Title: Quantum Mechanics and Spacetime in the 21st Century

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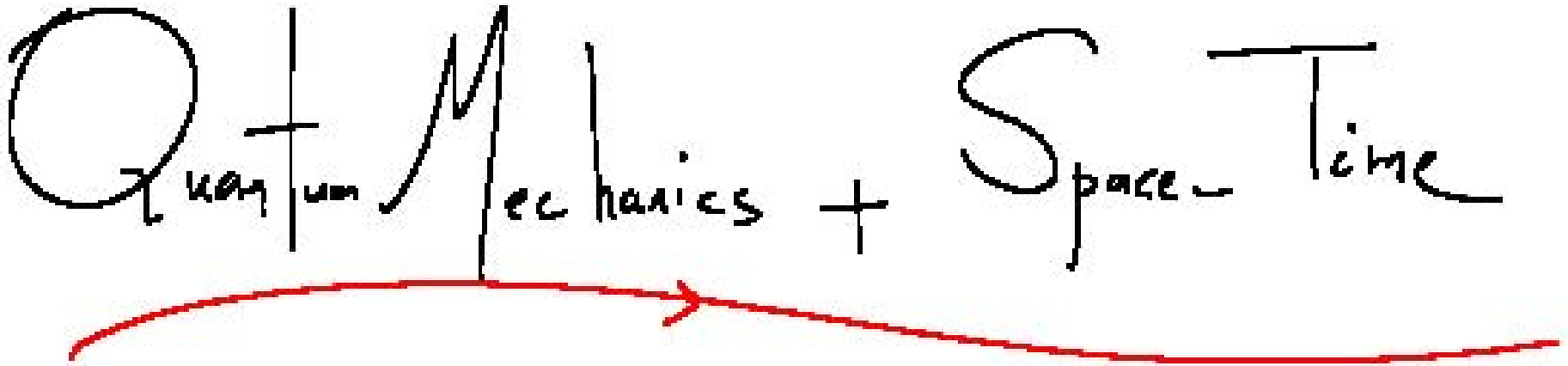
URL: http://pirsa.org/14110127

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 he universe's fabric of time and space.



in the

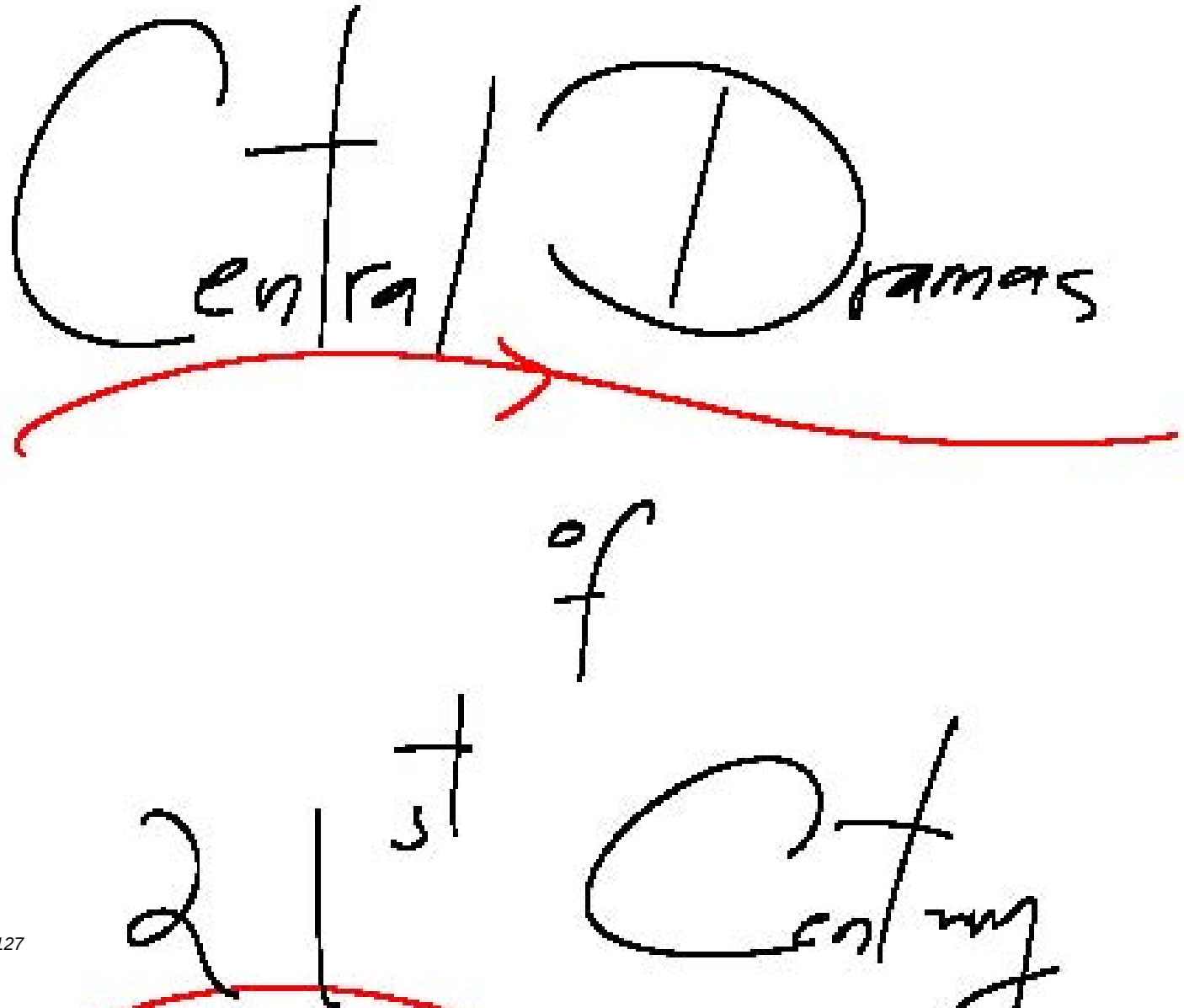
21st Century

Triumph of 20th Century

Relativity + Quantum Mechanics

↓

Universe is Inevitable


Central Dramas
of
21st Century

★ End of Space-time [Gravity]

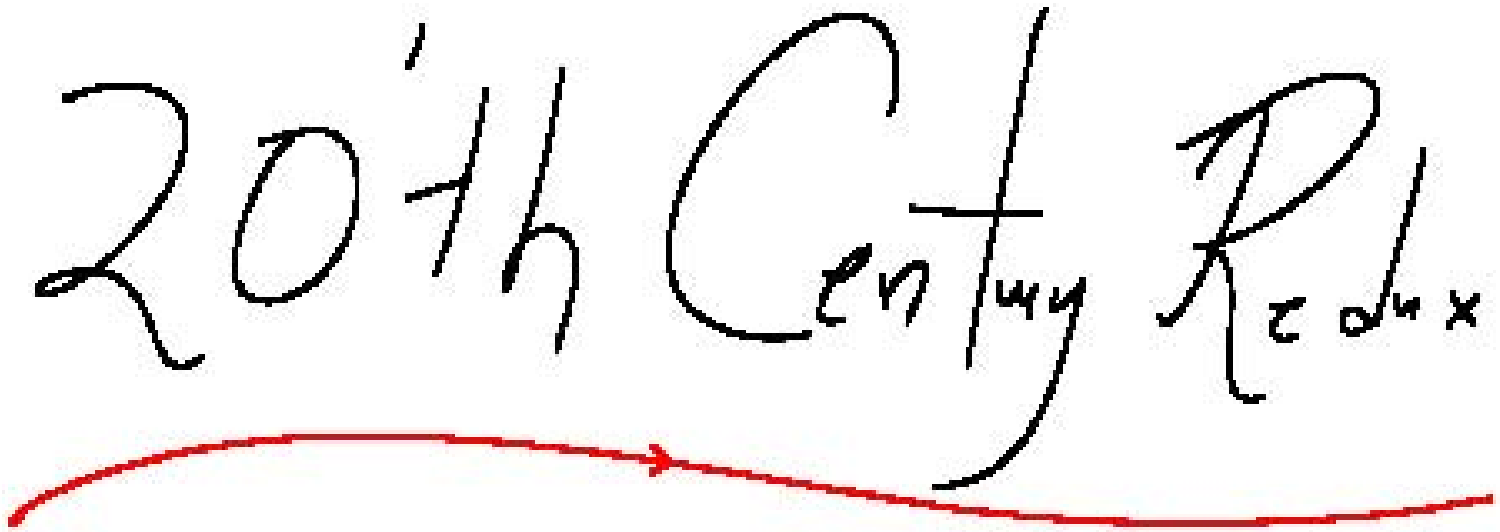
Limitations of QM [Cosmology]

★ Why is the Universe

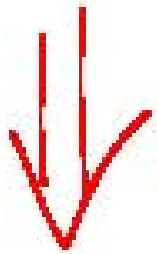
BIG, with BIG

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

[ALMOST IMPOSSIBLE TO

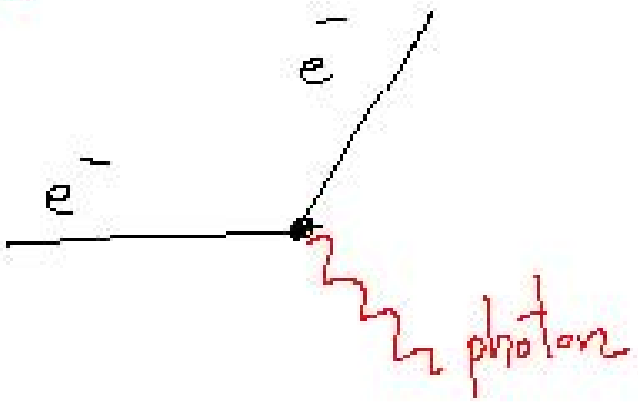

20th Century Redux

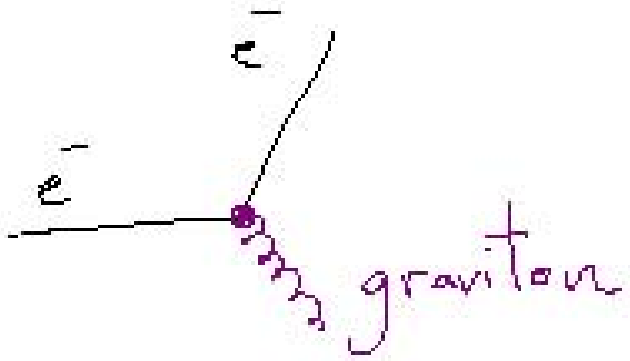
Relativity + QM

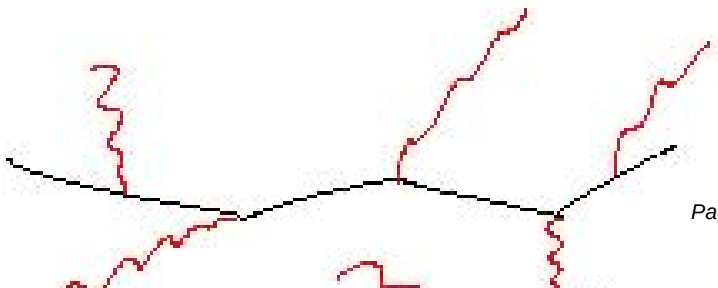


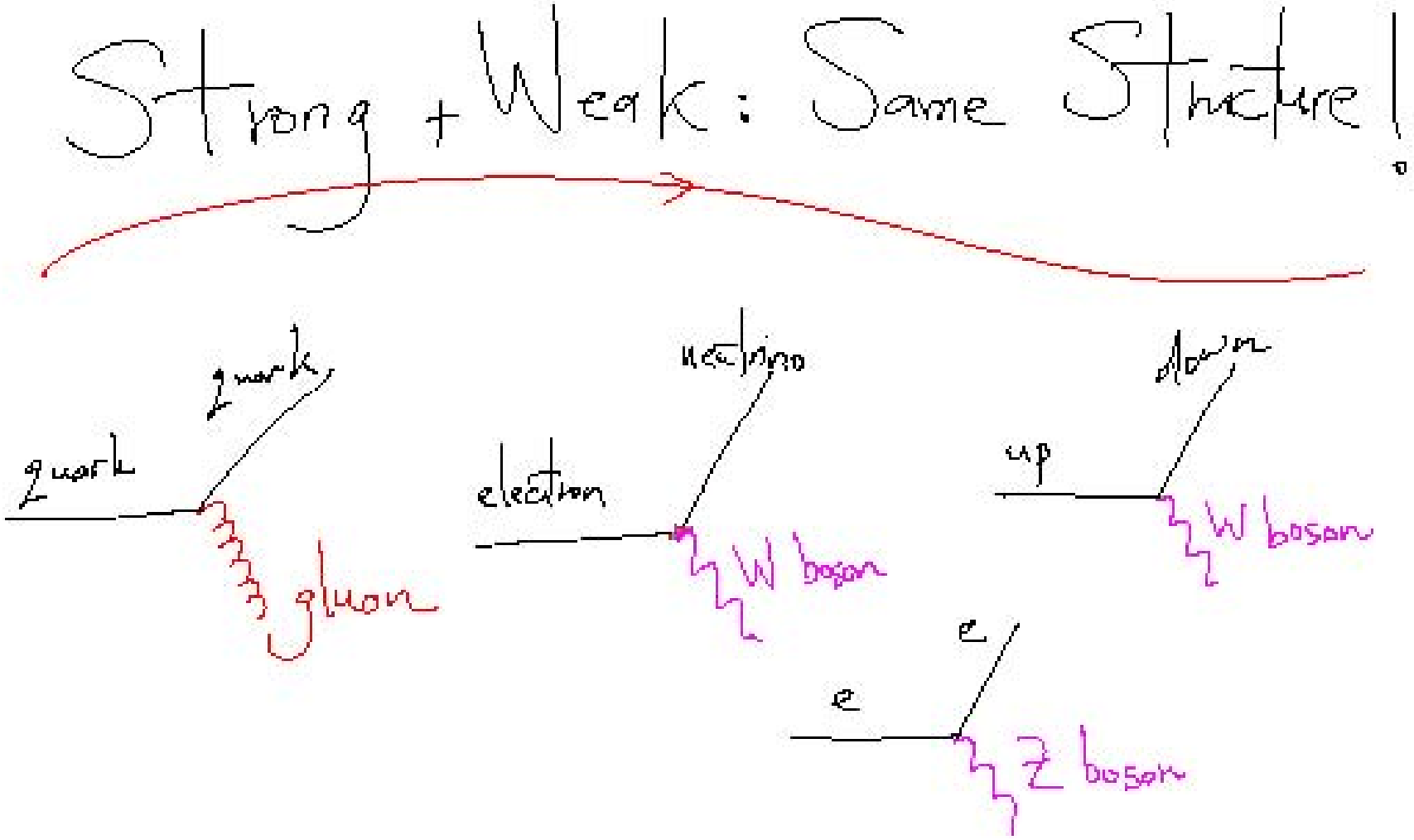
"Quantum Field Theory"

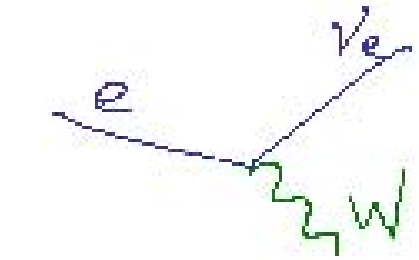
Gravity + Electromagnetism

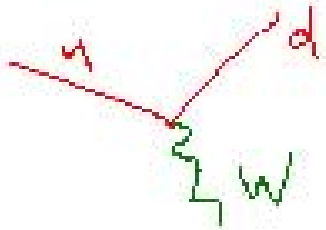


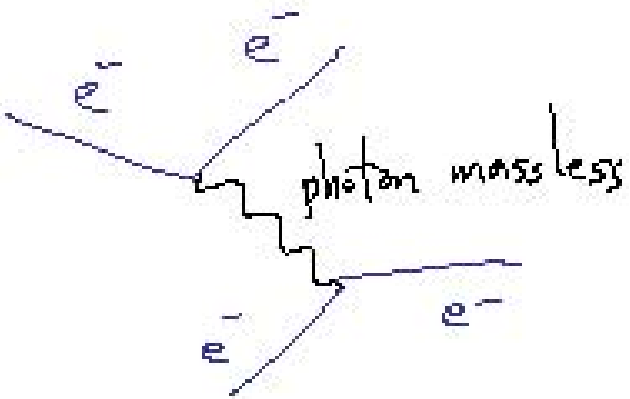





Strong + Weak: Same Structure!
quark
quark
gluon
electron
neutrino
W boson
up
down
W boson
e
e
Z boson



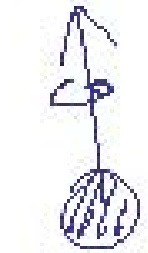




long-range force

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

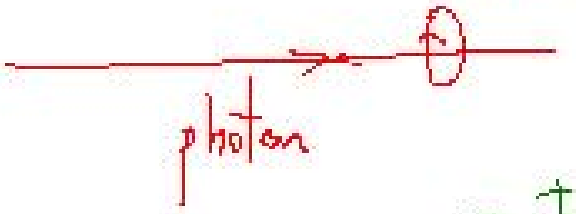
Particles have "Spin"



$\frac{1}{2}$ x th

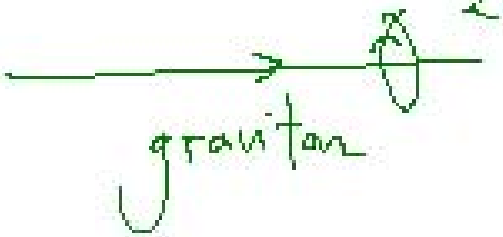
electron

1 x th

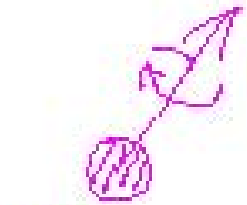


photon

2 x th



graviton



1 x th

W boson

Allowed:

0,

$\frac{1}{2}$,

1,

$\frac{3}{2}$,

2,

$\frac{5}{2}$,

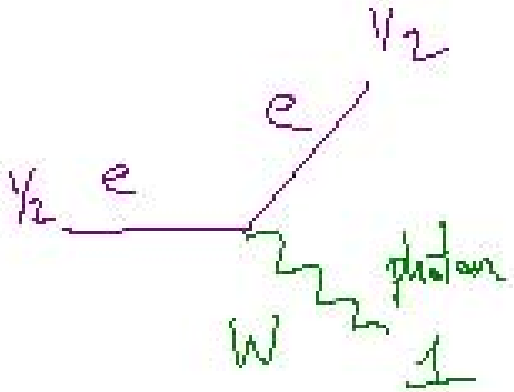
3,

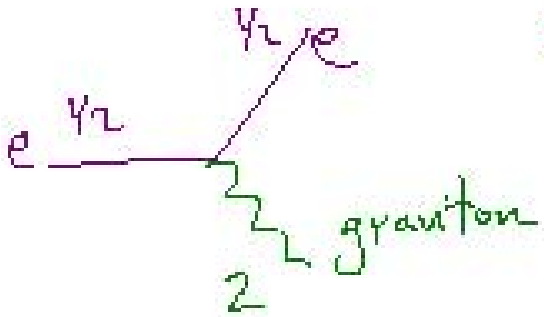
⋮

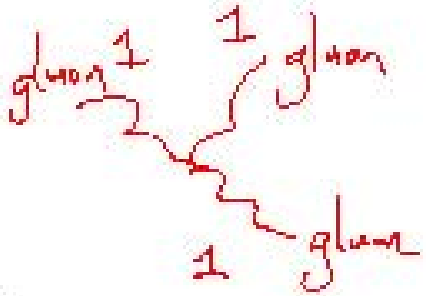
x th

Particles we see extremely simple !

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

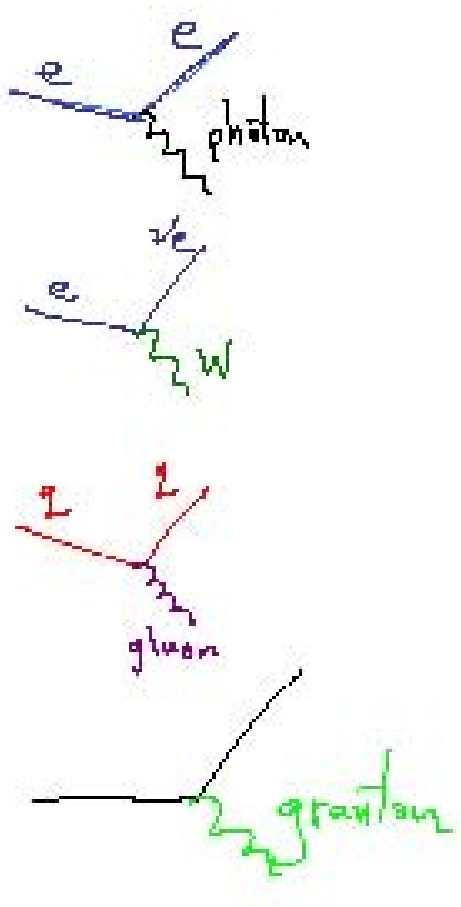


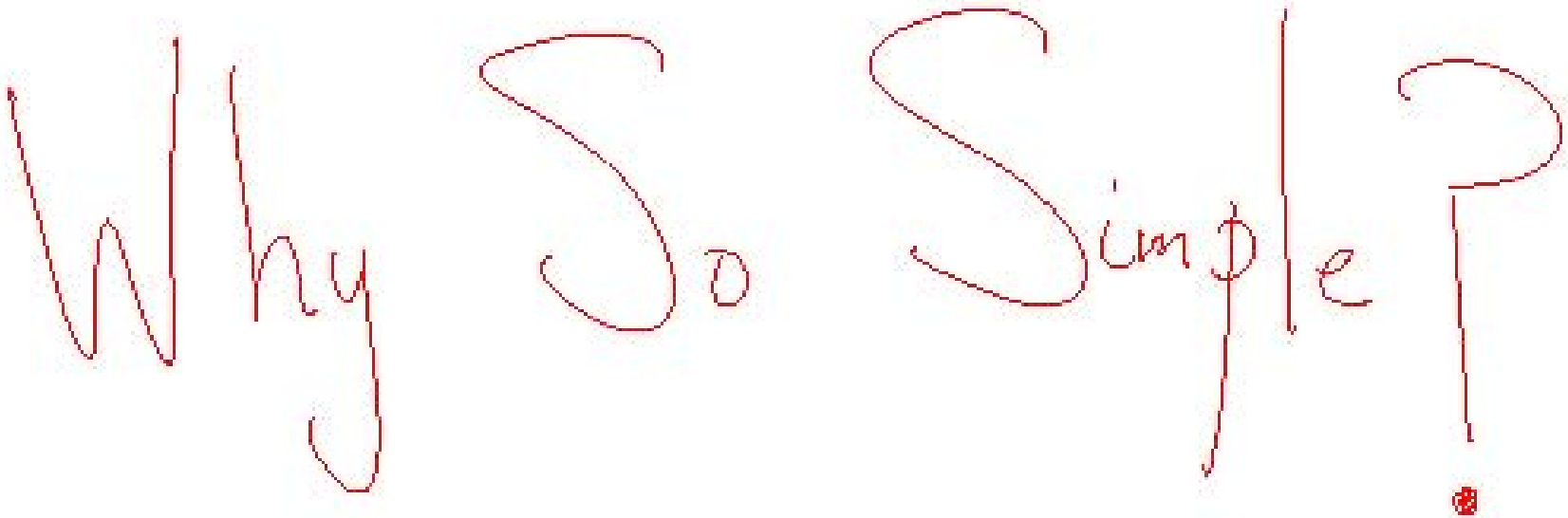




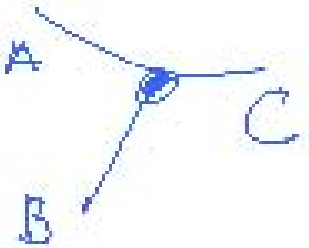
The Menu

	Gluons	"W's"	+ Photon"
	$SU(3)_c$	$\times$ $SU(2)_L$	$\times$ $U(1)_Y$
Q	3	2	$+\frac{1}{6}$
$3 \times U^c$	$\bar{3}$	-	$-\frac{2}{3}$
D^c	$\bar{3}$	-	$+\frac{1}{3}$
L	-	2	$-\frac{1}{2}$
E^c	-	-	$+1$

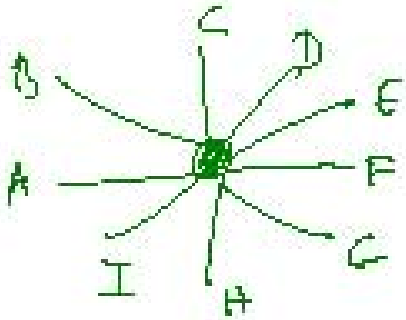



Why So Simple?

- Why simple fundamental interaction



why not



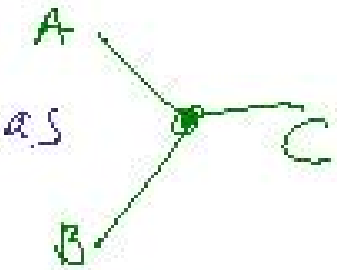
?

- Why such a tiny menu of spins ?

Whatever the Ultimate Theory

Relativity ↓ Quantum Mechanics

At "Long" distances, particles interacting as



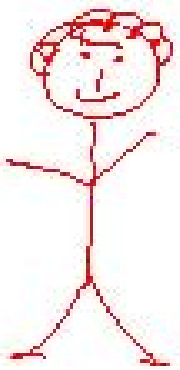
with Spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. ← using the "gravity"

Units!

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

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

Put $\hbar = c = 1$



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

Mass $\sim 10^{29}$ GeV

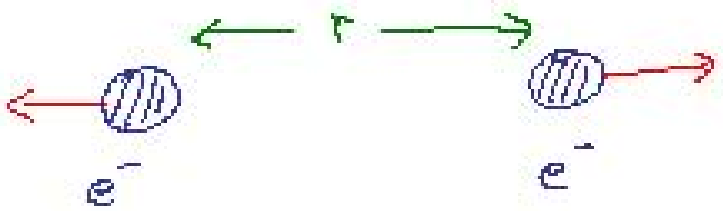
Lecture time $\sim 10^{27}\ \text{GeV}^{-1}$

$(m_p c^2) = 1$ GeV

(p) $\updownarrow 10^{-14}$ cm $\sim$ GeV^{-1}

LHC Energies

7000 GeV

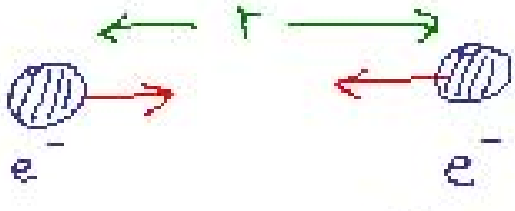


$$F^{electric}_{Force} \sim q^2 \frac{1}{r^2}$$

strength

$$q^2 \sim \frac{1}{137}$$

[a pure number]

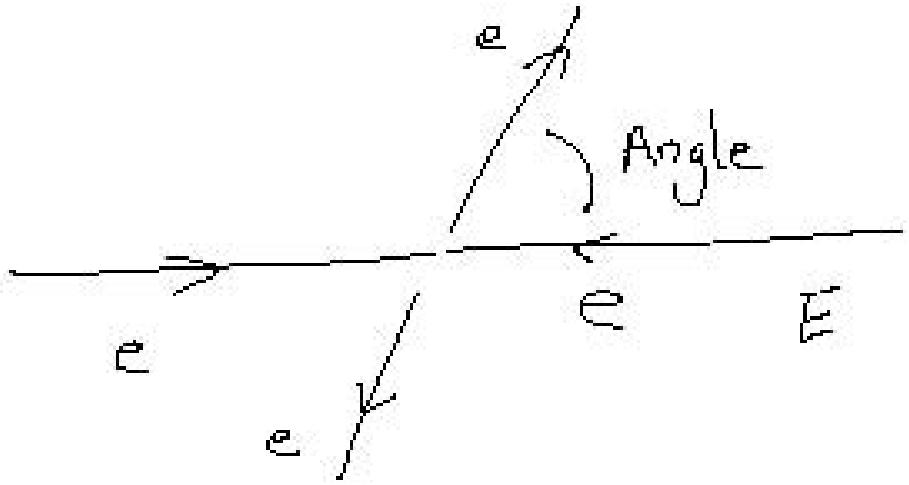


$$F^{grav}_{Force} \sim -G_N \frac{m_e^2}{r^2}$$

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

$$\frac{1}{\ell_{Pl}} \sim (10^{19}\ GeV)$$

Quantum Mechanics



Amplitude

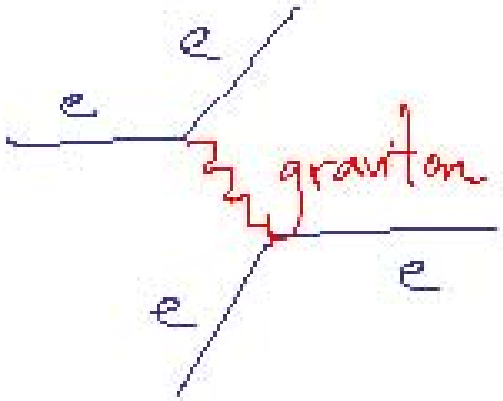
$\sim Z^2$

$\sim 1\%$

Small!

Probability = (Amplitude)^2

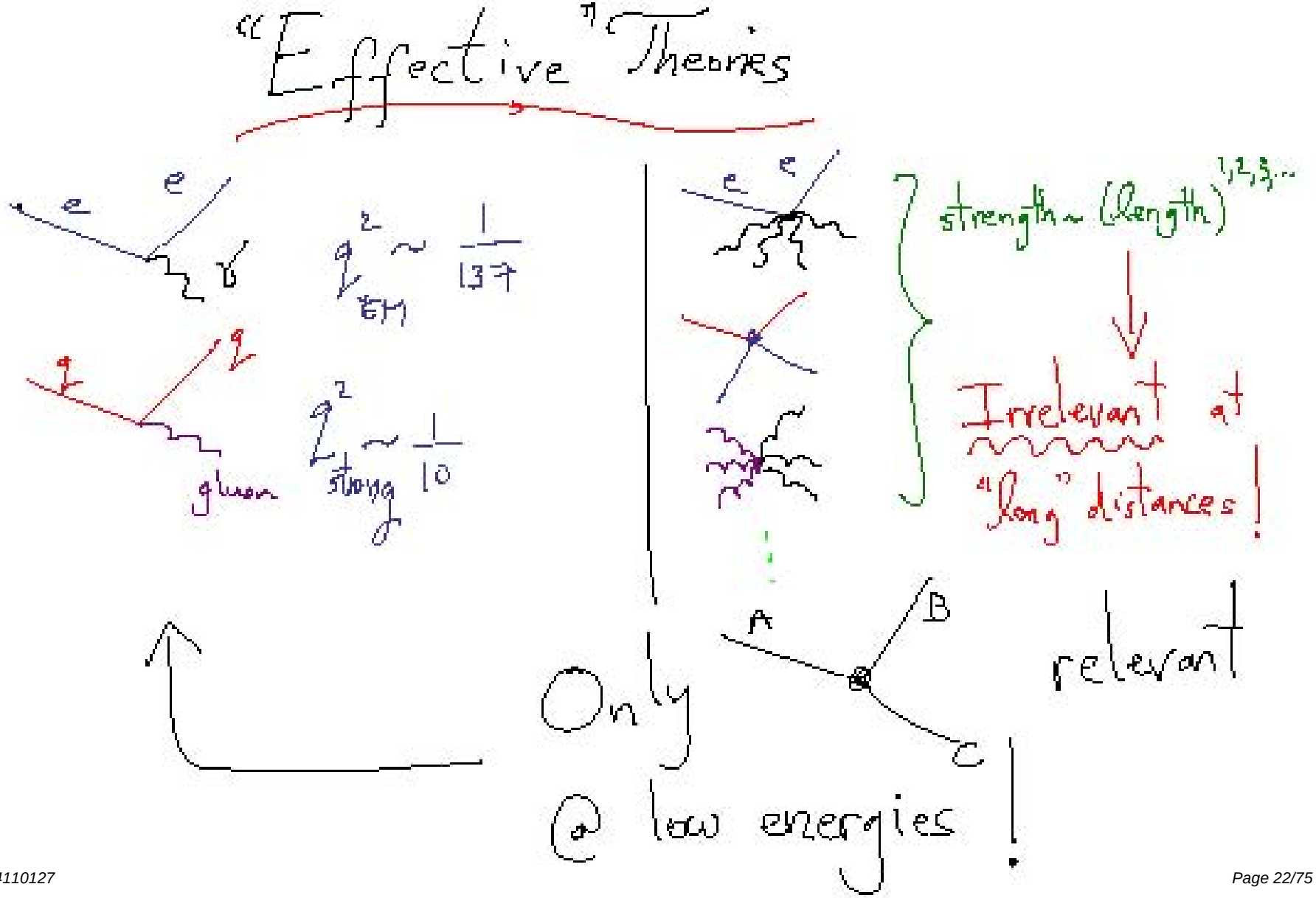
Mystery of "Quantum Gravity"



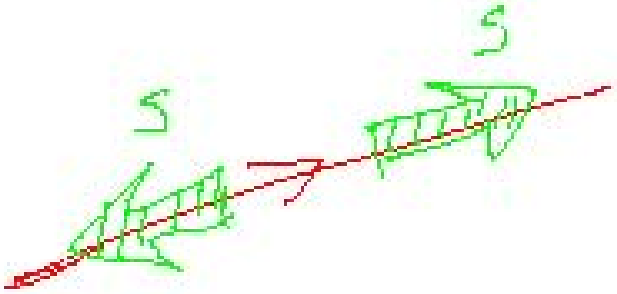
Amplitude ~ $G_N \times E^2$

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

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

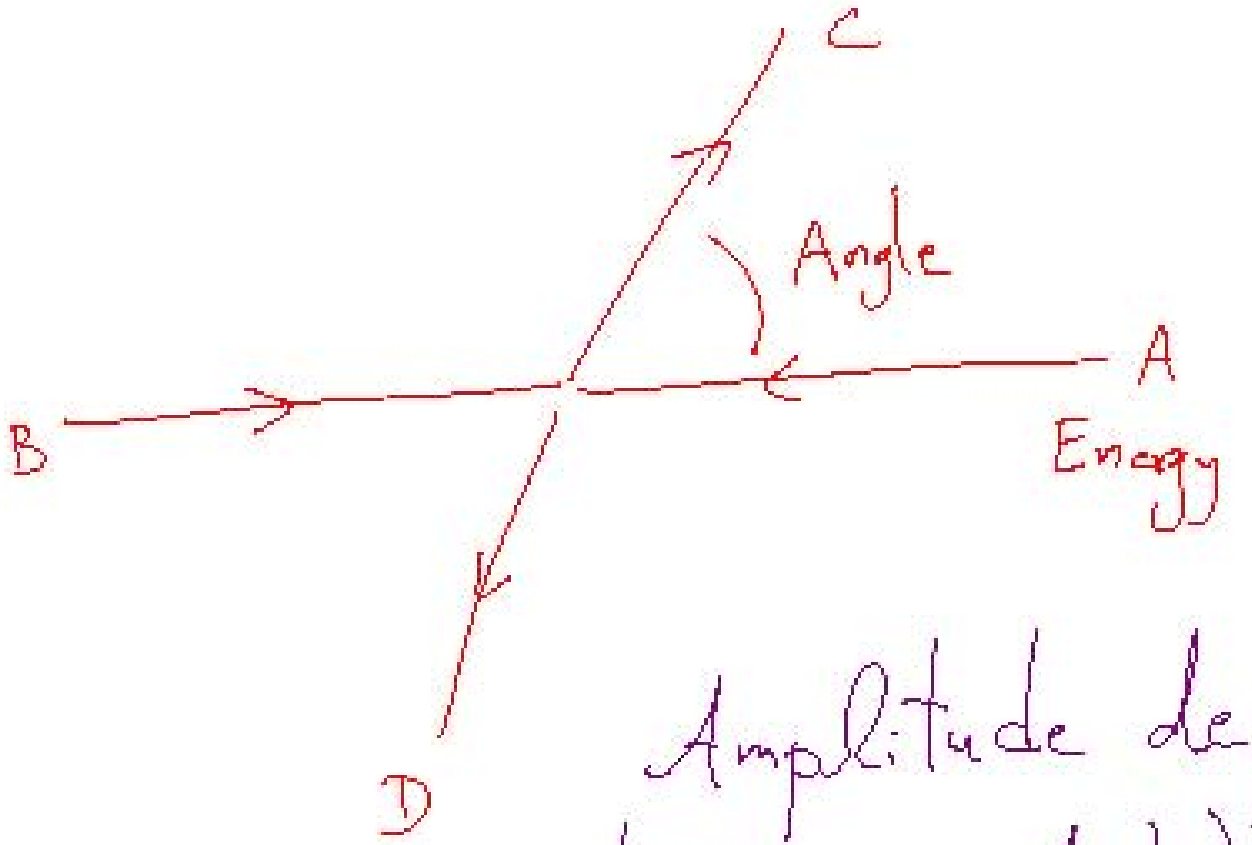

"Effective" Theories
e
e
γ
$g^2_{EM} \sim \frac{1}{137}$
q
q
gluon
$g^2_{strong} \sim \frac{1}{10}$
e
e
strength ~ (length)$^{1,2,3,\ldots}$
Irrelevant at "long" distances!
A
B
C
relevant
Only @ low energies!

At high energies ⟶ Approximate particles as massless

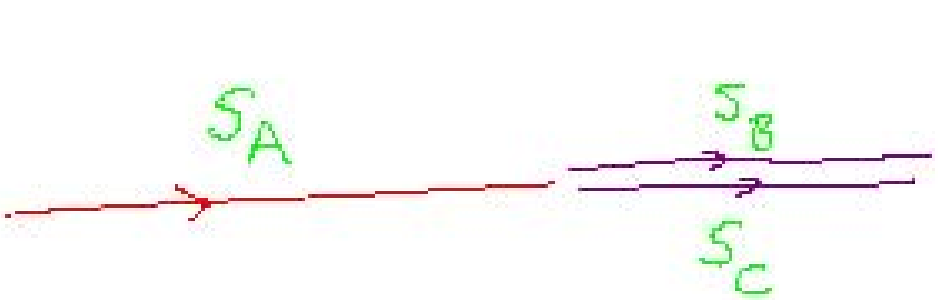


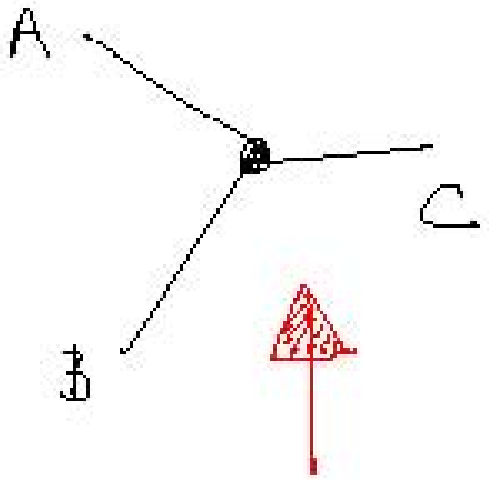
Energy = |momentum|

Spin ⟶ "helicity"

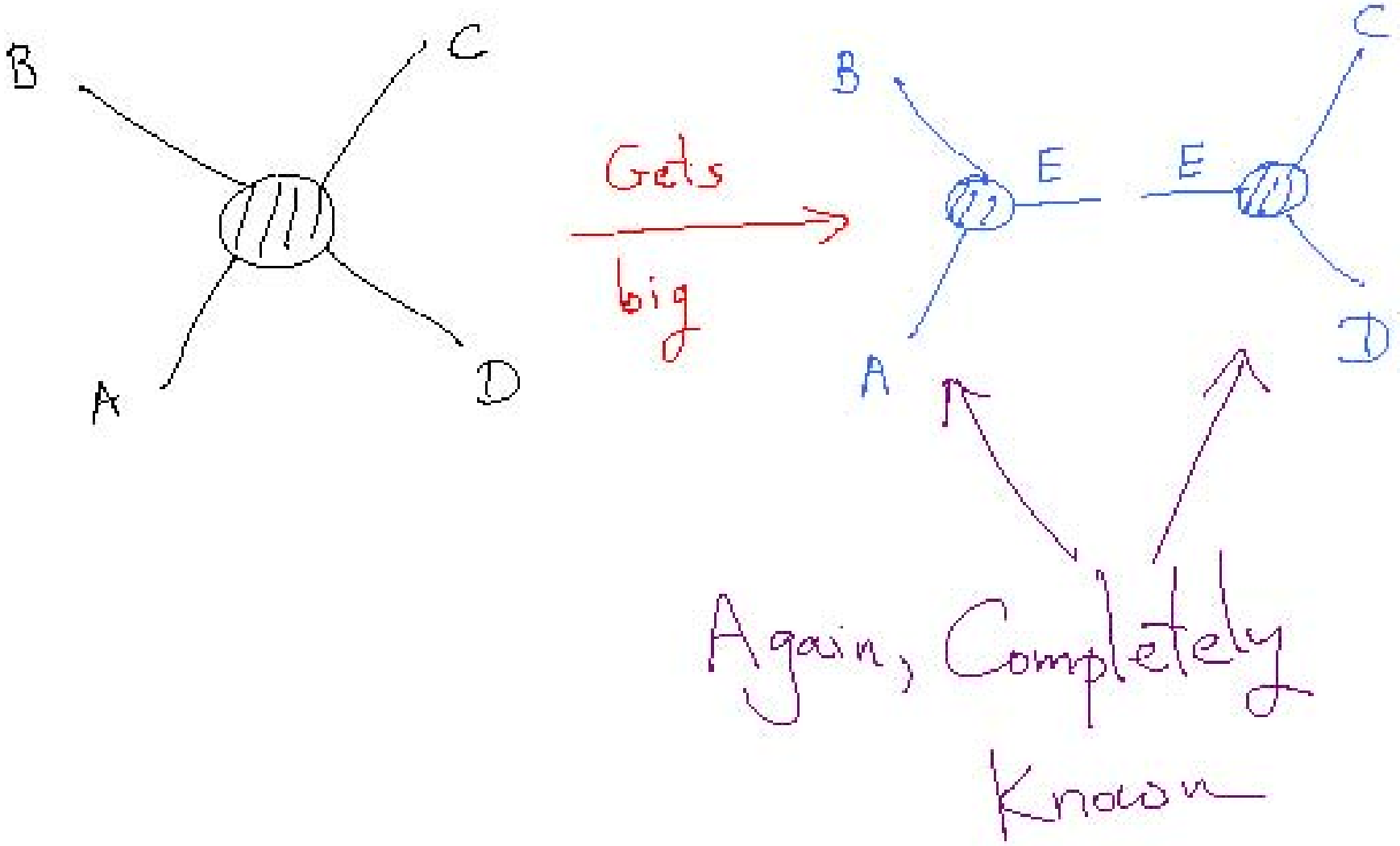


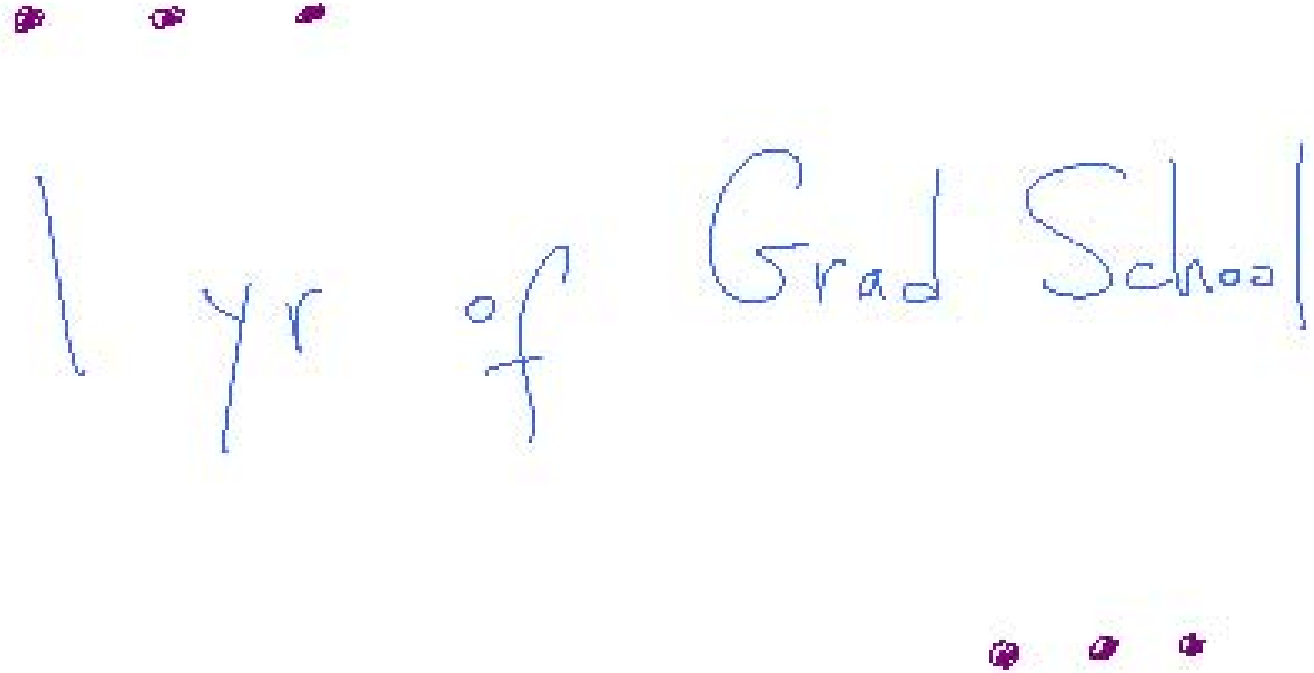
Amplitude depends of (Energy, Angle), Complicated!



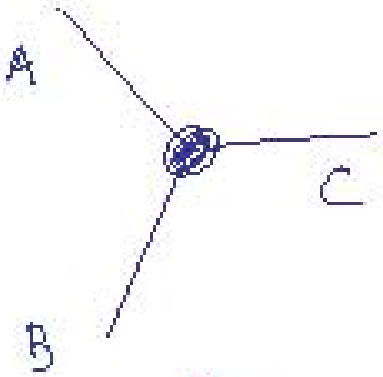


No (Energy, Angle) → COMPLETELY FIXED (up to strength) by helicities!


B
C
A
D
Gets
big
B
E
E
C
A
D
Again, Completely
Known


1 yr of Grad School

All Consistent Theories



Spins

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

Unique

+ some #'s for stregth of interaction !


What About The
Higgs ?

Important difference between massive & massless particles with spin:

massive

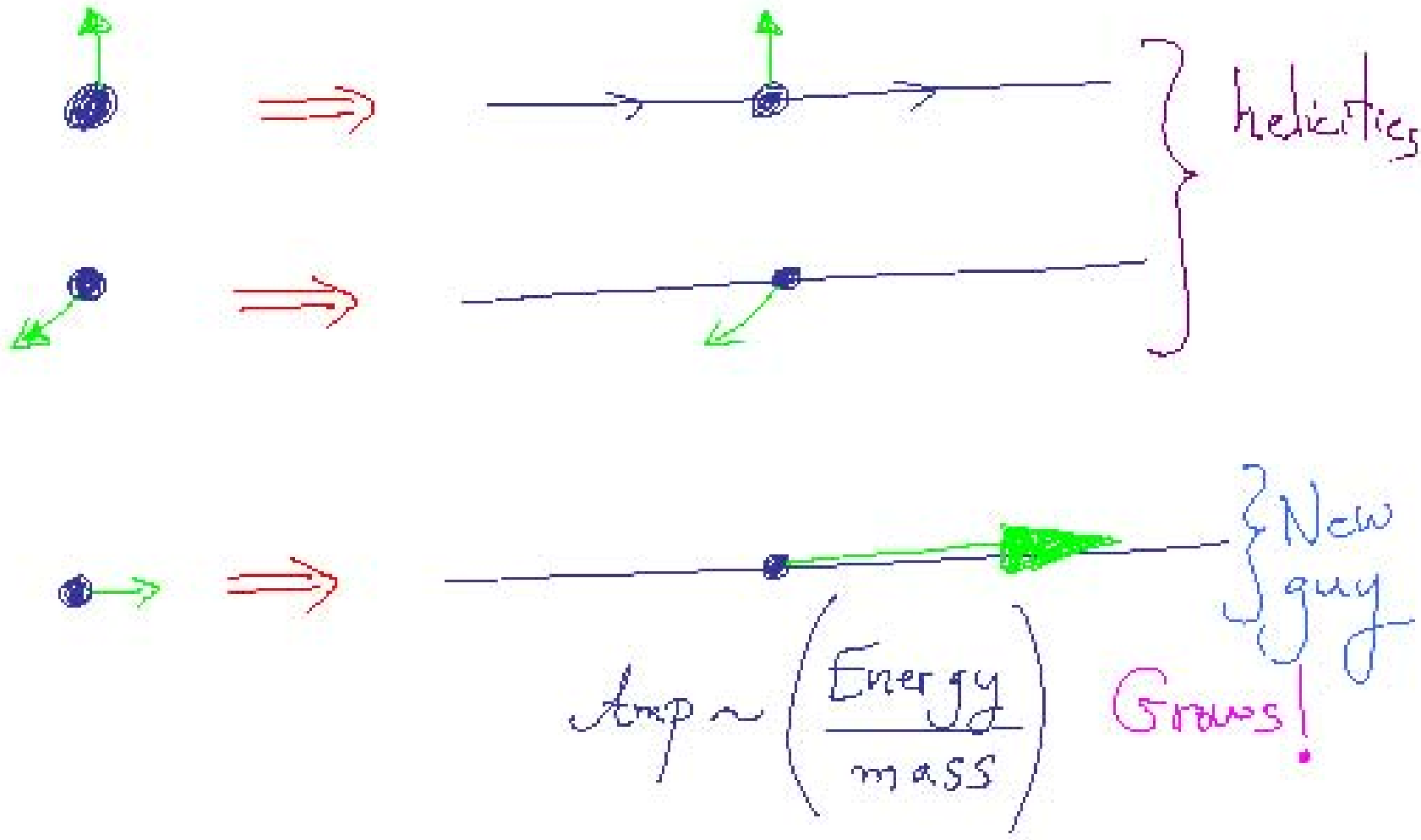
$S = 1$

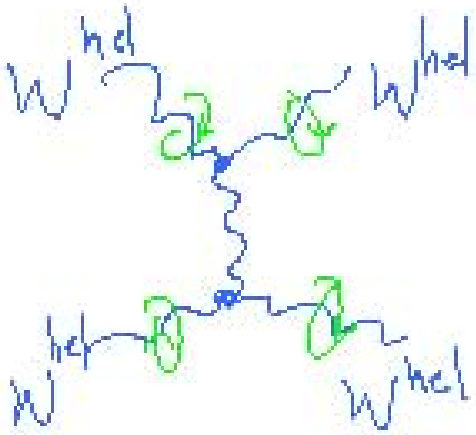
3 spin

massless

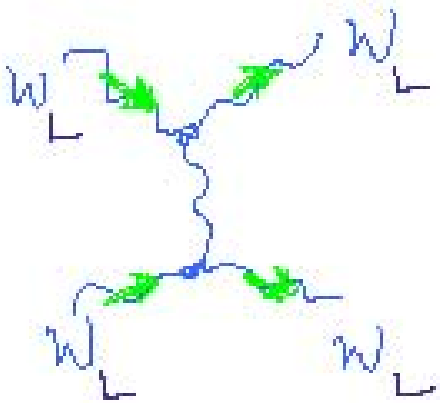
2 helicities

One extra guy!


helicities
New guy
Amp ~ (Energy / mass)
Gluons!



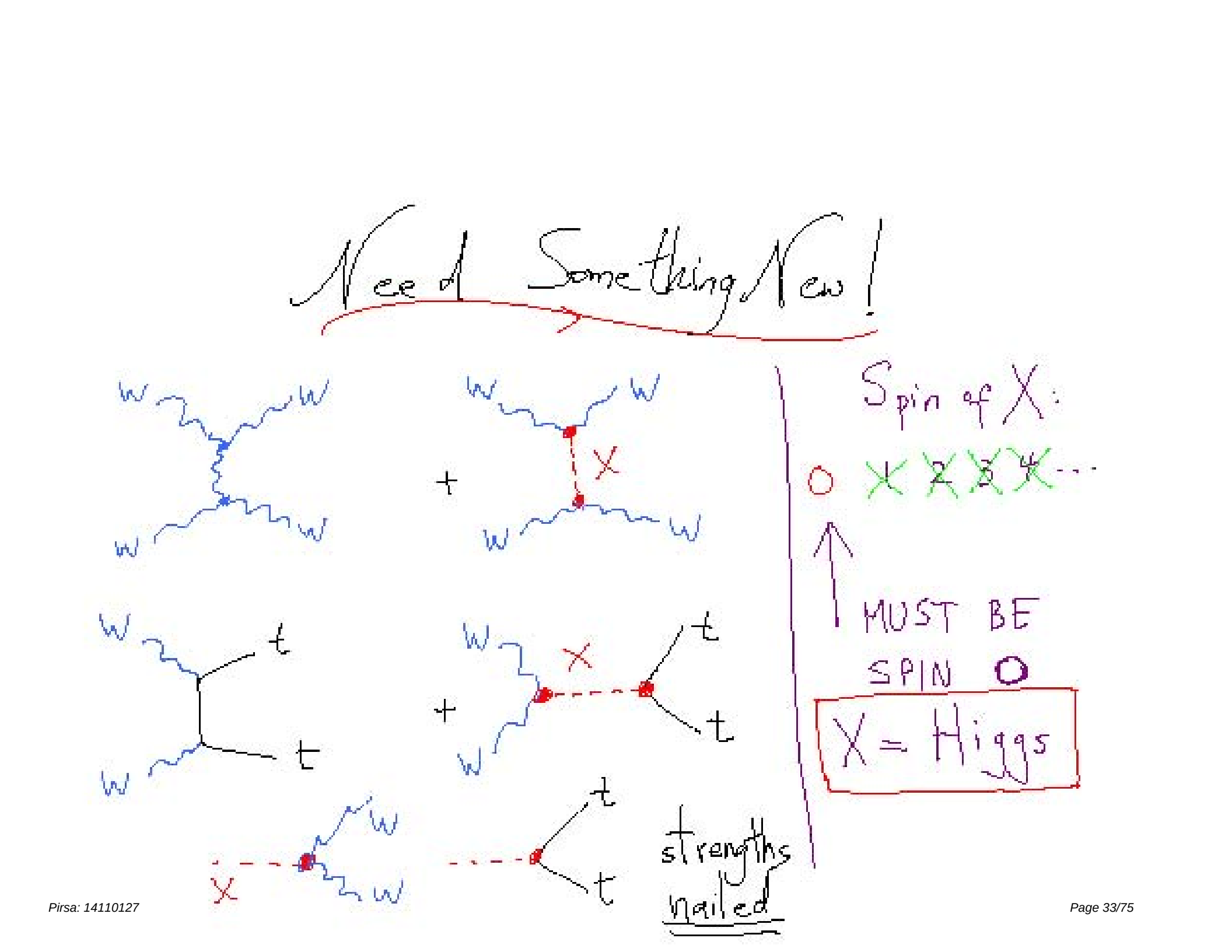
$$\text{Amplitude} \sim g^2 \sim 1\%$$

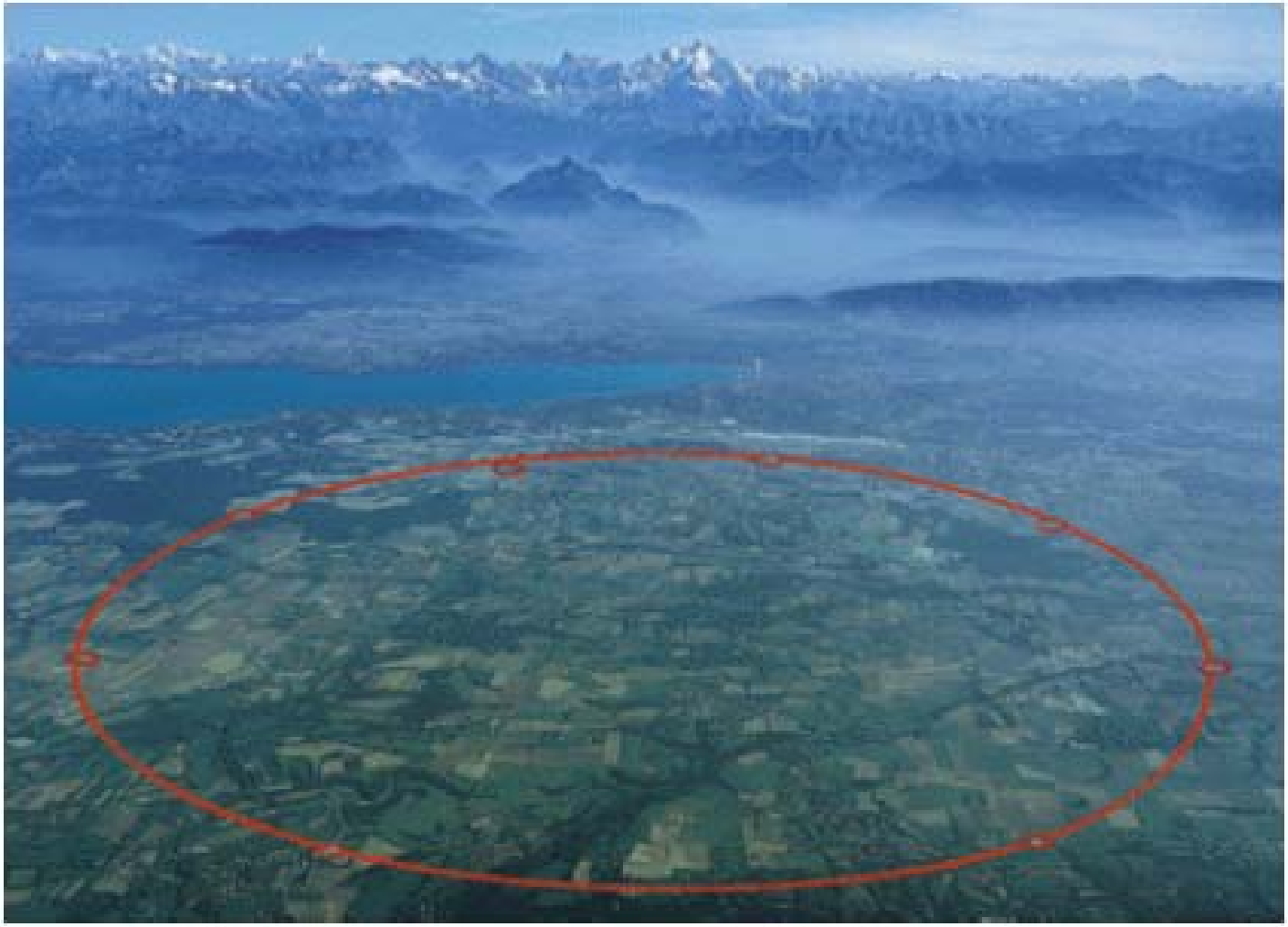


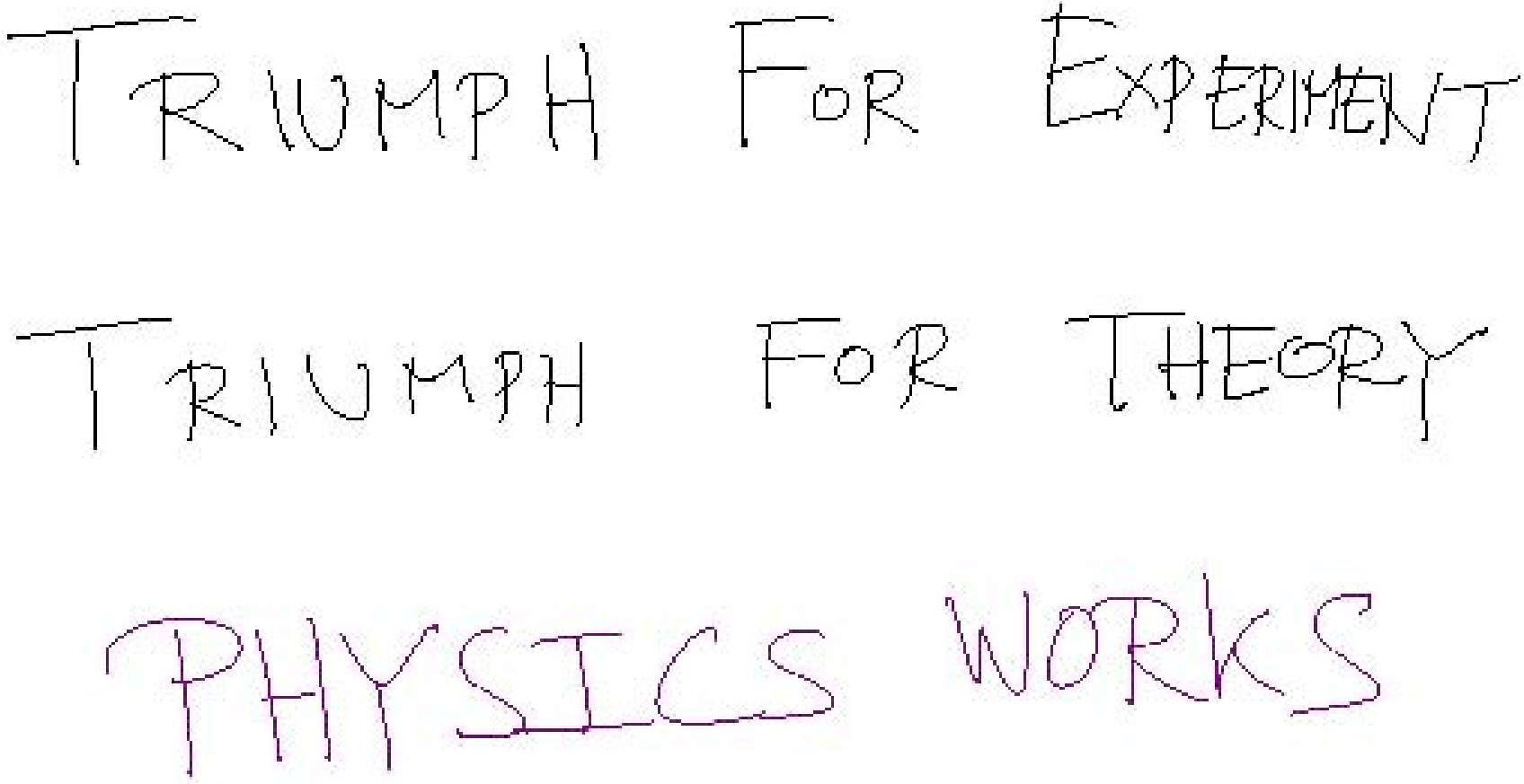
$$\text{Amplitude} \sim \underbrace{g^2}_{1\%} \times \left(\frac{\text{Energy}}{\text{Mass } W}\right)^2$$

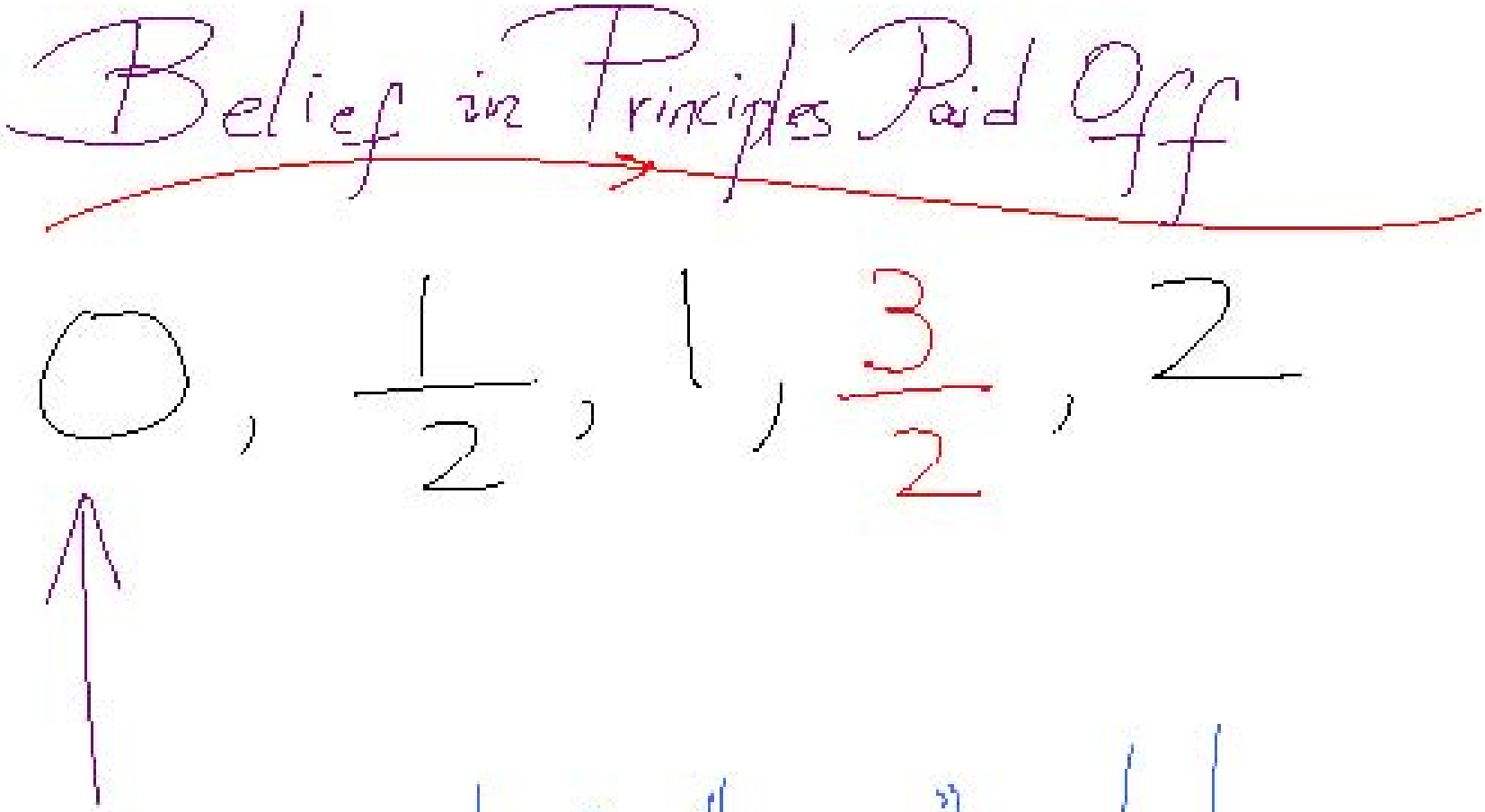
$$\gtrsim 1 \text{ (!)} \quad \text{if Energy} > 1200 \text{ GeV}!$$

(80 GeV)

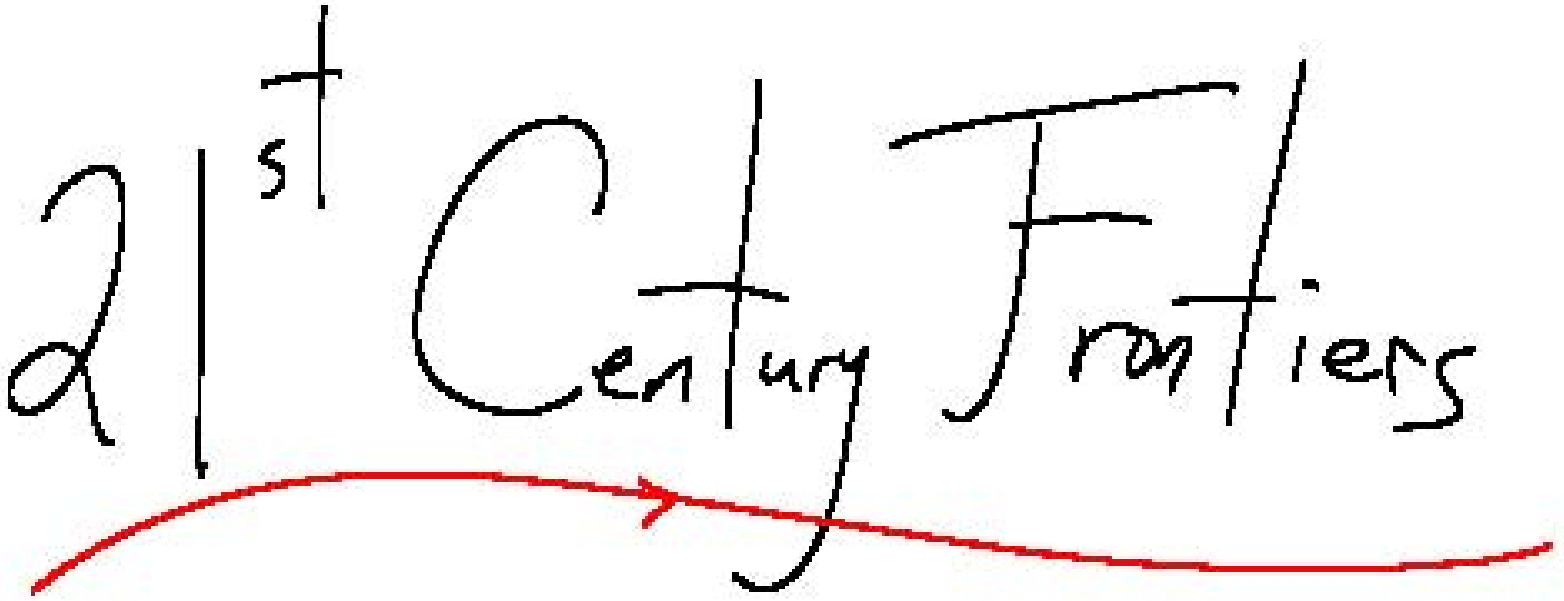

Need Something New!
W
W
W
W
+
X
W
W
W
W
t
W
t
W
+
X
t
W
t
W
X
W
t
t
strengths nailed
Spin of X:
0 1 2 3 4 ...
MUST BE SPIN 0
X = Higgs

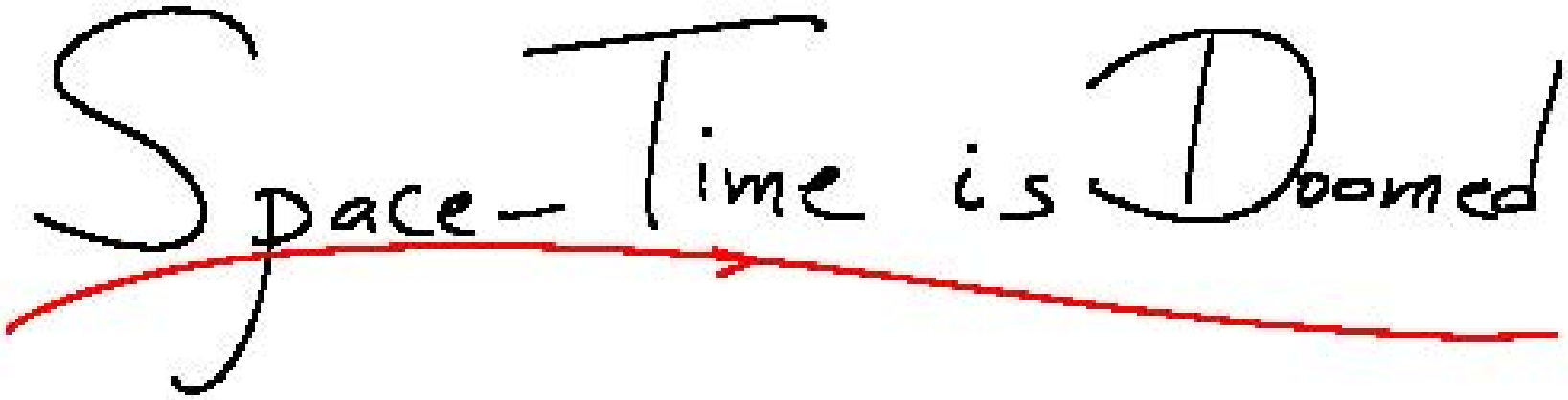


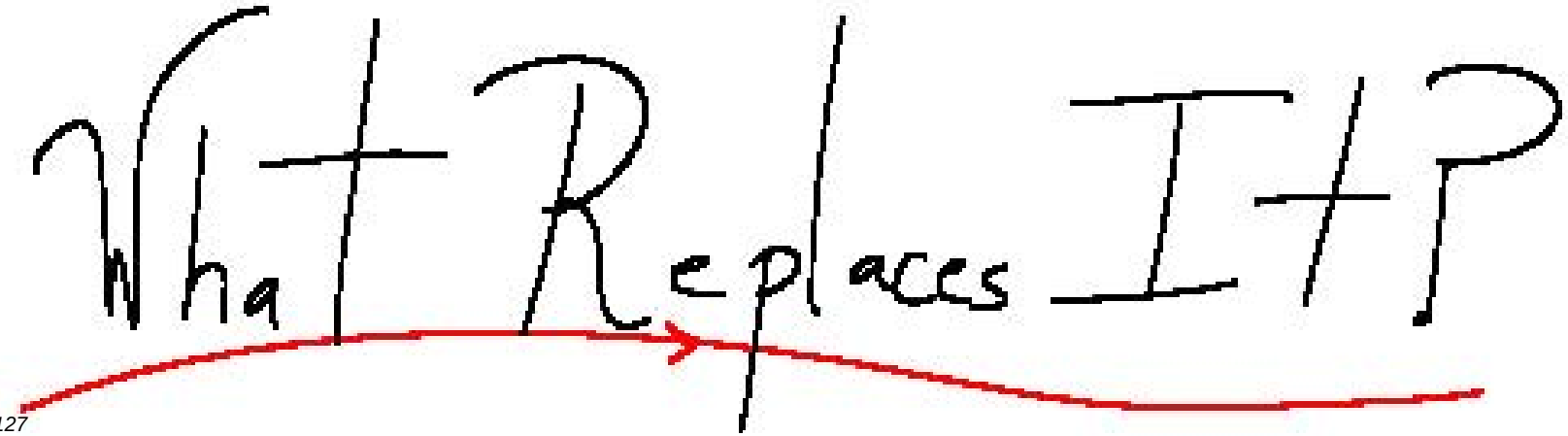

TRIUMPH FOR EXPERIMENT
TRIUMPH FOR THEORY
PHYSICS WORKS

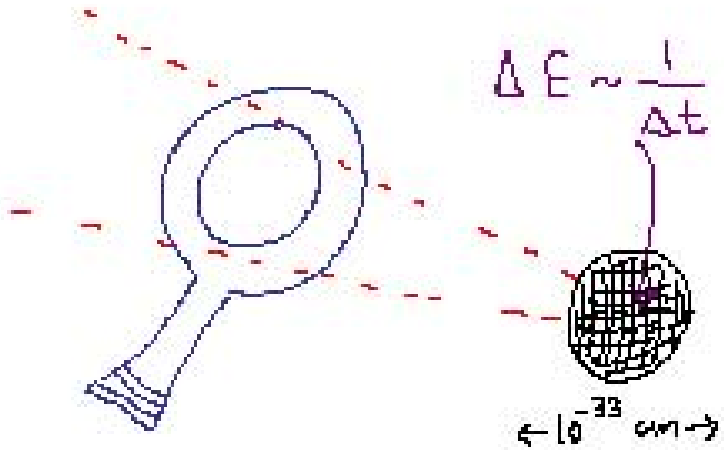

Belief in Principles Paid Off
0, 1/2, 1, 3/2, 2
Higgs is first "really new" particle we've seen!

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.


21st Century Frontiers


Space-Time is Doomed

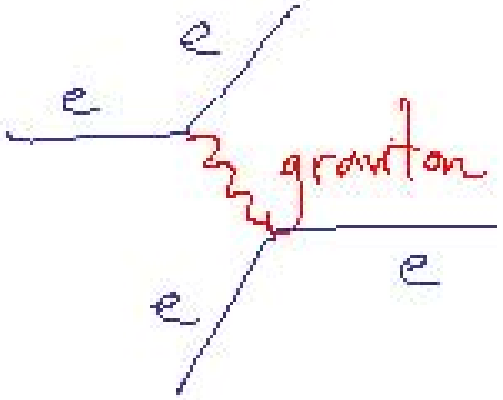

What Replaces IP



No Operational meaning to distance $< 10^{-33}$ cm, times $< 10^{-43}$ s, ...

Energy needed $\sim 10^{19}$ GeV

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

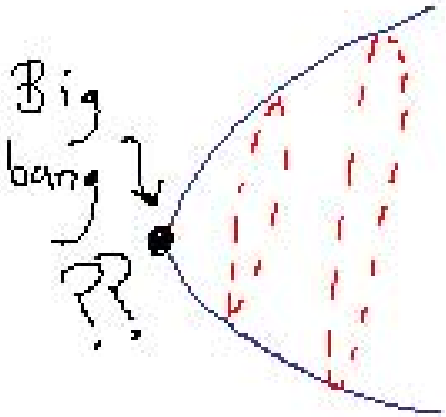


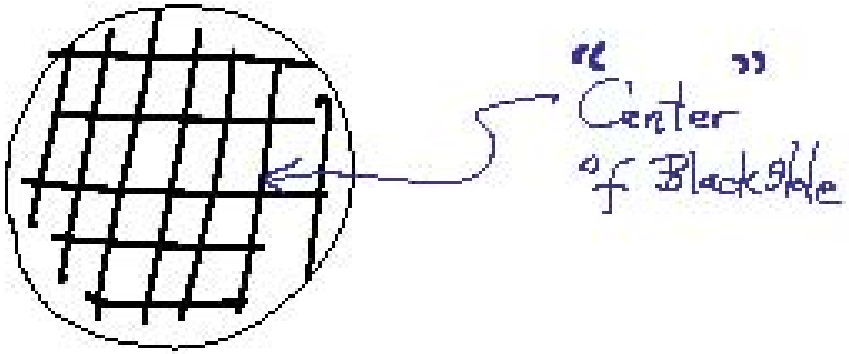
Amplitude $\sim (G_N \times E^2)$

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

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

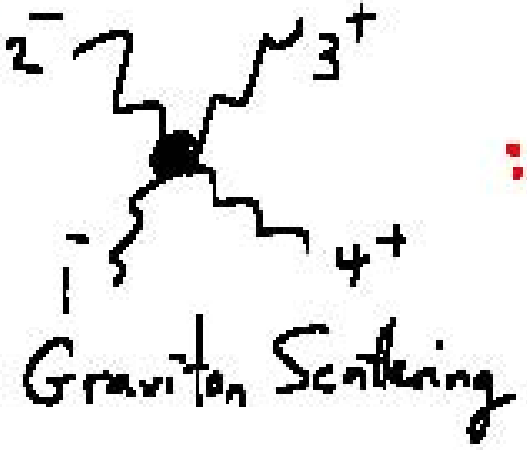
PLANCK ENERGY





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

A First Challenge in Quantum Gravity



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

Correct at low energies $s,t,u \ll 1/G_N$

Wrong @ high energies ! $s,t,u \gg 1/G_N$

Naive Attempts Fail

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

Standard

Modification to Suppress High Energy Growth

Violate "Unitarity" → Negative Probabilities

Discovery of Miraculous Formula

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

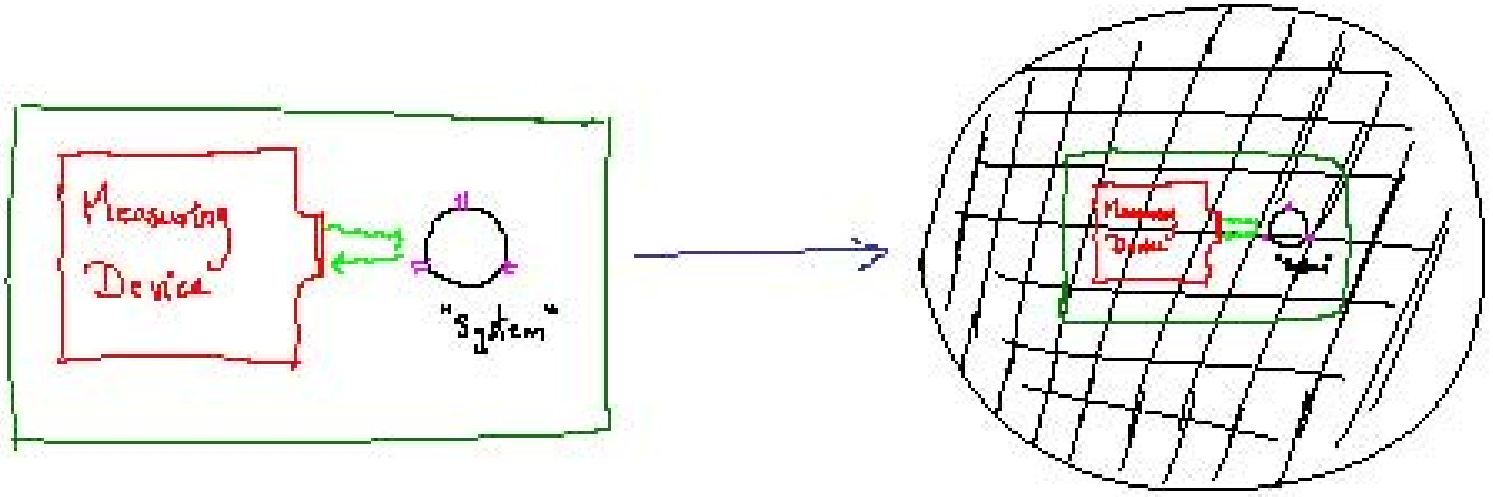
$$G_N \frac{(\langle 12\rangle[34])^4}{stu} \times \frac{\Gamma\left(1-\frac{s}{M^2}\right)\Gamma\left(1-\frac{t}{M^2}\right)\Gamma\left(1-\frac{u}{M^2}\right)}{\Gamma\left(1+\frac{s}{M^2}\right)\Gamma\left(1+\frac{t}{M^2}\right)\Gamma\left(1+\frac{u}{M^2}\right)}$$

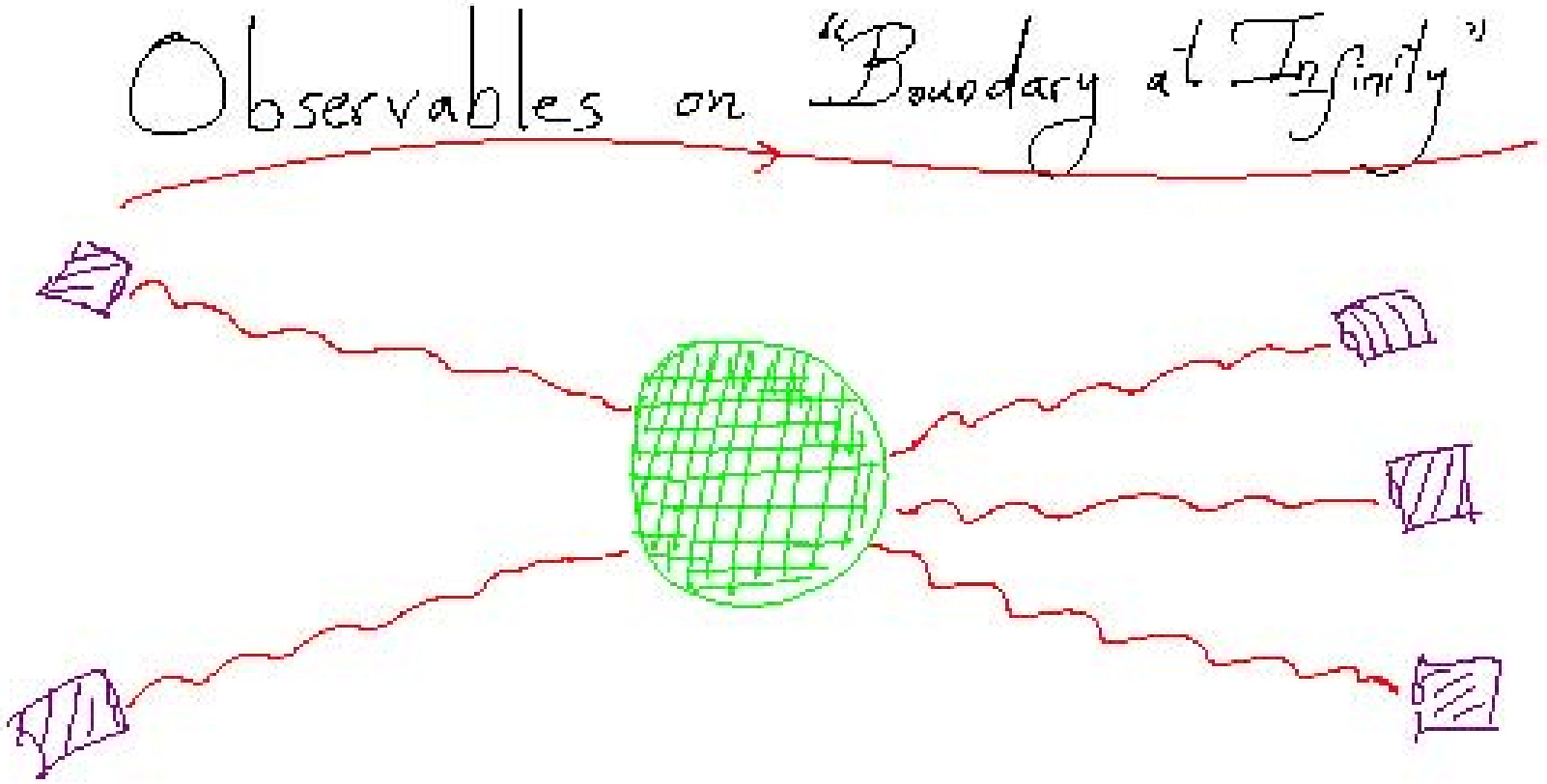
INCREDIBLY: NO NEG. PROB.!

Where did

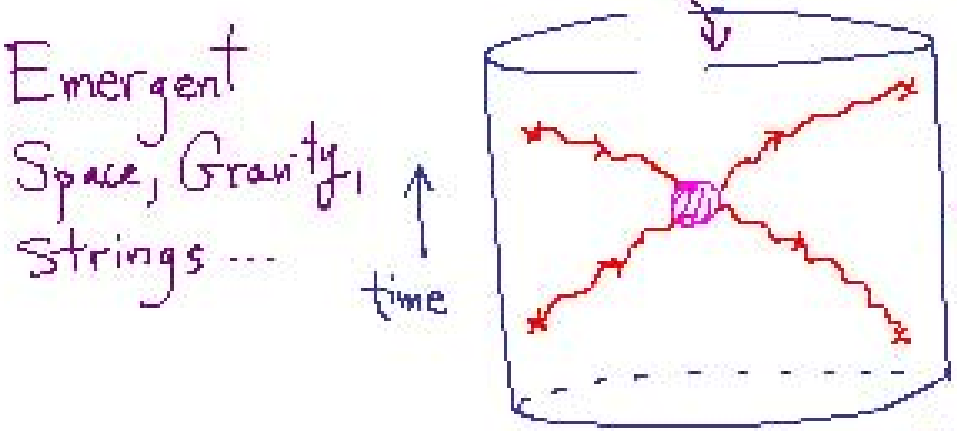
STRING

No Local Observables!

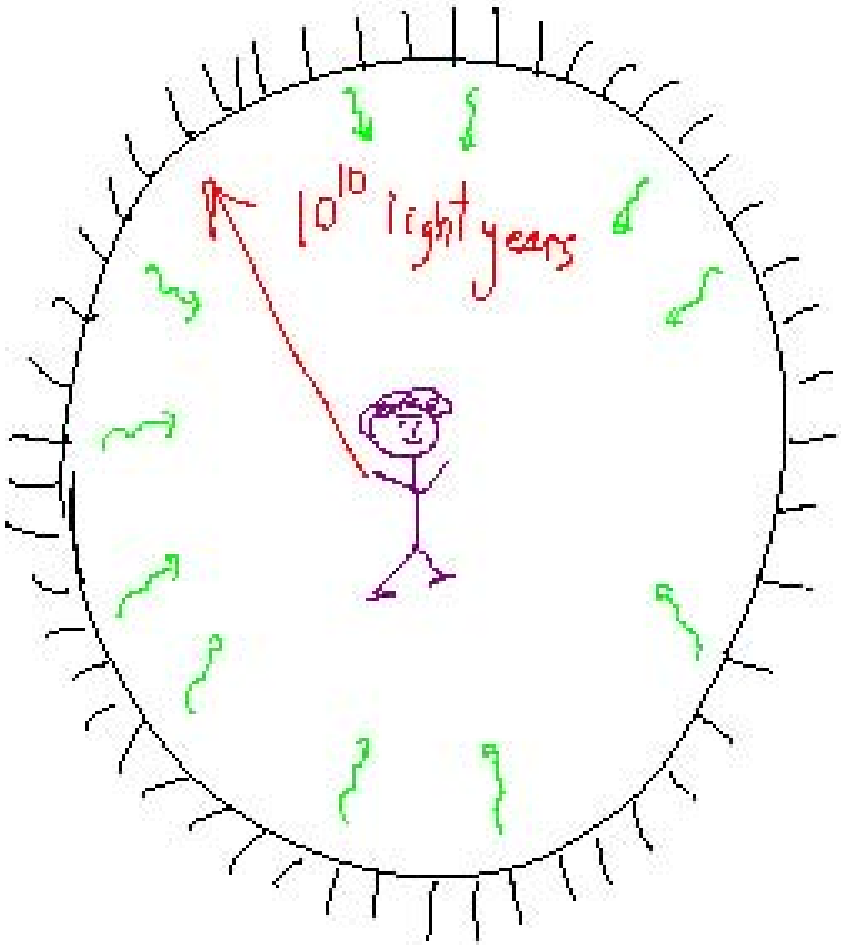



Observables on "Boundary at Infinity"

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

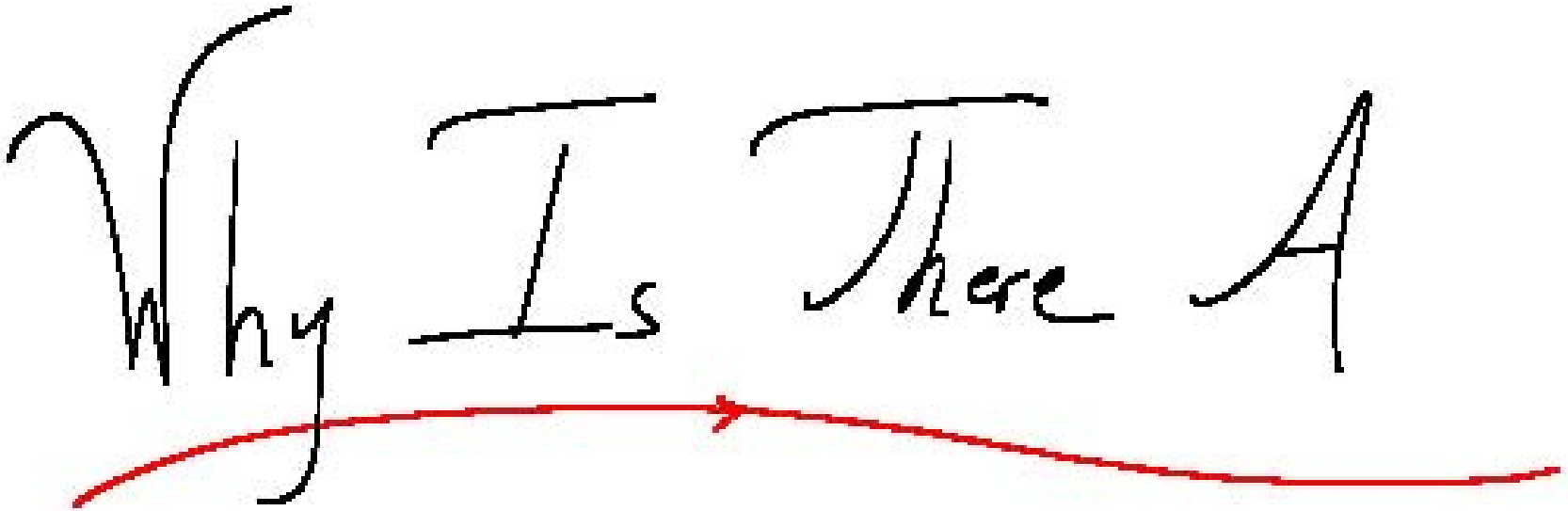


String Theory = Particle Physics



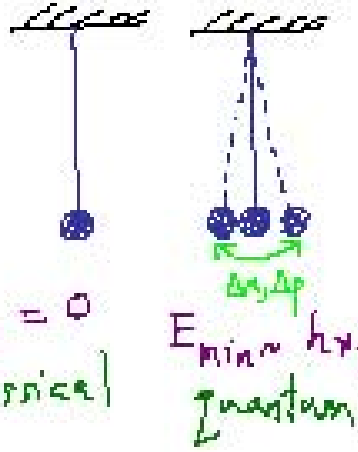
What are the correct observables?

Emergent Space-Time


Why Is There A
Macroscopic Universe?

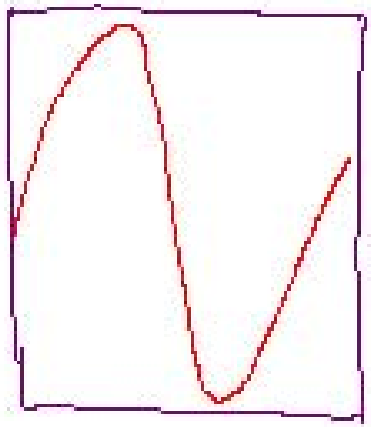
Vacuum is Too Exciting

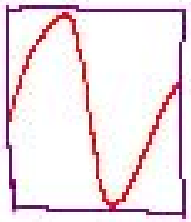
Even Vacuum has energy!



$E_{min} = 0$
classical

$E_{min} \sim h\nu_{freq.}$
quantum

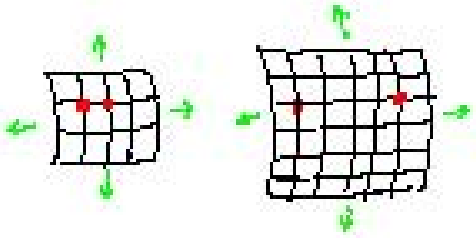




Bigger Fluctuations at Shorter Distances

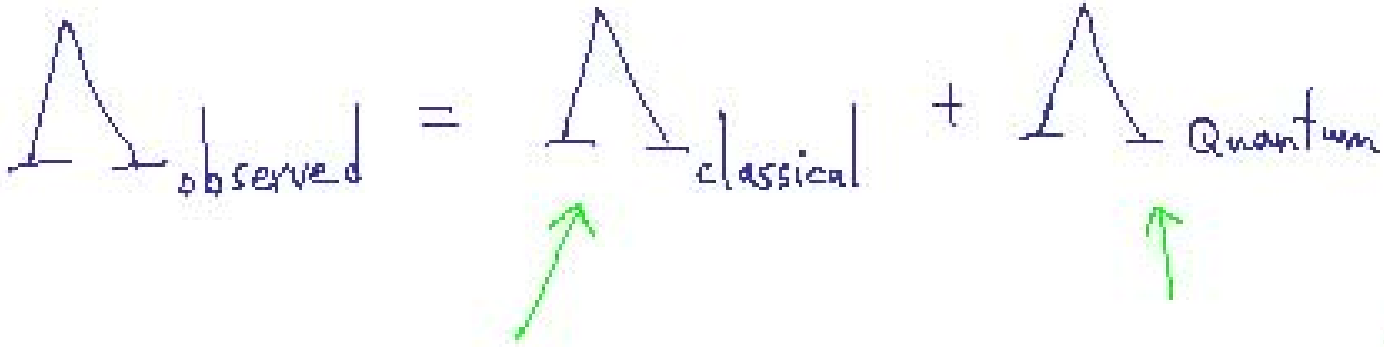
Estimating Λ

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

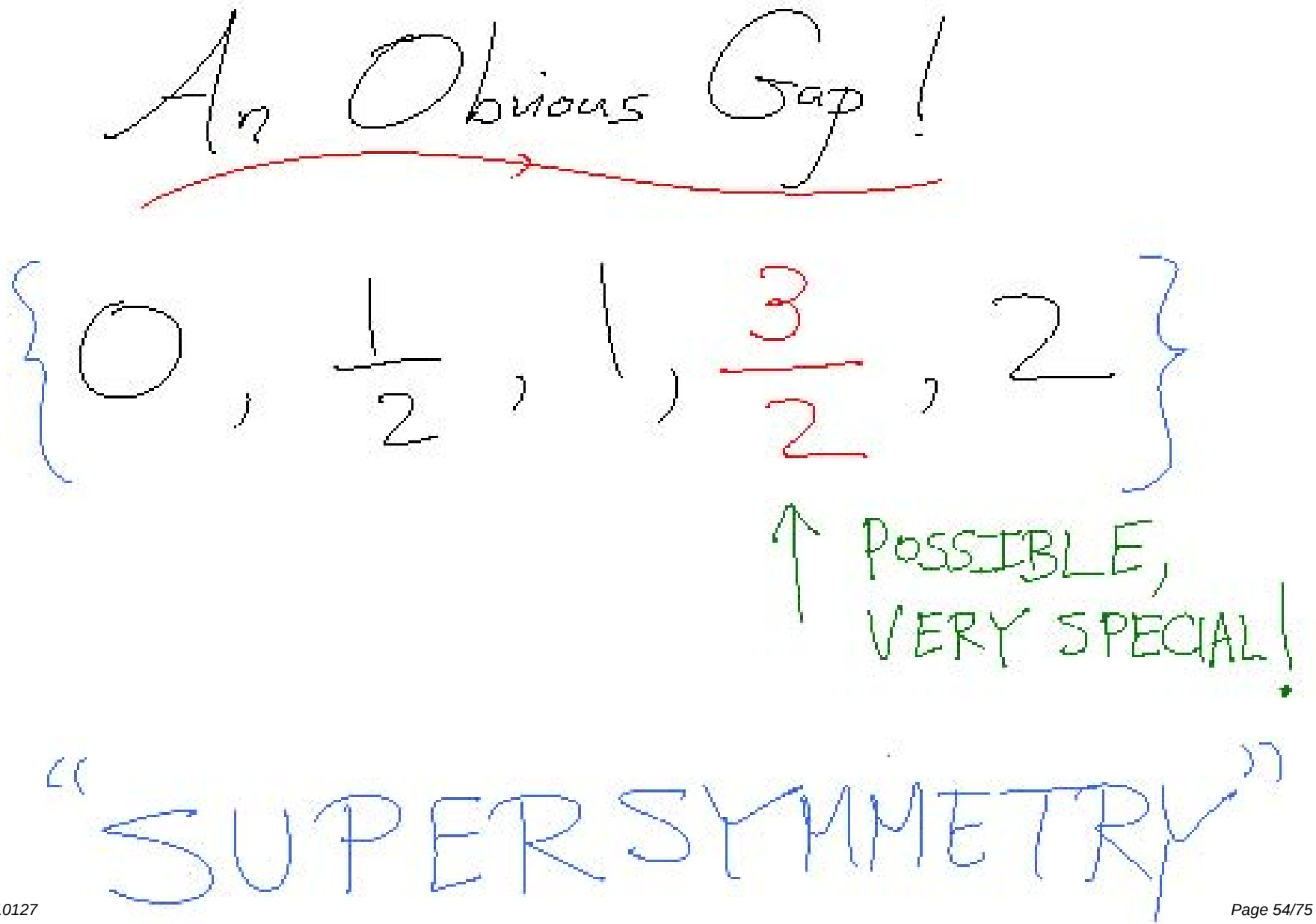


Explosive Acceleration —
Doubling size every 10^{-43} s !

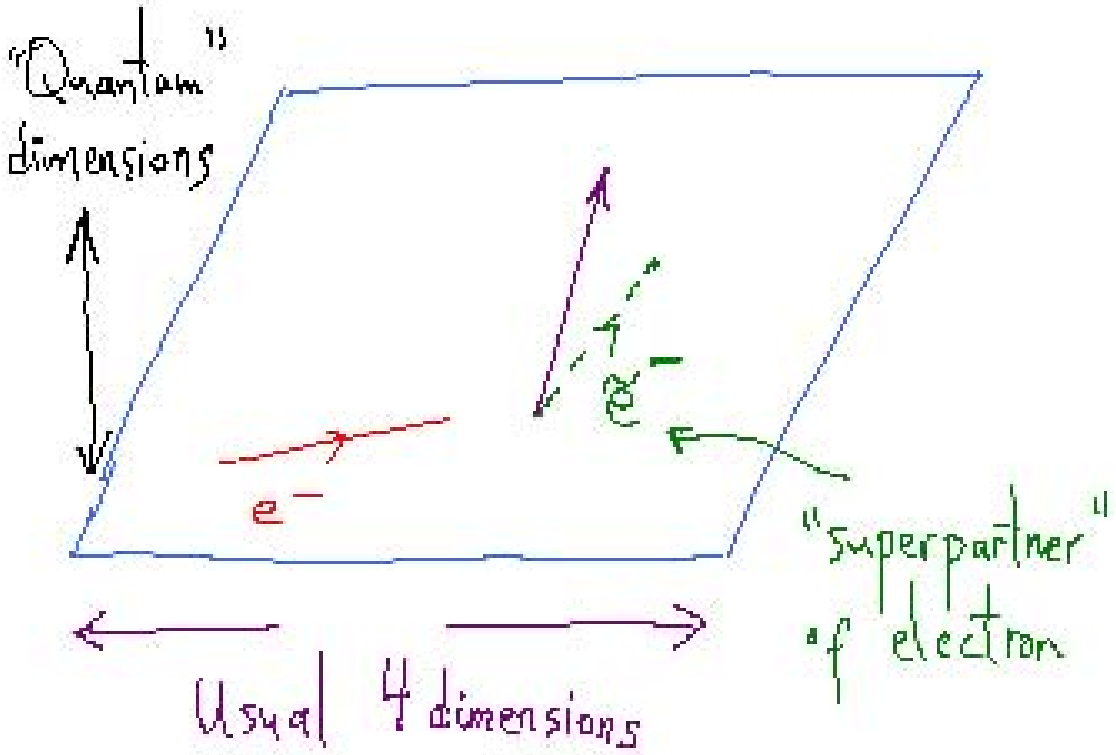
What We Do



SEEMS LUDICROUS


An Obvious Gap!
{0, 1/2, 1, 3/2, 2}
POSSIBLE, VERY SPECIAL!
"SUPERSYMMETRY"

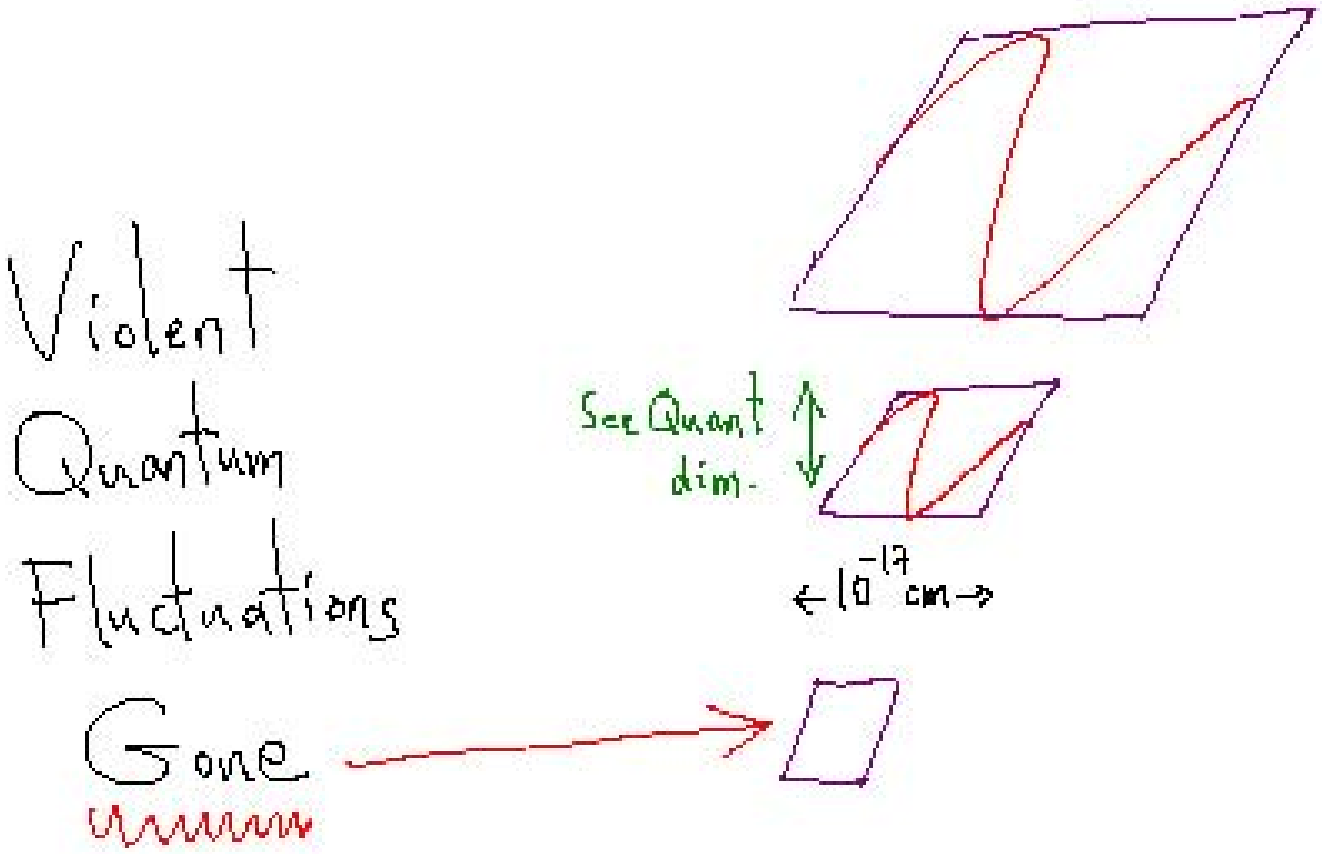
Supersymmetry

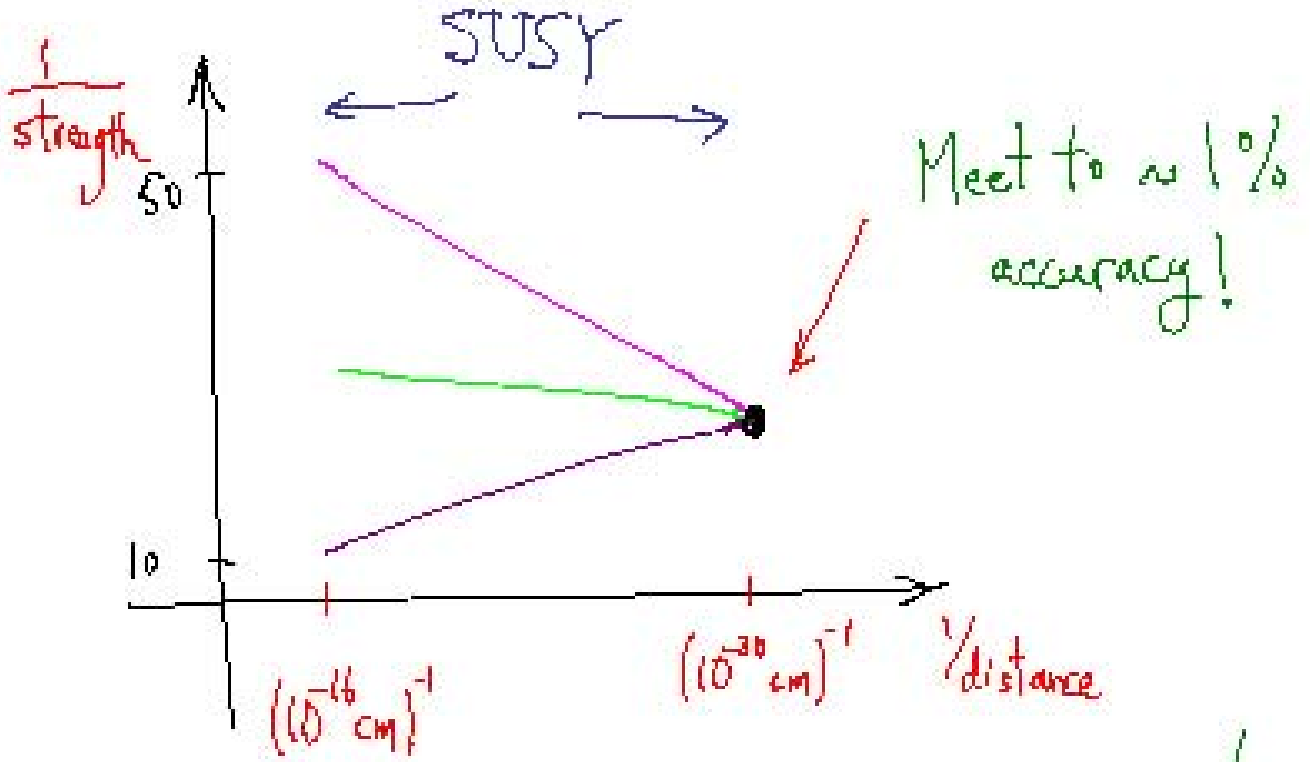


Quantum d_x, Quantum d_y, ...

$$d_x^Q d_y^Q = -d_y^Q d_x^Q$$

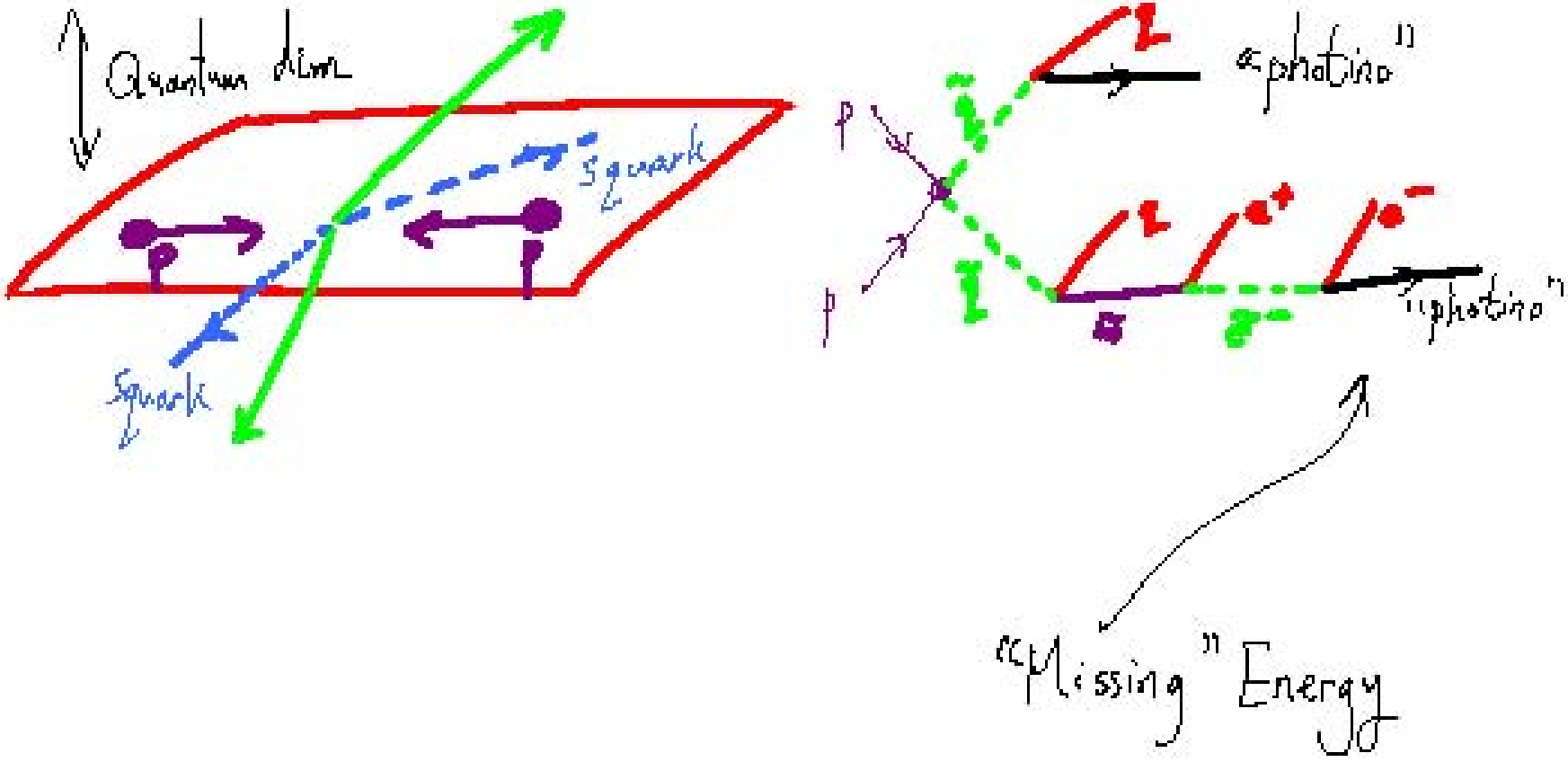
$$\left(d_y^Q\right)^2 = 0$$

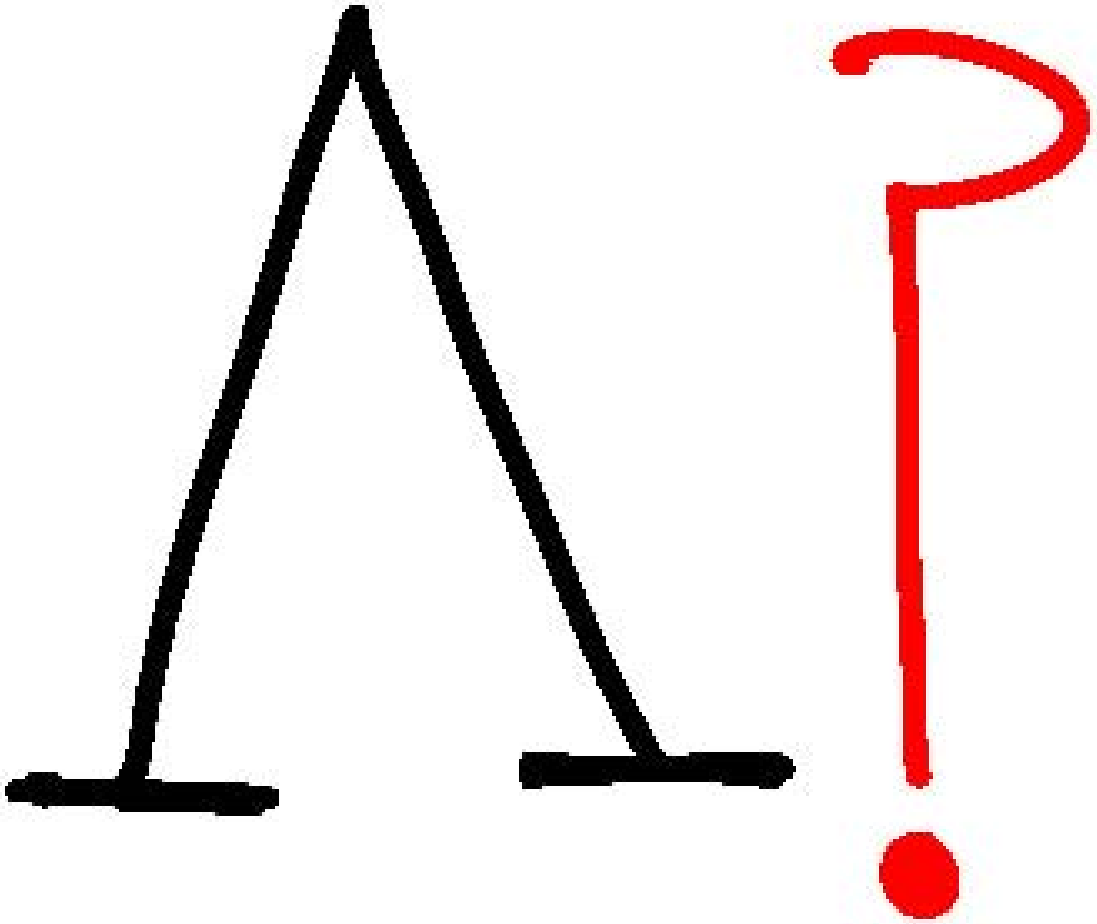

Violent
Quantum
Fluctuations
Gone
Sec Quant
dim.
$\leftarrow 10^{-17}$ cm $\rightarrow$

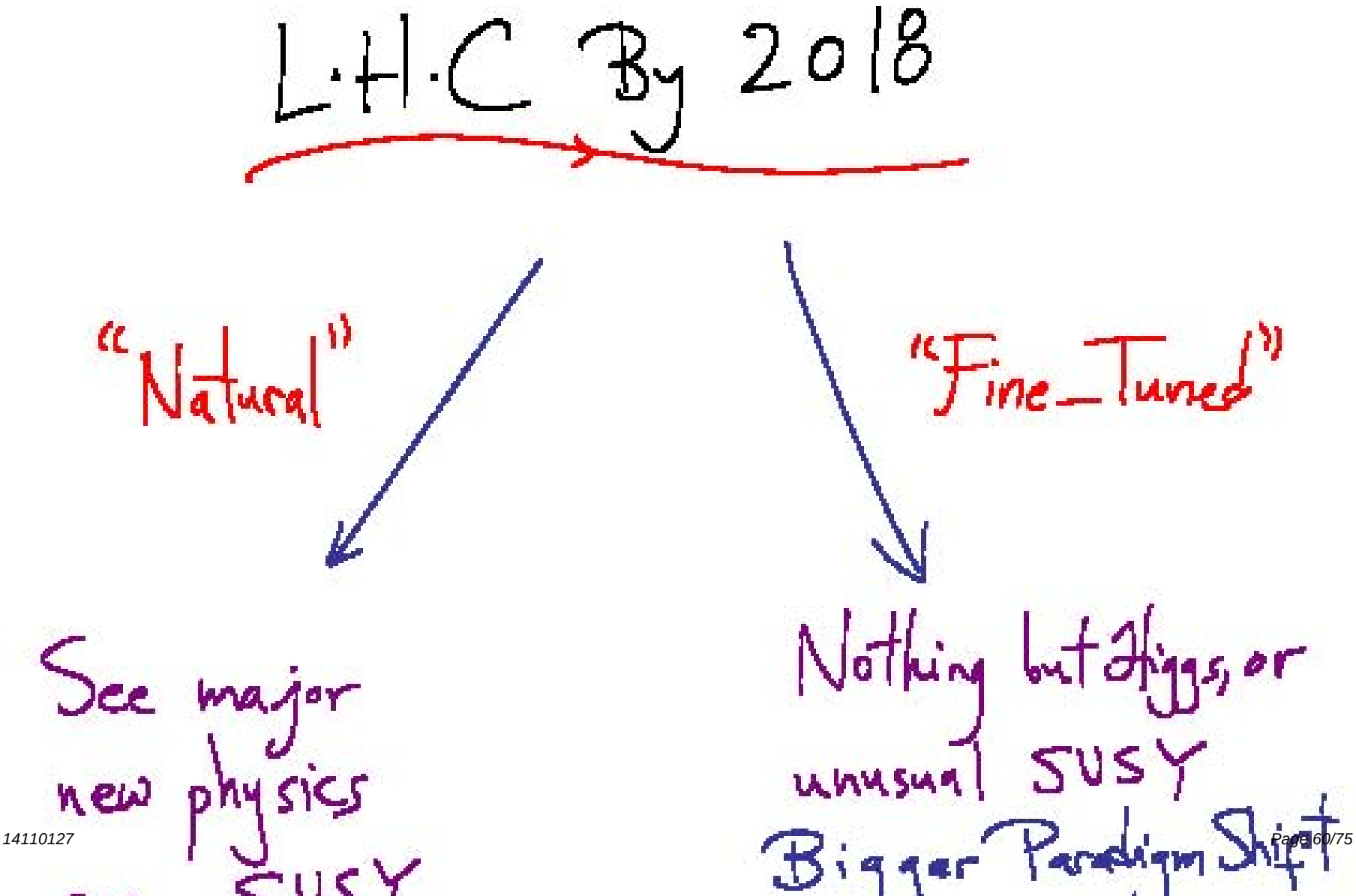


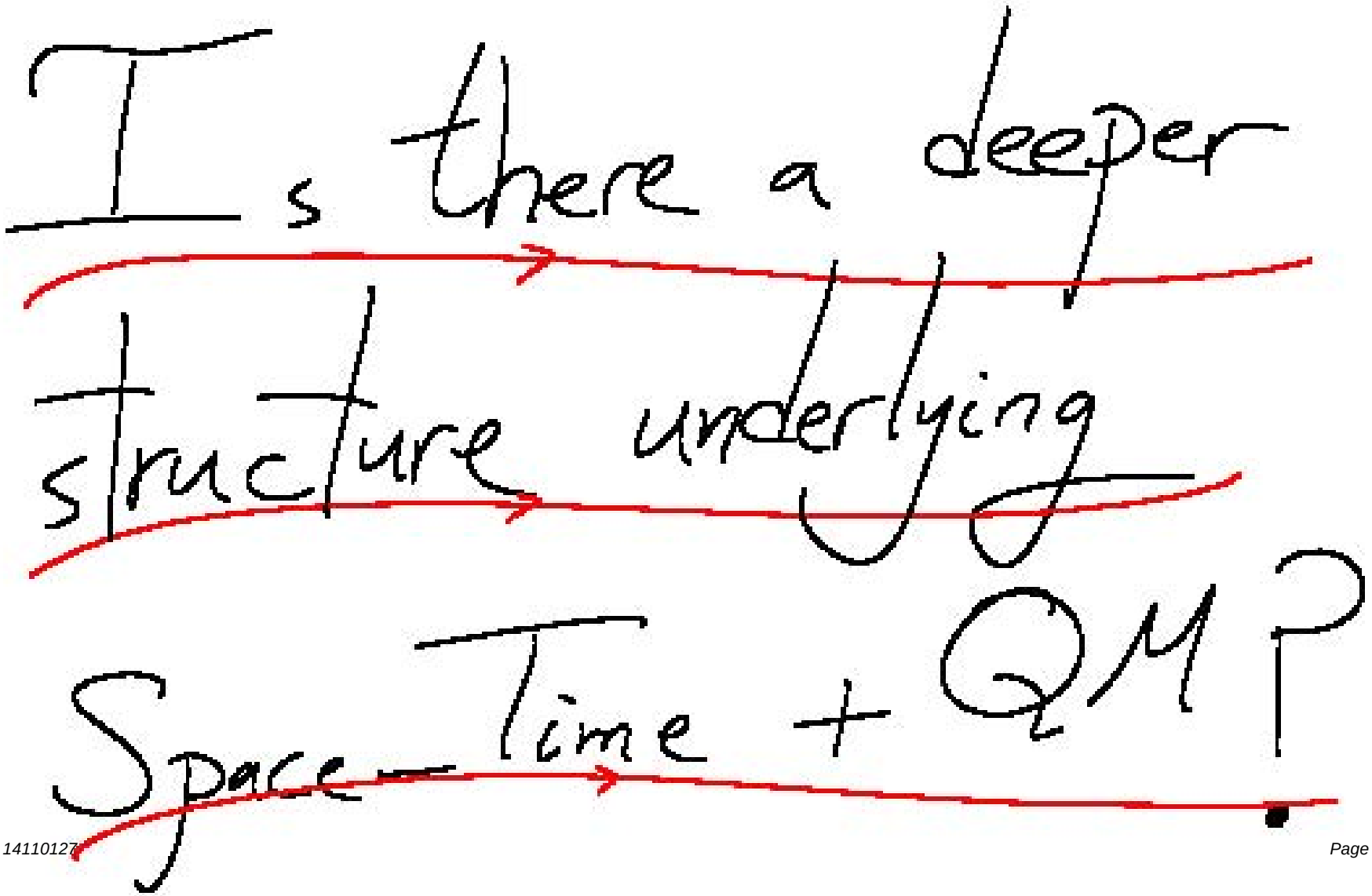
Unification of the Forces — Gravity not far behind!

SUSY at the LHC






L·H·C By 2018
"Natural"
"Fine_Tuned"
See major new physics
SUSY
Nothing but Higgs, or unusual SUSY
Bigger Paradigm Shift


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

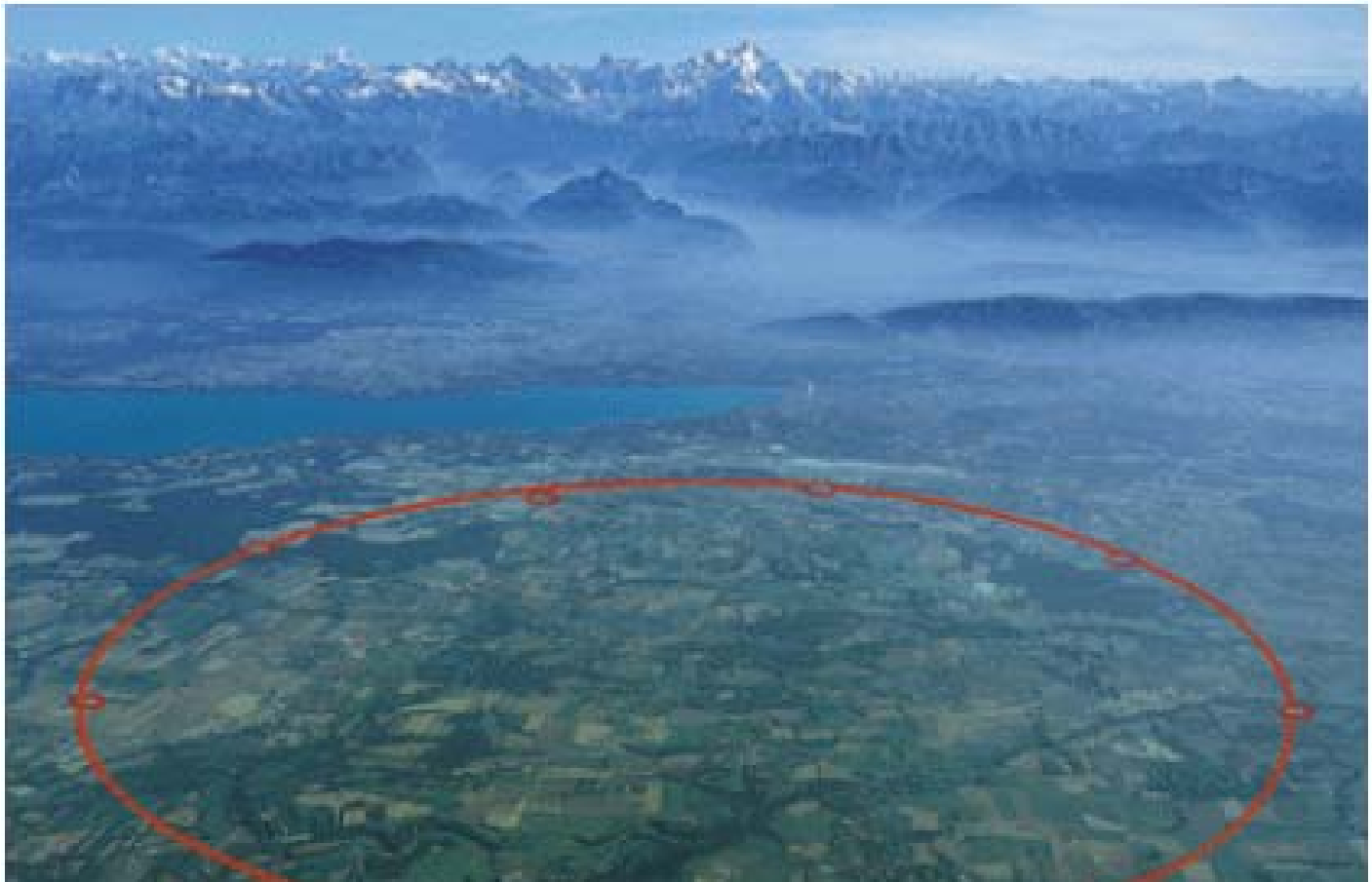
• Sometimes, the most crucial clues are "hiding in plain sight", as funny features of existing theoretical framework.

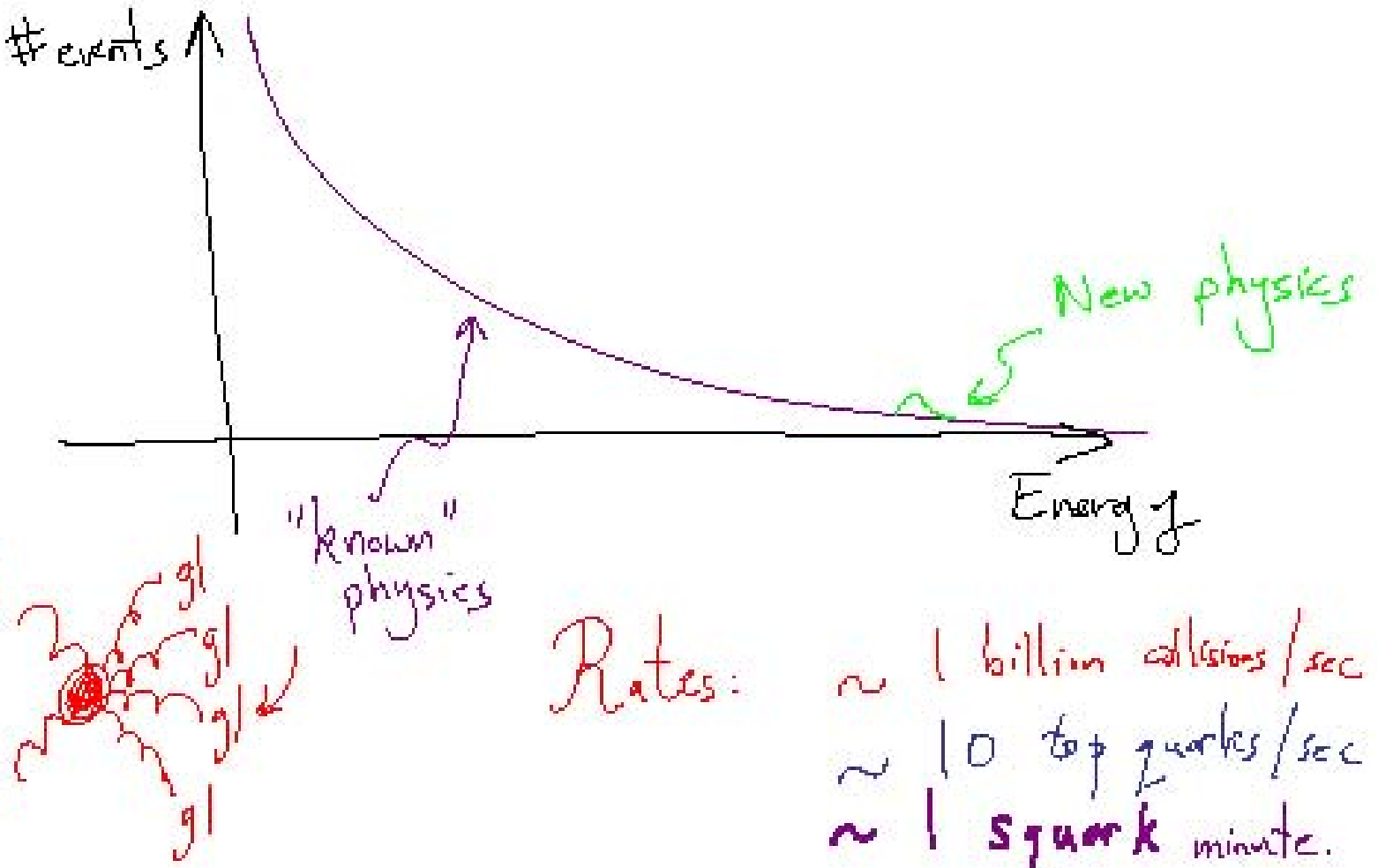
$$m^{grav} = m^{inertial}$$

↓ Principle of Equivalence

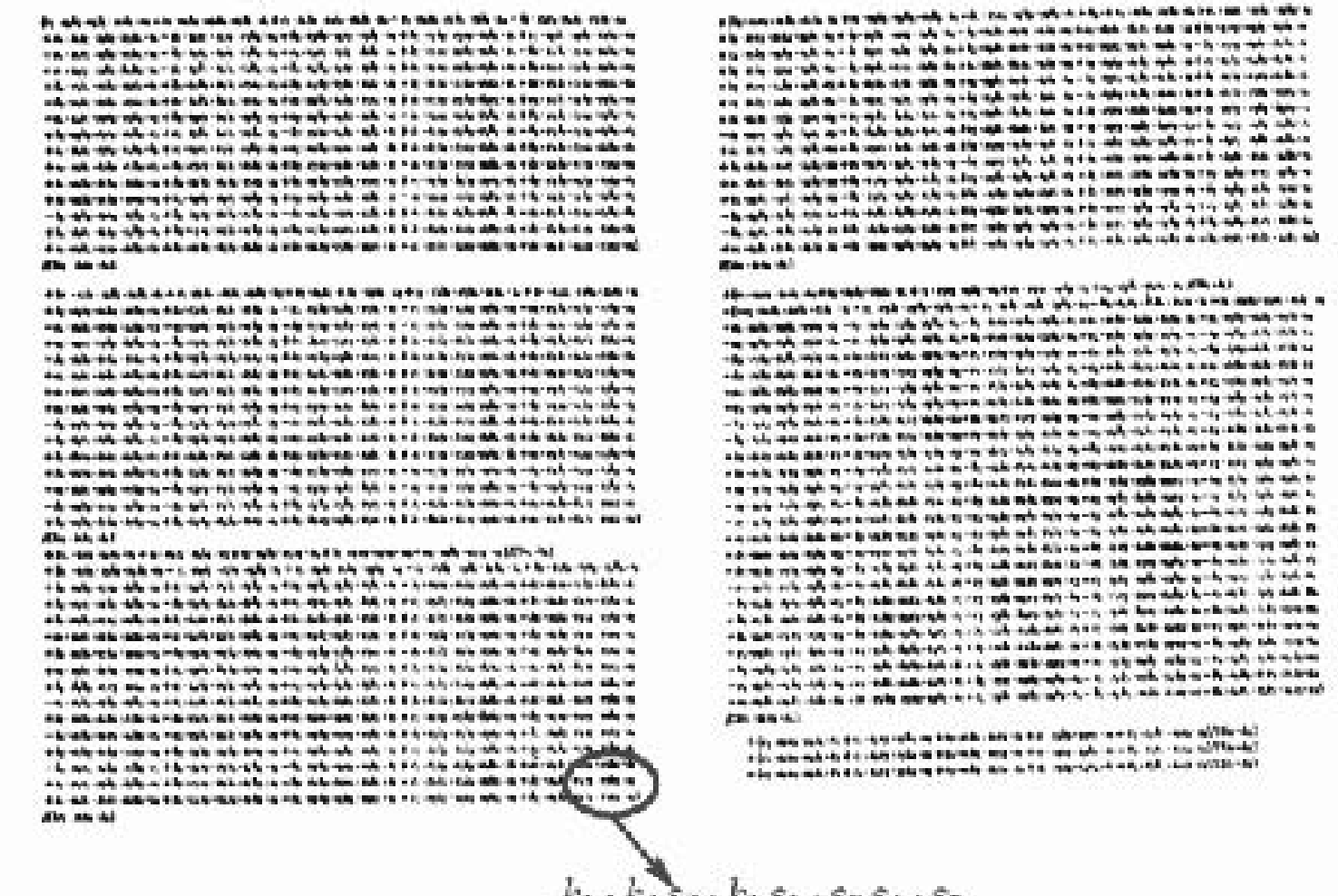
G. R.

L . H . C .




events
New physics
Energy
"Known" physics
g
g
g
g
g
g
g
Rates:
~ 1 billion collisions/sec
~ 10 top quarks/sec
~ 1 squark minute.

Result of a brute force calculation:



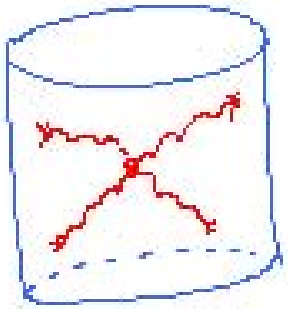
$$k_1 \cdot k_4 \varepsilon_2 \cdot k_1 \varepsilon_1 \cdot \varepsilon_3 \varepsilon_4 \cdot \varepsilon_5$$

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

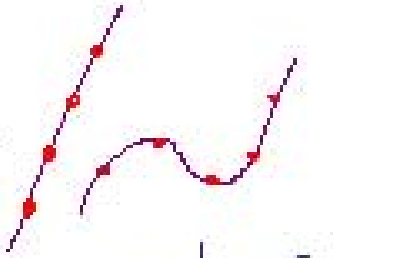
$$\frac{\langle 13\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 56\rangle\langle 61\rangle} \quad (!)$$

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

Sitting Under our Noses for 60 yrs

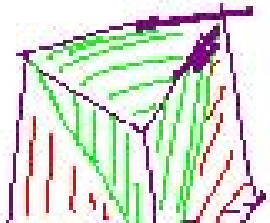


String Theory



Twistor Theory

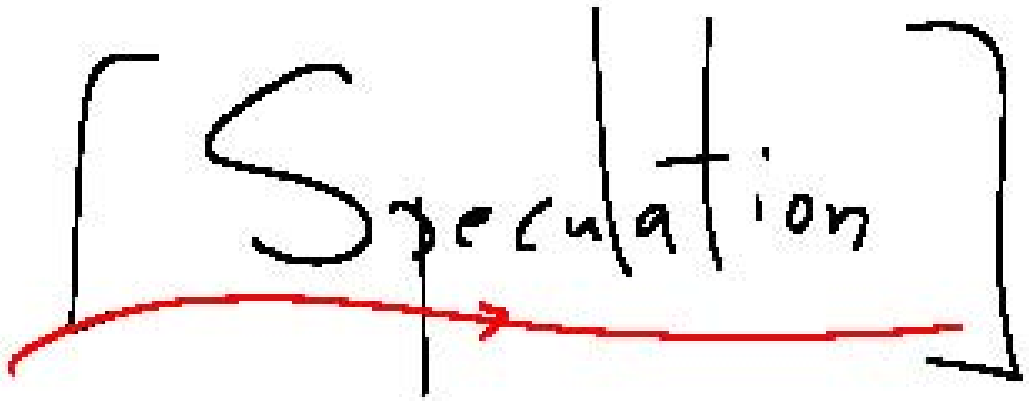
New Formulation of standard physics — emergent spacetime, QM



Many Other Threads of This Sort

Mining "Theoretical Data":

Amazing Physical + Mathematical



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 2 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.

Exhilirating Time

To Be Doing Physics:

"Next Step" will likely