

Physics Motivation

for the

CEPC

We are at a dramatic juncture
in the development of Fundamental

Physics — a combination of spectacular
theoretical triumphs and extraordinary
un-answered theoretical challenges around

Spacetime, Quantum Mechanics, Vacuum

The Higgs Particle - utterly unlike
any elementary Particle we have seen
before - is the central character
in this drama

The program of the CERN represents

the most important experimental
pursuit for the future of Fundamental Physics

Particle Physics = Study of

Fundamental Laws of Nature
governed by still-mysterious union of

Quantum Mechanics + Spacetime

Fifteenth → twentieth Century Physics

March of REDUCTIONISM

March of SYMMETRIES

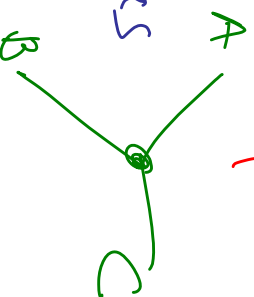
Whatever the Ultimate Theory Symmetries

Quantum Mechanics

Relativity

Reductionism

Massless particles interacting as



with spins

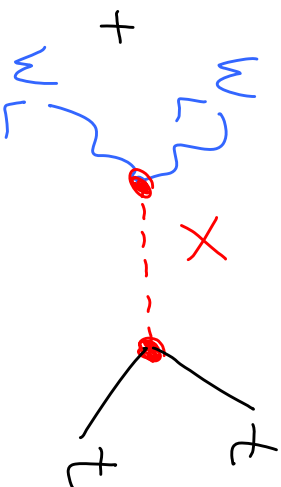
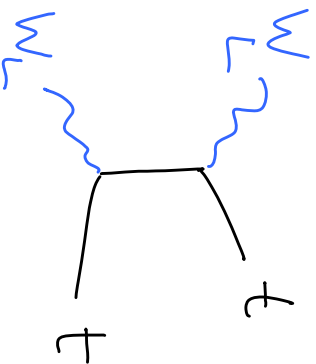
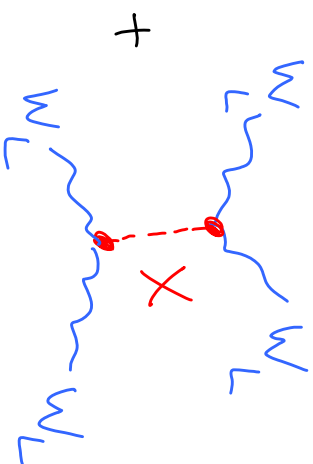
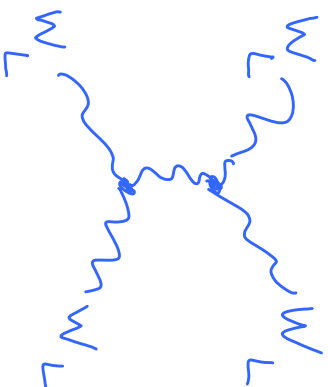
$0, \frac{1}{2}, 1, \frac{3}{2}, 2$

Yang-Mills

SUSY

unique, "granny"

Massive $\longleftrightarrow$ Massless

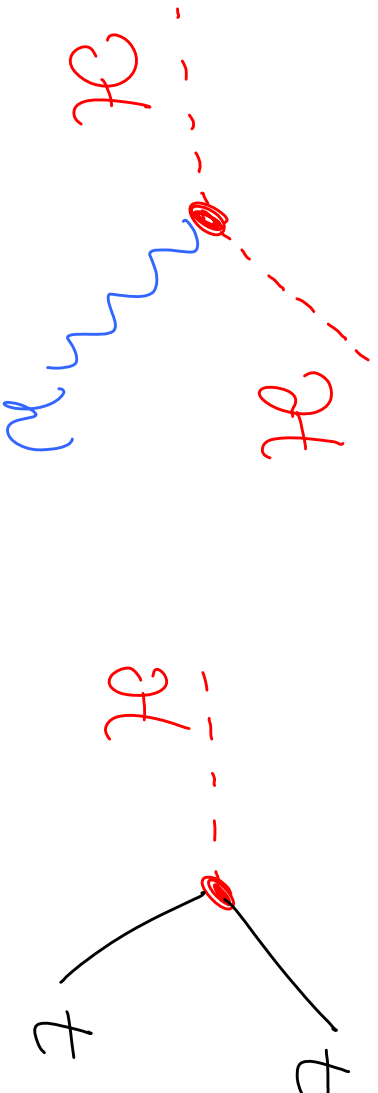


Spin of X :
 0 ~~1~~ ~~2~~ ~~3~~ ~~4~~ $\dots$

MUST BE
 SPIN 0

$X = Higgs$

At very high energies, H and N_L, Z_L are all unified into $\mathcal{H}$.



Prescribed Interactions for M/P articles

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

- * $\text{Doom of Spacetime, End of Reductionism}$
- * Why is the Universe Big?

REALLY NEW IDEAS NEEDED,
beyond paradigms of spacetime + internal symmetries

UV/IR



High Energies
 $\updownarrow$
Long Distances!

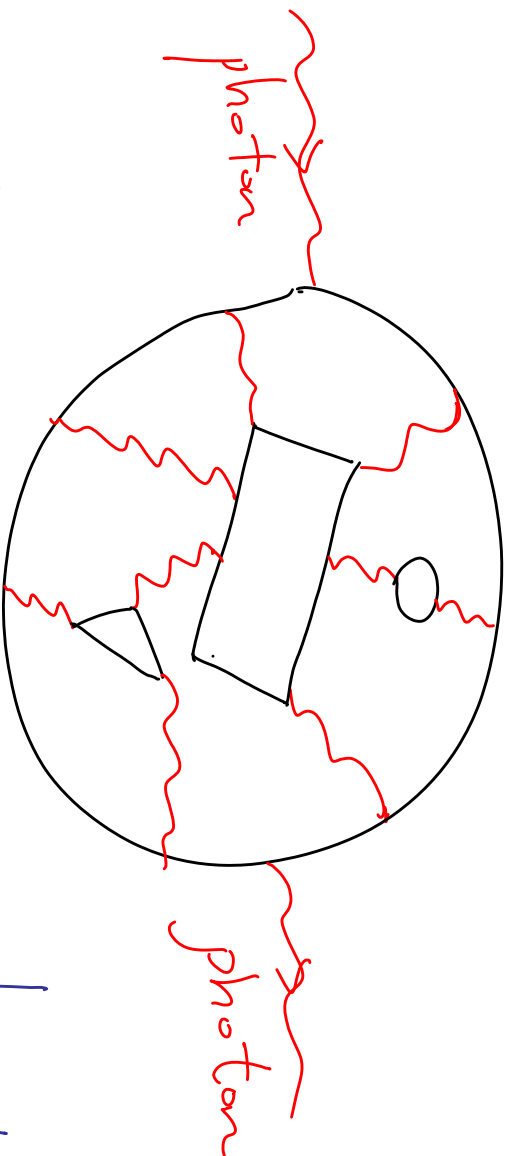
Reductionism + Wilsonian

EFT Paradigm is False

Fundamental Laws Nothing like that of
Condensed Matter Physics — FAR

DEEPER + MORE RADICAL

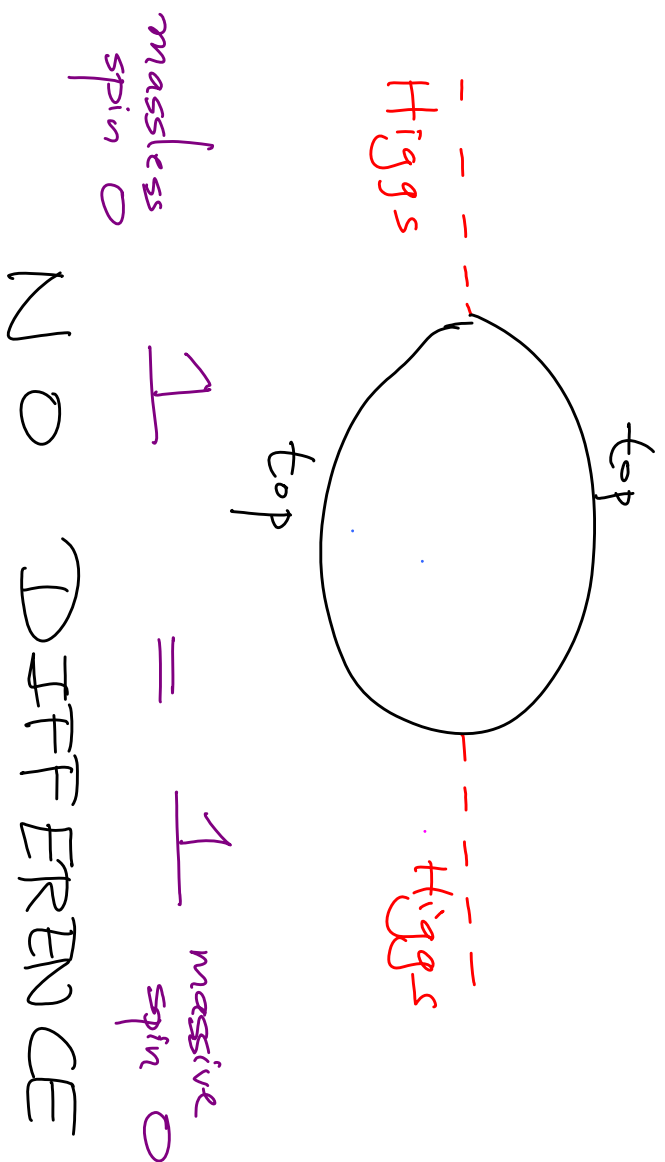
[But maybe only at Planck Scale]



Photon MUST stay massless, because

$$\begin{array}{ccc} \# \text{ massless} & & \# \text{ massive} \\ \text{helicities} & \xrightarrow{\quad} & \text{spins} \\ & 2 \neq 3 & \end{array}$$

[This is why gauge fields + chiral fermions
can be easily engineered in Cond. Matter!]

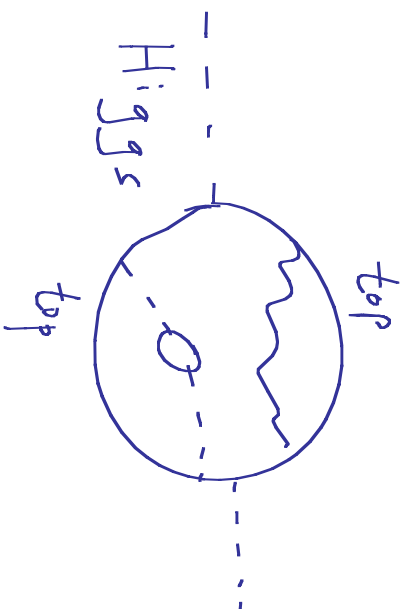


WHY
ISN'T
HIGGS
ENORMOUSLY
MASSIVE?
PLAUSIBLY

Higgs is Special! Does NOT naturally arise in Cond. Matter!

* Issue has concrete teeth in every theory that even attempts to predict that $m_h^2 < 0$!

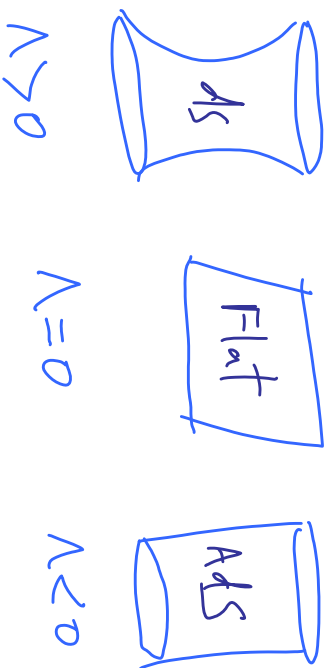
$\Lambda + \text{Higgs} \longrightarrow \text{Beyond Symmetries}$



1 dof whether $m_h^2 > 0, = 0, < 0$

No DIFFERENCE

Hierarchy Problem



Same amount of symmetry
 $[SO(5,1) \rightarrow \text{Poincaré} \rightarrow SO(4,2)]$

Cosmological Constant Problem

Emergent Spacetime?

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

Macroscopic Universe?

Higgs Discovery Cms

Our Relativistic Vacuum is ~~not~~ ^{extremely}

Different than anything we've seen elsewhere in physics

NOT JUST @ Planck Scale
ALREADY @ TeV scale

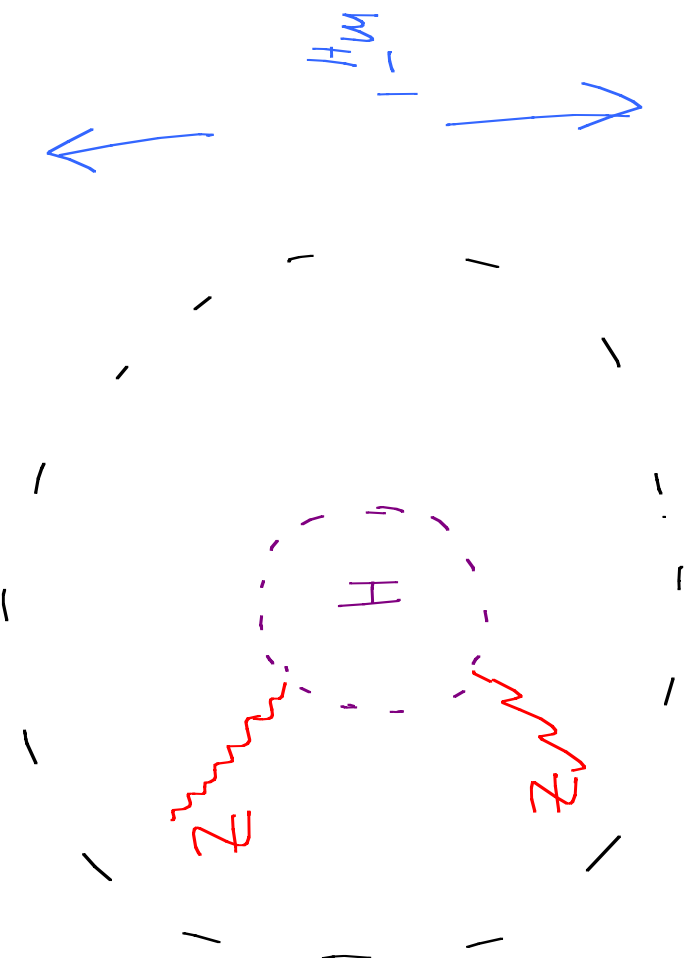
~~Higgs is Really New Physics!~~

* We've never seen anything like it

* Starbinger of Profound New Principles
at work in quantum vacuum

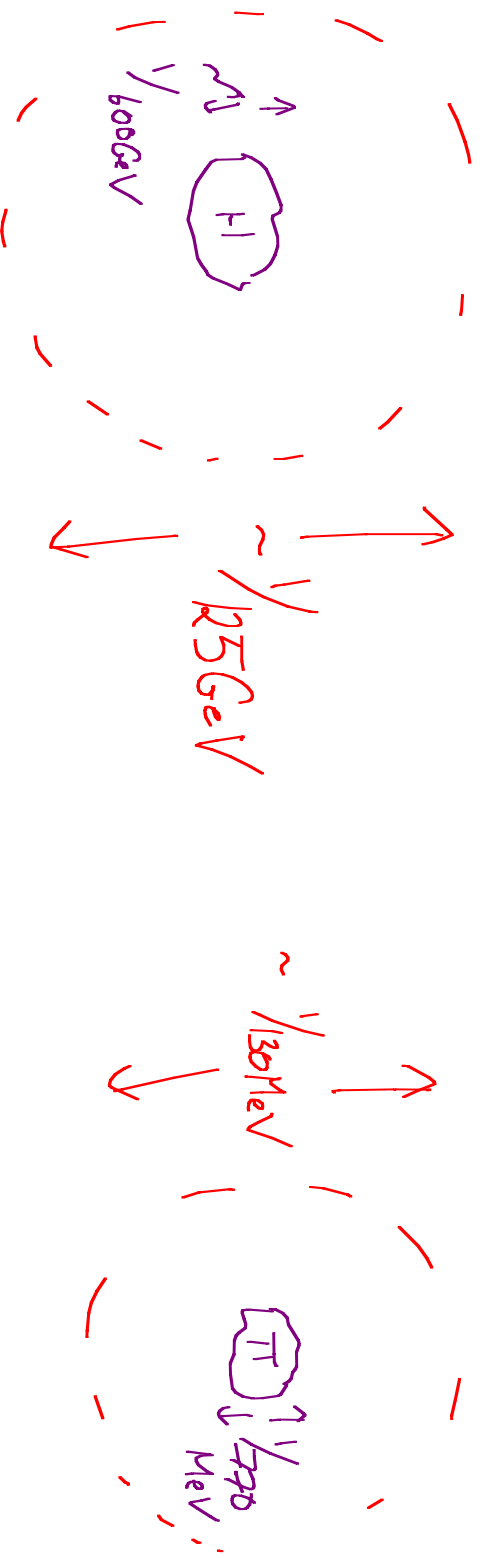
* MUST Look AT IT Closely!

Never Seen Pif-Like Scalar

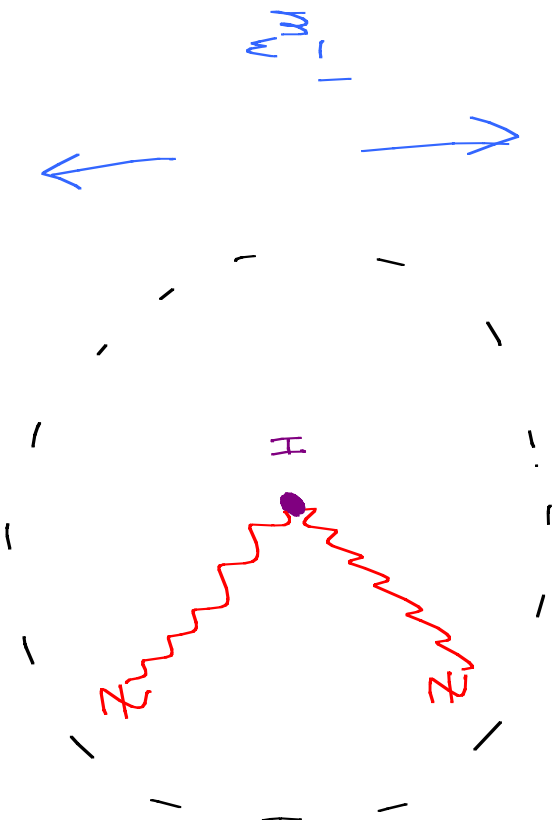


So, how
pointlike is
it?

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



Never Seen Pin-Like Scalar



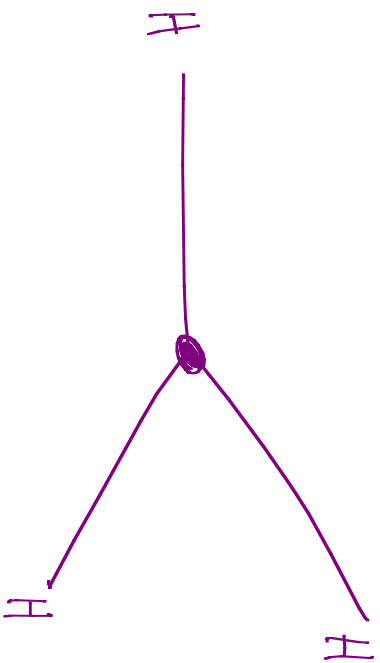
Higgs Factory
+

We will know

FOR SURE

if it's like a Pin

~~Never Seen Self-Injecting Undamped or Fides~~

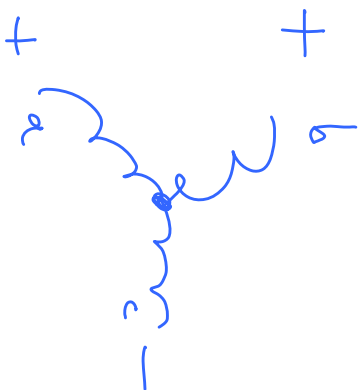


100 TeV Collider

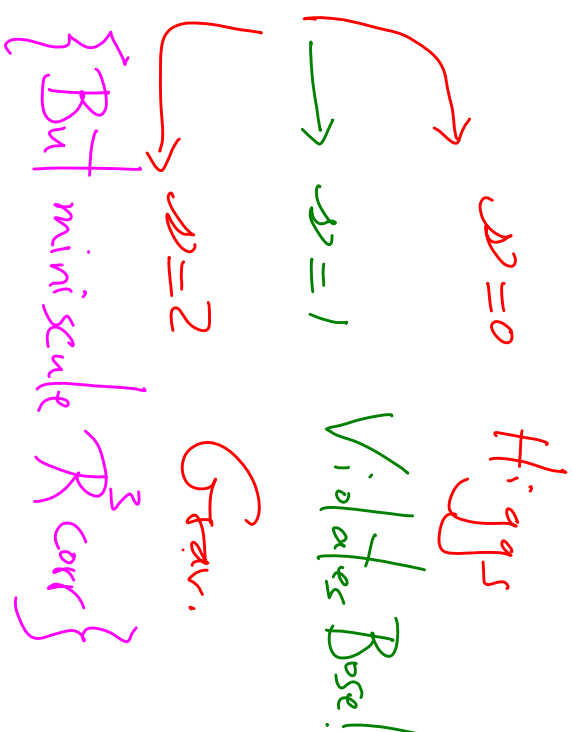
Measured to $\sim 5\%$

Higgs + Gravity: Unique in Self-Interaction!

YM, GR : charges helicity 1 + Color



$[\langle 12 \rangle \langle 23 \rangle \langle 31 \rangle]$



Also, 100 TeV collider

blasts into the high energy

frontier. New particles $\sim 10 \times \text{LHC reach}$.

Probes vacuum quantum fluctuations

with power $100 \times \text{LHC}$

The Challenge for **EXPERIMENT**
is totally clear. Meanwhile for

THEORY, the mystery of the
origin of $\sqrt{+m_h^2}$ — why is there a
macroscopic universe? — continues to pose
(an even more) radical challenge

* Crucial to Probe on-shell (Lorentzian)

+ off-shell (Euclidean) couplings of the

figgs.

Wilsonian paradigm is fundamentally

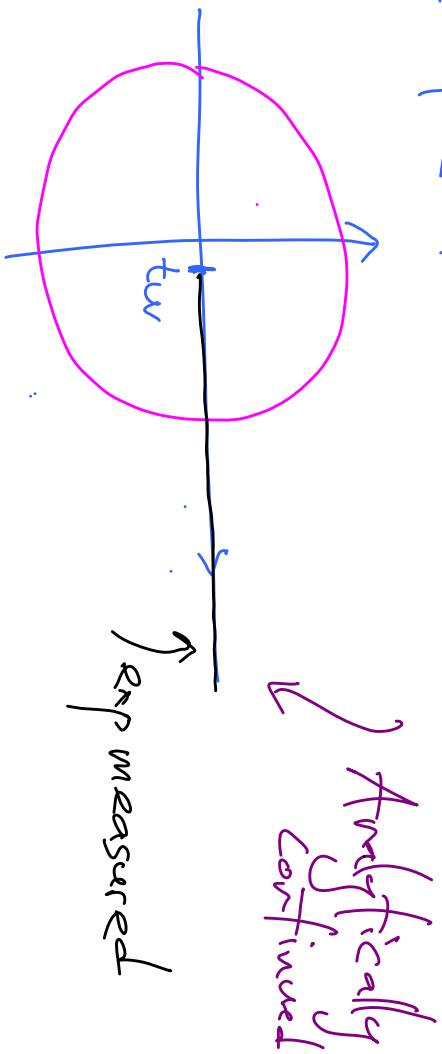
Euclidean, standard local QFT relies

on Euclidean $\rightarrow$ Lorentzian continuation,

but UV/IR can radically change this!

Example: $F^{\text{exp}}(t) = 1/t$ for $t > 0, t > t_{\text{av}}$

Effective Field Theory: "Oh, $F^{\text{exp}}(t) = 1/t$!



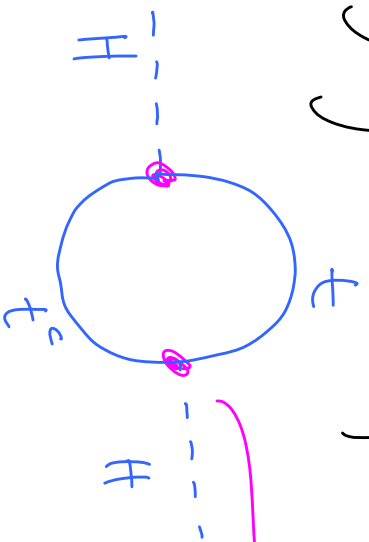
Analytically continued

$\frac{1}{2\pi i} \oint dt F(t) = 1$
 Big Circle
 Reliable EFT Comp.

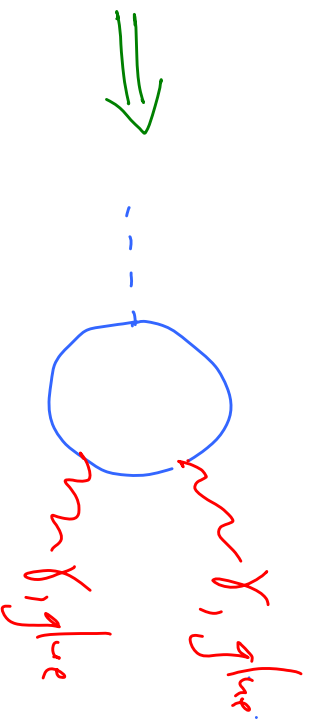
* WRONG! $F(t) = \frac{1 - e^{-t/t_{\text{av}}}}{t}$, $\oint dt F(t) = 0$

{ Mechanism for removing "bulk sing" in ADS/CFT }

* So, crucial to probe Euclidean, off-shell properties of Jiggs:



can it shut off for t, t_c off-shell by $\sim 500 \text{ GeV}$?
(NOT standard compositeness!)



$H \rightarrow \gamma\gamma$ modified @ $\sim 3\%$
 $H \rightarrow gg$ modified @ $\sim 10\%$
 Perfect for CFP

UV-IR, Tearing + Transcendality

UV-sensitivity + hierarchy problem:

$$V^{\text{1-loop}} = \text{Dir} M^4(k) \log M^2(k)$$

$$= \lambda_t^4 h^4 \log(\lambda_t^2 h^2) + \underbrace{(M \pm h)^4 \log(M \pm h)^2}_{\text{UV states}}$$

+ Why should tree cancel "loop"?

$\subset \lambda^2 M^2 h^2 + \dots$
calculable...

Tree = "Rational"

$\rightarrow$ Loop = "Transcendental"

... but long known "funny things" in

QFT computations

e.g. $\Gamma(\text{positronium}) = \dots \times \underbrace{\left(\frac{11}{2} - 9\right)}_{\text{Accidentally Small?}}$

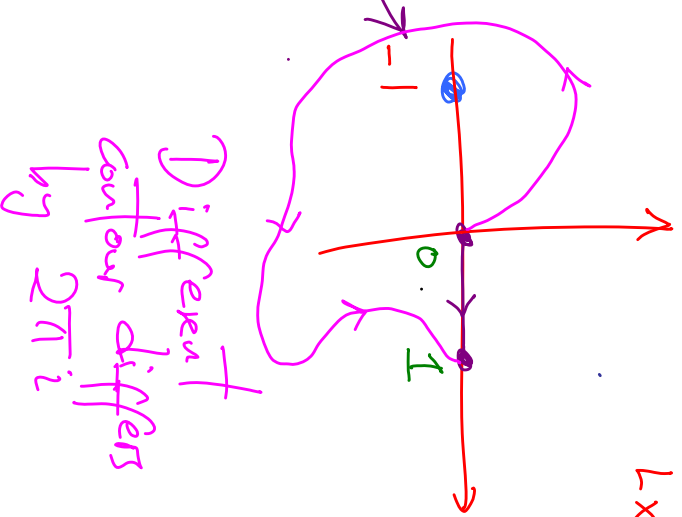
No! There is a mechanism @ work here....

Rational Approximations to Transc. Numbers

$$\log 2 = \int_0^1 \frac{dx}{1+x}$$

↑
transcendental

↖
because
of simple
pole @ $x = -1$



$$So \quad I = \int_0^1 \frac{dx}{1+x} \cdot P(x) = \phi(-1) \log 2 + \text{Rational}$$

$$= \int_0^1 \frac{dx}{(1+x)} \left[\frac{x(1-x)}{2} \right]^N = \pm \log 2 + \text{Rational}$$

$$< \left(\frac{1}{2}\right)^N$$

$\Rightarrow$ Huge "Apparent" tuning $\rightarrow$ Rational Approx to $\log 2$

e.g. $N=5$: $\log 2 - \frac{2329}{3360} \approx 16^{-5}$

This mechanism explains the " π^2 " + many other "little accidents" in QFT computations:

$$\Gamma \propto \int_0^1 dx \int_0^x dy \frac{(x-y)^2}{x^2(1-y)^2}$$

manifestly small, but

$$= \frac{1}{3} (\pi^2 - 9)$$

"big" transcendental part

Towards a New Framework

Look for a dual formulation of physics that represents physical amplitudes/observables without QM or Spacetime but abstract geometries. [cf. "positive"

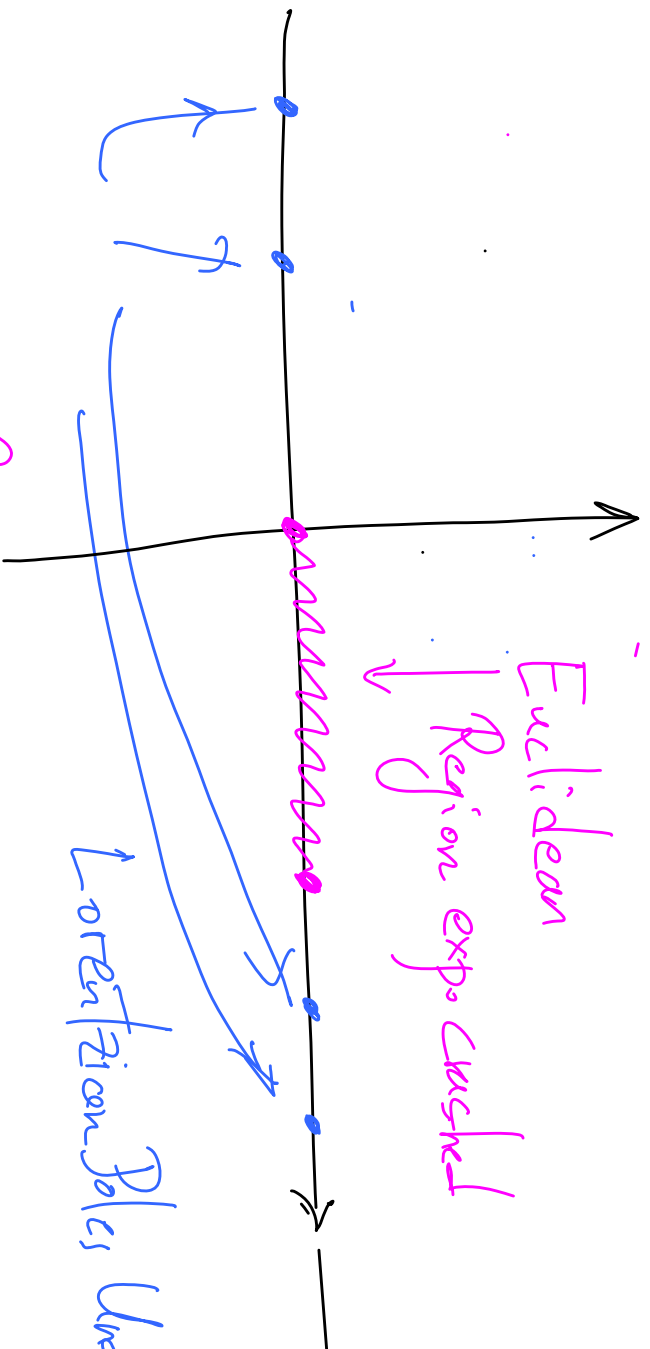
geometries, antitwined etc. seen in [14]

In this formulation -

$\sqrt{+m_h^2}$ obviously exp.

Small But not obviously local physics. Another formulation

separates into different number-theoretic parts + looks like local physics - But "appears fine tuned".



$$V(h) =$$

$$\int dk^2 \mathcal{F}(k^2) = \text{Log} + \text{Rational}$$

Euclidean

= exp. small but
apparently "fine-tuned"

Concrete Example

$$F(h) = \int_h^1 \frac{dx (x-h)^4}{1+x} \left(\frac{x(1-x)}{2} \right)^N$$

$$V(h) = F(h) + F(-h)$$

$$= \underbrace{\sum_{\pm} (1 \pm h)^4 \log(1 \pm h)}_{\text{"UV loop"}} + \underbrace{R_{\text{finite}}}_{\text{"free"}}$$

BUT GUARANTEED TO BE "TUNED"!

$$S_0 \text{ e.g. } N=5$$

$V(h)$

$$= \underbrace{142733/102960 + (97411 h^2)/73920 - (1557 h^4)/560 + h^6/15 + h^8/140 + (31 h^{10})/20160}_{\text{"free"}} + h^{12}/3960 + h^{14}/160160 - \log[4] h^4 \log[4] - 2 h^2 \log[64] + (-1+h)^4 \log[1-h] + (1+h)^4 \log[1+h]$$

$$= (142733/102960 - \log[4]) + (614851/73920 - 2 \log[64]) h^2 + (2329/1680 - \log[4]) h^4 - h^{10}/20160$$

$$= 10^{-6} + 10^{-5} h^2 + \dots + h^{10}$$

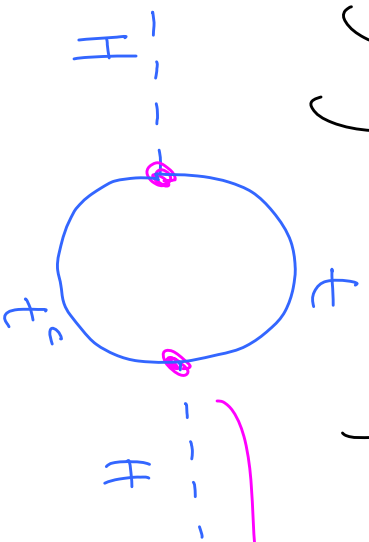
"tuned" $N!$

"tuned" m_h^2

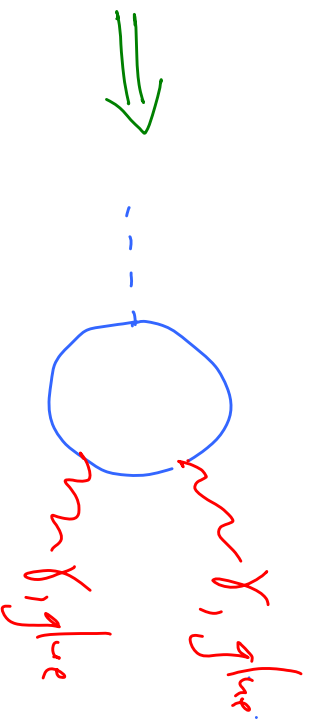
Surprise: h^6, h^8 MISSING!

"1-loop"

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Hidden Symmetries?

- * We have already seen, even in "boring, vanilla, mon-SUSY" models like ϕ^3 theory - hidden symmetries, invisible in Feynman diagrams - but manifest in formulation in terms of new gauge/factorial structures.
 - * Could hidden symmetries be relevant to Higgs? If present - could lead to "tuning" for higher-dim Higgs ops! e.g. dim 6 absent but dim 8 present.
- New Stakes for Precision Higgs Measurements

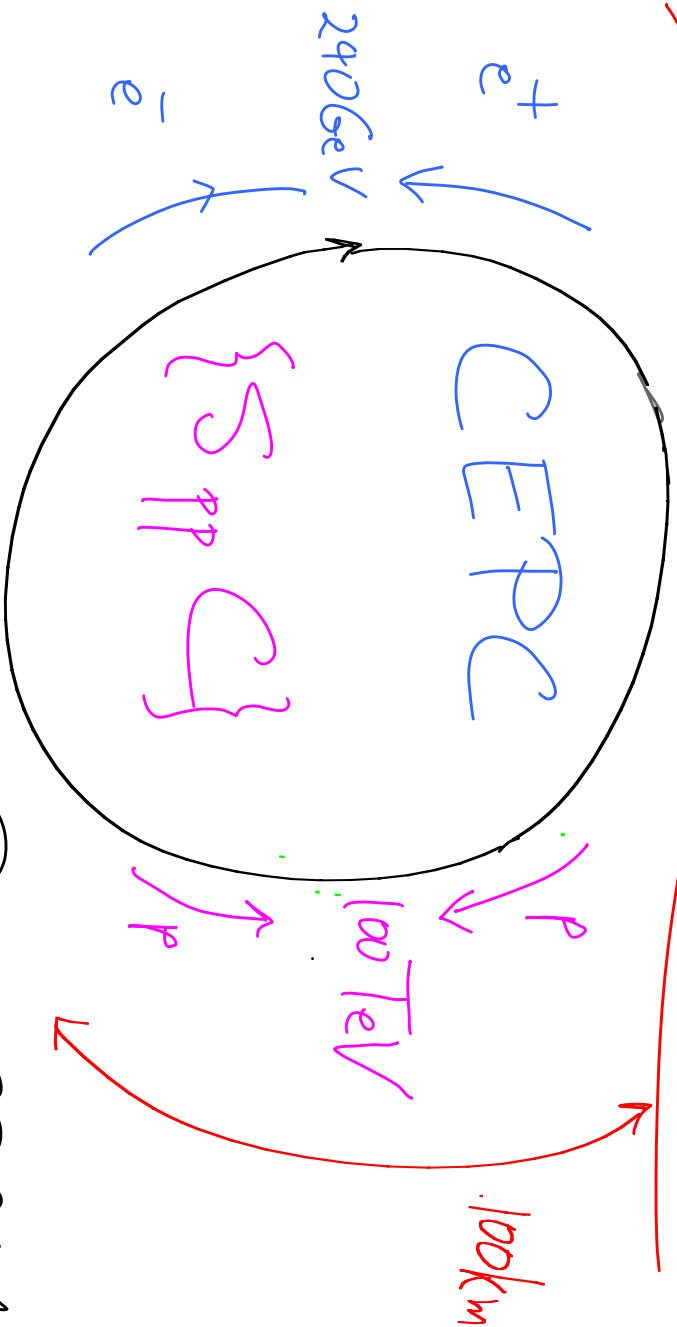
Outlook

For forty years, theorists thought they knew what the Higgs was about — just had to find theory that computed m_h^2 — and almost every such theory predicted new particles @ the LHC, not seen. This is a profound surprise and a deep clue about the most basic and fundamental aspects of physics.

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.

The **Higgs** is the most important
character in this drama — we can
put it under most incisive +
precise experimental scrutiny.

MOST CRITICAL



EXPERIMENTAL PROGRAM

