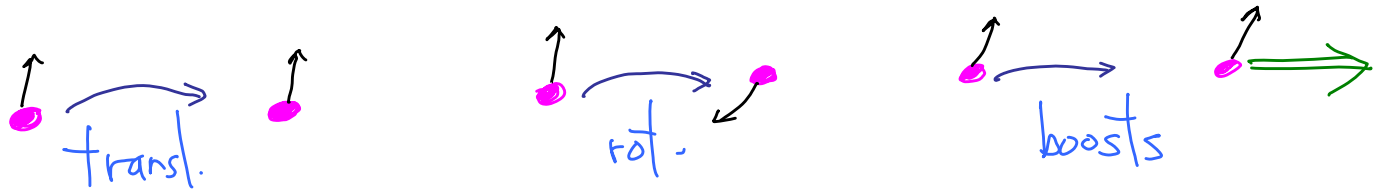
Why is the Higgs Special?

What is Particle Physics?

What is a Particle?

Spacetime Symmetries



Quantum Mechanics

$$|p^\mu, \sigma\rangle \; ; \quad U(\Lambda)|p,\sigma\rangle = D_{\sigma\sigma'}|\Lambda p, \sigma'\rangle$$

"Particles are Unitary reps of Poincaré group"

Quantum Mechanics Spacetime

Particle Physics = Study of

Fundamental Laws of Nature

governed by still-mysterious union of

Quantum Mechanics + Spacetime

17'th → 20'th Century Physics

March of REDUCTIONISM

March of SYMMETRIES

Whatever the Ultimate Theory

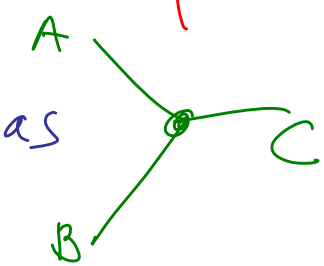
Relativity

Quantum Mechanics

Symmetries

Reductionism

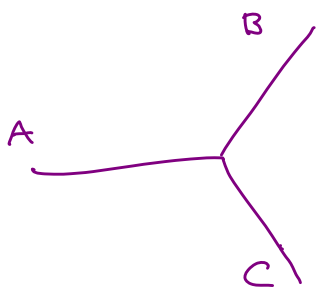
↳ Massless particles interacting as



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

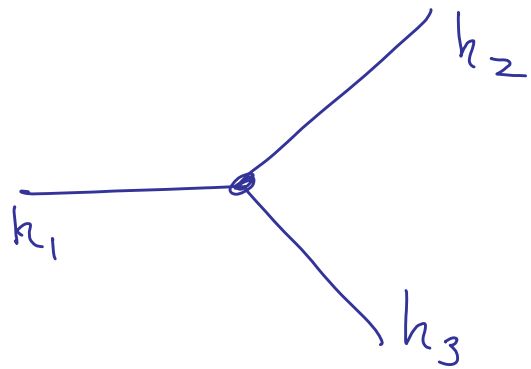
Massless Particles

$$p_{\alpha\dot\alpha} = \begin{pmatrix} p_0+p_3 & p_1-ip_2 \\ p_1+ip_2 & p_0-p_3 \end{pmatrix} = \lambda_\alpha \tilde\lambda_{\dot\alpha}$$



Either $\lambda_A \propto \lambda_B \propto \lambda_C$

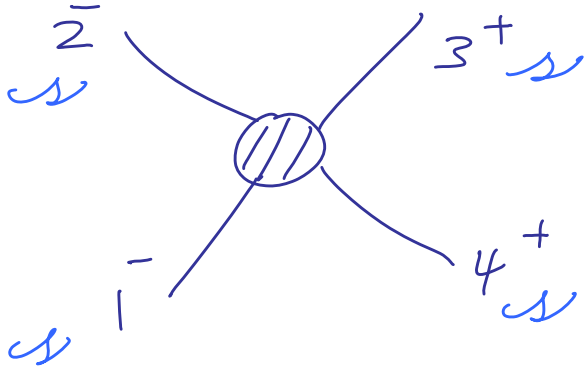
$\tilde\lambda_A \propto \tilde\lambda_B \propto \tilde\lambda_C$



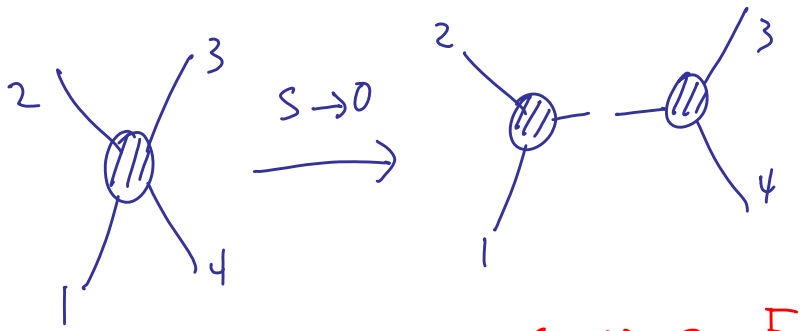
$$g \langle \lambda_1 \lambda_2 \rangle^{h_3-h_1-h_2} \langle \lambda_2 \lambda_3 \rangle^{h_1-h_2-h_3} \langle \lambda_3 \lambda_1 \rangle^{h_2-h_1-h_3}$$

Completely Determined

By Poincaré



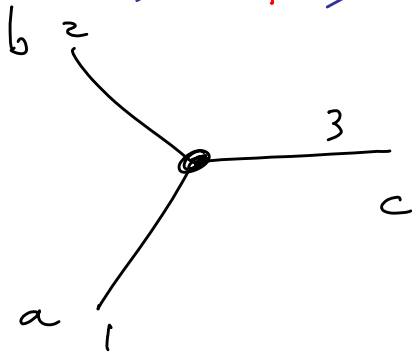
$$\left(\langle 12\rangle [34]\right)^{2s} F(s,t,u)$$



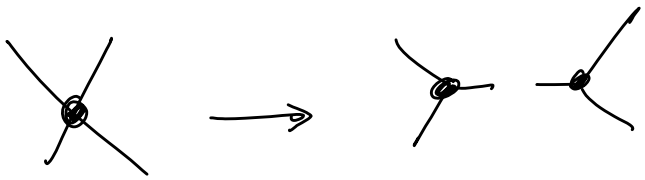
$$\Longrightarrow F(s,t,u) \to \begin{cases} \frac{1}{s} \cdot \frac{g^2}{t^s} \\ \frac{1}{t} \quad \frac{g^2}{u^s} \\ \frac{1}{u} \quad \frac{g^2}{s^s} \end{cases}$$

$$\Longrightarrow \text{Only} \begin{cases} s=0, \quad F = g^2\left(\frac{1}{s}+\frac{1}{t}+\frac{1}{u}\right) \\ s=2 \quad F = \frac{g^2}{stu} \end{cases} !$$

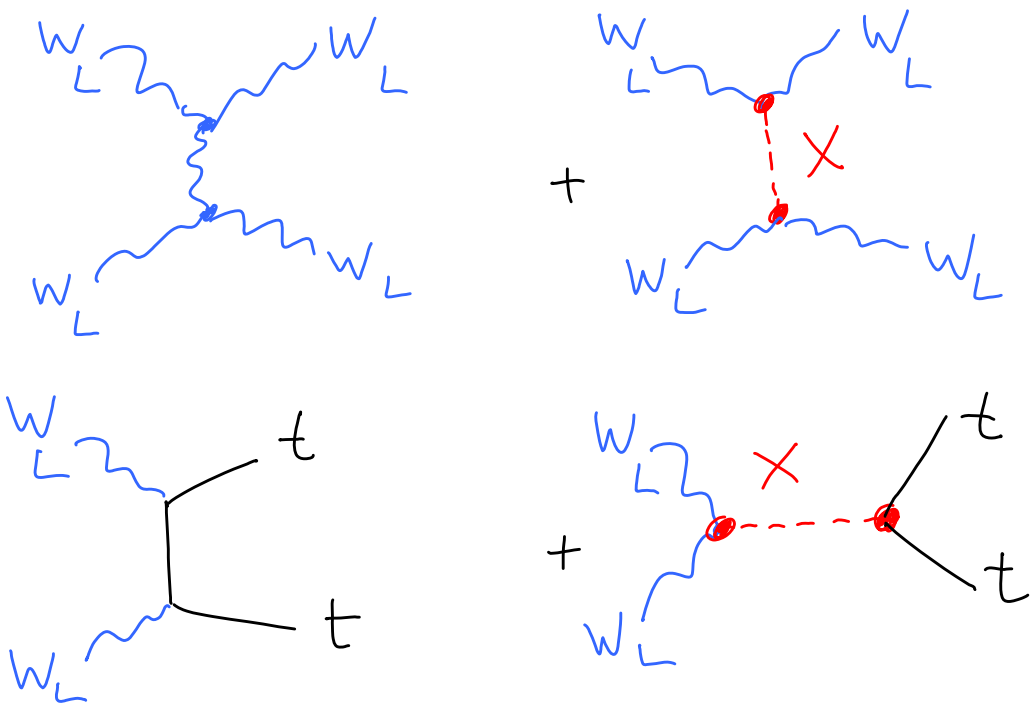
Spin 1



$$\left(g\, f^{abc}\right) \frac{\langle 12\rangle^3}{\langle 13\rangle\langle 23\rangle}$$



$\Rightarrow$ f^{abc} satisfies Jacobi



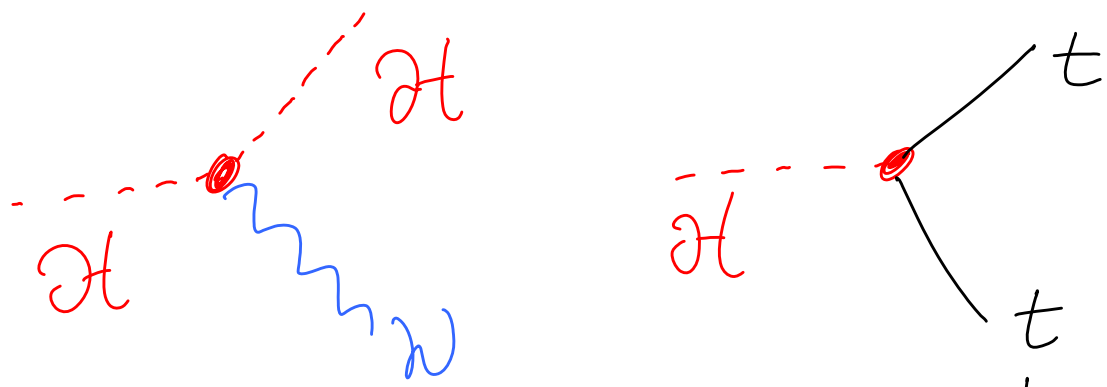
Spin of X:

0 ~~1~~ ~~2~~ ~~3~~ ~~4~~ ...

MUST BE SPIN 0

$\boxed{X = \text{Higgs}}$

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



Usual Allowed Interactions

Belief in Principles Paid Off

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

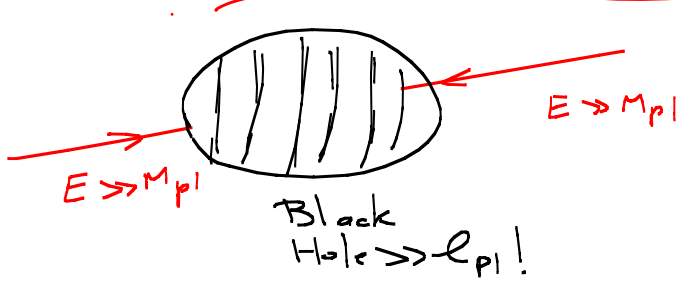
Higgs is first "really new" particle we've seen!

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

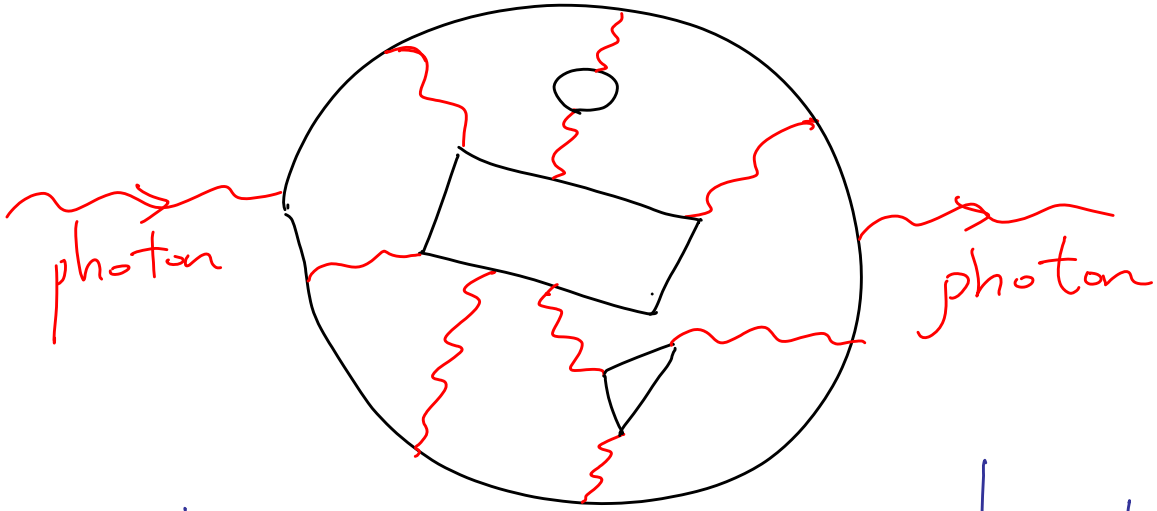


High Energies ↕ Long Distances!

Reductionism + Wilsonian EFT Paradigm is False

Fundamental Laws Nothing like that of Condensed Matter Physics — FAR DEEPER + MORE RADICAL

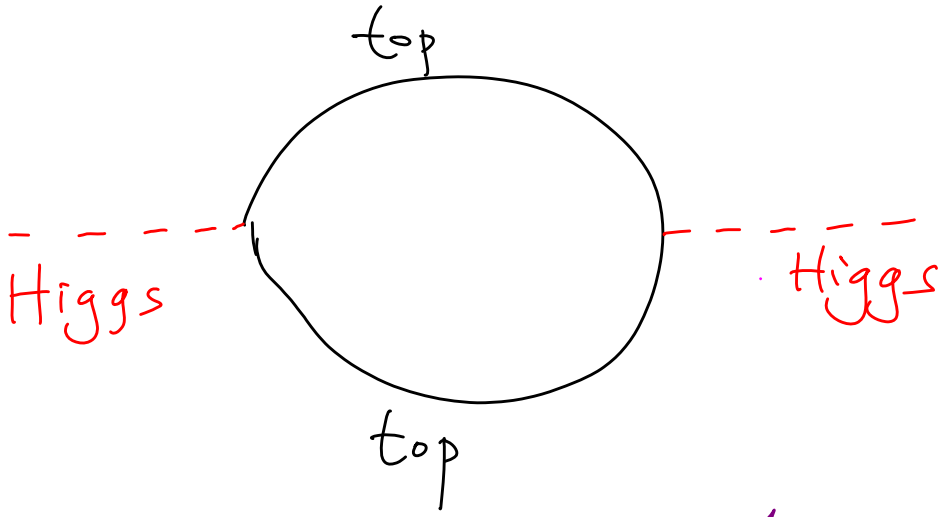
[But maybe only at Planck Scale?]



Photon MUST stay massless, because

massless helicities $\rightarrow 2 \neq 3 \leftarrow$ # massive spins

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



massless spin 0 $\quad 1 \quad = \quad 1 \quad$ massive spin 0

NO DIFFERENCE

WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

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

$$\left(E/V\right) = \int d^3k \, \frac{1}{2}\sqrt{k^2 + \underbrace{m_B^2}_{g^2|h|^2}} - \frac{1}{2}\sqrt{k^2 + \underbrace{m_F^2}_{\lambda^2|h|^2}}$$

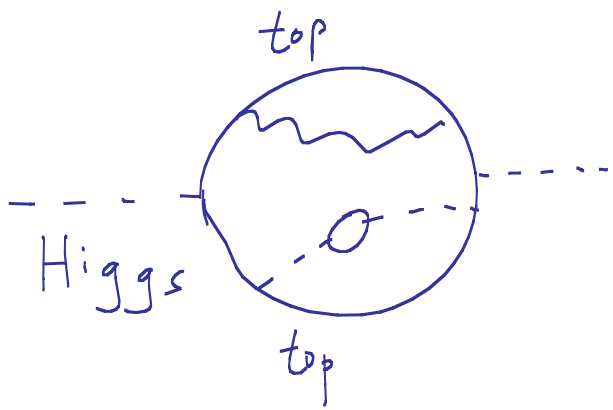
$$= \Lambda_{UV}^4 + (g^2 - \lambda^2)\,\Lambda_{UV}^2\,|h|^2 + \cdots$$

Cosmological Constant Problem

Hierarchy Problem

WHY IS THERE A MACROSCOPIC UNIVERSE?

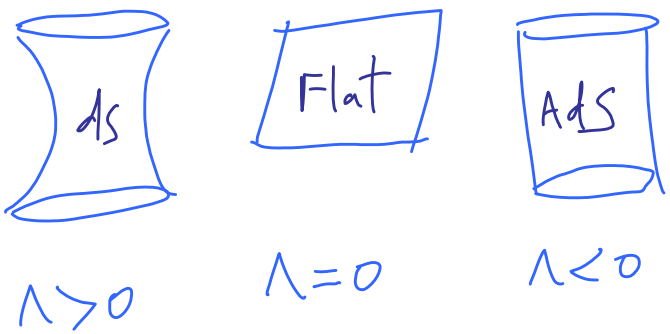
Λ + Higgs $\longrightarrow$ Beyond Symmetries



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

NO DIFFERENCE

Hierarchy Problem



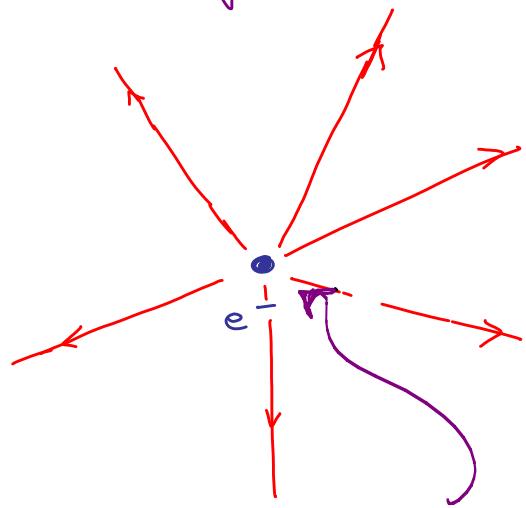
Same amount of symmetry

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

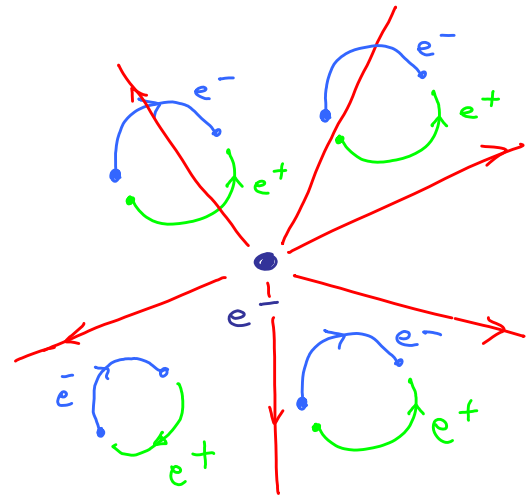
Cosmological Constant Problem

Naturalness Has Worked Beautifully

Infinite Energy In Electric Field



$$\xrightarrow[\text{Rel.}]{\text{Q.M.}}$$

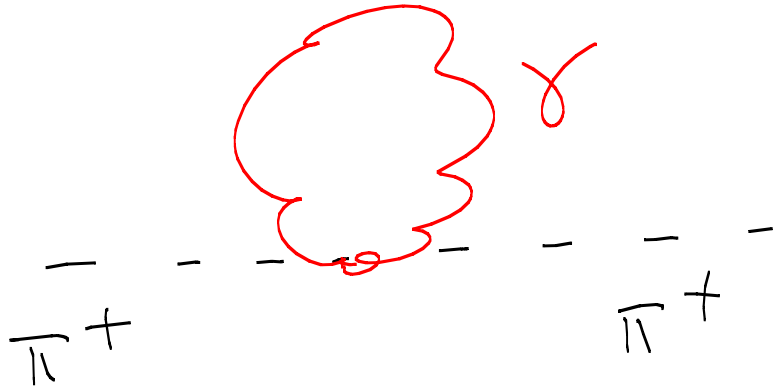


$$\frac{e^2}{4\pi a_{cl}} \sim m_e c^2 \Longrightarrow a_{cl} \sim \frac{e^2}{4\pi m_e c^2}$$

$$a_{compton} \sim \frac{\hbar}{m_e c}$$

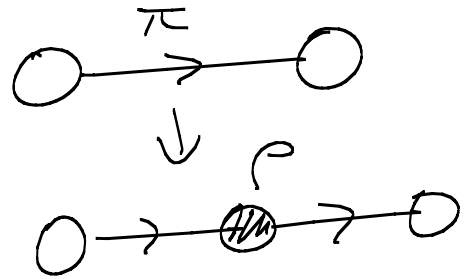
$$\sim \left[\frac{e^2}{4\pi\hbar c}\right]^{-1} \times a_{cl} \; !$$

cut off α^{-1} earlier than needed

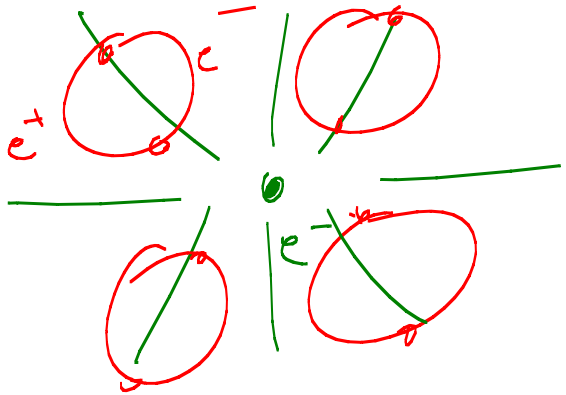


$$\delta m_\pi^2 \sim \frac{e^2}{16\pi^2}\Lambda^2 \rightsquigarrow \Lambda \lesssim 1\,\mathrm{GeV}$$

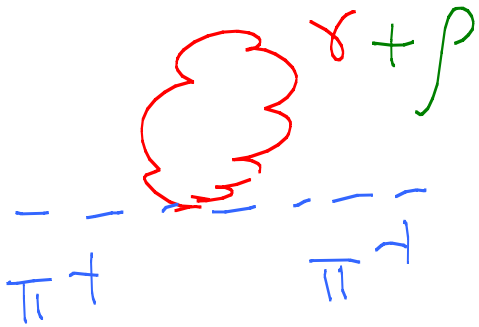
ρ meson cuts it off



$\sim \frac{1}{\sqrt{N}}$ earlier than needed



$\longrightarrow$ SUSY

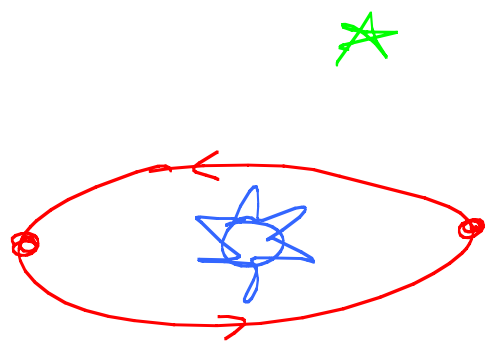


$\longrightarrow$ Pseudo Goldstone

Higgs

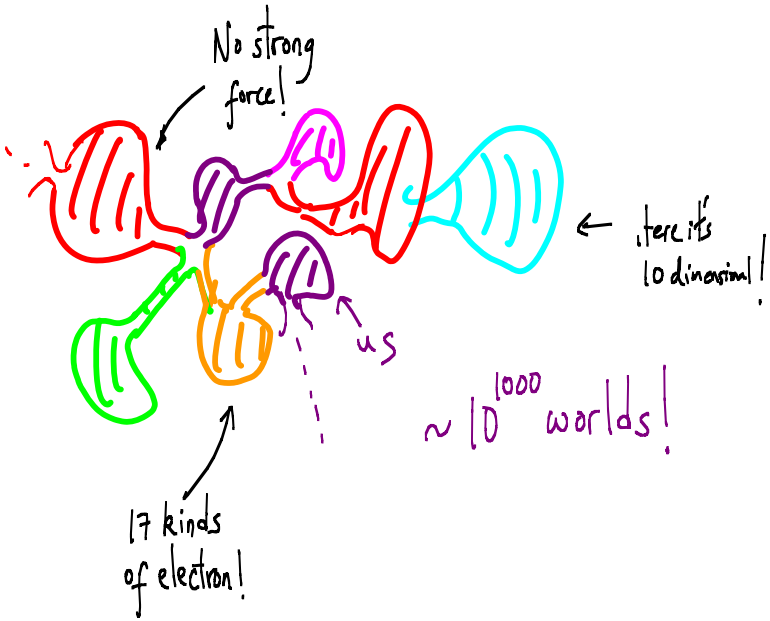
Naturalness has failed dramatically

- Aristarchos had heliocentric model of solar system – rejected because parallax not seen – CRAZY that stars should be so far away!

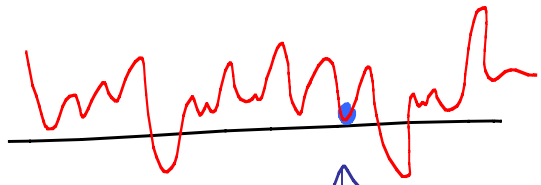


NATURALNESS

r
<



$\sim 10^{1000}$ worlds!



Everywhere Lethal + Empty except ...

Here, accidentally, Universe not empty

Further Study of Higgs could give strong (but circumstantial) push to this picture

Emergent Spacetime?

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

Macroscopic Universe?

Higgs Discovery Crucial

Our Relativistic Vacuum is Qualitatively

Different than anything we've seen elsewhere in physics

NOT JUST @ Planck scale

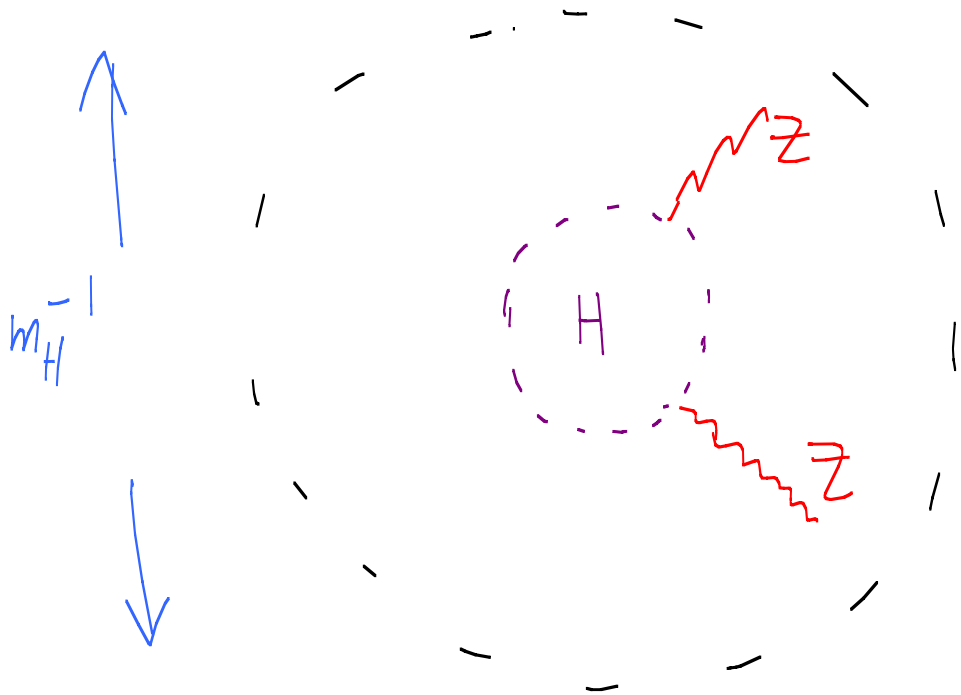
ALREADY @ TeV scale

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

Higgs is Really New Physics!

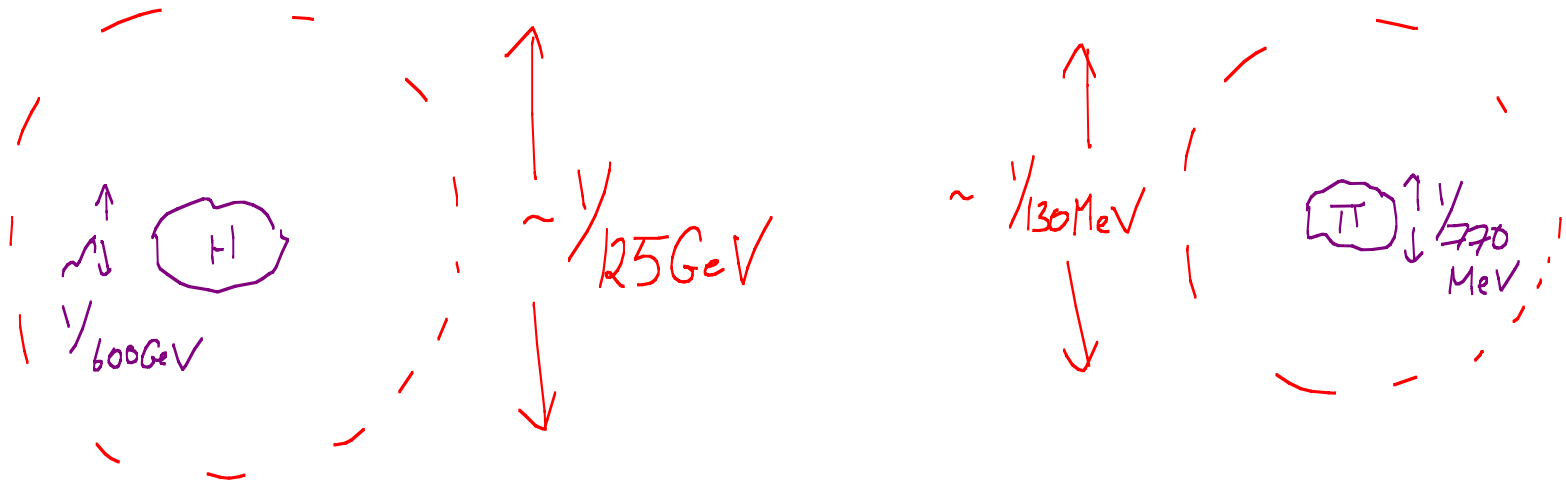
* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum
* MUST LOOK AT IT CLOSELY!

Never Seen Point-Like Scalar

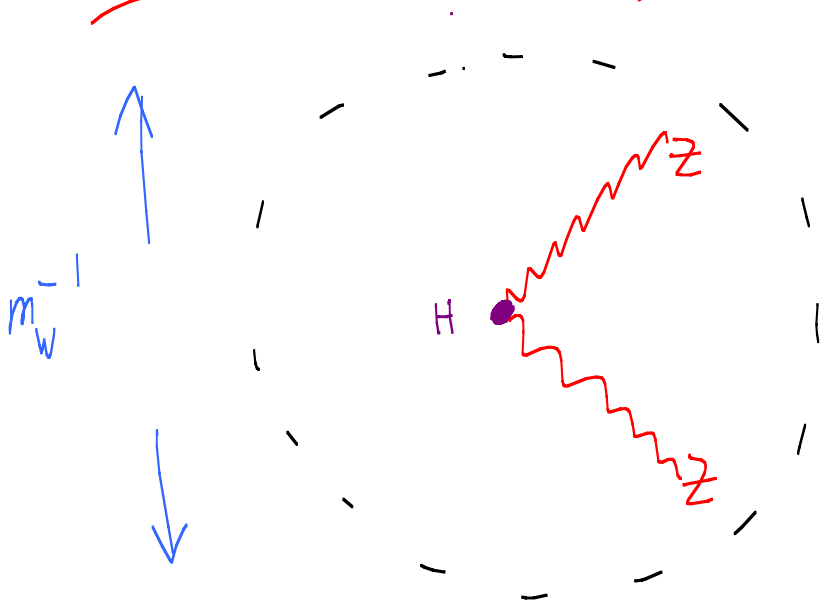


So, how pointlike is it?

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



Never Seen Point-Like Scalar

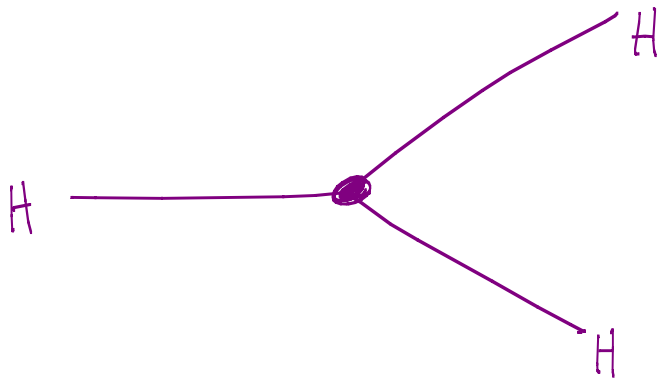


Higgs Factory

+

We will know FOR SURE if it's "like a Pion"

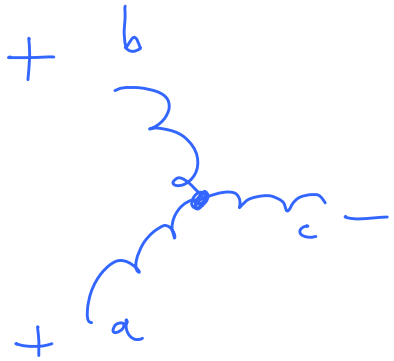
Never Seen Self-Interacting Fundamental Particles



100 TeV Collider

Measured to ~5%

Higgs + Gravity: Unique in Self-Interaction!



YM, GR : changes helicity! + Color

$$\left[\langle 12\rangle\langle 23\rangle\langle 31\rangle\right]^{s}$$

$s=0$ Higgs

$s=1$ Violates Bose!

$s=2$ Grav.

{But miniscule R^3 corr}

Also, 100 TeV collider blasts into the high energy frontier. New particles ~ 10 X LHC reach.

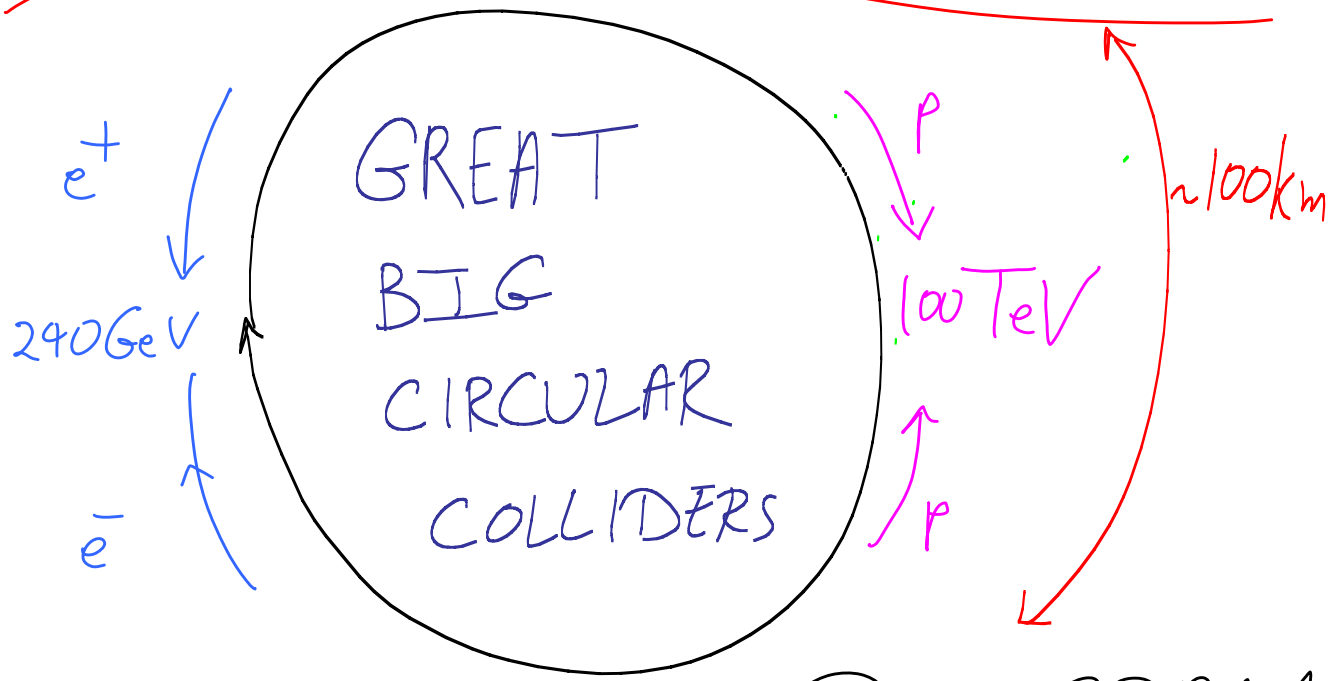
Probes vacuum quantum fluctuations with power 100 X LHC

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



EXPERIMENTAL PROGRAM