

Title: Quantum Mechanics and Spacetime in the 21st Century

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Abstract: Prepare to be amazed. Nima Arkani-Hamed is one of the world's most innovative scientists, with an infectious enthusiasm for decoding the mysteries of the universe. Renowned for his dynamic and accessible speaking style, Arkani-Hamed is among the most sought-after experts on topics including dark matter, extra dimensions, particle colliders, and the interconnectedness of them all. He was featured prominently in the critically acclaimed 2013 documentary *Particle Fever*, chronicling the search at the LHC for the Higgs boson. Arkani-Hamed will explore how recent research into quantum mechanics (nature's most fundamental forces and phenomena) promises to shed new light on our understanding of the universe's fabric of time and space.

Quantum Mechanics + Space-Time



in the

21<sup>st</sup> Century

Triumph of 20<sup>th</sup> Century

Relativity + Quantum Mechanics

↓  
Universe is Inevitable

Central / O Ramas

2<sup>nd</sup> of Central

★ End of Spacetime [Gravity]

Limitations of QM [Cosmology]

★ Why is the Universe

BIG, with BIG

it?

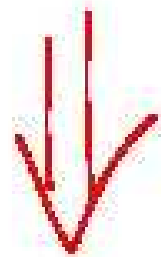
\* Shockingly constrained  
by what we already know -  
unlike ever before!

[ALMOST IMPOSSIBLE TO  
[LITERARY WOULD]

20<sup>th</sup> Century Redux

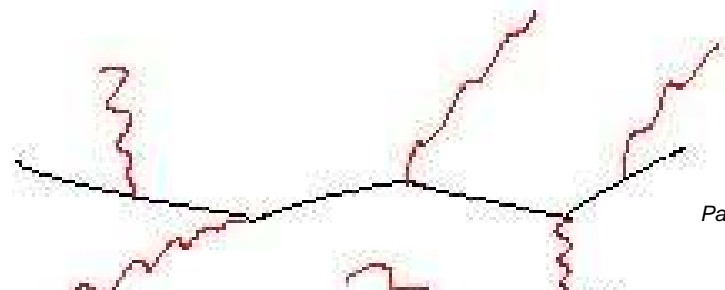
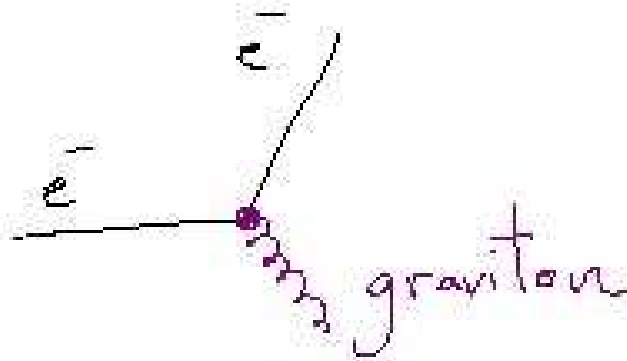
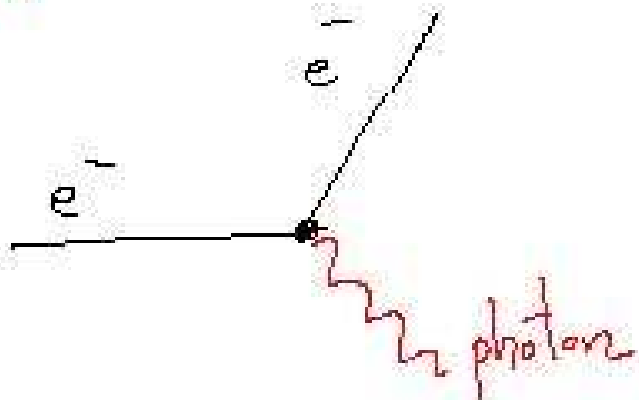


Relativity + QM

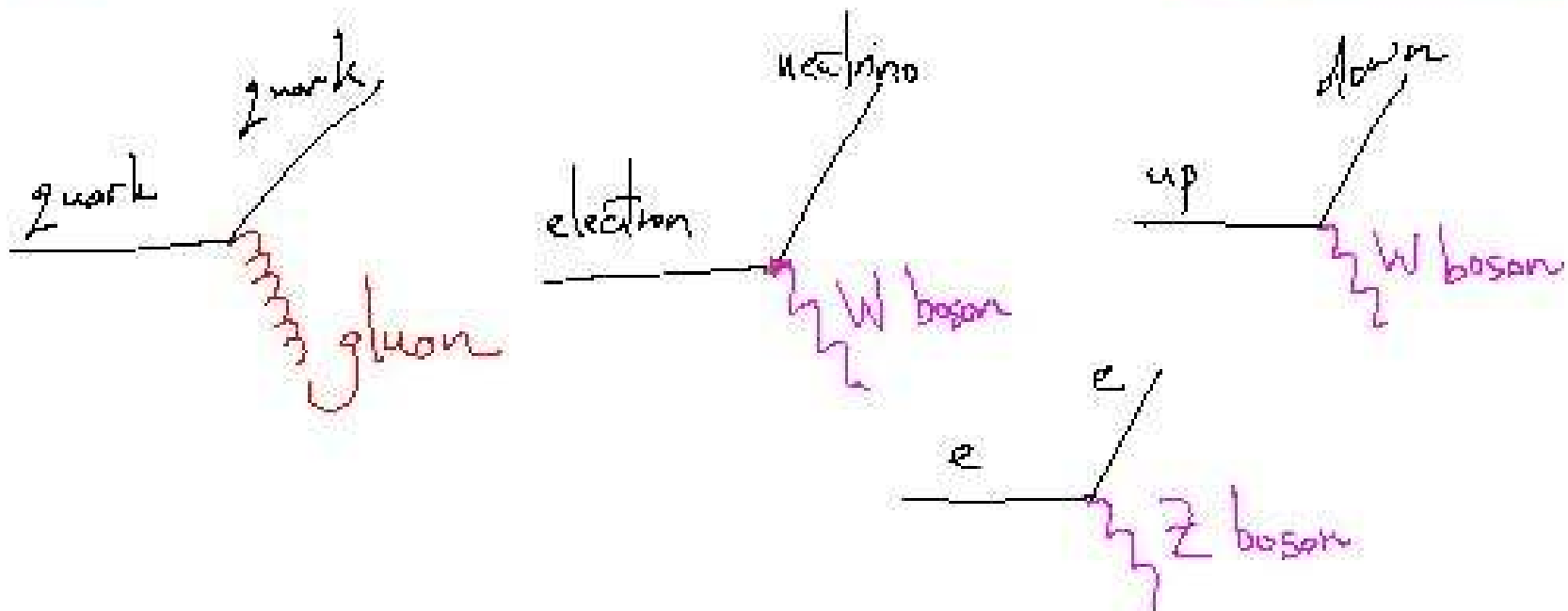


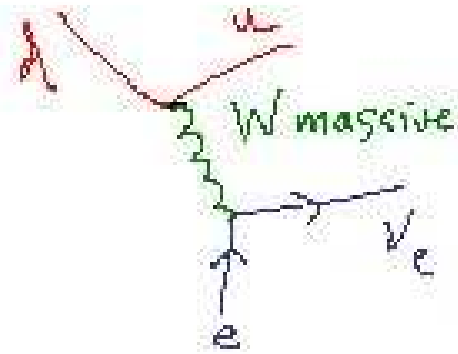
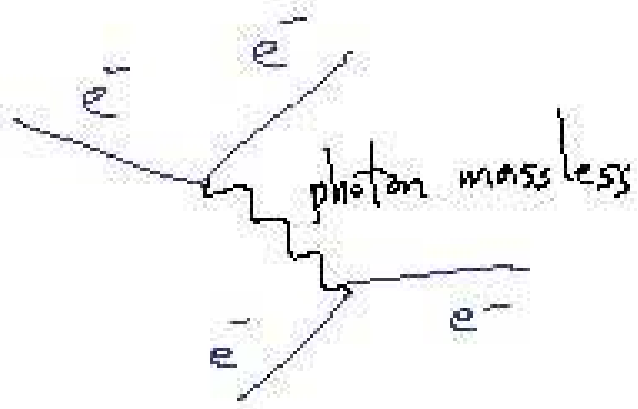
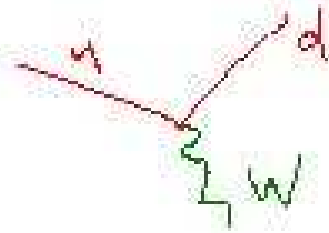
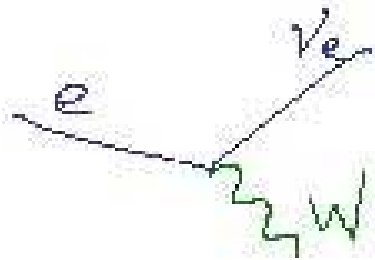
“Quantum Field Theory”

# Gravity + Electromagnetism



# Strong + Weak: Same Structure!

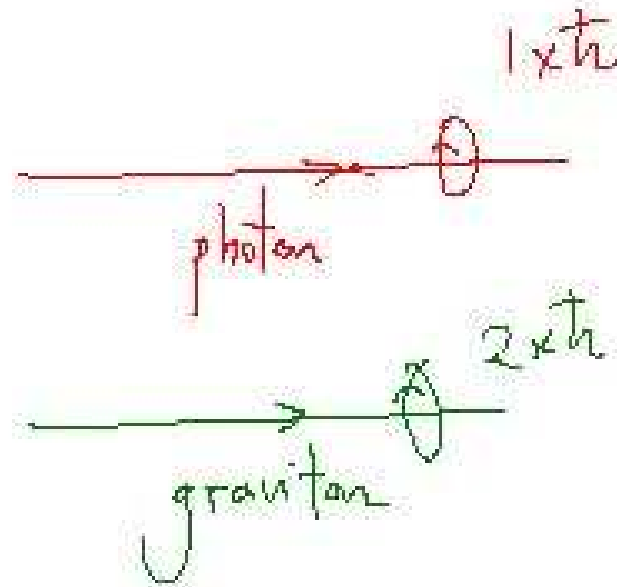
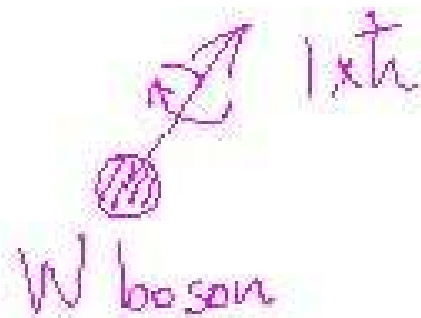
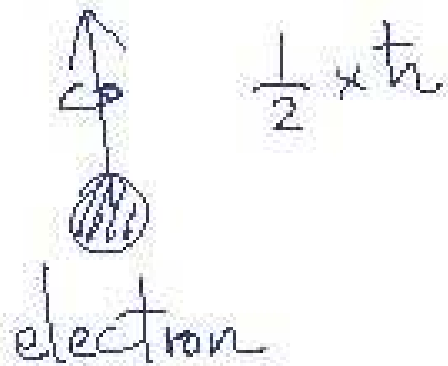




long-range force

short-range!  
 $(\sim 10^{-16} \text{ cm})$

Particles have "Spin"

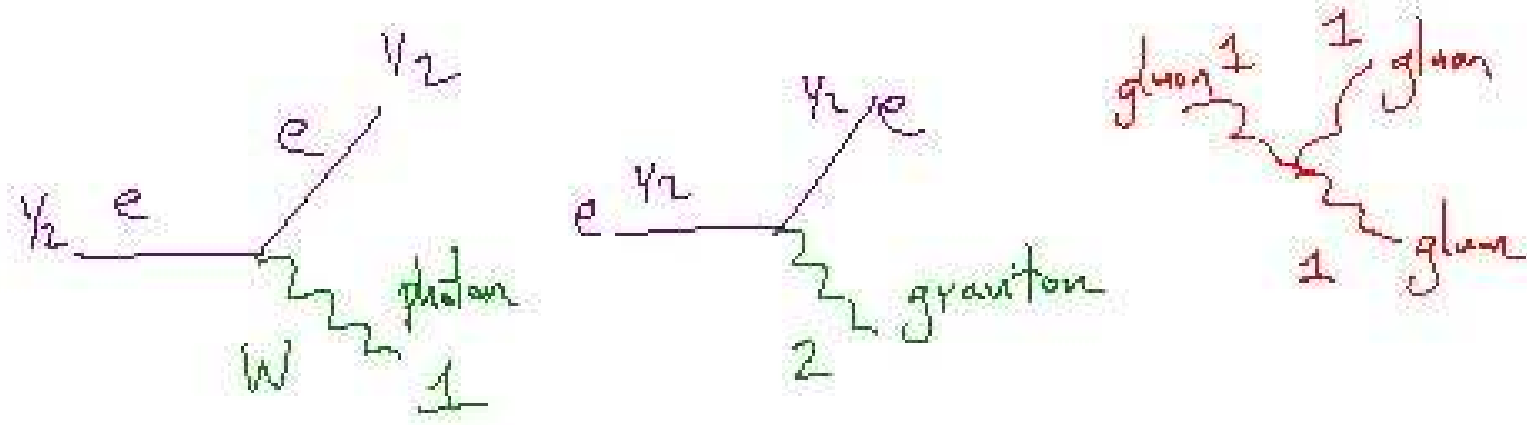


Allowed:

0,  $\frac{1}{2}$ , 1,  $\frac{3}{2}$ , 2,  $\frac{5}{2}$ , 3, ...  $\times h$

Particles we see extremely simple!

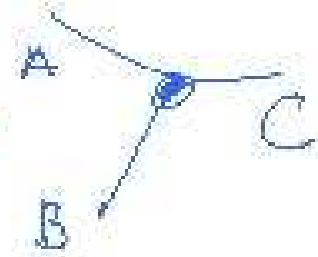
Just:  $\frac{1}{2}, 1, 2$



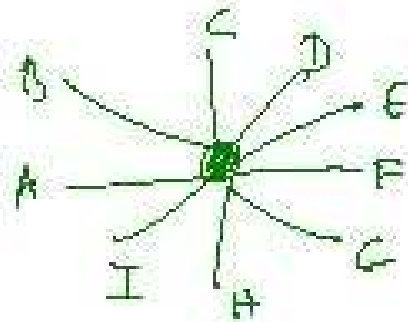


Why So Simple?

• Why simple fundamental interaction

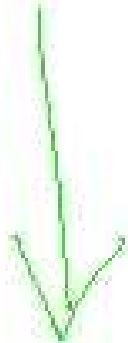


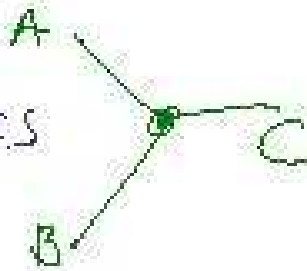

why not



?

• Why such a tiny menu of spins?

Whatever the Ultimate Theory  
Relativity  Quantum Mechanics

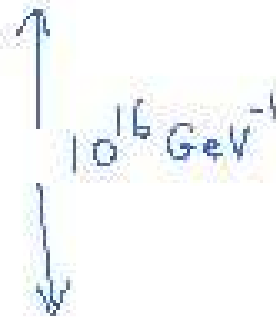
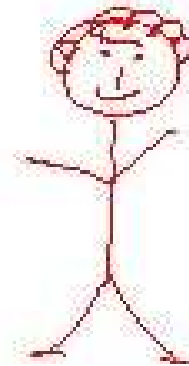
At "Long" distances, particles interacting as   
with spins  $0, \frac{1}{2}, 1, \frac{3}{2}, 2$ .  unique, "gravity"

# Units!

$$\text{time} = \frac{\text{distance}}{c}$$

$$\text{Energy} = \frac{\hbar}{\text{time}}$$

$$\text{Put } \hbar = c = 1$$



$10^{16} \text{ GeV}^{-1}$

Mass  $\sim 10^{29} \text{ GeV}$

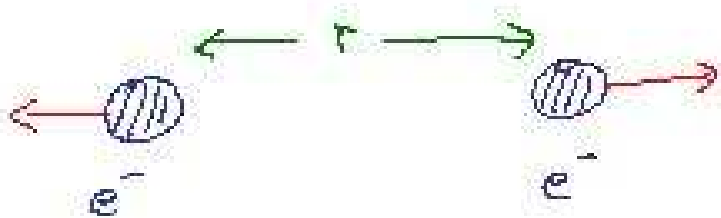
Lecture time  $\sim 10^{29} \text{ GeV}^{-1}$

$$(m_p c^2) = 1 \text{ GeV}$$

$\textcircled{P} \downarrow 10^{-14} \text{ cm}$   
 $\sim \text{GeV}^{-1}$

LHC Energies

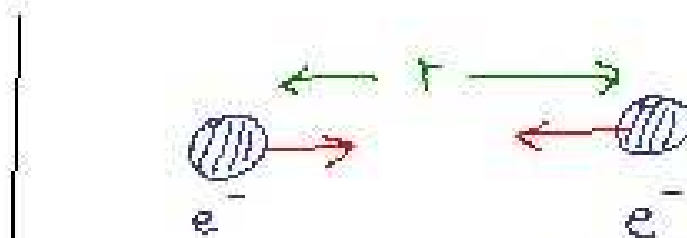
7000 GeV



electric Force  $\sim q^2 \frac{1}{r^2}$

$q^2 \sim \frac{1}{137}$  [a pure number!]

*strength*

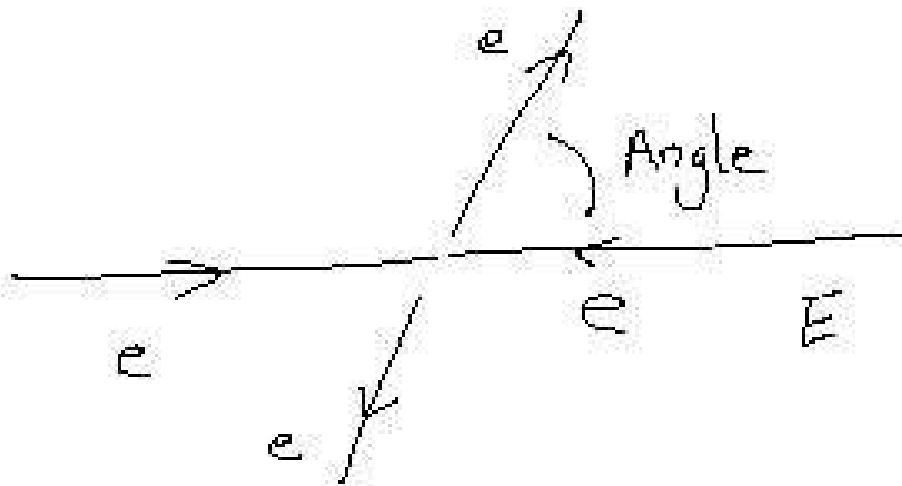


grav Force  $\sim -G_N \frac{m_e^2}{r^2}$

$\sim (10^{-33} \text{ cm})^2 \sim (\ell_{\text{Planck}})^2$

$\frac{1}{\ell_p} \sim (10^{19} \text{ GeV})$

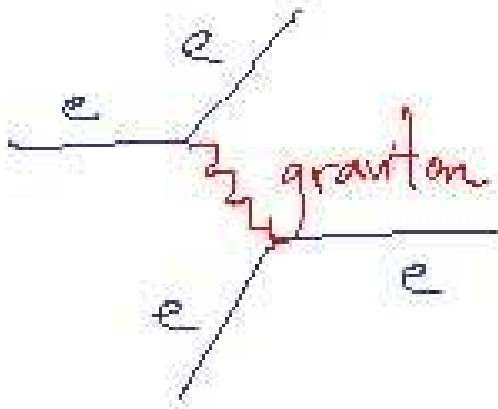
# Quantum Mechanics



$$\text{Probability} = (\text{Amplitude})^2$$

Amplitude  
 $\sim g^2$   
 $\sim 1\%$   
small

# Mystery of "Quantum Gravity"

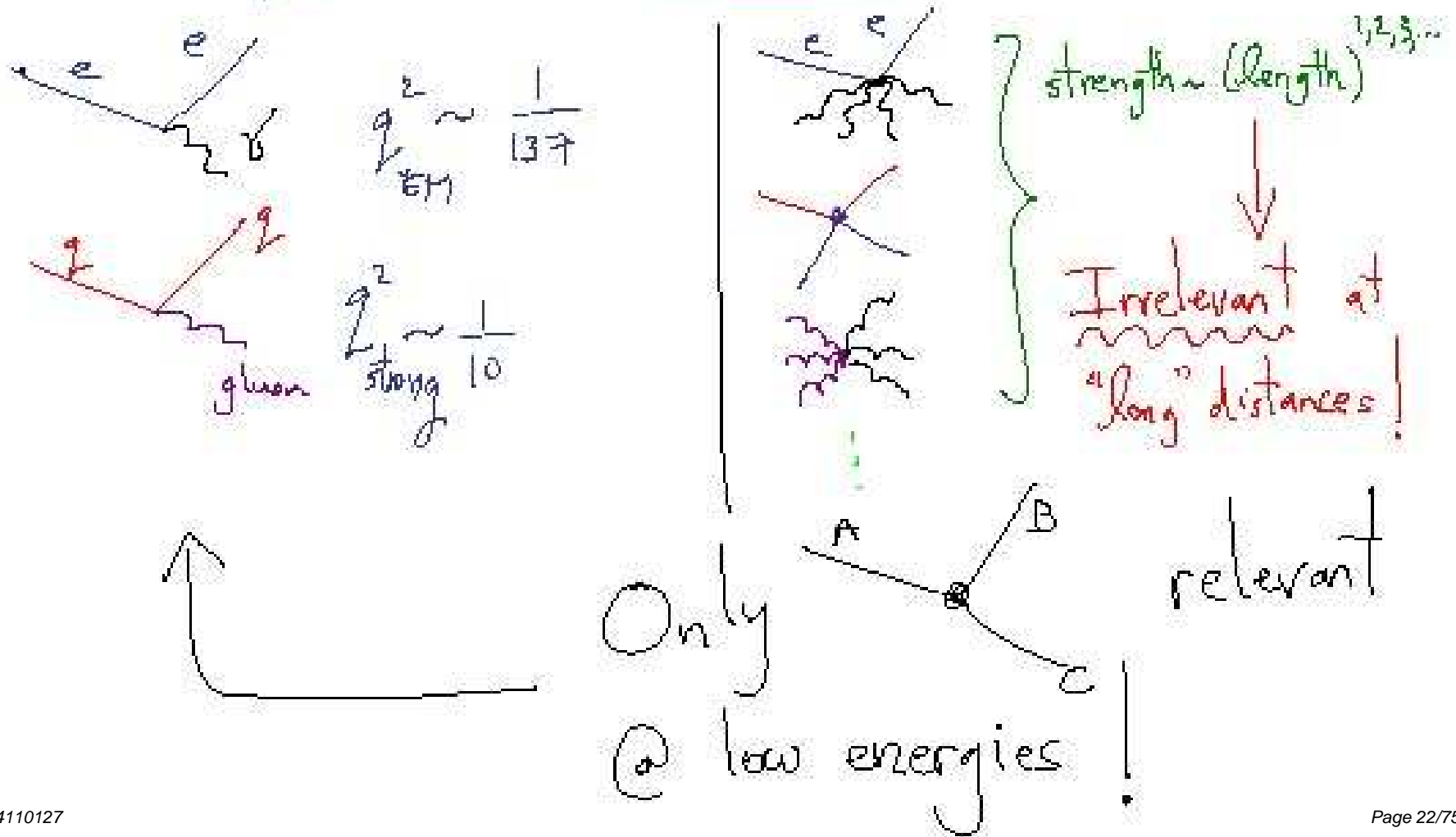


$$\text{Amplitude} \sim G_N \times E^2$$

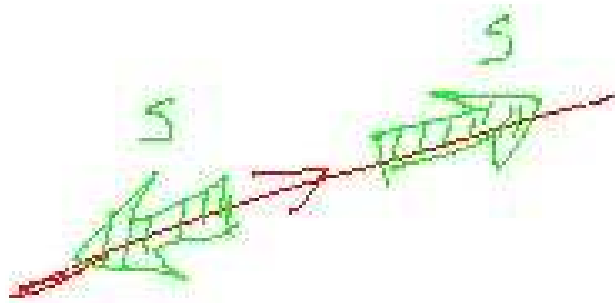
tiny for  
 $E \ll (10^{19} \text{ GeV})$   
Planck Energy

Bigger than 1 (!)  
for  $E \gg (10^{19} \text{ GeV})$

# "Effective" Theories

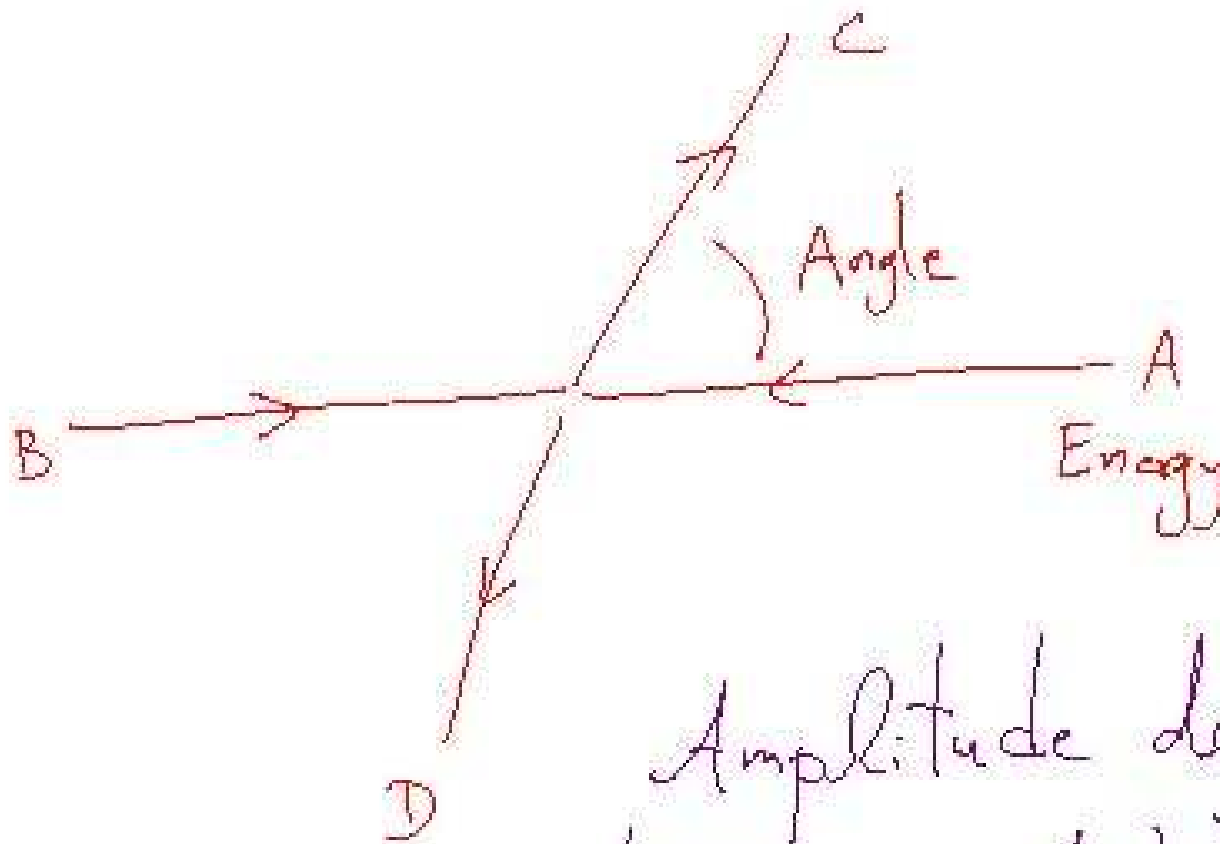


At high energies  $\rightarrow$  Approximate particles  
as massless

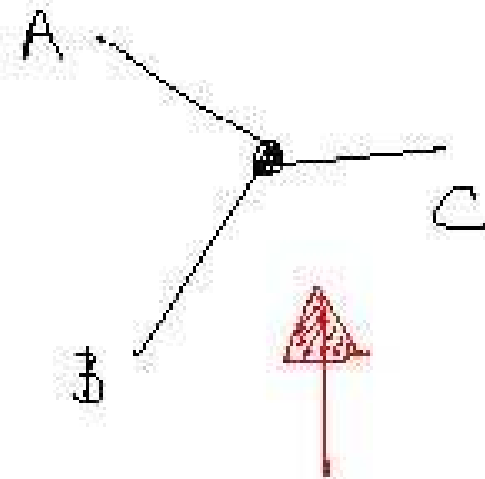
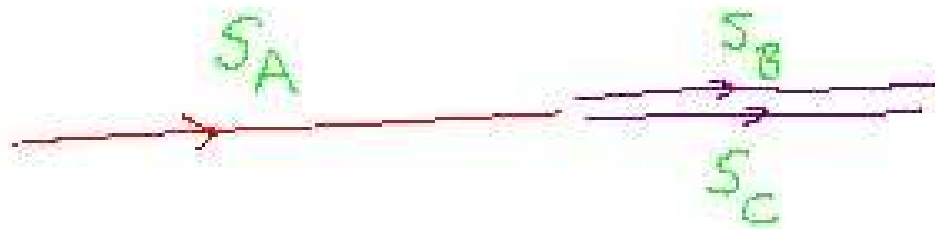


$$\text{Energy} = |\text{momentum}|$$

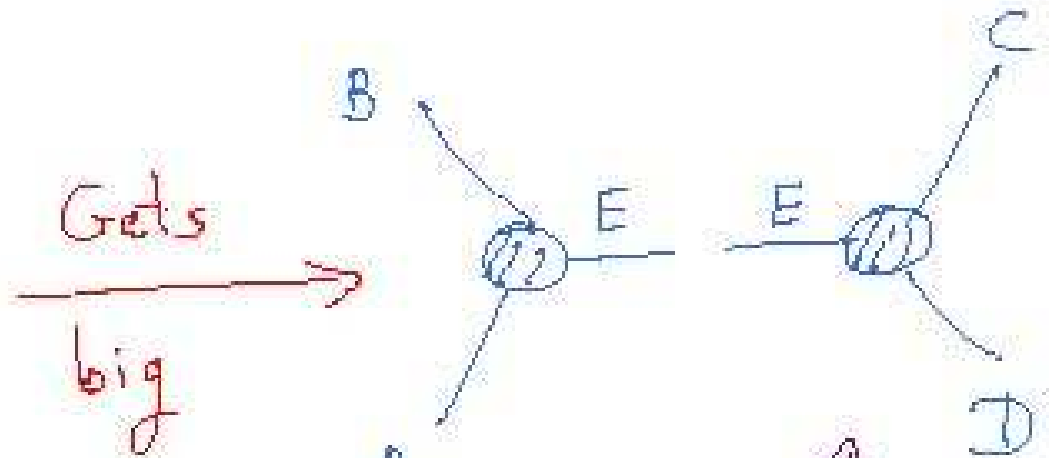
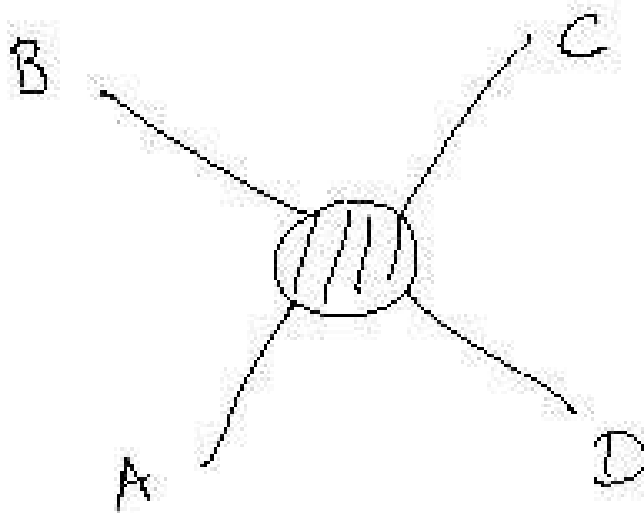
Spin  $\rightarrow$  "helicity"



Amplitude depends of  
(Energy, Angle), Complicated!



No (Energy, Angle)  $\rightarrow$  COMPLETELY  
 FIXED  
 (up to strength)  
 by helicities!



Again, Completely  
Known



1 yr of Grad School

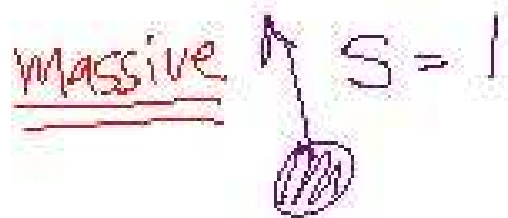




What About The

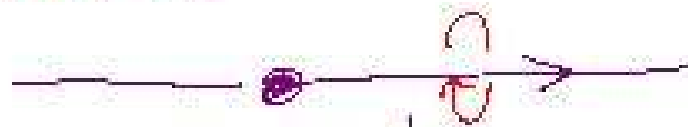
Higgs?

Important difference between massive + massless particles with spin:



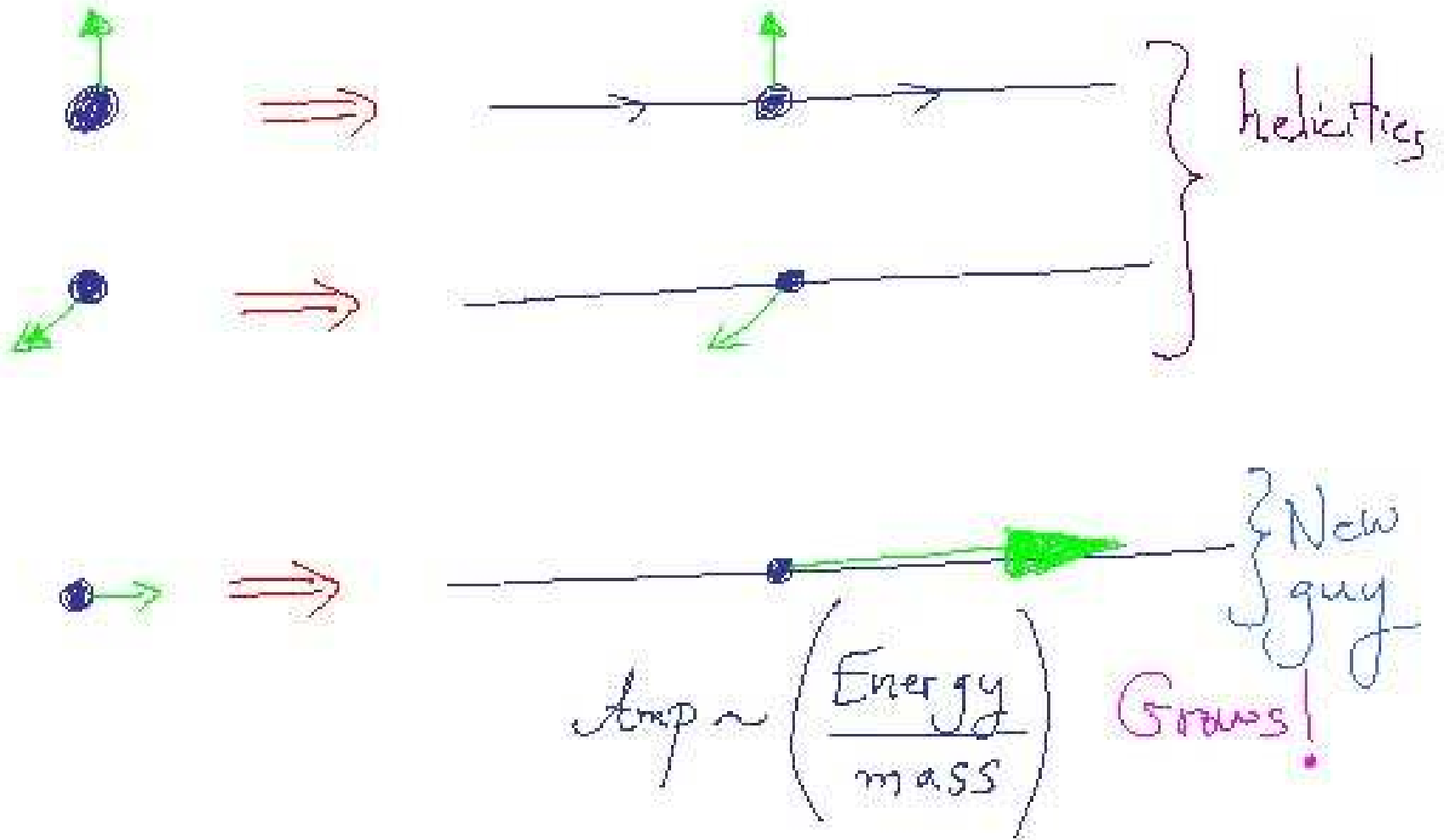
3 spin

massless



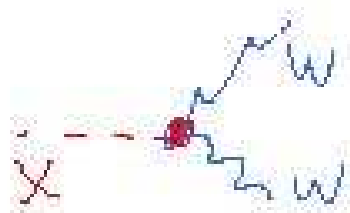
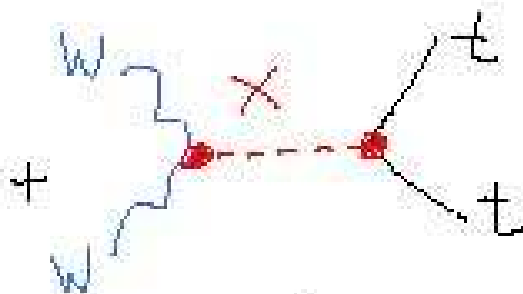
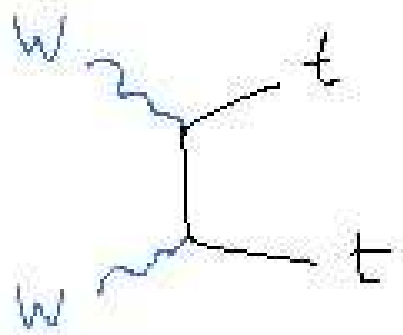
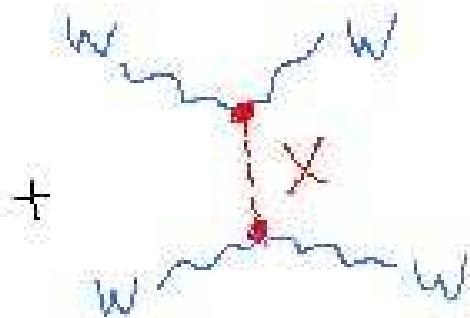
2 helicities

One extra guy!





# Need Something New!



strengths  
nailed

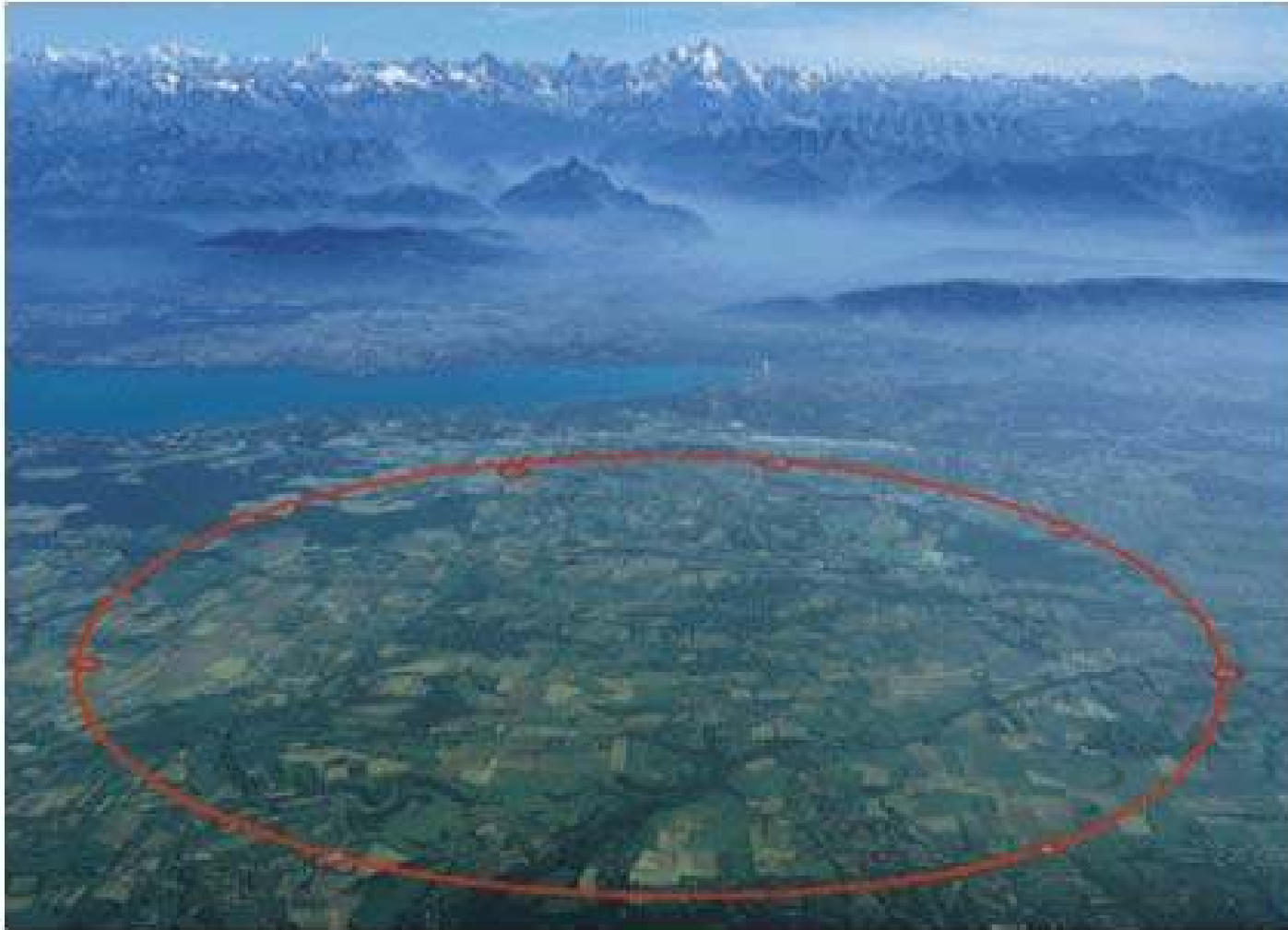
Spin of X:

- 
- ~~1~~
- ~~2~~
- ~~3~~
- ~~4~~ ...



MUST BE  
SPIN ○

X = Higgs



TRUMP H For EXPERIMENT

TRUMP H For THEORY

PHYSICS WORKS


Belief in Principles Paid Off

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

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

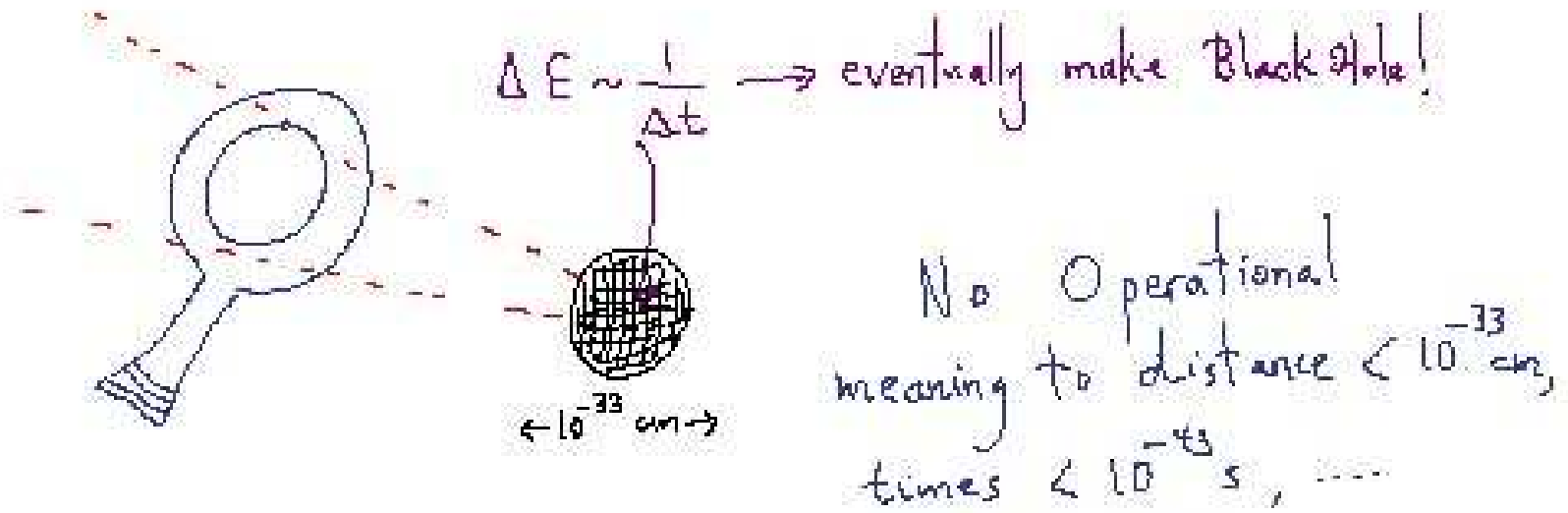
With the discovery of the Higgs,  
for the first time in our history,  
we have a self-consistent theory  
that can be extrapolated to  
exponentially higher energies.

21<sup>st</sup> Century Frontiers

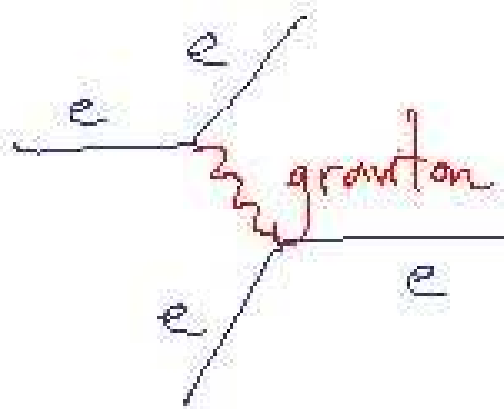


Space-Time is Doomed

What Replaces ITP



Energy needed  $\sim 10^{19}$  GeV  
 (L.H.C. Energies  $\sim 10^3$  GeV...)

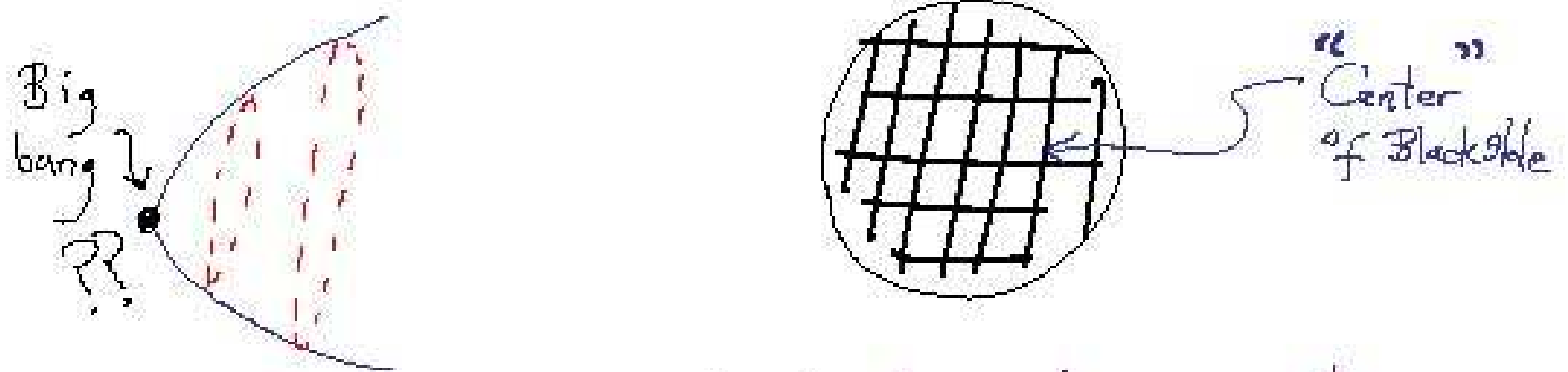


$$\text{Amplitude} \sim (G_N \times E^2)$$

tiny for  
 $E \ll (10^{19} \text{ GeV})$

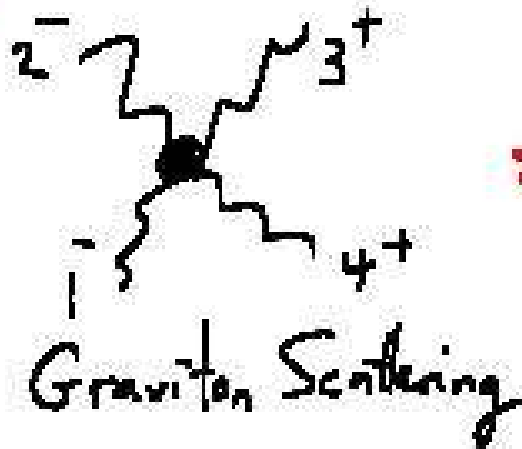
Bigger than 1 (!!!)  
 for  $E \gg (10^{19} \text{ GeV})$

PLANCK  
 ENERGY



Our theories just break down when gravity is strong and quantum gravity effects are dominant.

# A First Challenge in Quantum Gravity



$$: \text{Amp} = G_N \frac{(\langle 12 \rangle [34])^4}{stu}$$

Correct at  
low energies  
 $s, t, u \ll \frac{1}{G_N}$

Wrong @ high  
energies!  
 $s, t, u \gg \frac{1}{G_N}$

# Naive Attempts Fail

$$G_N (\langle 12 \rangle [34])^4 \frac{1}{stu} = \left( \frac{1}{1 - \frac{s}{\Lambda^2}} \right) \left( \frac{1}{1 - \frac{t}{\Lambda^2}} \right) \left( \frac{1}{1 - \frac{u}{\Lambda^2}} \right)$$

Standard

Modification to Suppress  
High Energy Growth

Violate "Unitarity" → Negative Probabilities!

# Discovery of Miraculous Formula

$$\Gamma(n) = (n-1)!$$

$$G_N(\langle 12 \rangle [34])^4 \times \frac{\Gamma\left(1 - \frac{s}{M^2}\right) \Gamma\left(1 - \frac{t}{M^2}\right) \Gamma\left(1 - \frac{u}{M^2}\right)}{\Gamma\left(1 + \frac{s}{M^2}\right) \Gamma\left(1 + \frac{t}{M^2}\right) \Gamma\left(1 + \frac{u}{M^2}\right)}$$

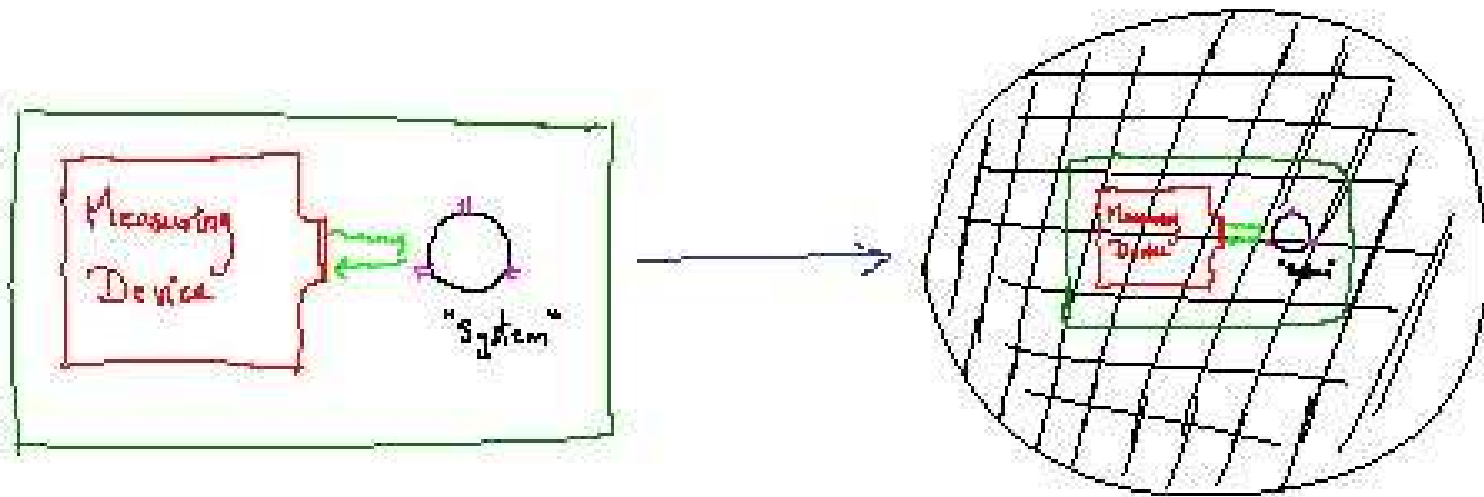
INCREDIBLY: NO NEG. PROB.!

Where did

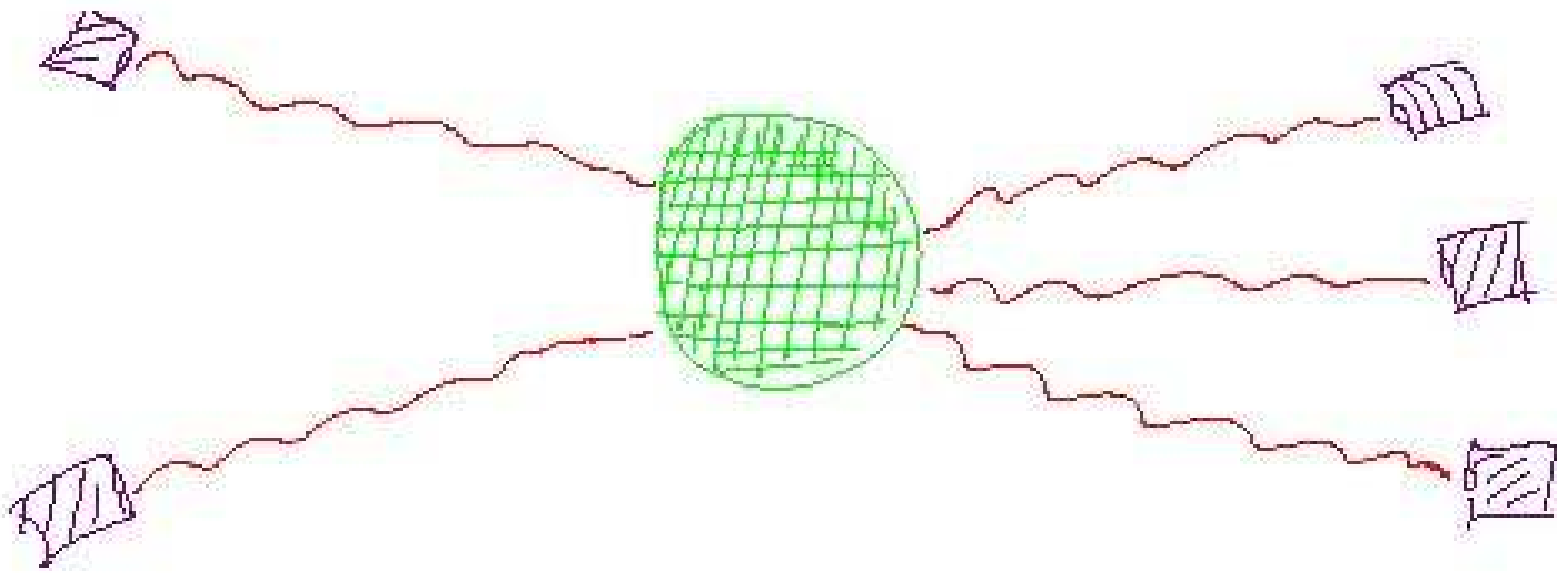


STRING

No Local Observables!

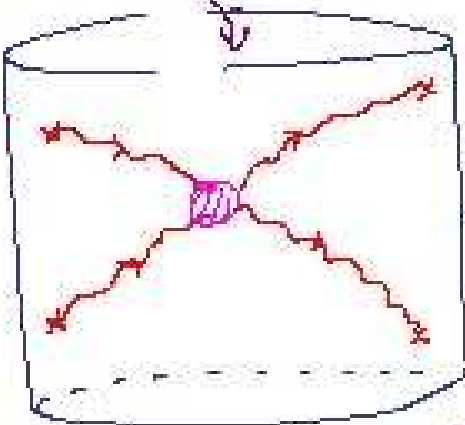


# Observables on "Boundary at Infinity"



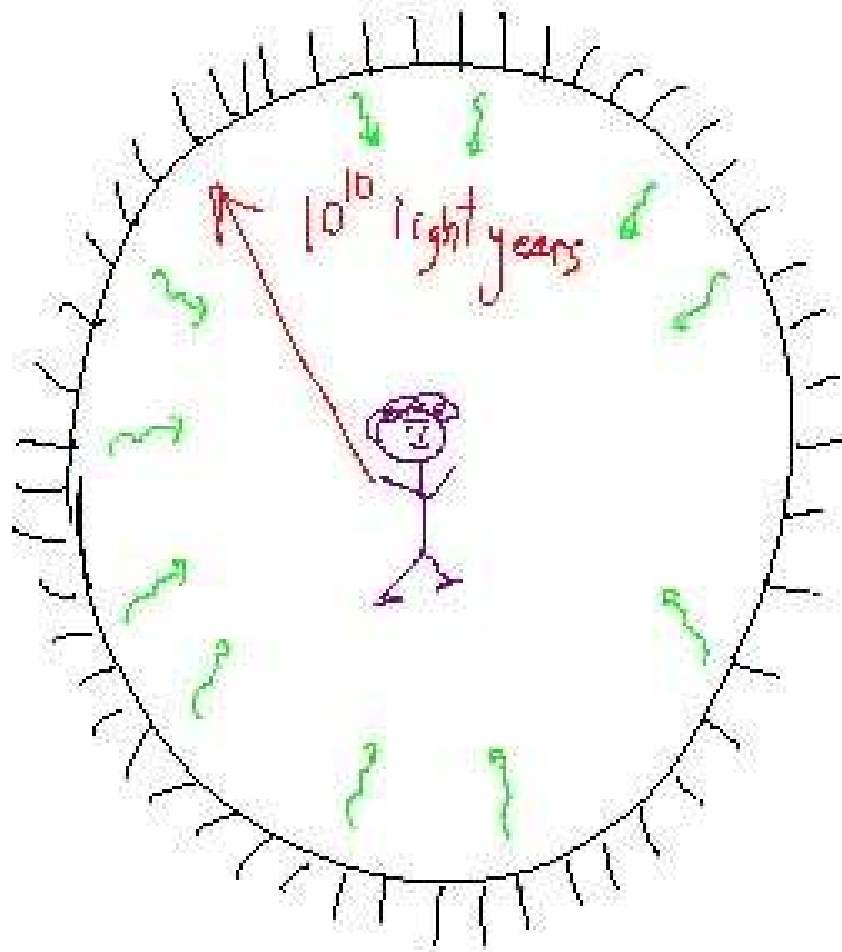
$$(Quantum\ Gravity)_{D+1} = (Quantum\ Field\ Theory)_D$$

Emergent  
Space, Gravity,  
Strings ...  
↑  
time



'Anti-de Sitter  
Space'

$$String\ Theory = Particle\ Physics$$



What are  
the correct  
observables?

Emergent

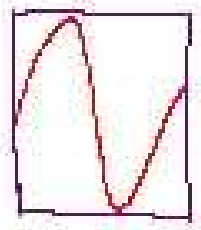
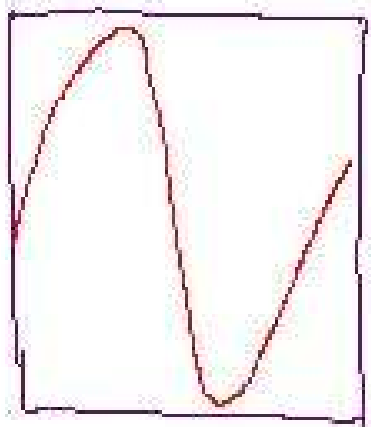
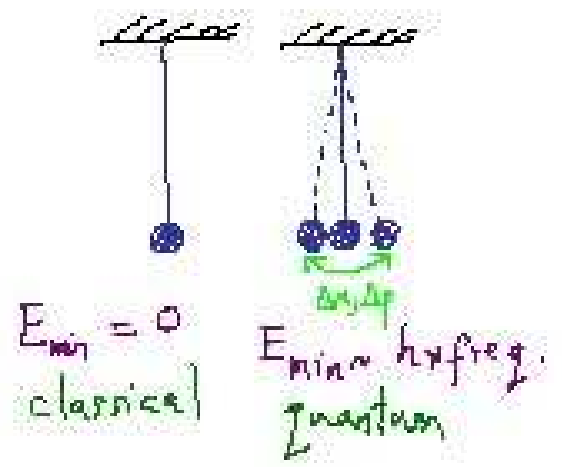
Space-Time

Why Is There A

Macroscopic Universe?

# Vacuum is too Exciting

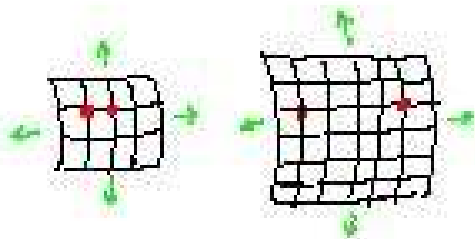
Even Vacuum has energy!



Bigger Fluctuations at Shorter Distances

# Estimating $\Delta$

$$\text{"Vacuum Energy Density"} \sim \frac{\text{Energy}}{\text{Volume}} \sim \left[ \frac{\text{Planck}}{\text{Planck Volume}} \right]$$



Explosive Acceleration -  
Doubling size every  $10^{-43}$  s !

# What We Do

$$\Lambda_{\text{observed}} = \Lambda_{\text{classical}} + \Lambda_{\text{Quantum}}$$

$$\begin{array}{r} \underbrace{-2.6493781 \dots 526 \dots}_{120 \text{ decimals}} \\ + \underbrace{2.6493781 \dots 534 \dots}_{120 \text{ decimals}} \end{array}$$

SEEMS LUDICROUS

{ [ \_\_\_\_\_ ] }

An Obvious Gap!

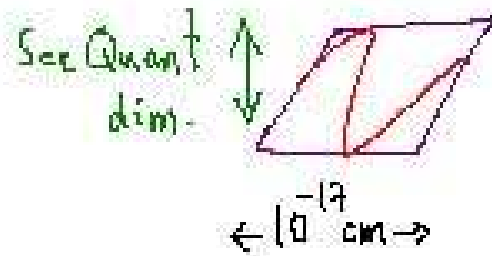
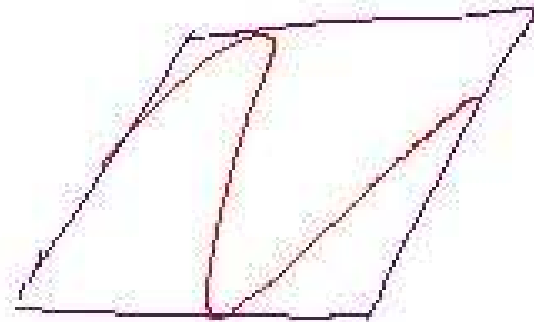
$\{0, \frac{1}{2}, 1, \frac{3}{2}, 2\}$

↑ POSSIBLE,  
VERY SPECIAL!

“SUPER SYMMETRY”

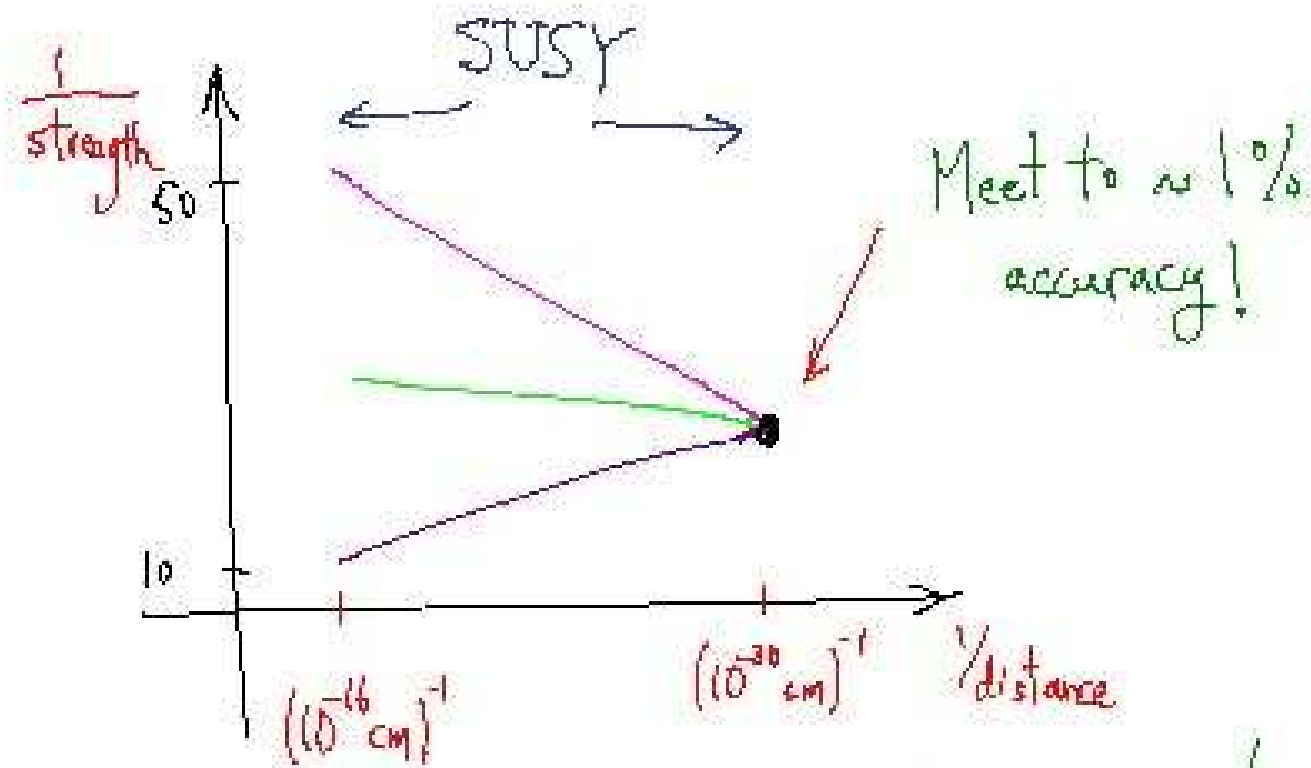


Violent  
Quantum  
Fluctuations



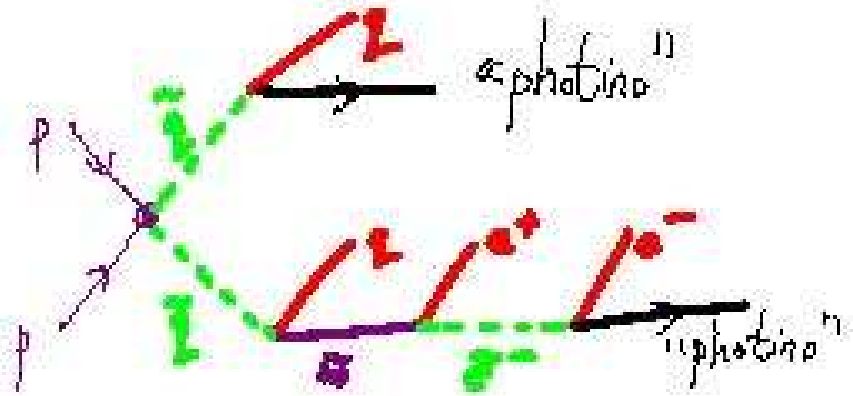
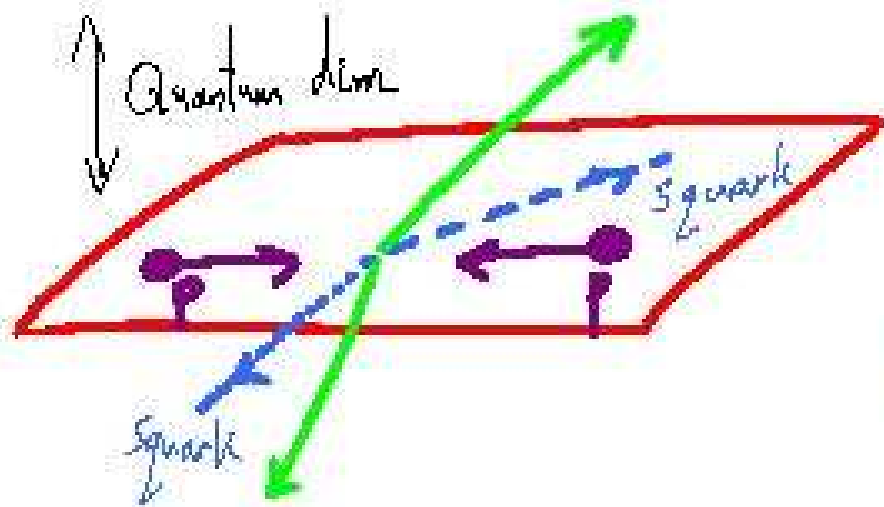
Gone  
~~uuuuuu~~



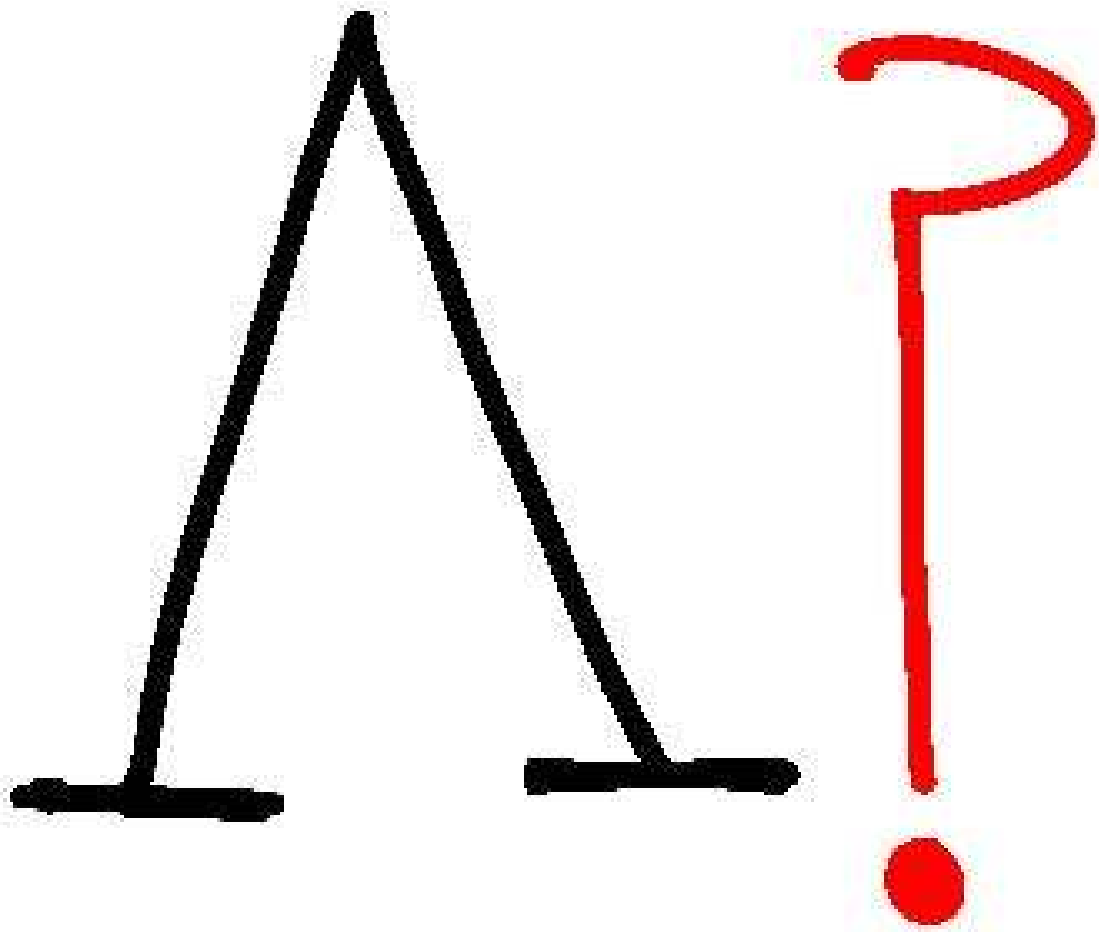


Unification of the Forces - Gravity not far behind!

# SUSY at the LHC



"Missing" Energy



# LHC By 2018

“Natural”



See major  
new physics  
SUSY

“Fine-Tuned”

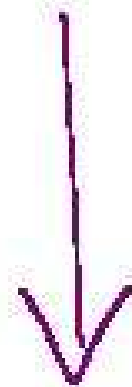


Nothing but Higgs, or  
unusual SUSY  
Bigger Paradigm Shift

Is there a deeper  
structure underlying  
Space-Time + QM?

• Sometimes, the most crucial clues are "hiding in plain sight", as funny features of existing theoretical framework.

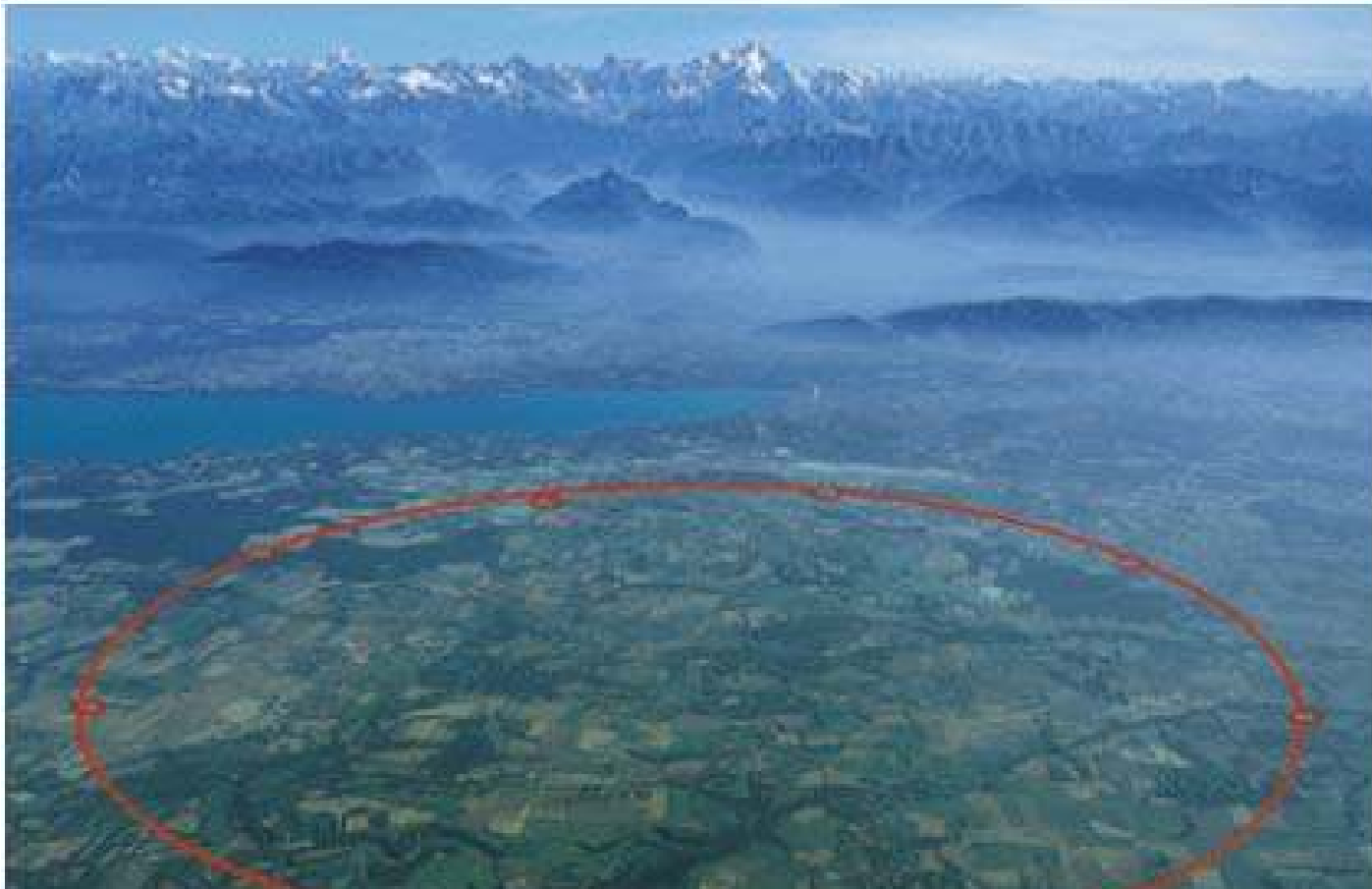
$$m_{\text{grav}} = m_{\text{inertial}}$$

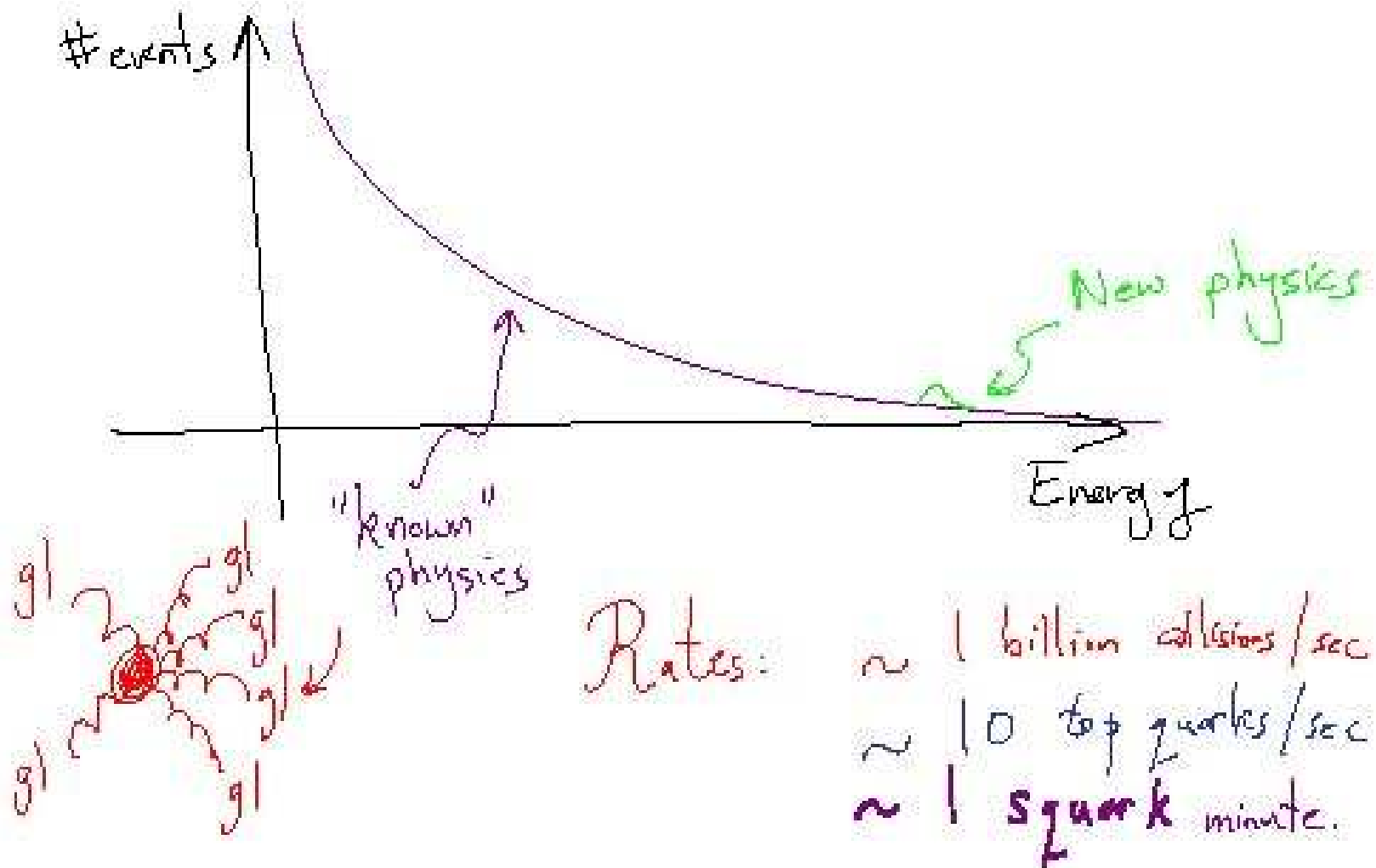


Principle of Equivalence

G. R.

L. H. C.





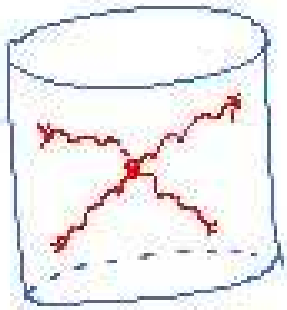


$$(1^- 2^+ 3^- 4^+ 5^+ 6^+)$$

$$\frac{\langle 13 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 56 \rangle \langle 61 \rangle} \quad (!)$$

Feynman's way of doing physics makes  
 usual rules of spacetime + QM  
 ... + + + obviously hiding

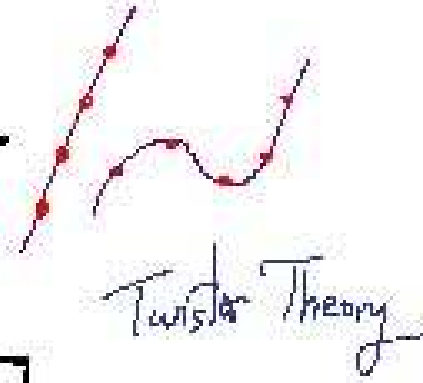
# Sitting Under our Noses for 60 yrs



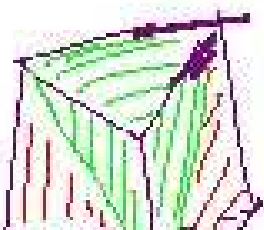
String Theory



New Formulation of  
standard physics —  
emergent spacetime, QM



Twistor Theory



Many Other Threads of This Sort

Mining "Theoretical Data":

Amazing Physical + Mathematical

# [ Speculation ]

We will come to see that

QM + Spacetime emerge

hand-in-hand from more primitive ideas

This is a singular  
time in the development  
of Fundamental Physics

The questions on the  
Table are the deepest  
ones — underpinnings of  
space + time, origins +

These questions couldn't have  
even been meaningfully  
articulated 50 yrs ago.

Today, we have finally have  
the theoretical framework to let us

We also have fantastic  
experimental probes on a  
number of fronts, that may  
give us important clues.

Exhilarating Time

J. B. D. Physics:

"Next Step" will likely