}^4 + (g^2 - \lambda^2)\Lambda_{UV}^2 |h|^2 + \cdots$$

Λ_{UV}^4 : Cosmological Constant Problem

Λ_{UV}^2 : Hierarchy Problem

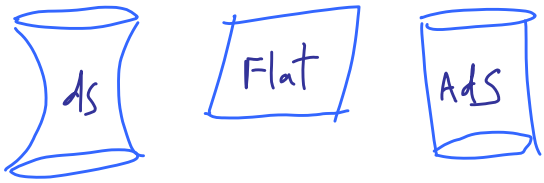
WHY IS THERE A MACROSCOPIC UNIVERSE?

Λ + Higgs ⟶ Beyond Symmetries



1 d.o.f whether $m_h^2 > 0, = 0, < 0$

NO DIFFERENCE



$\Lambda > 0$ $\Lambda = 0$ $\Lambda < 0$

No change in amount of symmetry [$SO(5,1) \to$ Poincaré $\to SU(4,2)$]

10 generators

Emergent Spacetime?

We are clearly missing something HUGE about Quantum Mechanics of our Relativistic Vacuum!

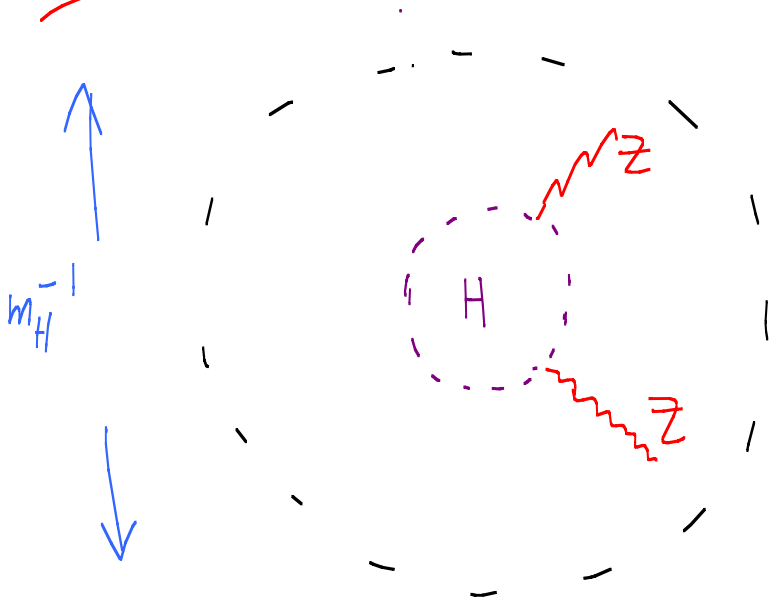
Macroscopic Universe?

The Higgs is the most important character in this Drama — since it can be put under the MOST INCISIVE + PRECISE EXPERIMENTAL SCRUTINY

Higgs is Really New Physics!

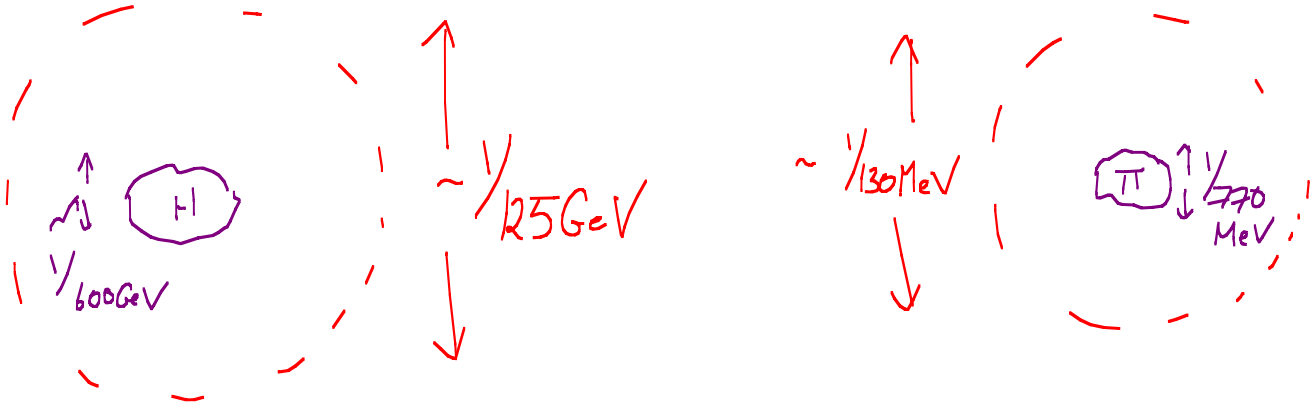
* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum
* MUST LOOK AT IT CLOSELY!

Never Seen Point-Like Scalar

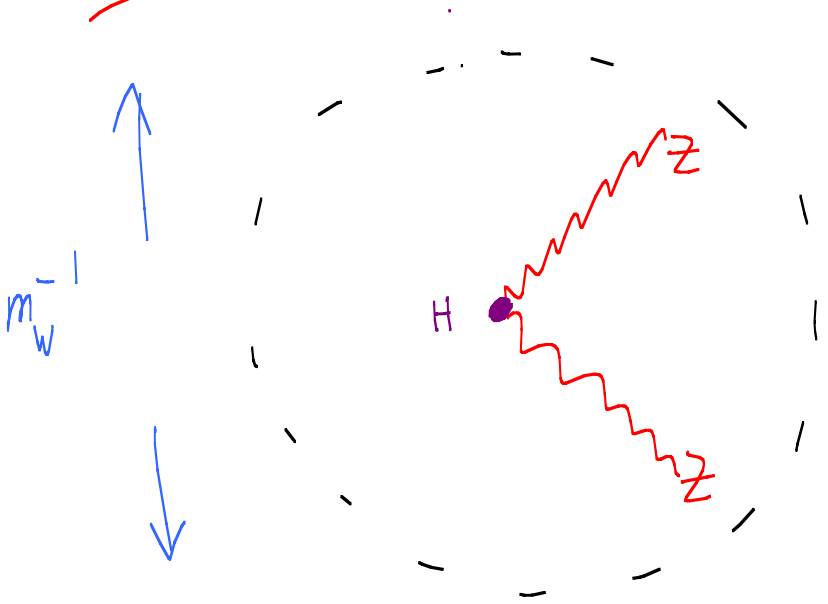


So, how pointlike is it?

But with LHC resolution, Higgs could be about as elementary as a "pion":



Never Seen Point-Like Scalar

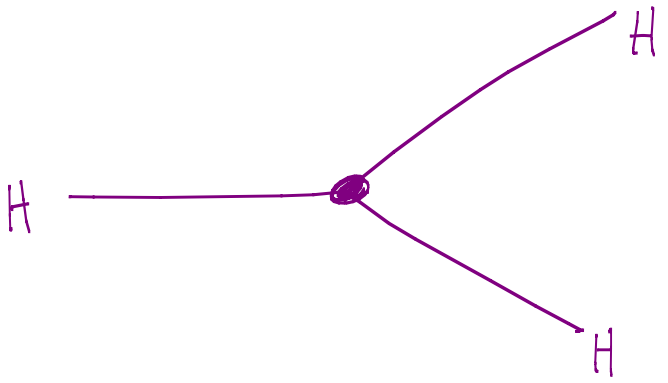


Higgs Factory

+

We will know FOR SURE if it is "a pion"

Never Seen Self-Interacting Fundamental Particles



100 TeV Collider

Measured to ~ 5-10% level!

Also, 100 TeV collider

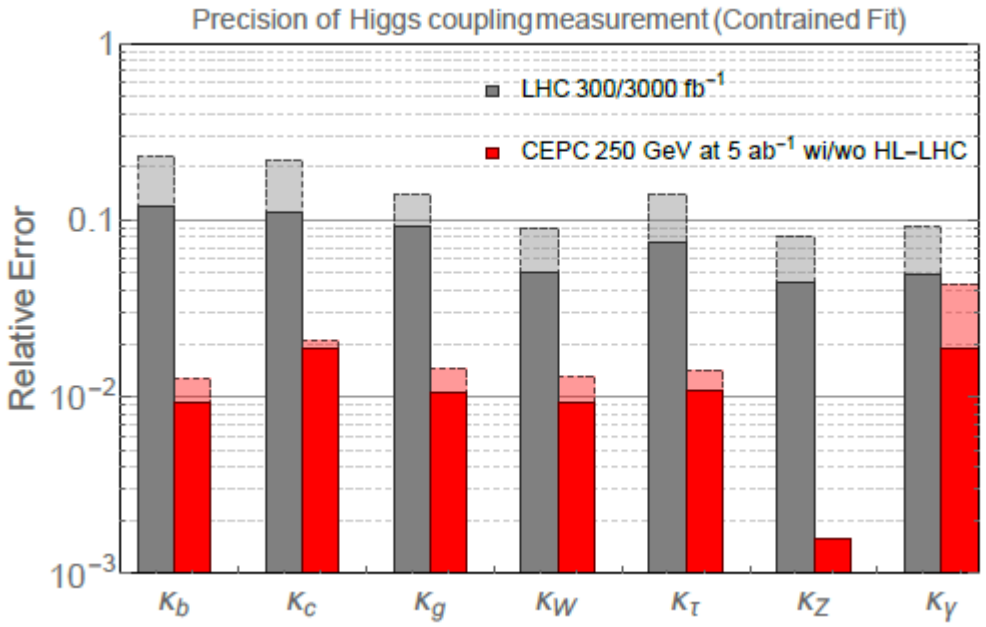
blasts into the high energy

frontier. New particles ~ 10 X LHC reach.

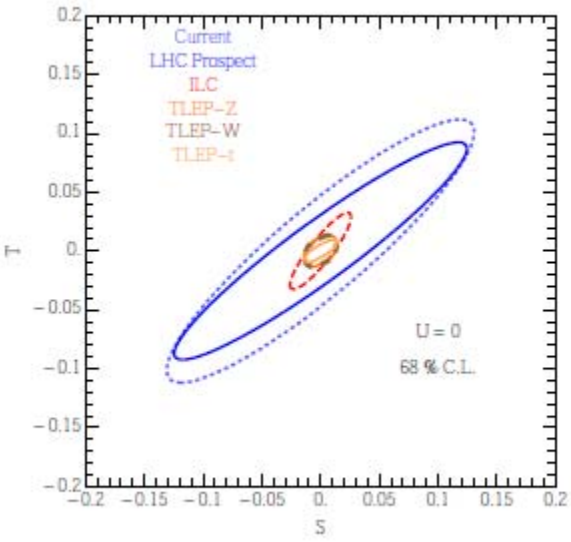
Probes vacuum quantum fluctuations

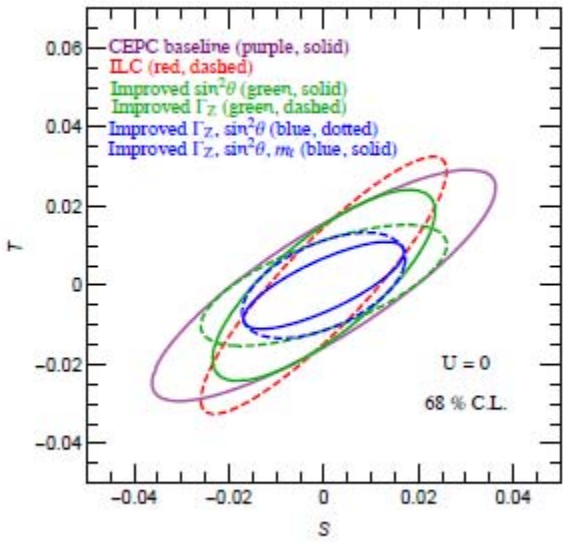
with power 100 X LHC

Higgs / Z factory Leap in Precision



Higgs / Z factory Leap in Precision





The Electroweak Transition

What is Shape of Potential?

$V(h) \longrightarrow m^2 h^\dagger h + \lambda (h^\dagger h)^2$ Landau-Ginzburg ...

NOT INNOCUOS!

$V(h) \xrightarrow{?} \lambda (h^\dagger h)^2 + \frac{1}{\Lambda^2}(h^\dagger h)^3$

$V(h) \xrightarrow{?} \lambda (h^\dagger h)^2 \log \frac{h^\dagger h}{\Lambda^2}$

} LHC won't tell us!

($O(1)$ Deviations in HHH coupling)

How is Electroweak Symmetry Restored?

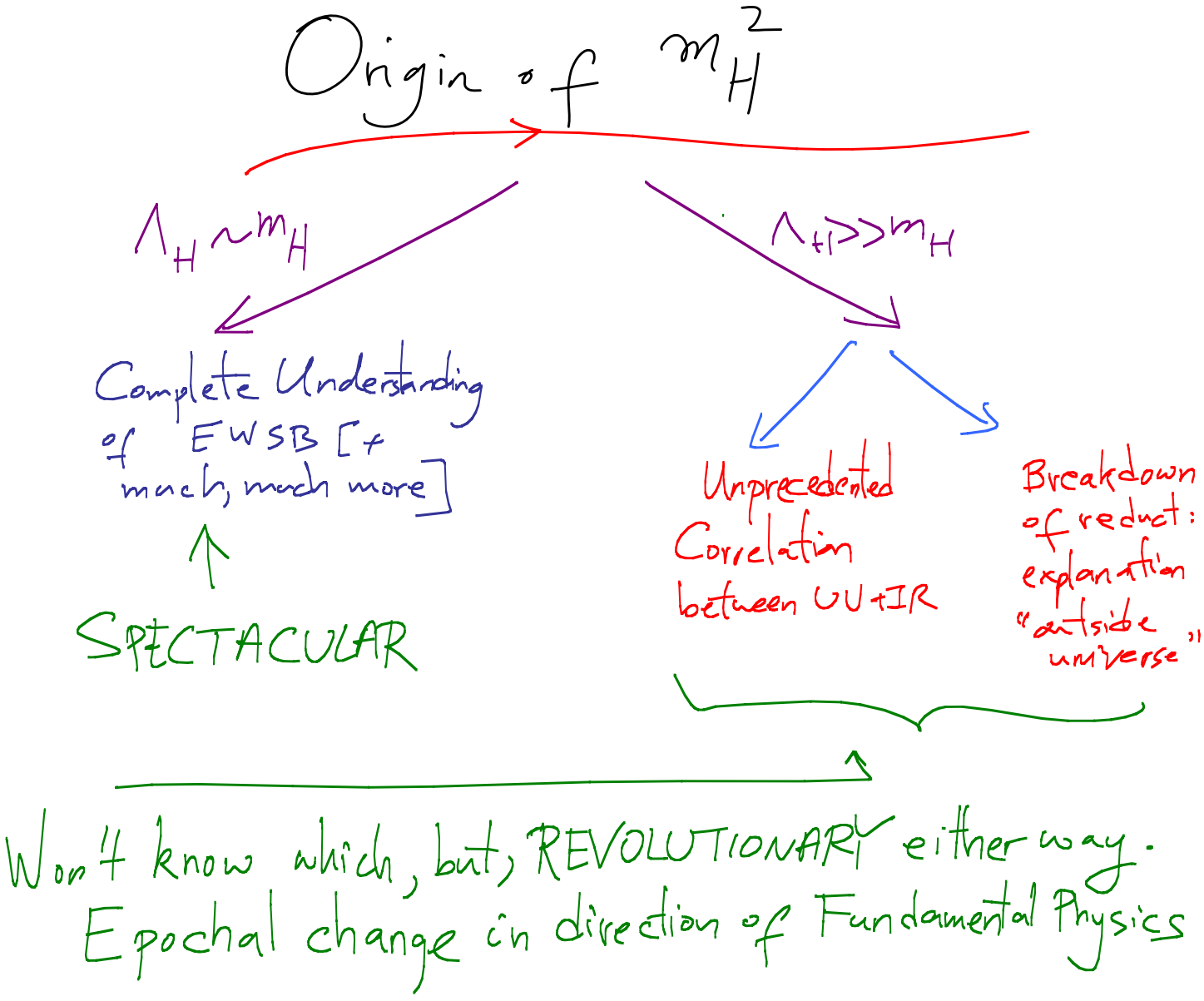
Was Transition 1st or 2nd Order?

LHC Won't Come Close to Settling This

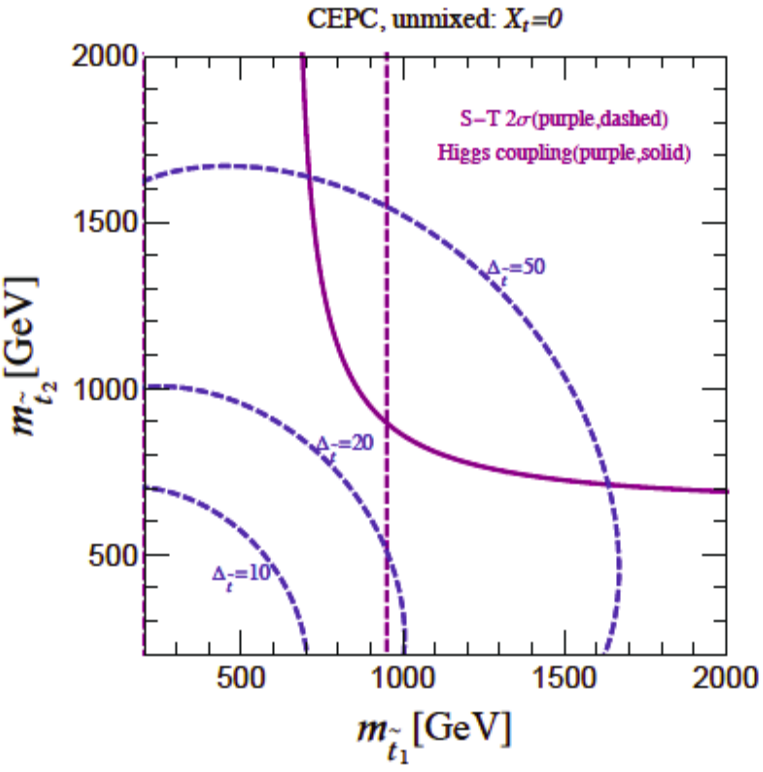
PERFECT TARGET FOR HIGGS FACTORY+

And Follow-Up With 100 TeV

{Expect $\delta Z_h \gtrsim \frac{\sqrt{\lambda}}{4\pi} \sim 5\%$!}

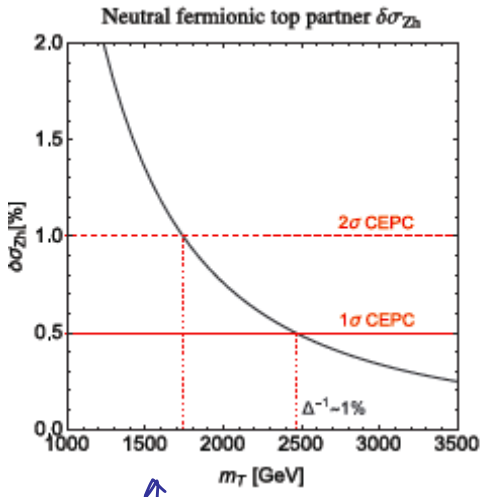

Origin of m_H^2
$\Lambda_H \sim m_H$
$\Lambda_{UV} >> m_H$
Complete Understanding of EWSB [+ much, much more]
SPECTACULAR
Unprecedented Correlation between UV + IR
Breakdown of reductionism: explanation "outside universe"
Won't know which, but, REVOLUTIONARY either way.
Epochal change in direction of Fundamental Physics

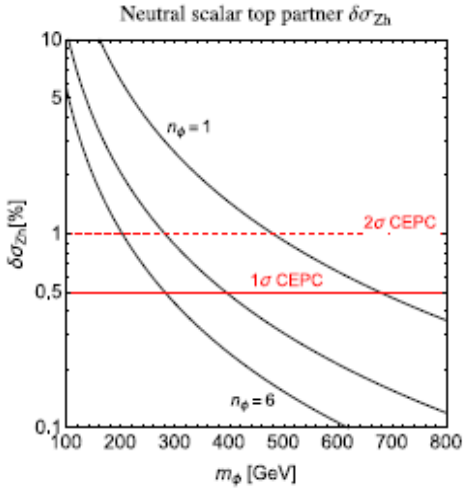
Stops have nowhere to Hide!



higgs/Z coupling shifts, Can't be hidden in hadronic muck

Naturalness "No-Lose" Thm





Expect $\delta Z_h \sim \frac{v^2}{f^2}$

"Higgs is not pion"

Some New Lines of Attack

(1) Cosmological Dynamics

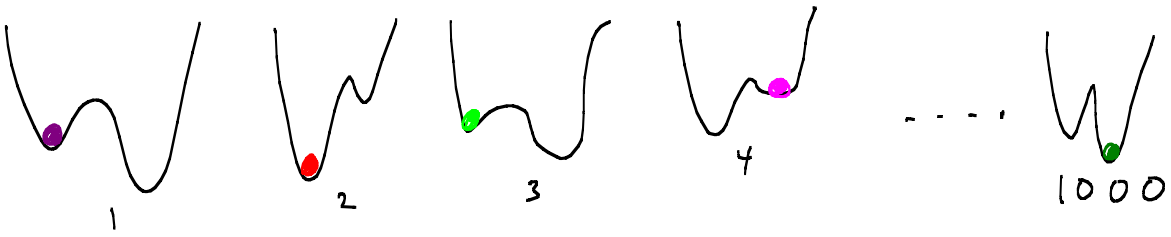
(2) Analyticity, Causality + the Higgs

(3) Hidden Symmetries in (B)SM ?

Landscape Dynamics

The landscape populated by eternal inflation

2^N vacua.... can in principle be seen by experiments in our universe



$\Rightarrow 2^{1000}$ different values of energy

Energy $\sim \left(\frac{1}{2}\right)^{1000}$ — just statistically!

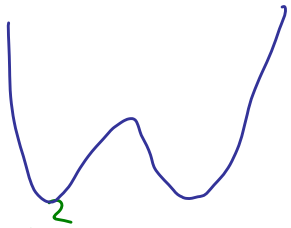
Landscape: $\sim 10^2 - 10^3$ SM singlet scalars!

* They could all be @ GUT/string scale....

* But some part might be pegged to higgs mass for good reasons. Singlets S_i dominant coupling is to higgs unfamiliar: $S_i H^\dagger H, S_i S_j H^\dagger H$.

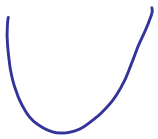
* Central "landscape" novelty: $\sim 10^2 - 10^3$ S's!

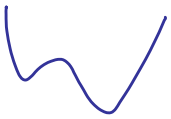
Motivation for light landscape: Correlating Hierarchy + CC



$\lambda_i\left(S_i^2 - \mu_i^2\right)^2 + a_i S_i h_u h_d$

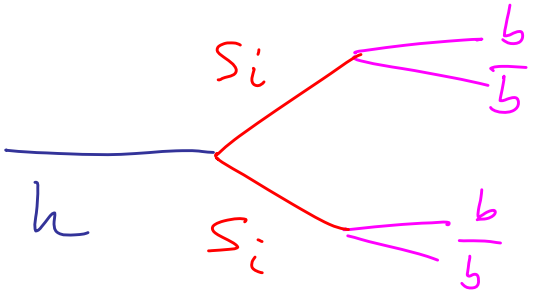
$m^2_{h_u,d} > 0$ NO scanning for CC

$|m^2_{h_u,d}| \gg \mu^2$  NO scanning for CC

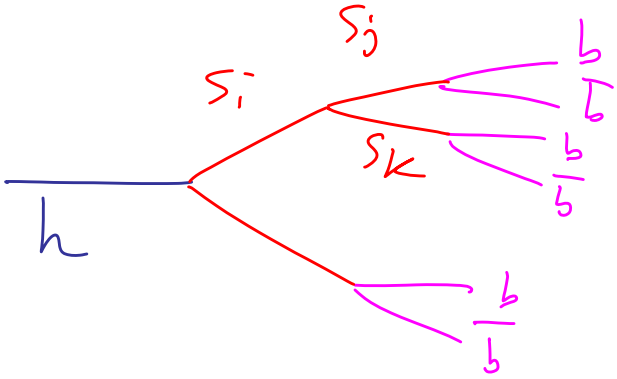
$m^2_{h_u,d} \sim \mu^2$  CAN scan for CC

MUST tune m_h^2 in order to be able to tune the Cosmological Constant!

Higgs Bomb Signal @ Higgs Factory



hundreds of $b\bar{b}$ resonances!



6 b events show $s_i s_j s_k$ interactions

$\Rightarrow$ ~ $\Rightarrow$ direct exp. proof of exponentially many vacua!

Analyticity, Causality + Higgs

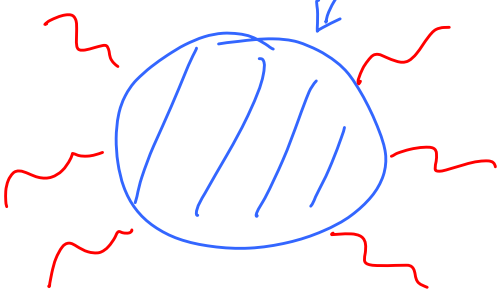
Foundations of Fund. Physics:

Lorentz Invariance } SHARP

Unitarity } SHARP

Causality

MORE MURKY....



how do we know this is "causal"?

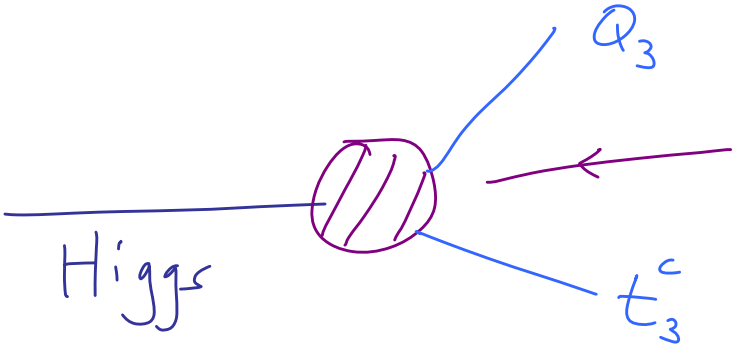
How is Causality encoded in S-matrix?

Q - from 1960's ... still don't know precise answer today!!

analyticity ... But, related to + can be checked experimentally!

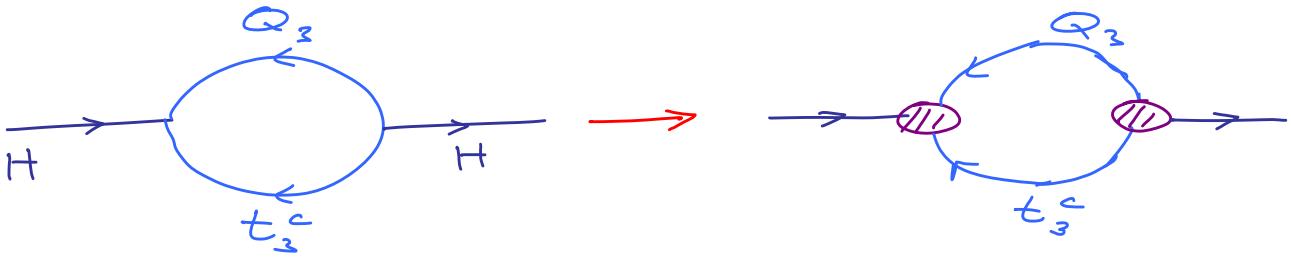
Important to Check these for the Higgs now! As w/ strong int. in 1960's

"Fat Higgs" for Hierarchy



shuts off when off-shell by ~ 400 GeV

* Not even close to probing this @ LHC! Need Higgs factory/100 TeV

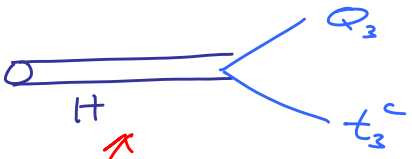


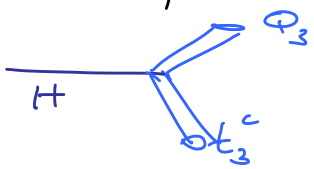
$$\frac{3}{8\pi^2}\int d^4p\ \frac{\lambda_t^2}{p^2} \longrightarrow \frac{3}{8\pi^2}\int d^4p\ \frac{\lambda_t^2}{p^2}\left(F(p^2/\Lambda^2)\right)^2$$

$$\Longrightarrow \Lambda \gtrsim 400\ \text{GeV}$$

Higgs, top individually "pointlike" but have mutually non-local couplings. [Violates S-matrix causality rules in all ex I've seen].

*Note: NOT standard compositeness of higgs or of tops (or both).



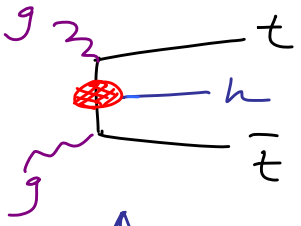


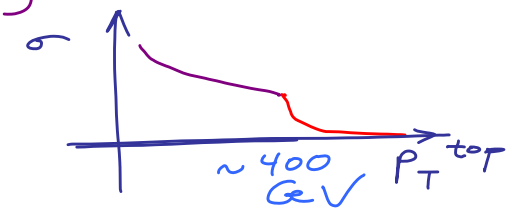
Already probing with Zh coupling @ CEPC

highly constrained by eg $Z \to b\bar{b}$

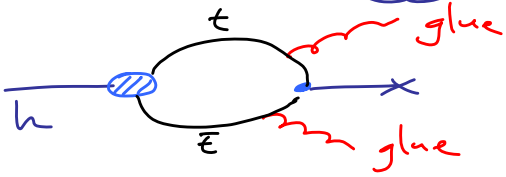
Experimentally: probe $t\bar{t}h$ vertex off-shell!

Direct: 100 TeV





Indirect: Higgs Factory



$$K_g \sim \left(\frac{m_t^2}{\Lambda^2}\right) \sim 10\%$$

$$K_\gamma \sim \text{few } \%$$

} Trivial @ Higgsfact.

↑ + Mutually non-analytic!!

Higgs probe of Foundations: Causal, Relativistic QM

Hidden Symmetries in (B)SM?

Witten '95: Maybe world SUSY, 3d $\not\Longrightarrow$ Bose-Fermi deg. (tiny, grav.)

strong coupling → Big Bose/Fermi Splitting, but grow 4th dim!

4D Picture ⟷ (Duality) ⟷ 3D Picture

4D Picture: Weakly Coupled, but $\Lambda = 0$ mysterious!

3D Picture: Strongly Coupled, but $\Lambda = 0$ obvious!

Prediction:

$E_{Casimir}[R] = 0$!

False for SM

Q: Is it possible to add particles/interactions, with any tunings you like, to make this happen?

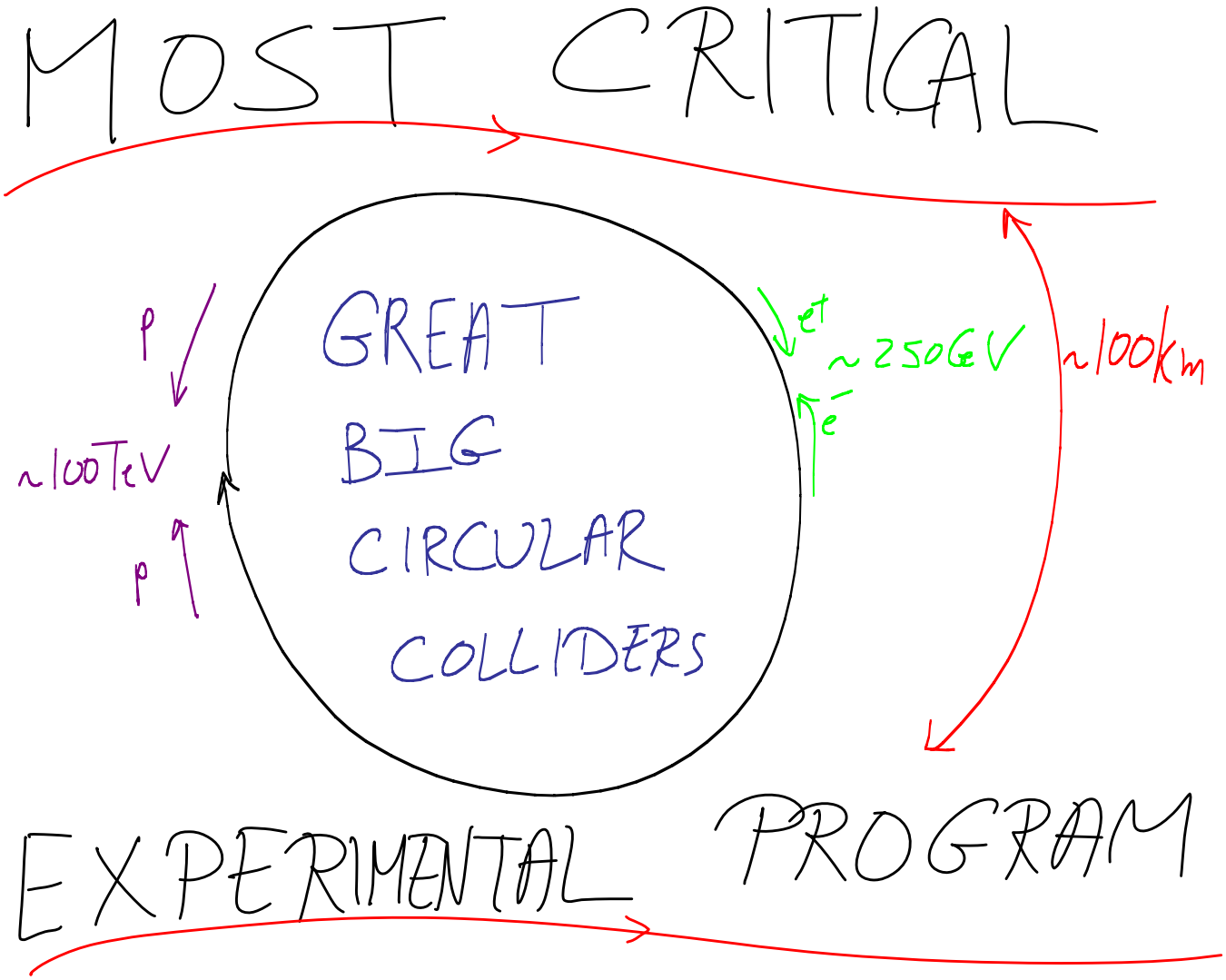
Either Impossible, Or Ridiculously Predictive!

→ Light hidden sectors w/ couplings related to SM ⇝ "Higgs Portal" signals

Outlook

In (not just) my view, the scientific issues we face today are the most difficult + profound ones our field has seen since the 1930's

The questions raised by the accelerating universe, and the higgs discovery, both go to the heart of our understanding of the nature of spacetime, quantum mechanics + the vacuum.


MOST CRITICAL
GREAT
BIG
CIRCULAR
COLLIDERS
p
~100TeV
p
e+
~250GeV
e-
~100km
EXPERIMENTAL PROGRAM