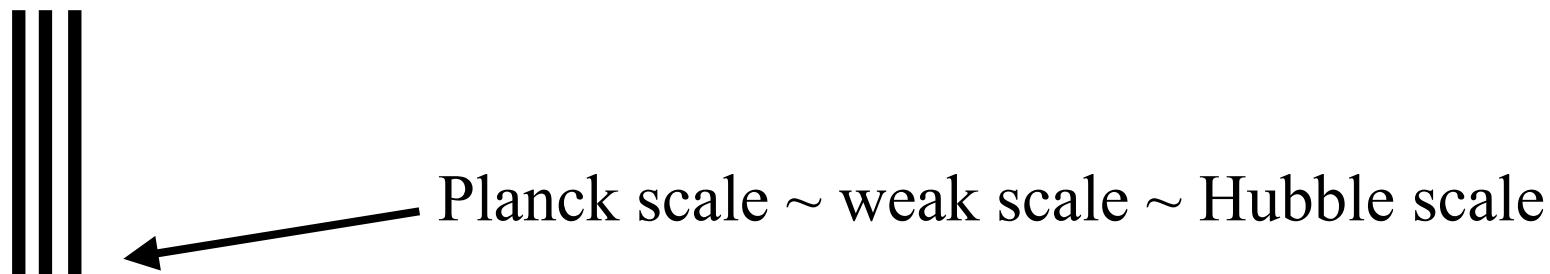
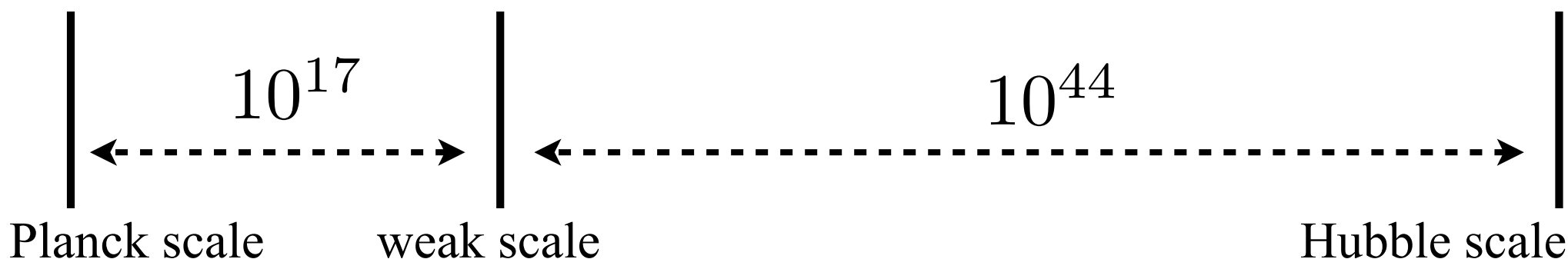


Reminder: Last Week

Quantum Mechanics + Space-time leads us to expect:



We observe:



Current theory accounts for huge difference w/implausible cancellation
Need modifications QM or Space-time to avoid fine tuning

Reminder: Last Week

Problems associated to each fundamental scale.

Planck Scale:

What replaces spacetime ? (“Quantum Gravity”)

Weak Scale:

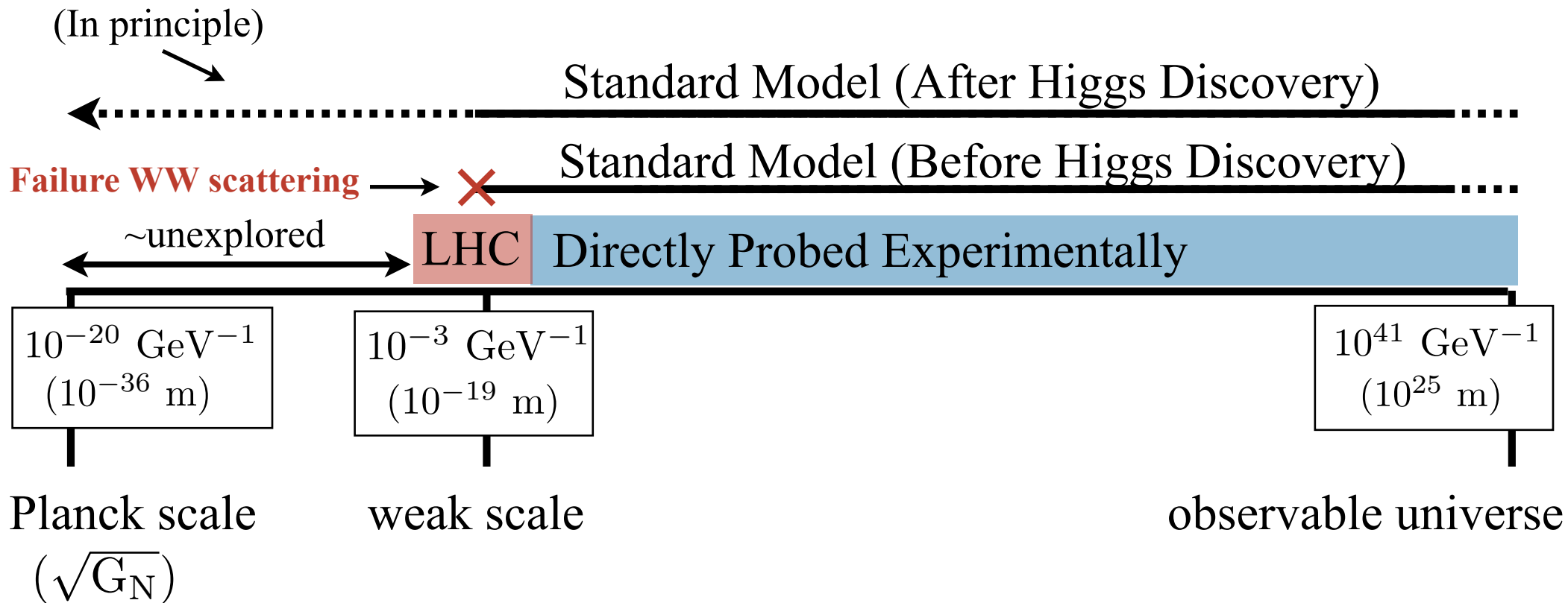
Why is Gravity so weak ? (“Hierarchy Problem”)

Hubble Scale:

Why is the universe so big ? (“Cosmological Constant Problem”)

Current theory accounts for huge difference w/implausible cancellation
Need modifications QM or Space-time to avoid fine tuning

Focus: Problem associated w/weak scale



Most tractable now:

- Currently directly probing this scale with the LHC
- Understand the physics at this scale incredibly well

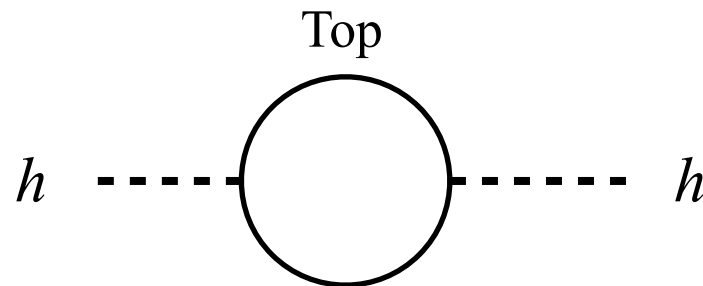
Working theory that's been verified experimentally

Focus: Problem associated w/weak scale

(In principle)

Reminder: Vacuum fluctuations of Higgs mass (m_H^2)

Failure



Top

$h \cdots \cdots h \sim \Lambda^2 \Rightarrow m_H \sim 10^{20} \text{ GeV}$

Planc
(\sqrt{G})

$$m_H^2 = 2.569678321 \dots 554 \dots \times \ell_{\text{Pl}}^2$$

+ 30 digits

$$- 2.569678321 \dots 453 \dots \times \ell_{\text{Pl}}^2$$

30 digits

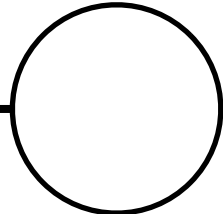
Working theory that's been verified experimentally

Focus: Problem associated w/weak scale

(In principle)

Reminder: Vacuum fluctuations of Higgs mass (m_H^2)

Failure


$$h \text{ --- } \text{Top} \text{ --- } h \sim \Lambda^2 \Rightarrow m_H \sim 10^{20} \text{ GeV}$$

10^{-20}
(10^{-

Very different type problem than we discussed before:

“Naturalness” Problem:

- Theory is fully logically consistent
- Need bizarre (un-natural) choice of input parameters

Un-like situation before Higgs where theory broke down

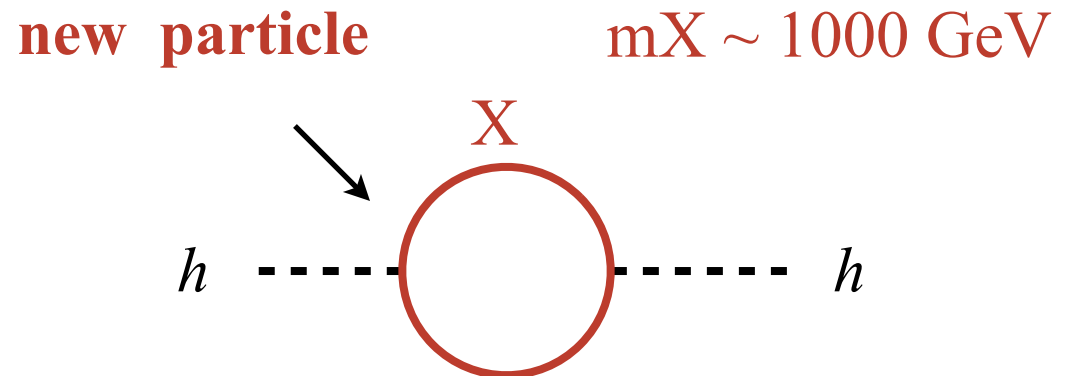
$P(\omega\omega \rightarrow \omega\omega) > 1$ / Inconsistent mass description

What scale do we need Modification?

$$\begin{array}{ccccc}
 mH^2 & = & \text{-----} & + & \text{---} \bigcirc \text{---} \\
 \sim (\text{weak-scale})^2 & & mH^2_{\text{Classical}} & & \sim \Lambda^2
 \end{array}$$

Can avoid need for fine tuning only if $\Lambda \sim \text{weak-scale}$.

Need changes to stop vacuum
fluctuations below: 10^{-3} GeV^{-1}
(10^{-19} m)

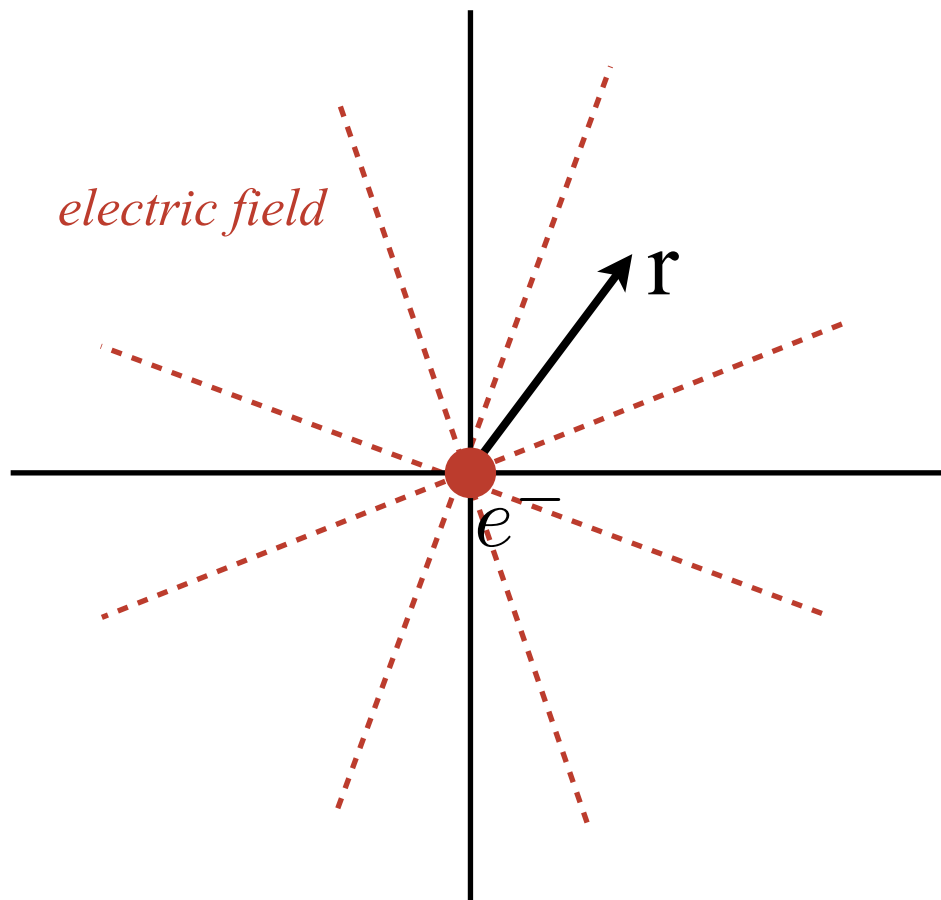


(Pencil metaphor: analogous to the pencil glue/string)

Naturalness Problems in History

Same type of problems have occurred before in history of physics
Same types of arguments for scale of new physics worked

Example: Energy stored in the electric field around electron



$$E \sim \frac{\alpha}{r} \sim \frac{\alpha}{\Lambda}$$

Naively seems infinite

Energy of electron at rest: $\sim m_e$

Introduce cut off

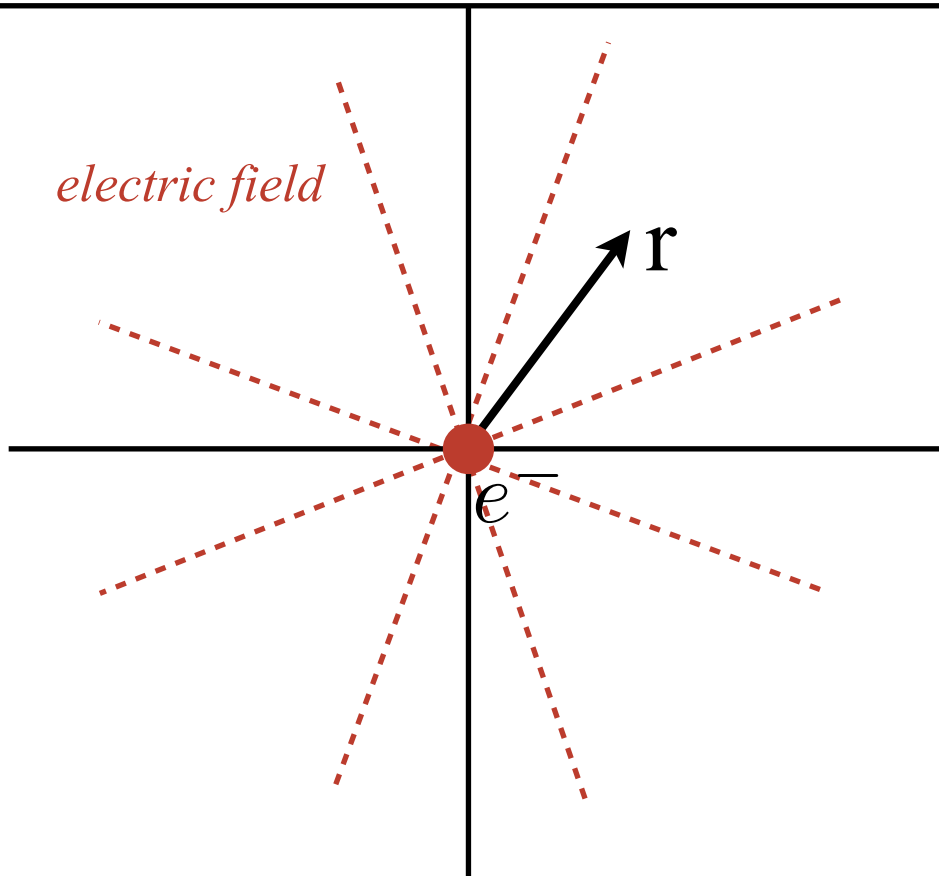
Need $\Lambda \geq \alpha/E$ to avoid fine tuning

Naturalness Problems in History

Same type of problems have occurred before in history of physics

Quantum electrodynamics, quantum chromodynamics, general relativity

Naturalness requires new physics kick in $\Lambda \geq \alpha/m_e$
Picture of point like electron must break down at this scale



$$E \sim \frac{\alpha}{r} \sim \frac{\alpha}{\Lambda}$$

Naively seems infinite

Energy of electron at rest: $\sim m_e$

Introduce cut off

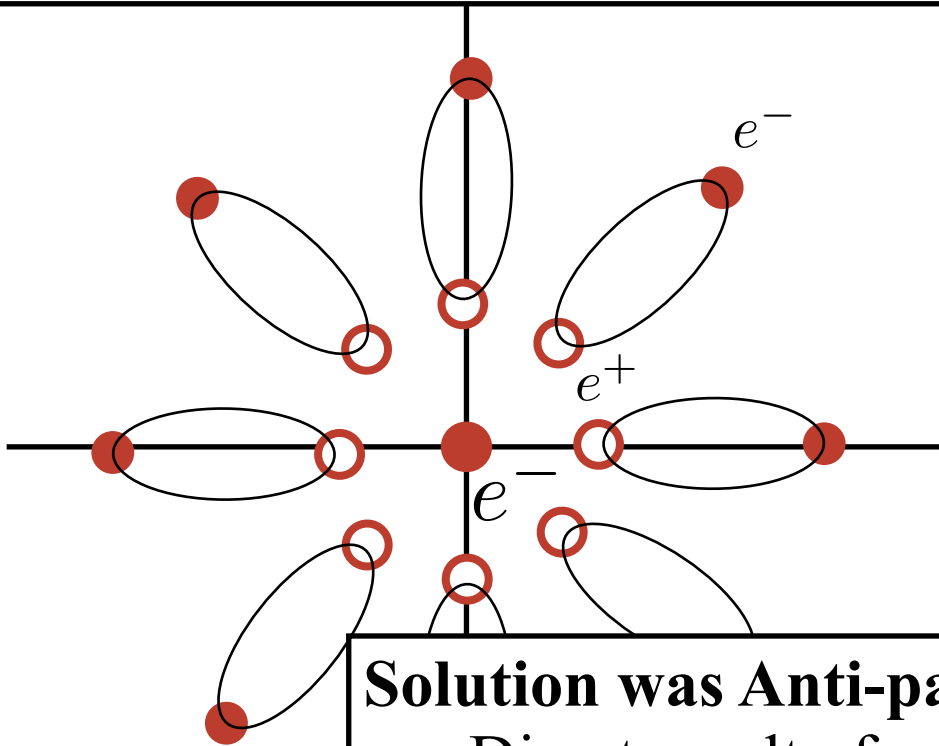
Need $\Lambda \geq \alpha/E$ to avoid fine tuning

Naturalness Problems in History

Same type of problems have occurred before in history of physics

~~Quantum electrodynamics formulae for calculating radiative corrections~~

Naturalness requires new physics kick in $\Lambda \geq \alpha/m_e$
Picture of point like electron must break down at this scale



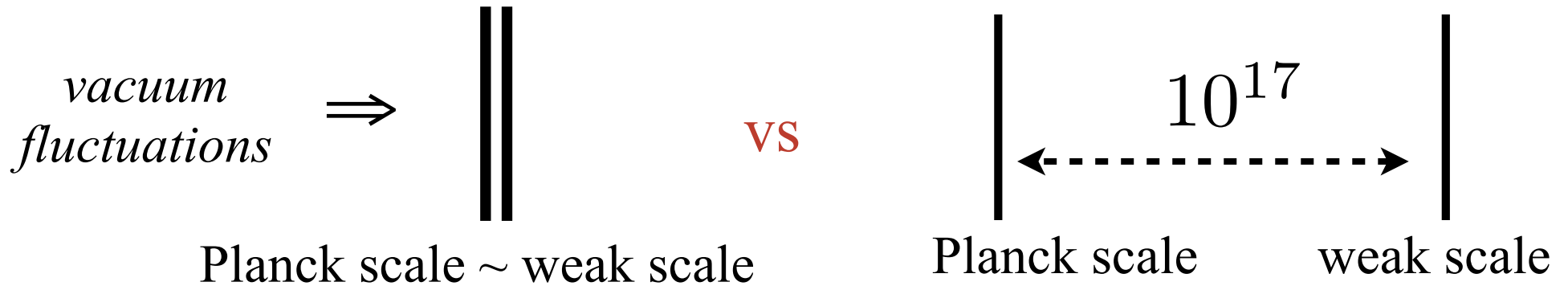
Exactly what happens !

At scale $\Lambda \sim 1/m_e$ start seeing
particle-anti-particle cloud

Solution was Anti-particles :

- Direct result of extension of Space-time (adding QM)
- Doubled the number of particles in the theory

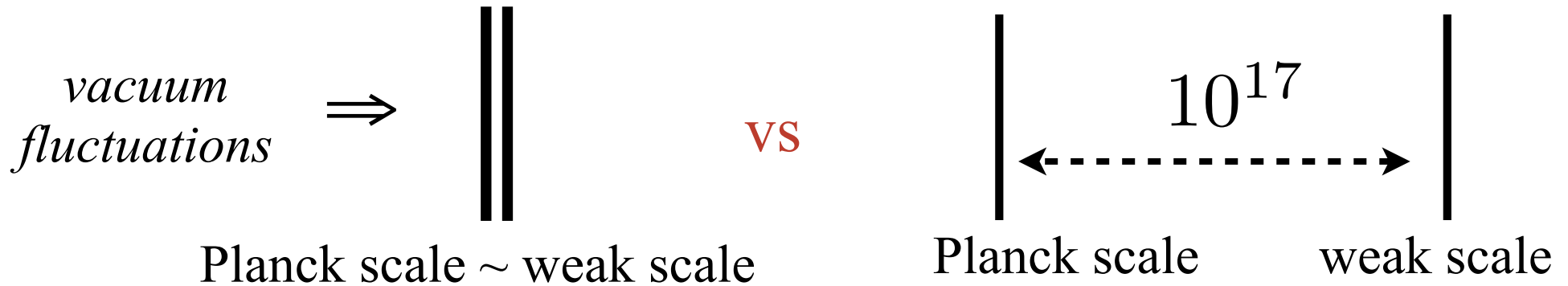
Potential Solutions



Expect any potential solutions to be dramatic

- Basic feature of space time get us in this mess
- Not like $\omega\omega$ scattering where could just add one new particle

Potential Solutions



“Compositeness” Higgs made of smaller particles

Weak scale not fundamental / Similar to size of the proton

New underlying physics responsible for Higgs/Higgs potential

⇒ New forces / New matter

Extra dimensions

Planck scale is really at the weak scale

Gravity appears weak b/c gravitons can propagate in extra dim.

Go through example of how works in detail

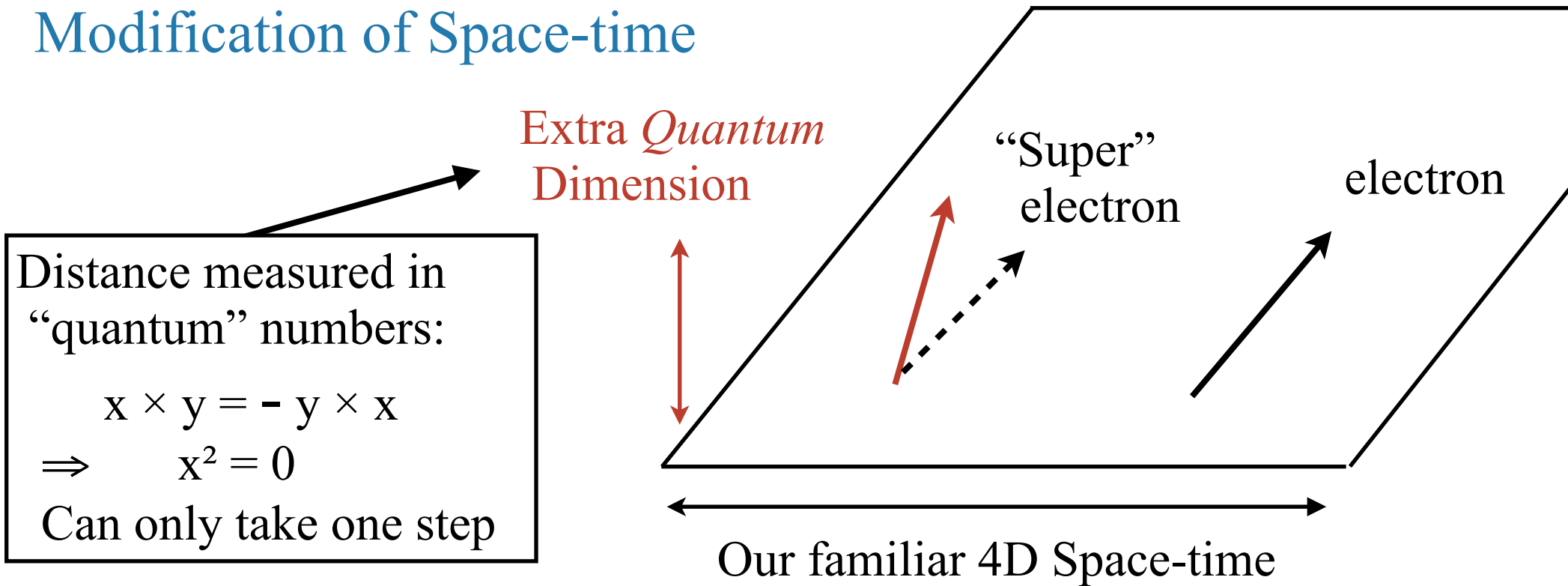
Supersymmetry

Has been a favorite within the field

Vacuum corrections suppressed below weak scale

Super Symmetry

Modification of Space-time



Doubles number of particles:

- Standard Model particles
- Super-partners w/step in extra dimension

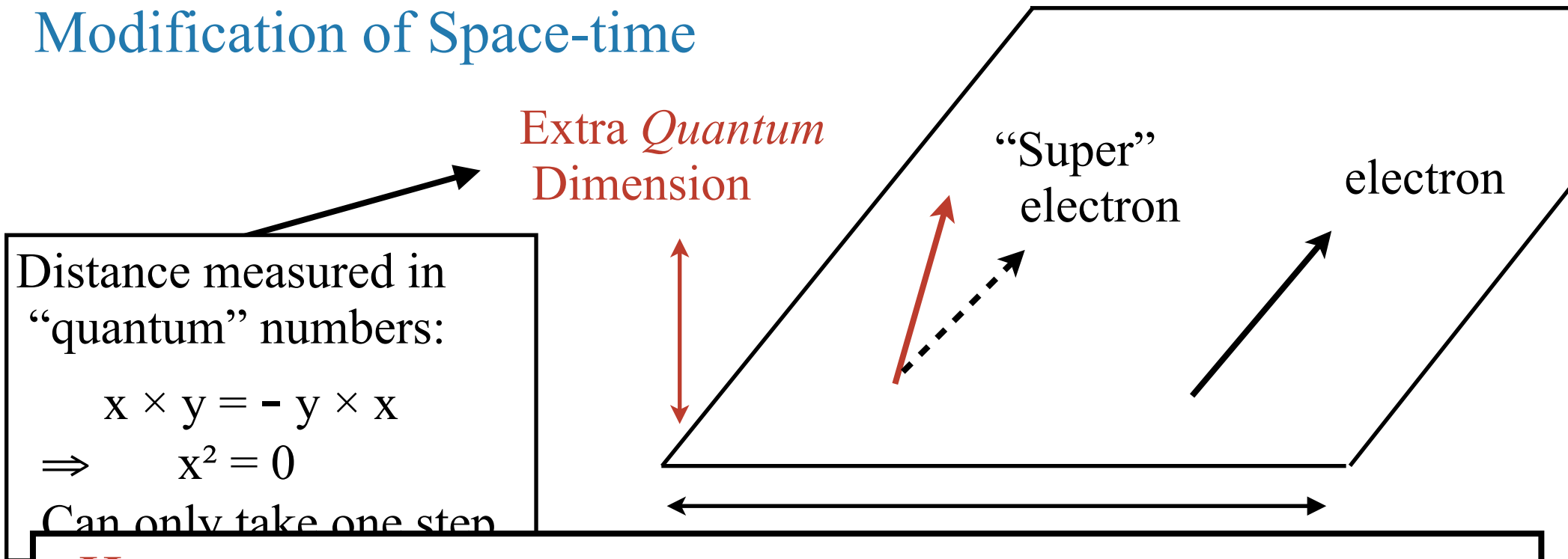
Measured in normal numbers

$$x \times y = y \times x$$

All regular rules of QFT apply / Symmetry relating particles/Super particles

Super Symmetry

Modification of Space-time



- Havent seen super-partners
- Could be another example of long-distance illusion:
eg: difference between forces
- Idea: going to short enough distances start seeing symmetry
- To avoid fine-tuning needs to happen around weak scale

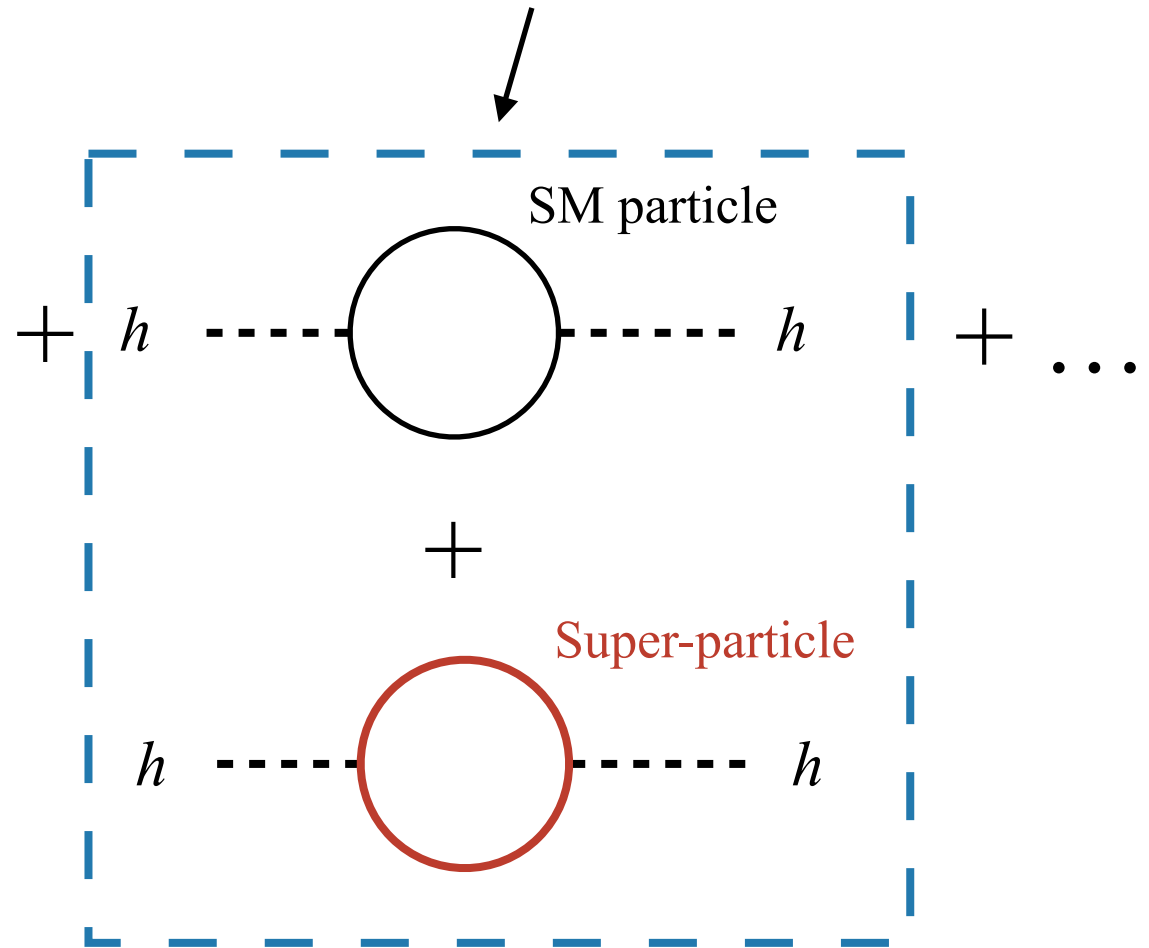
All regular rules of QFT apply / Symmetry relating particles, Super particles

How Does This Help ?

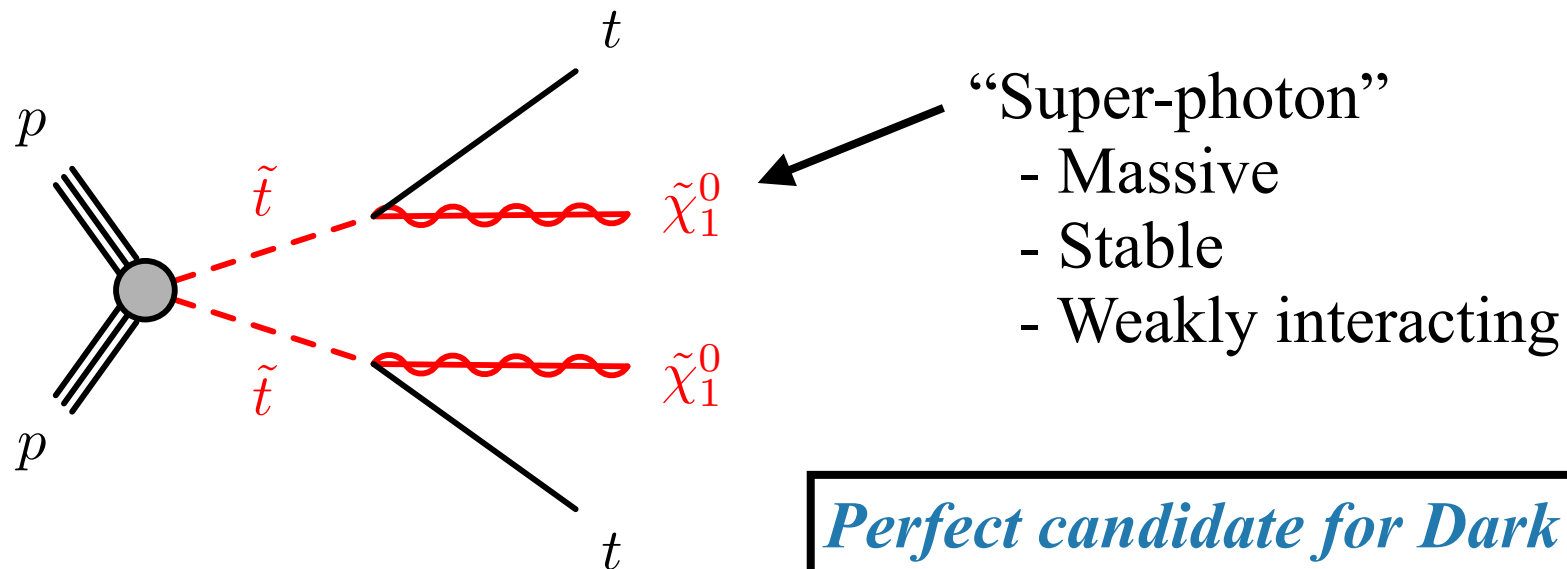
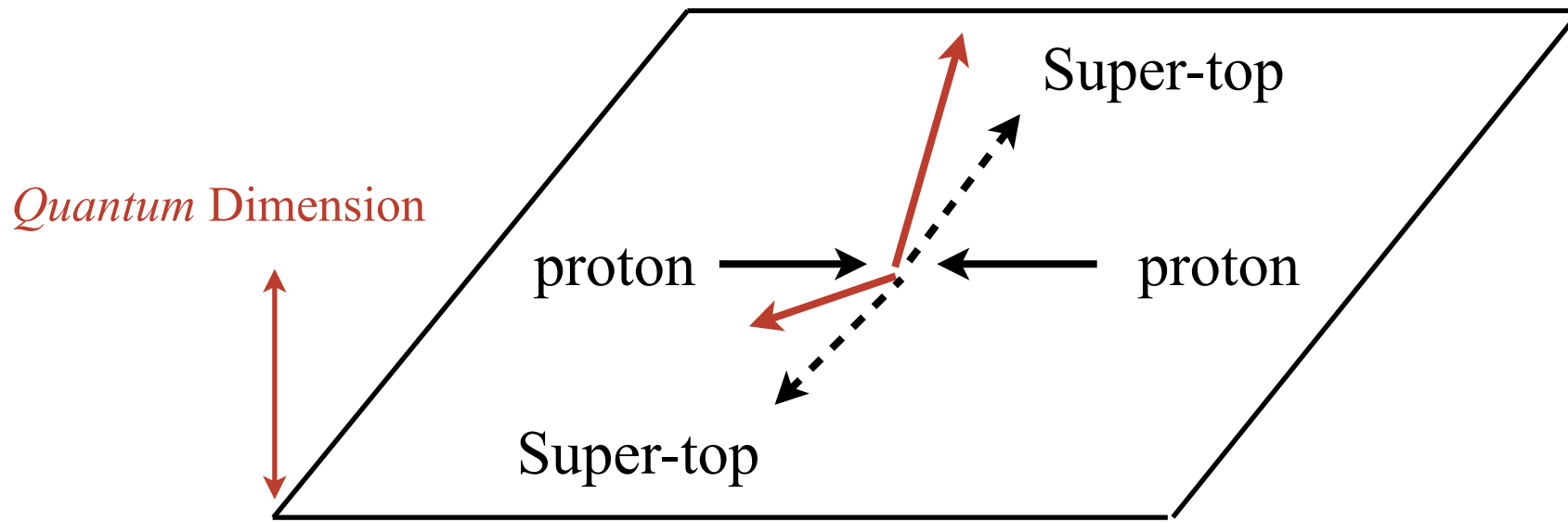
$\sim(\text{weak-scale})^2$

$\sim(\text{weak-scale})^2$

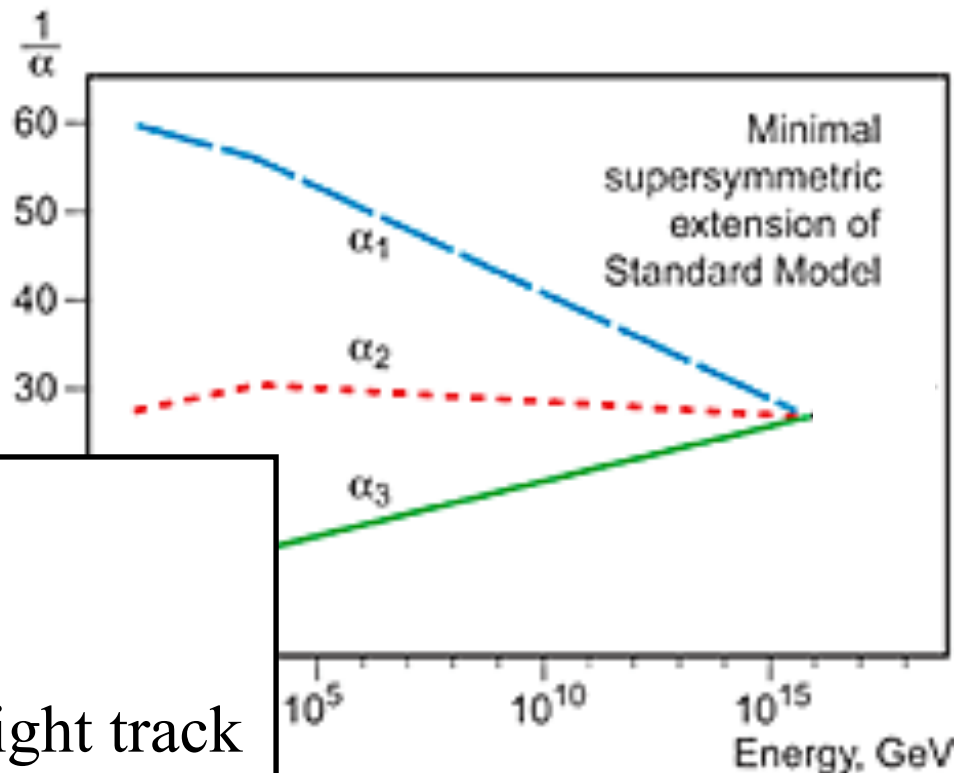
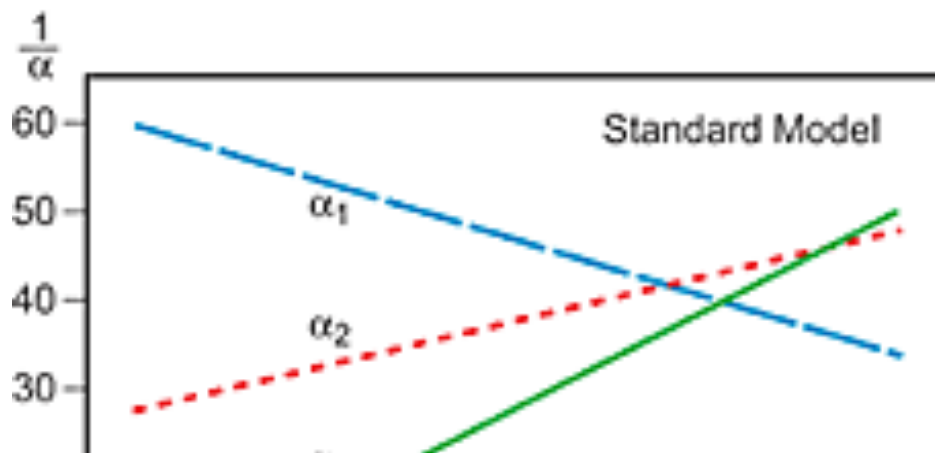
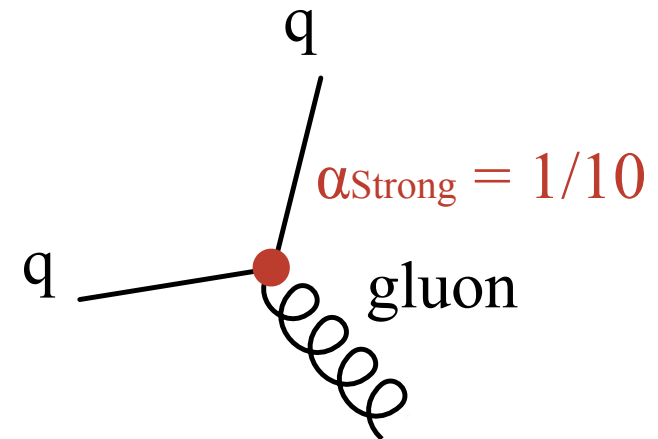
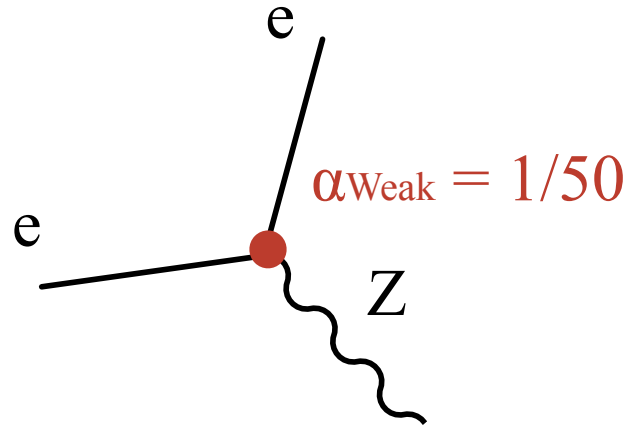
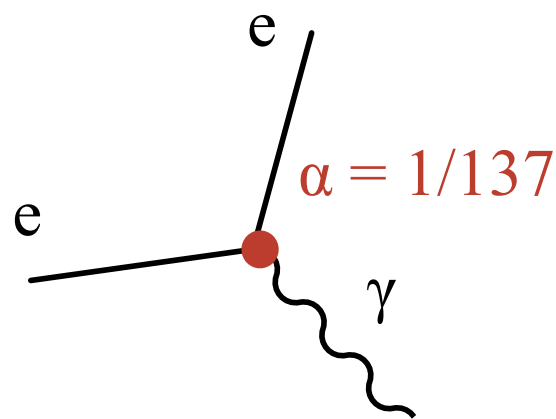
$$m_H^2 = \frac{m_{H^2}^{\text{Classical}}}{\dots} + \dots$$



Super Symmetry at the LHC



Interaction Strengths



Did not have to happen!

- Not put in by hand
- Could be coincidence
- Seems like strong sign we are the right track

Higgs as Window to New Physics

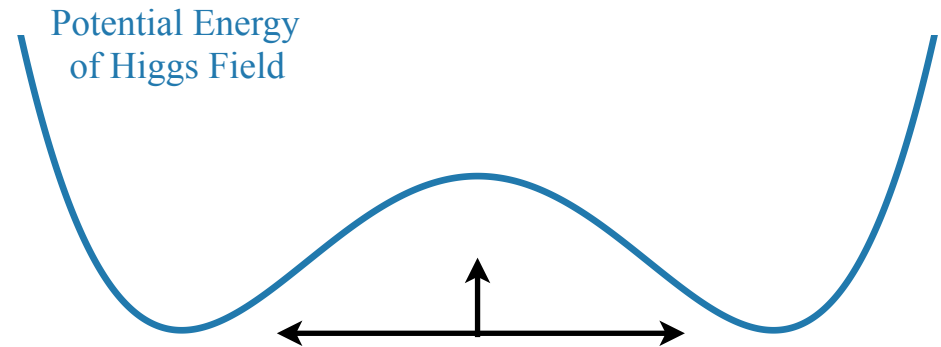
Higgs boson directly related to all potential solutions

Problem fundamentally related to Higgs field

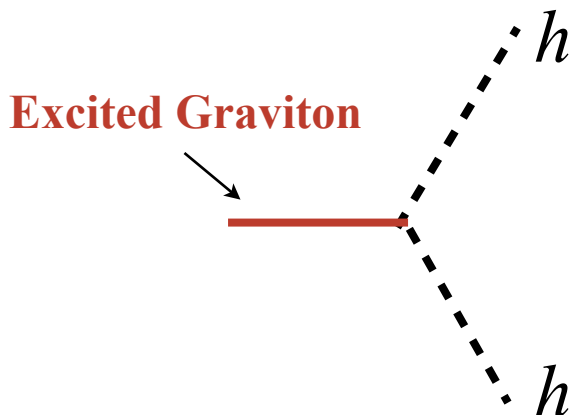
Higgs Boson is the harbinger of the Higgs field (how we study it)

Compositeness:

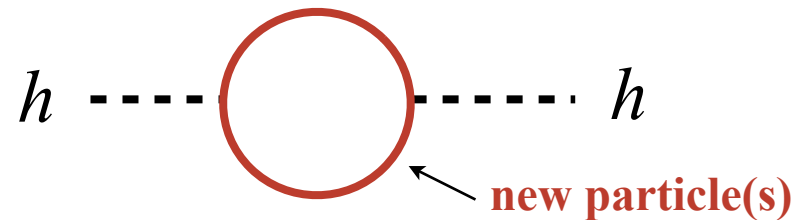
- Deeper origin for shape of potential
(probe experimentally with hh events)



Extra Dimensions:



SuperSymmetry:



Higgs as Window to New Physics

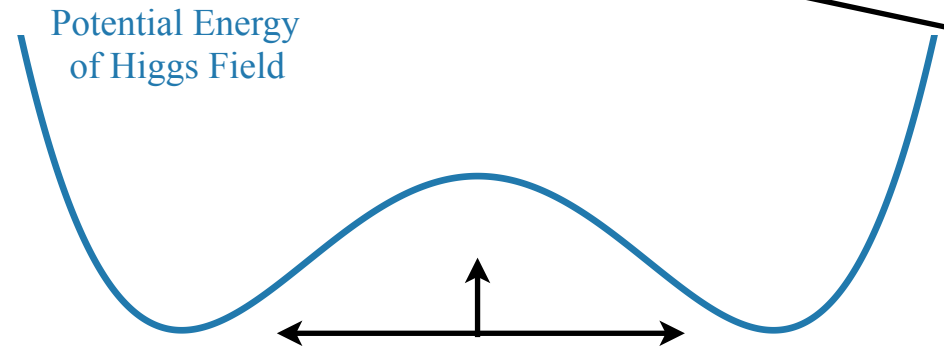
Higgs boson directly related to new physics

Go through examples of each of these

Problem fundamentally related to Higgs mechanism
Higgs Boson is the harbinger of the Higgs field (how we

Compositeness:

- Deeper origin for shape of potential
(probe experimentally with hh events)



Extra Dimensions:

SuperSymmetry:

This is what the Higgs boson is good for ! (Deeper level-answer)

Studying Higgs boson production/decays addresses why gravity is so weak.
Not a boring technical detail ! Responsible for ~all structure that around us.

h

new particle(s)