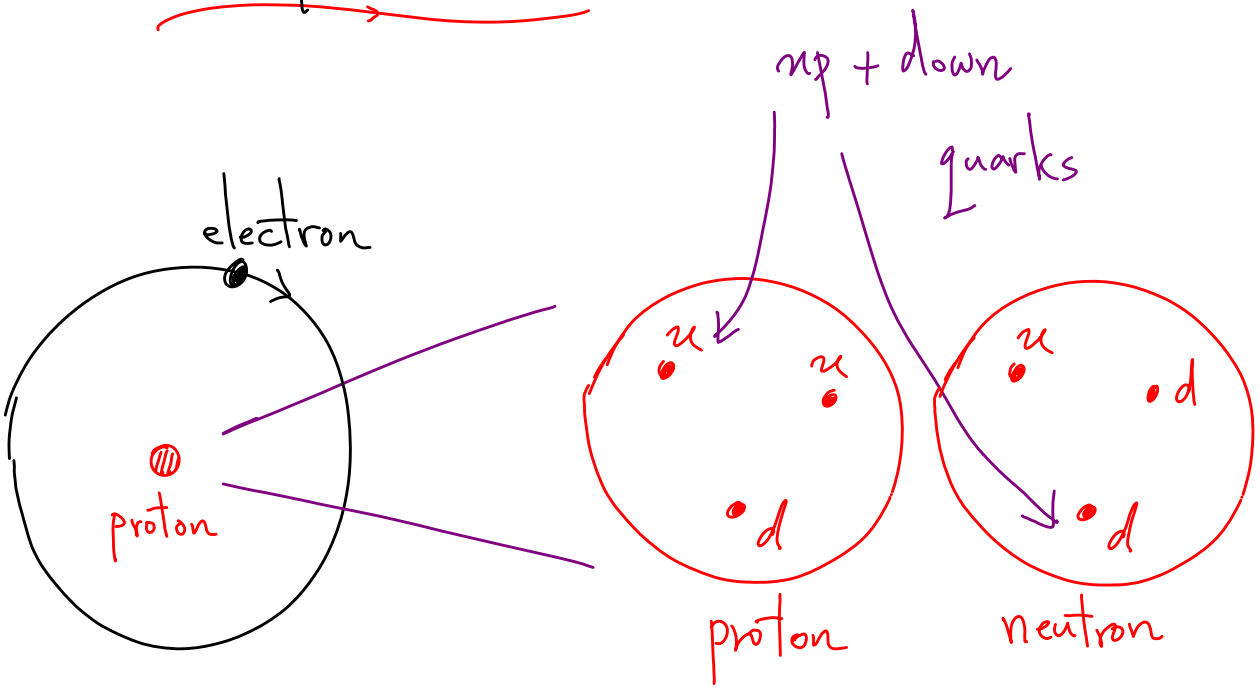
Fundamental Physics + the LHC:

A Progress Report

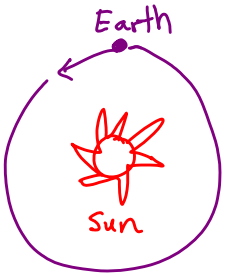
The Inevitability of The Higgs

Matter

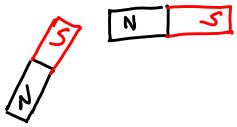


4 Basic Interactions

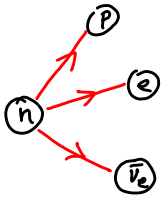
Gravity

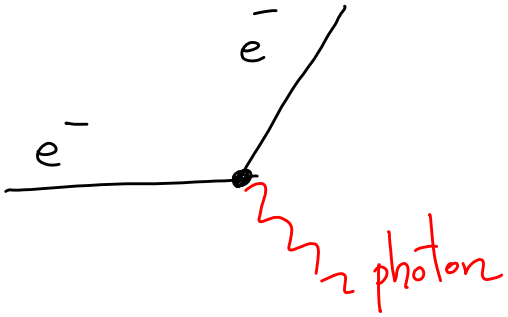


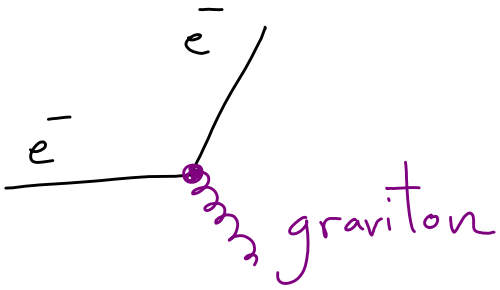
Electromagnetism

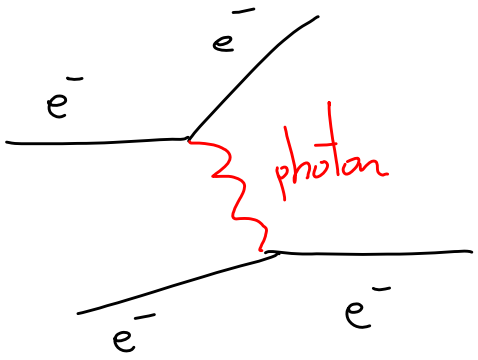


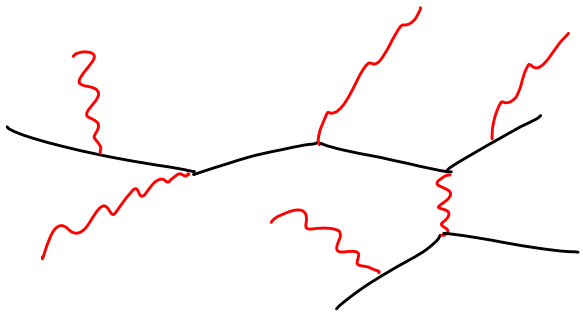
Weak + Strong



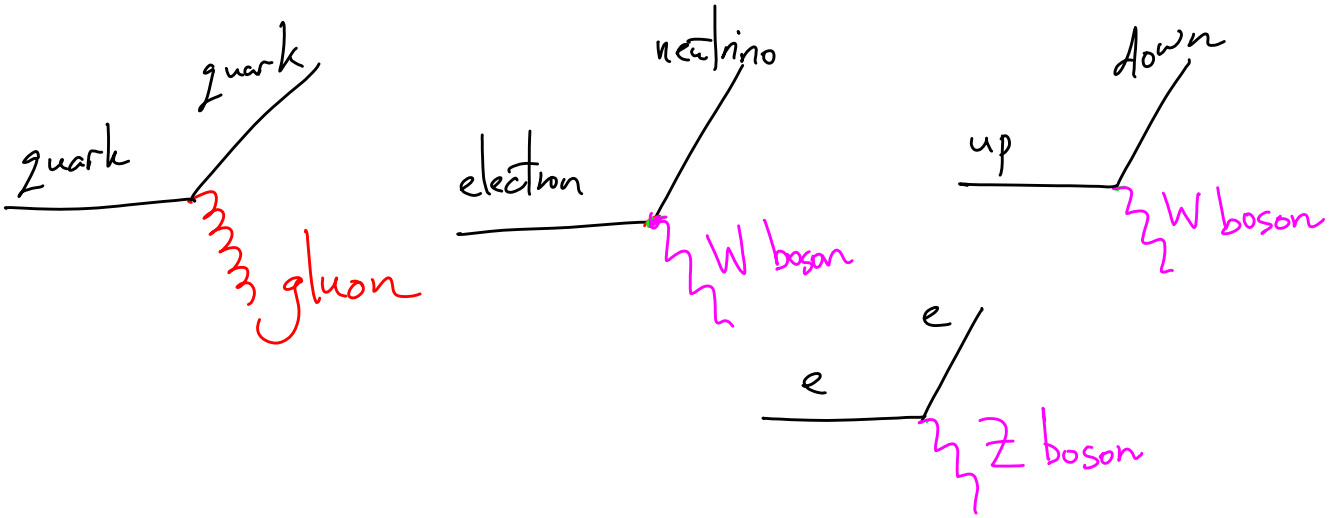

e⁻
e⁻
photon

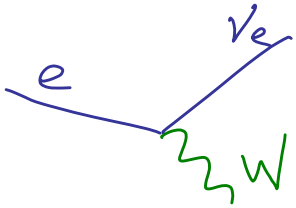

e⁻
e⁻
graviton

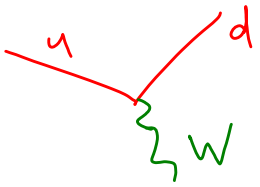

e⁻
e⁻
photon
e⁻
e⁻

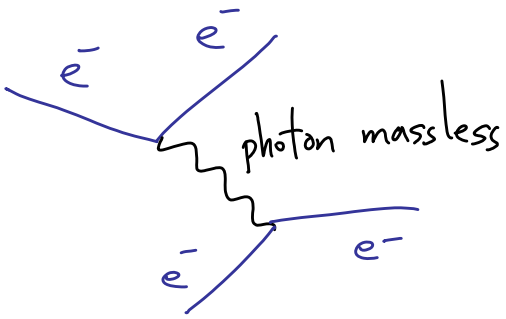


Strong + Weak: Same Structure!

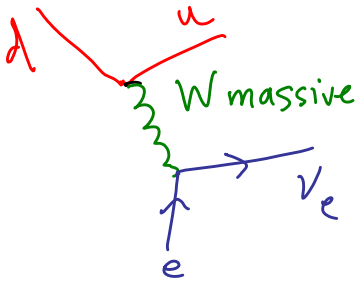






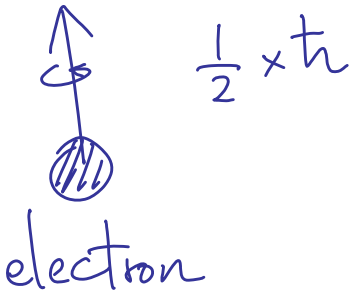


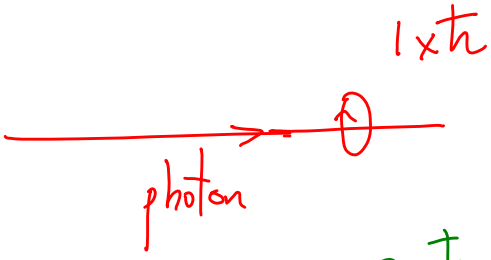
long-range force

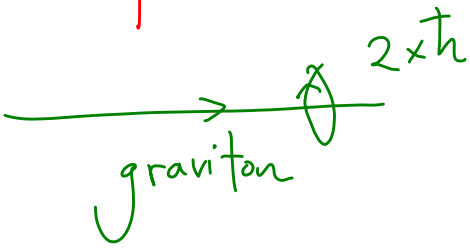


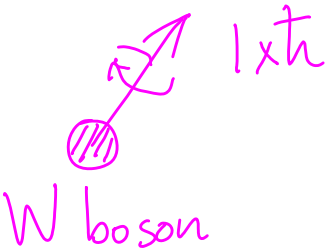
short-range!
($\sim 10^{-16}$ cm)

Particles have Spin









Allowed:

0,

$\frac{1}{2}$,

1,

$\frac{3}{2}$,

2,

$\frac{5}{2}$,

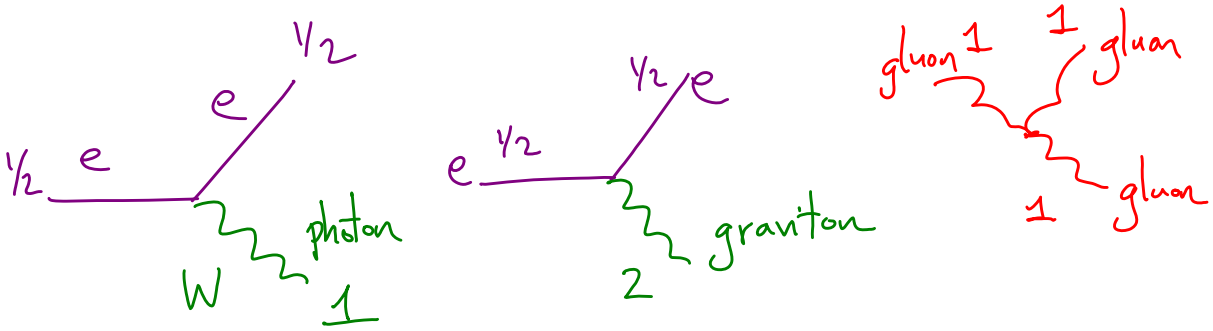
3,

⋮

x ħ

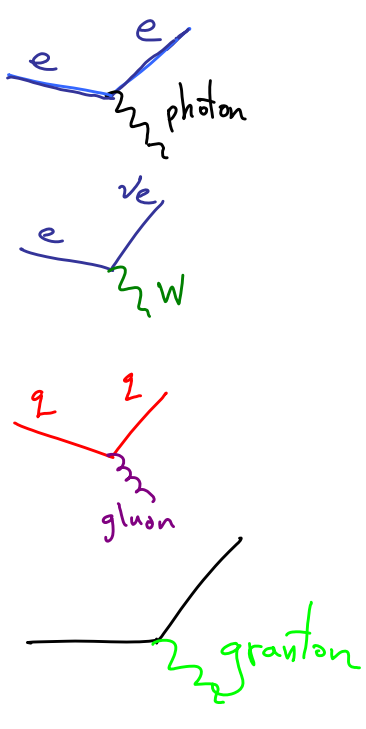
Particles we see extremely simple!

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



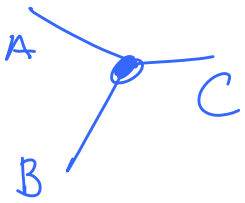
The Menu

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

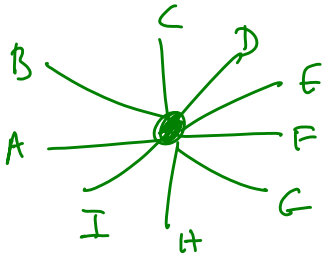


Why So Simple?

- Why simple fundamental interaction



why not



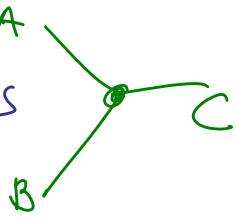
?

- Why such a tiny menu of spins ?

The Power of Relativity + Quantum Mechanics

Whatever the Ultimate Theory

Relativity ↓ Quantum Mechanics

At "Long" distances, particles interacting as 

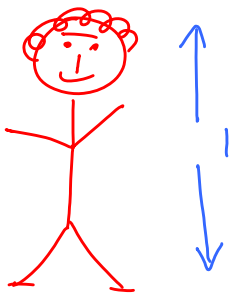
with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. ← unique, "gravity"

Units!

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

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

Put $\hbar = c = 1$



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

Mass $\sim 10^{29}$ GeV

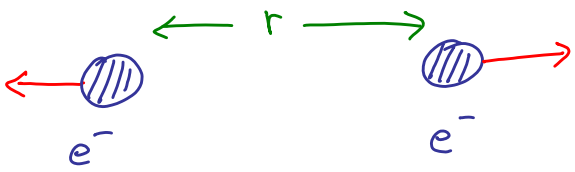
Lecture time $\sim 10^{27}\ \text{GeV}^{-1}$

$(m_p c^2) = 1$ GeV

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

LHC Energies

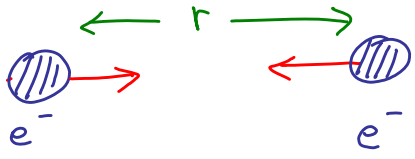
7000 GeV



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

strength

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

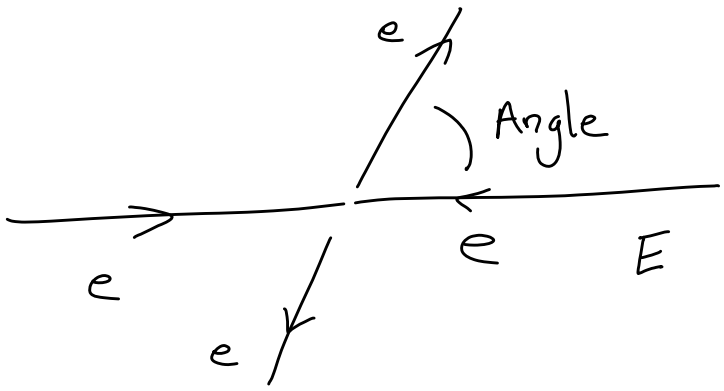


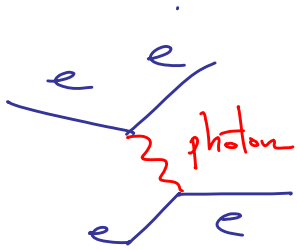
$$\text{Force}^{\text{grav}} \sim -G_N \frac{m_e^2}{r^2}$$

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

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

Quantum Mechanics





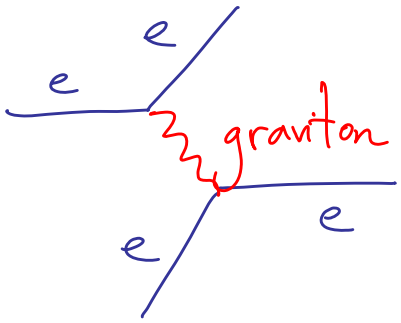
Amplitude

$\sim Q^2$

$\sim 1\%$

small

Probability = (Amplitude)^2



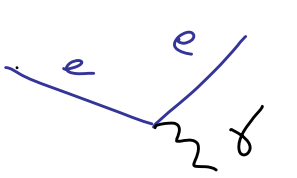
Amplitude $\sim G_N \times E^2$

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

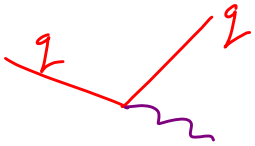
Bigger than 1 (!!!) for $E \gg (10^{19}\,\text{GeV})$

PLANCK ENERGY

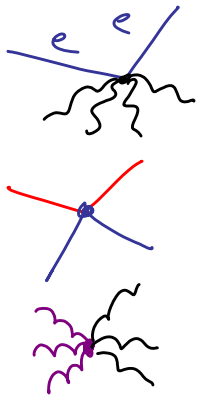
"Effective" Theories



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

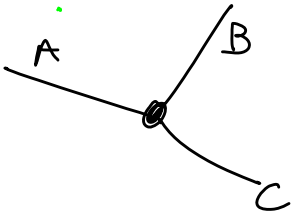


$q^2_{strong} \sim \frac{1}{10}$



strength ~ (length)$^{1,2,3,\ldots}$

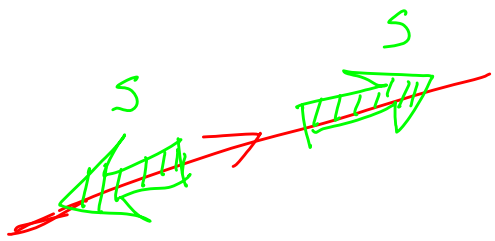
Irrelevant at "long" distances!



relevant

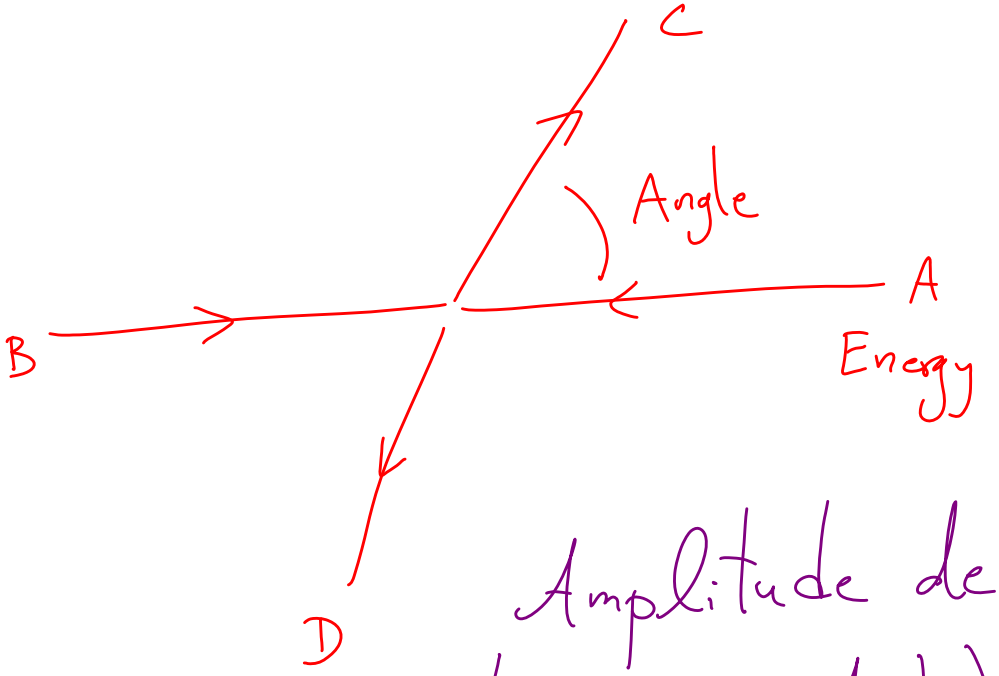
Only @ low energies!

At high energies ⟶ Approximate particles as massless

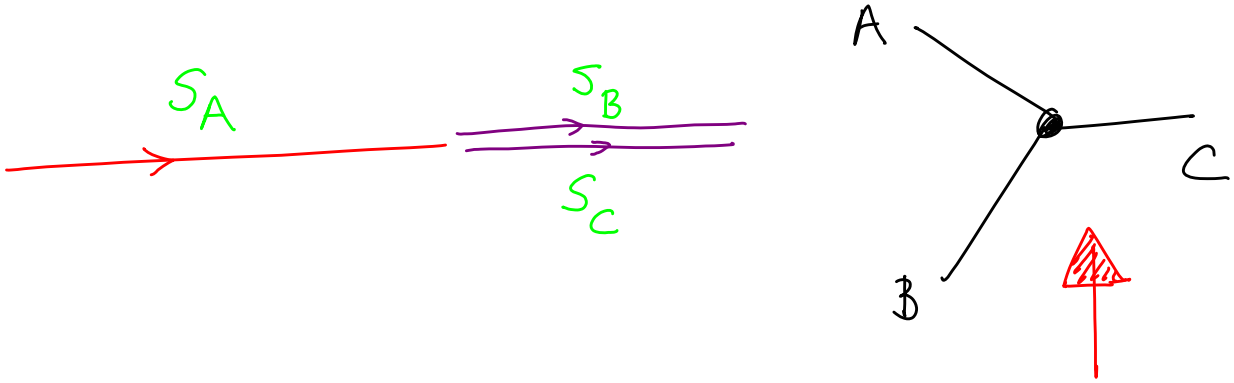


Energy = |momentum|

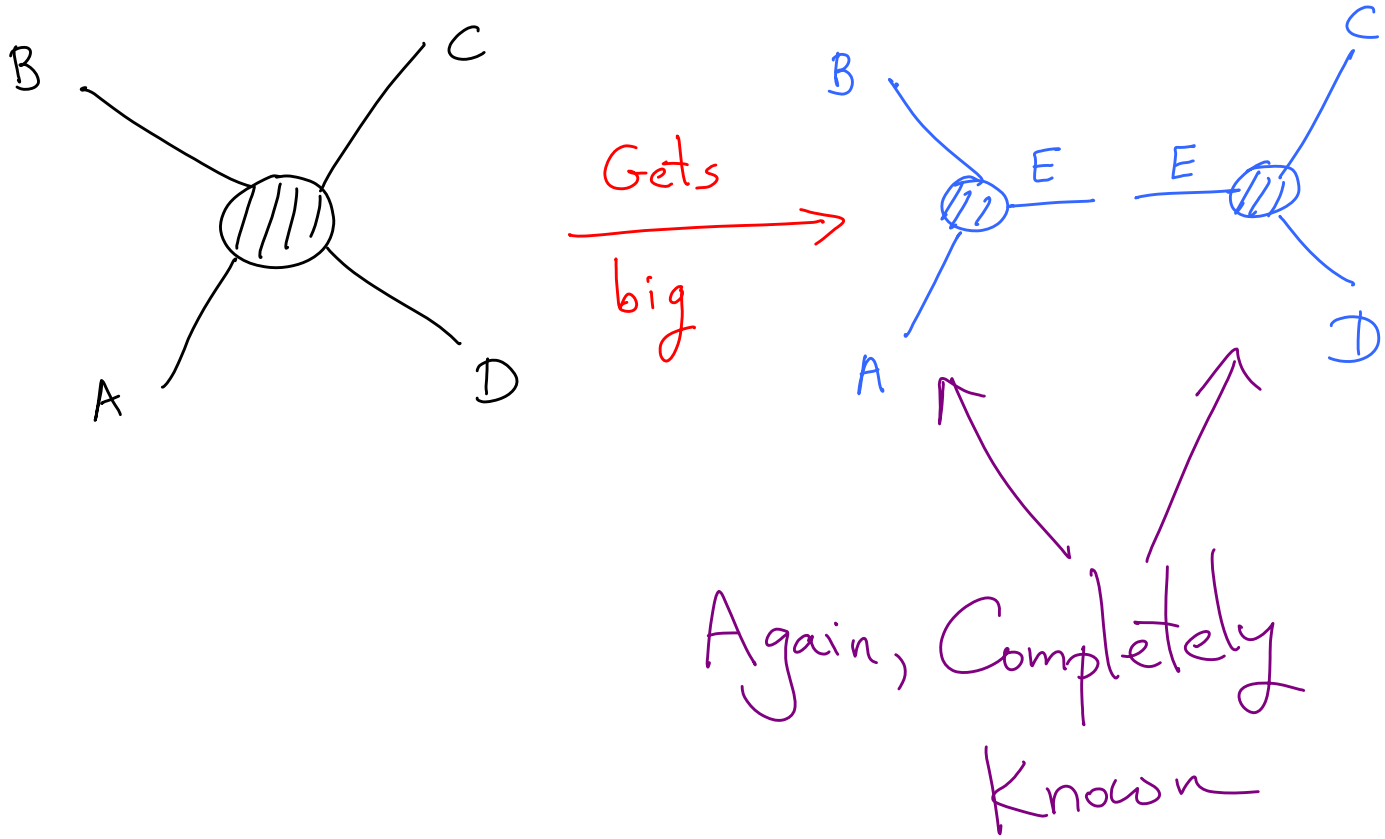
Spin ⟶ "helicity"



Amplitude depends of (Energy, Angle), Complicated!

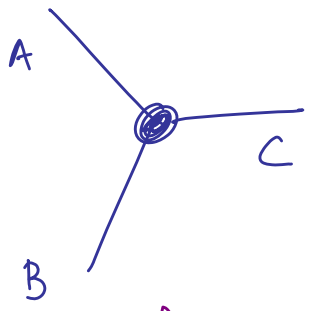


No (Energy, Angle) $\longrightarrow$ COMPLETELY FIXED (up to strength) by helicities!


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

1 yr of Grad School

All Consistent Theories



Spins

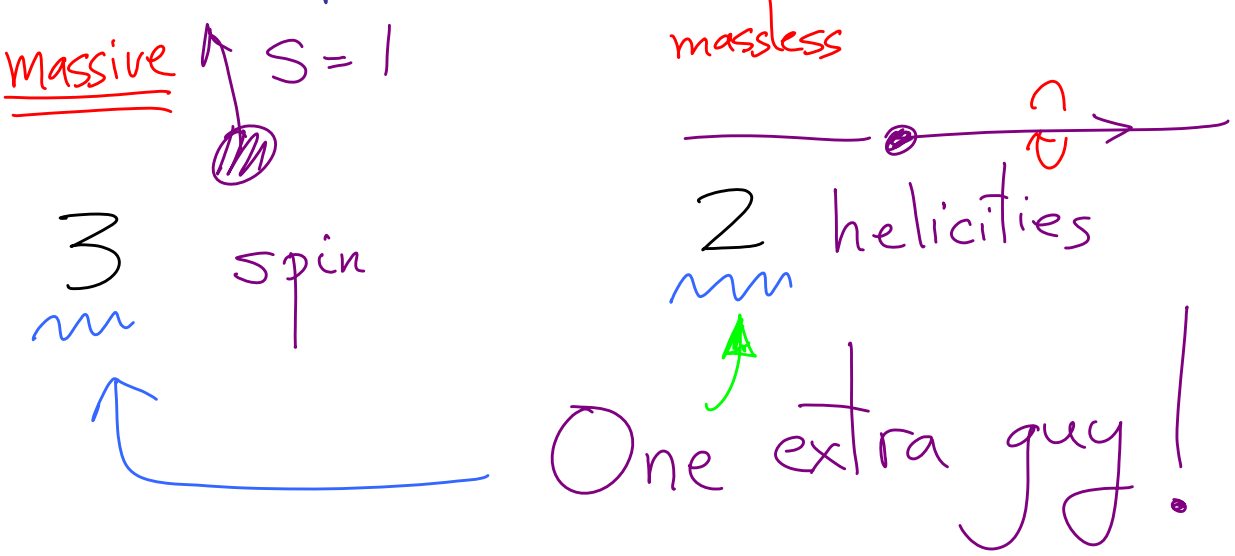
$\{0 \quad \frac{1}{2} \quad 1 \quad \frac{3}{2} \quad 2\}$

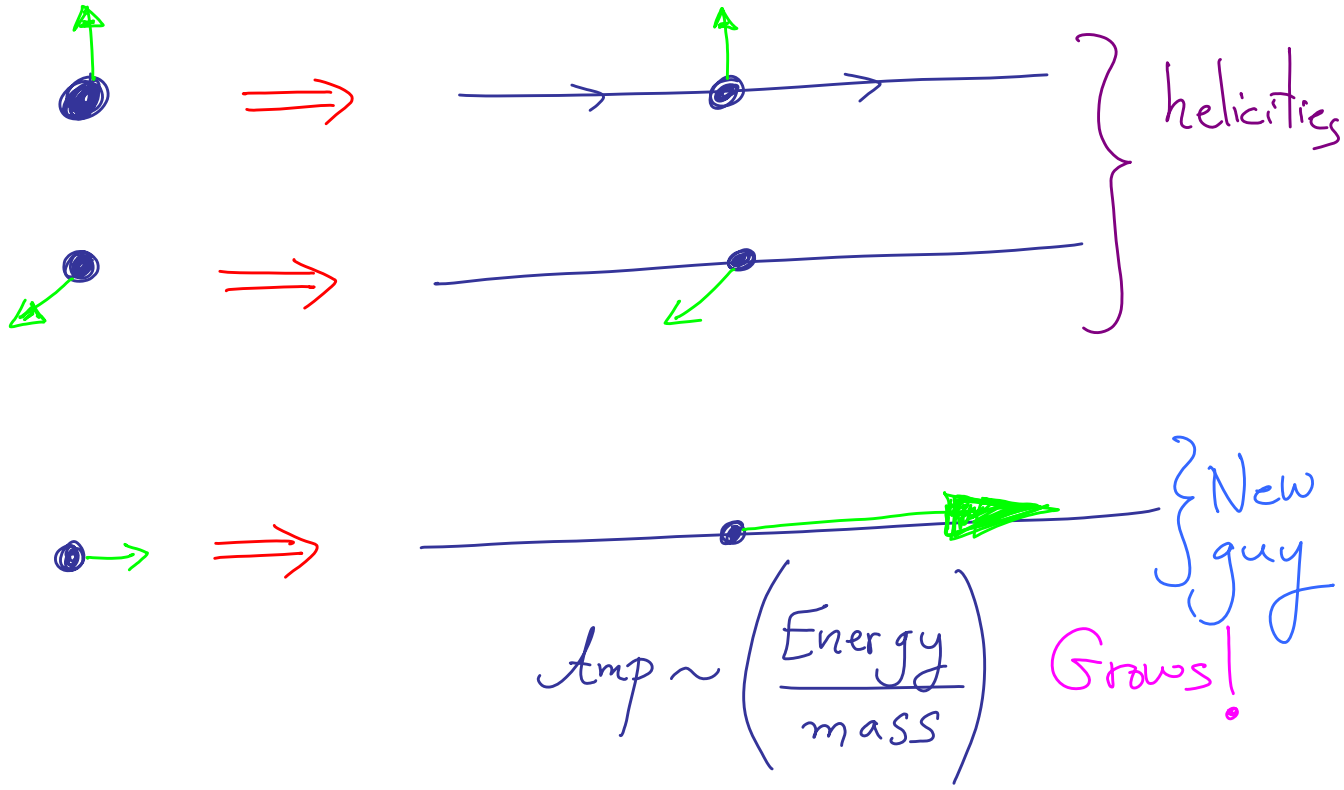
Unique

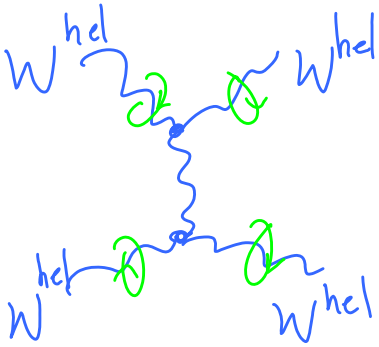
+ some #'s for strength of interaction !

What About The Higgs?

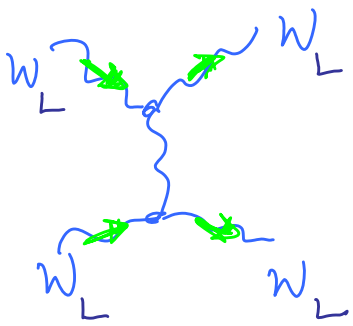
Amazing difference between massive + massless particles with spin:




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



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



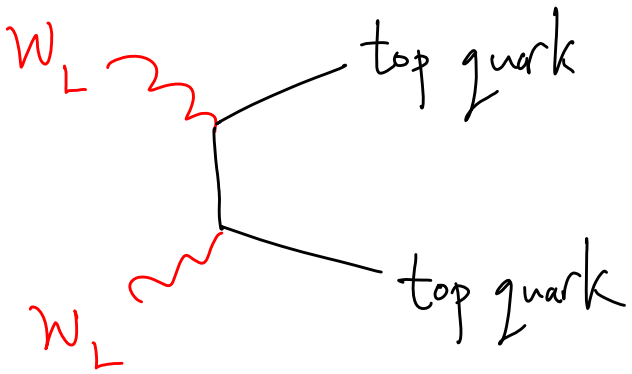
$$\text{Amplitude} \sim q^2 \times \left(\frac{\text{Energy}}{\text{Mass W}}\right)^2$$

q^2: 1%

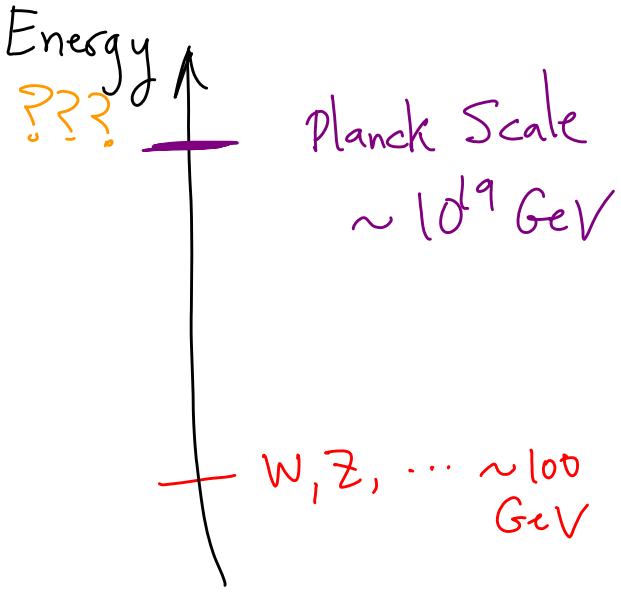
Mass W: 80 GeV

> 1 (!!!) if Energy > 1200 GeV!

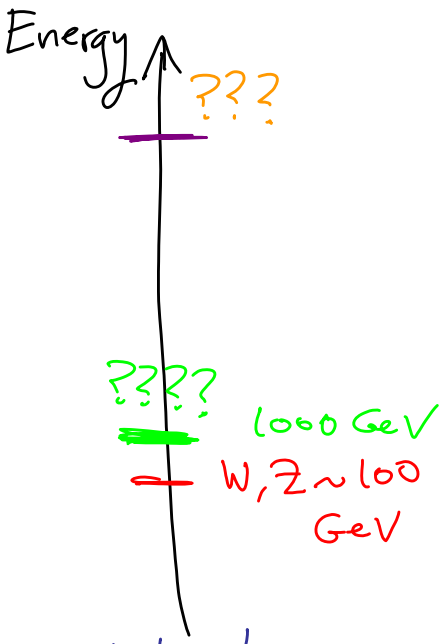
... Other Problems of this Sort ...



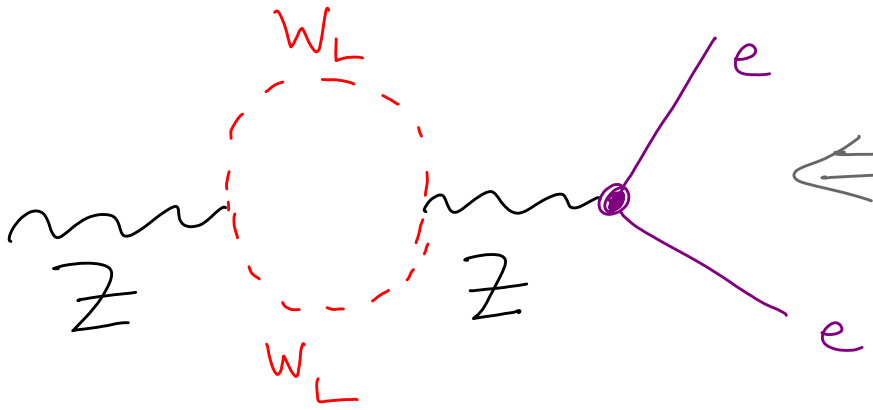
Again, Amplitudes become nonsense (>1) around 1000 GeV



Naive Expectation



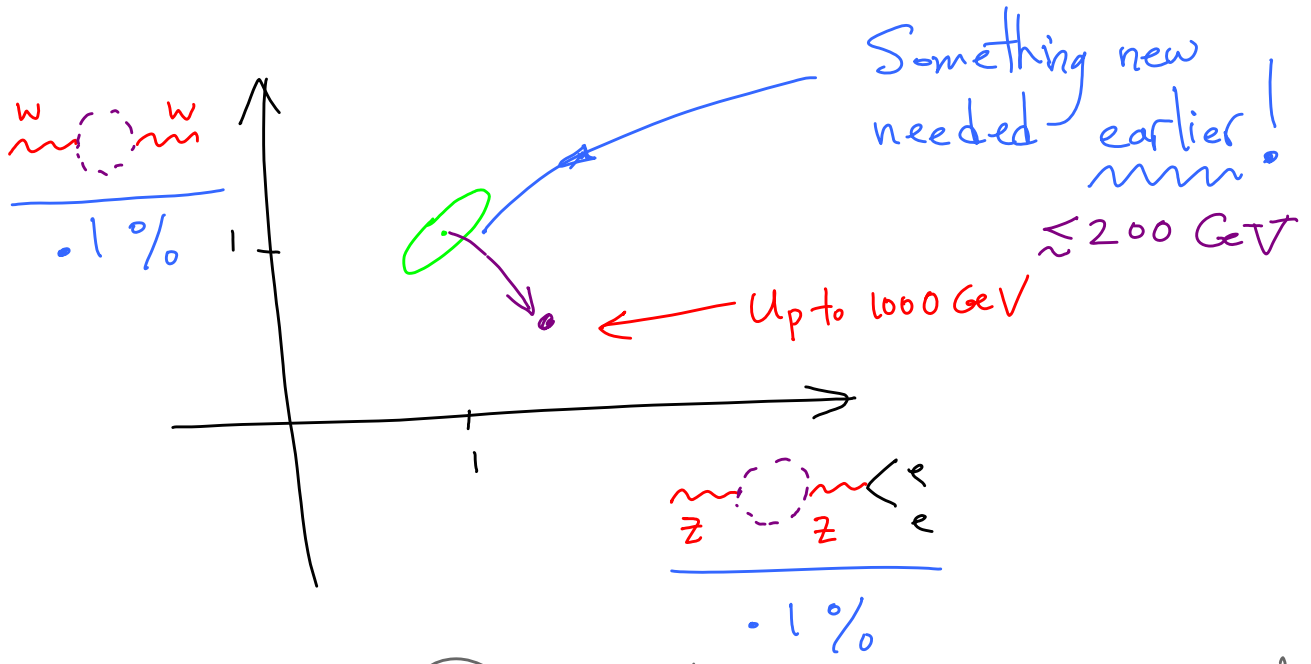
Actual Situation



Detailed Theory Calculations ~1989-1990

Assume nothing new till 1000 GeV

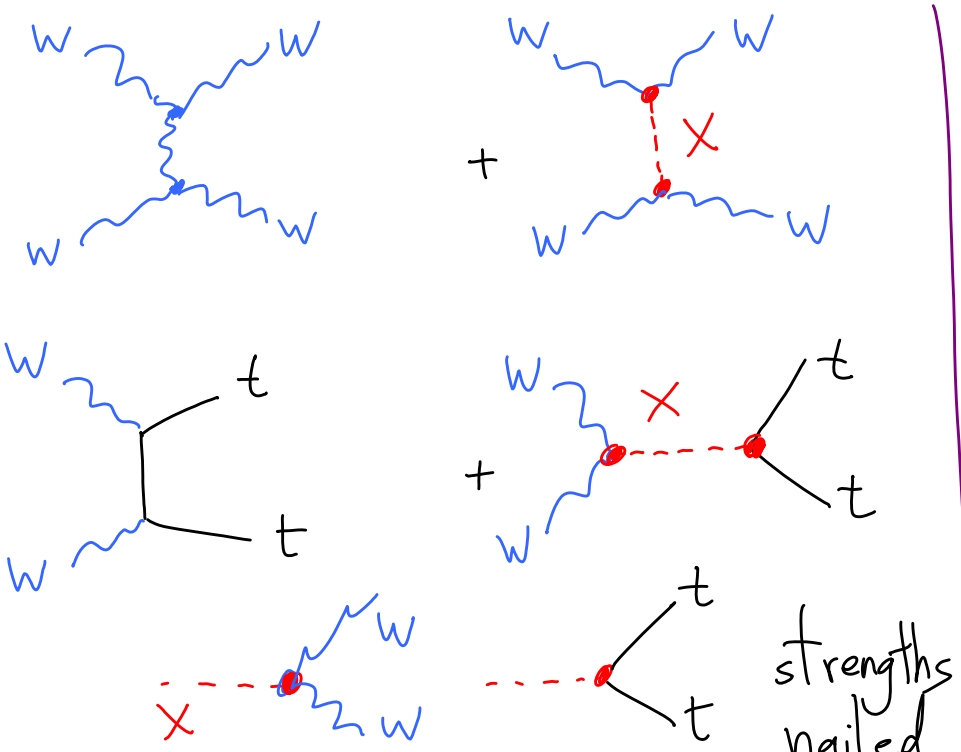
$\Longrightarrow$ 1% level corrections



Exquisitely Precise Expt. Measurements

~ 1989 - 1991

Need Something New Earlier!



strengths nailed

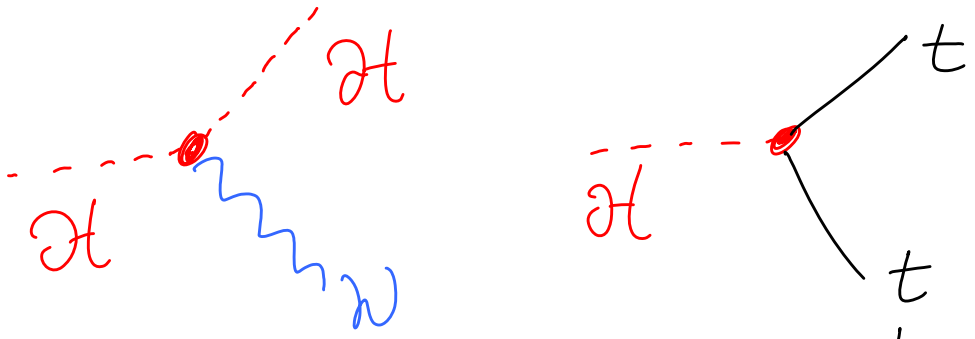
Spin of X:

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

MUST BE SPIN 0

X = Higgs

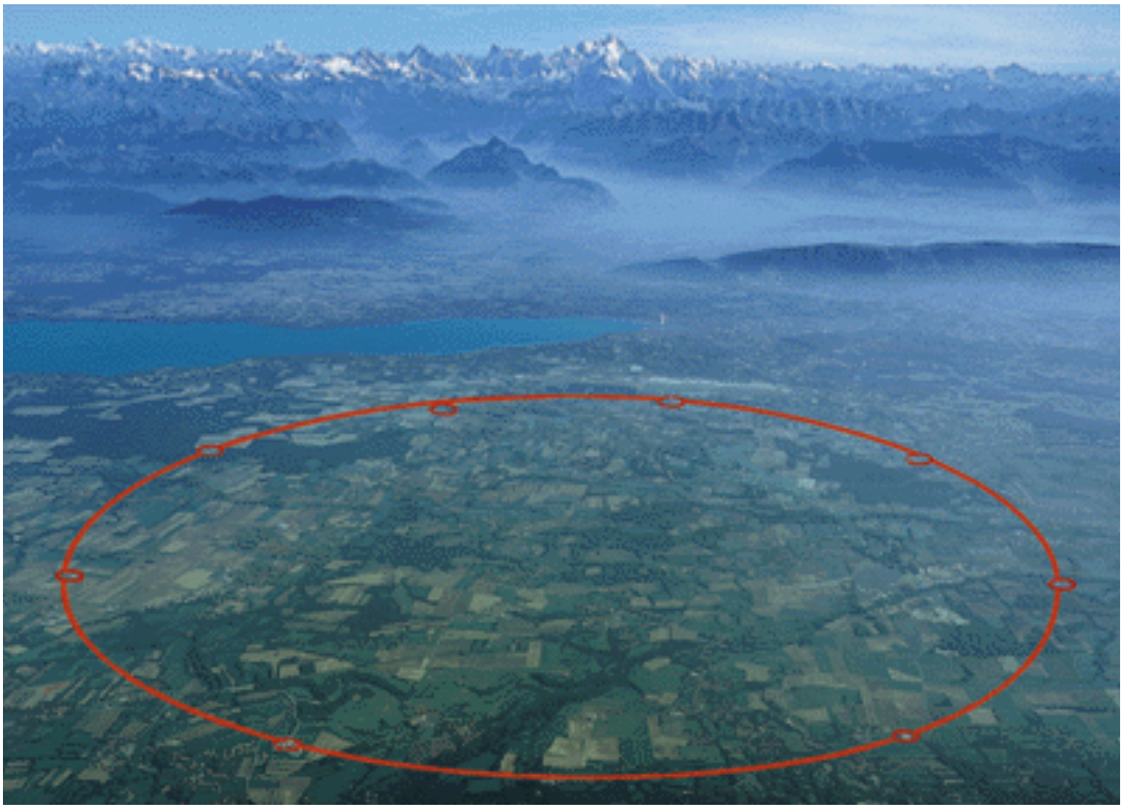
At very high energies, H and W_L, Z_L are all united into $\mathcal{H}$.



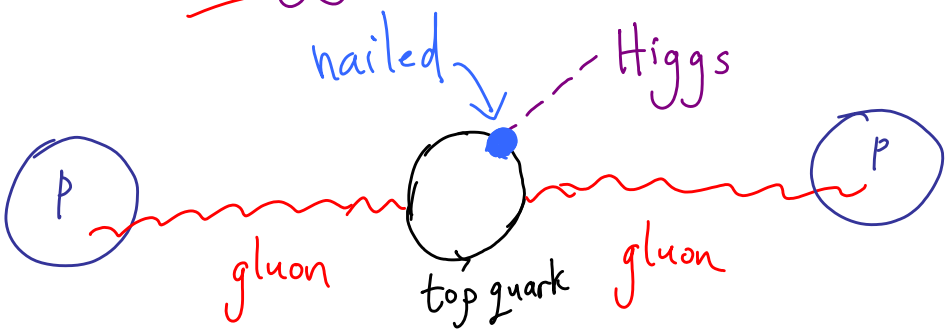
Usual Allowed Interactions

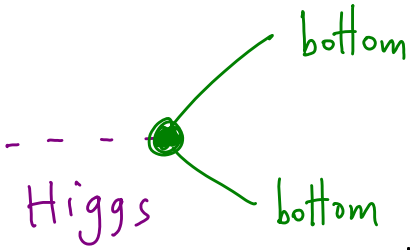
This was a Brave Proposal:

No Fundamental Spin 0 had ever been seen!

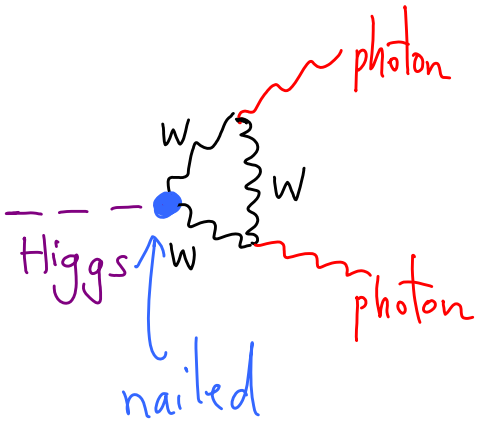


Higgs at the L·H·C

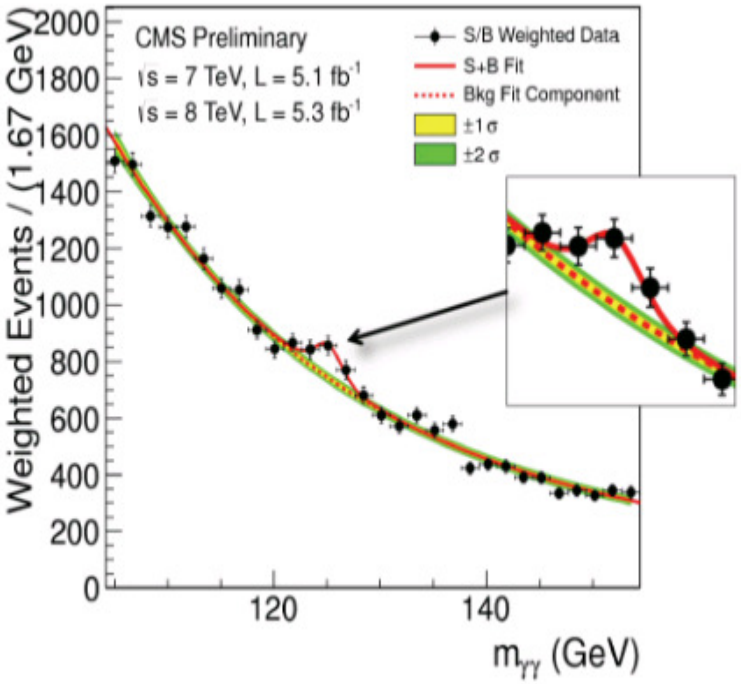




Very Hard to See!



← rare, but can see it!


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1σ
±2σ
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)

There it is!

TRIUMPH FOR EXPERIMENT

TRIUMPH 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!

Why is there a Macroscopic Universe?

"Naturalness" + it's Discontents

* Why are particles (nearly) massless relative to Planckian Scales?

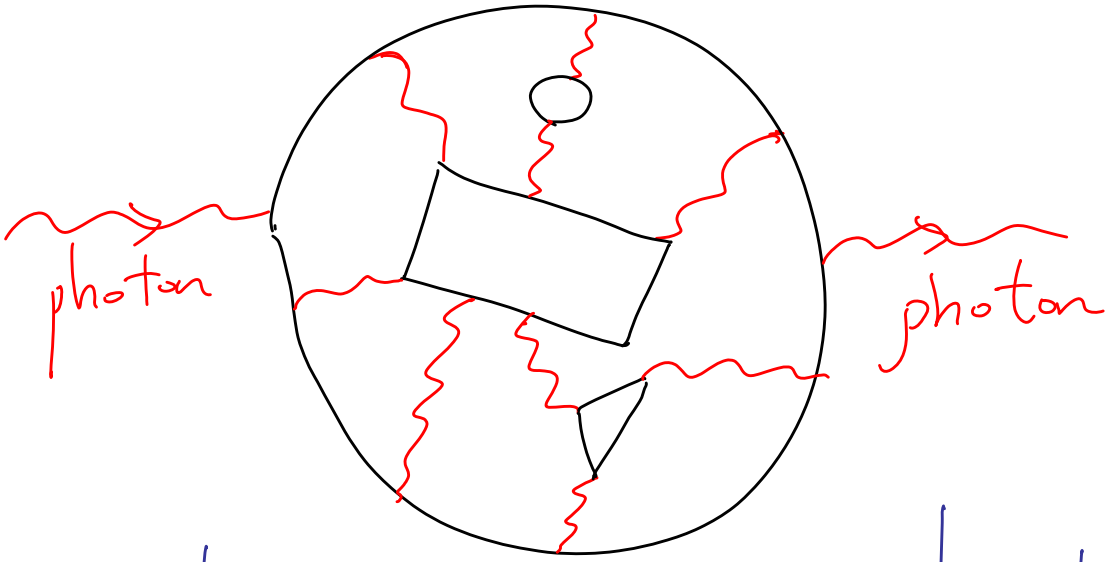
* [Why is there a Macroscopic Universe?]

Quantum Mechanics ⟹

"Totalitarian Principle":

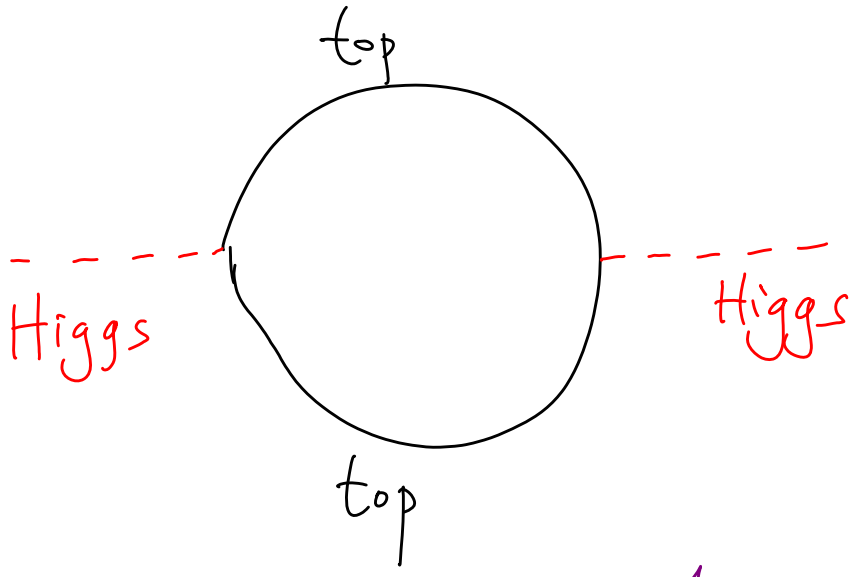
Everything that CAN happen

MUST happen



But photon MUST stay massless, because

massless helicities → 2 ≠ 3 ← # massive spins

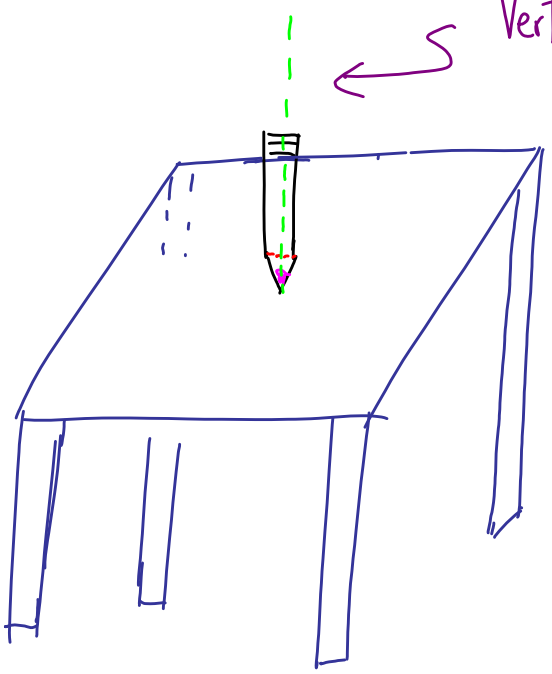


massless spin 0 $\frac{1}{\quad} = \frac{1}{\quad}$ massive spin 0

NO DIFFERENCE

WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

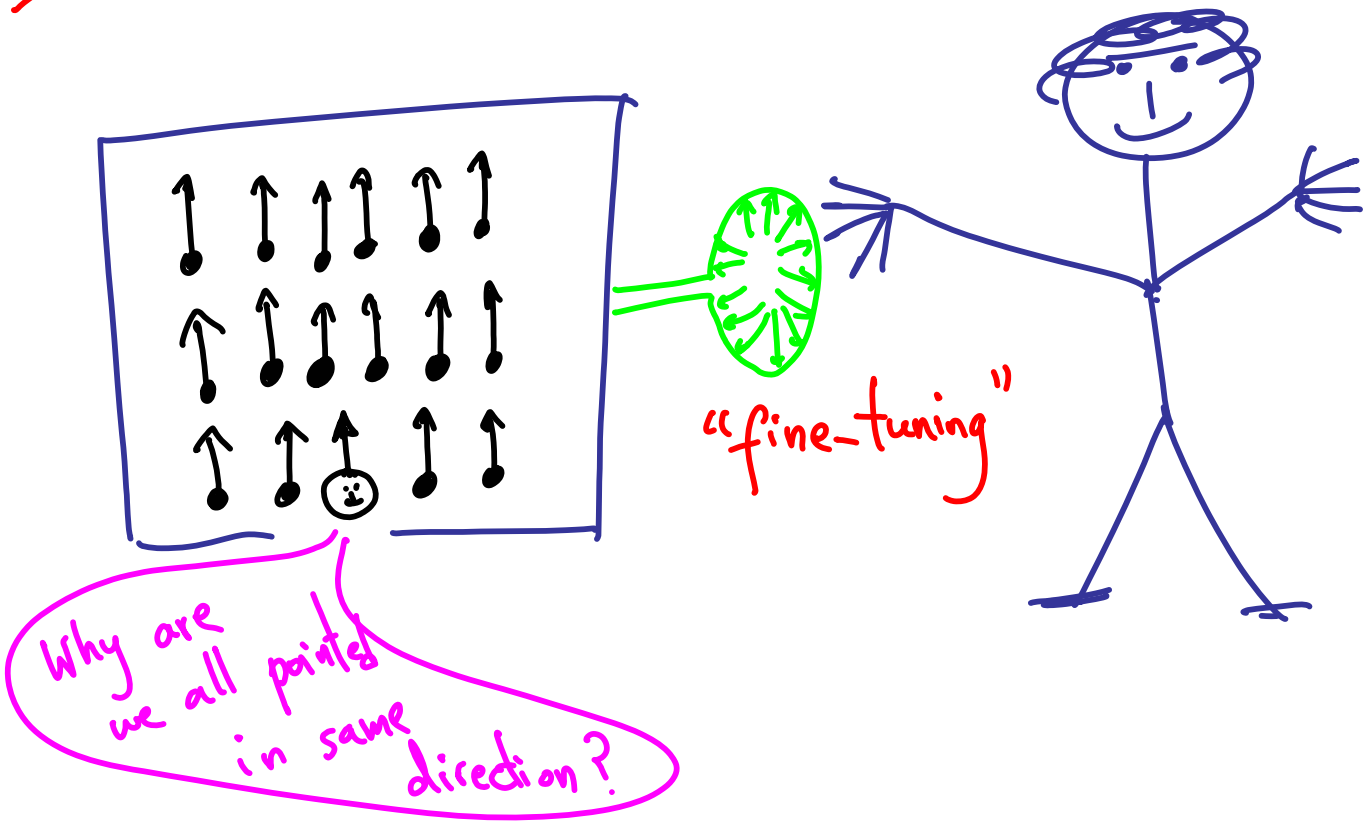
"Fine Tuning"



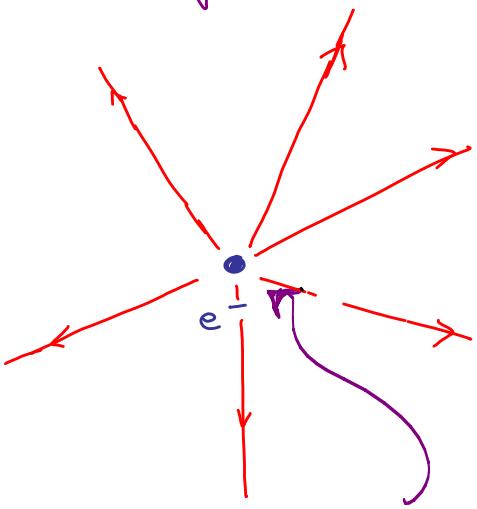
Vertical to accuracy 10^{-30} degrees!

CRAZY (?)

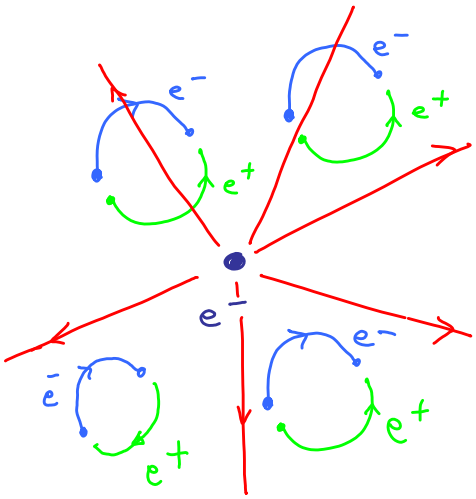
Never seen before in "state of nature"



Infinite Energy In Electric Field



Q.M.
Rel.

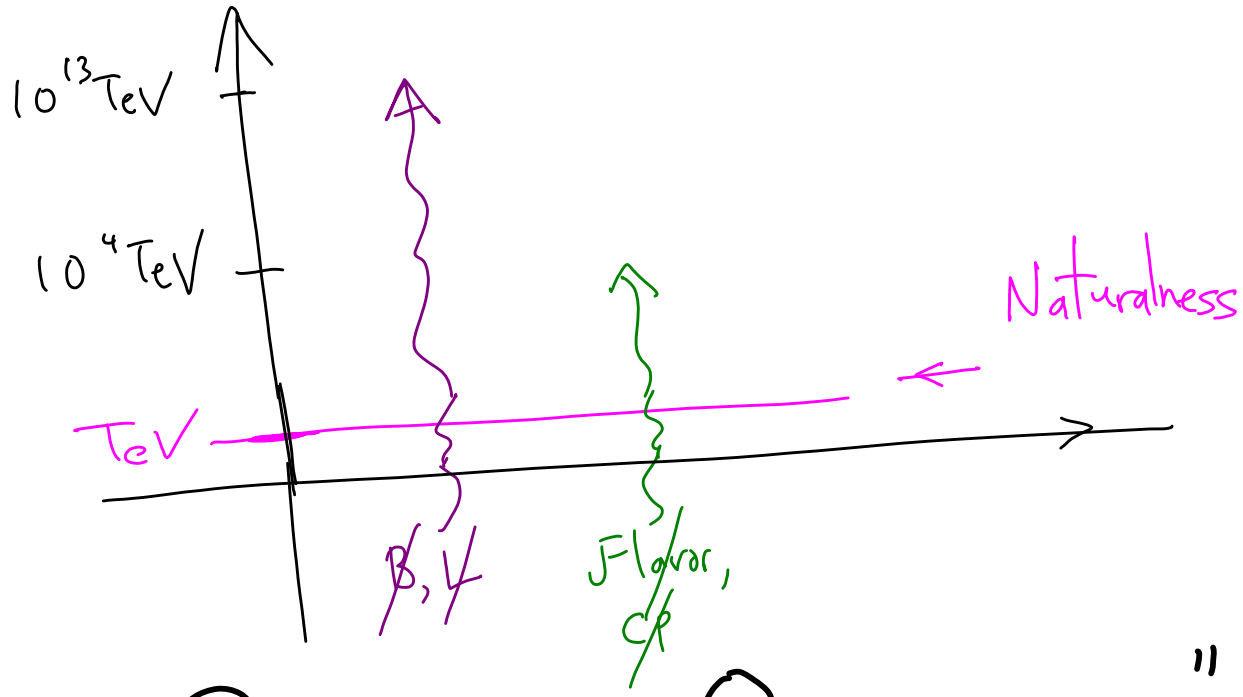


$$\frac{e^2}{4\pi a_{cl}} \sim m_e c^2 \Rightarrow a_{cl} \sim \frac{e^2}{4\pi m_e c^2}$$

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

$$\sim \alpha^{-1} \times a_{cl} !$$

Tension Driving Field For 30 yrs



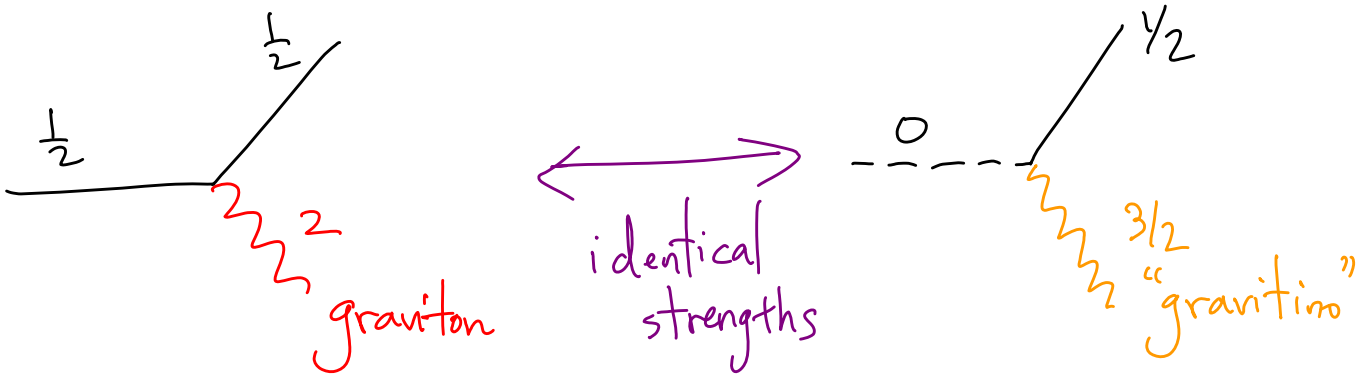
"Not Problems – Opportunities"

An Obious Gap!

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

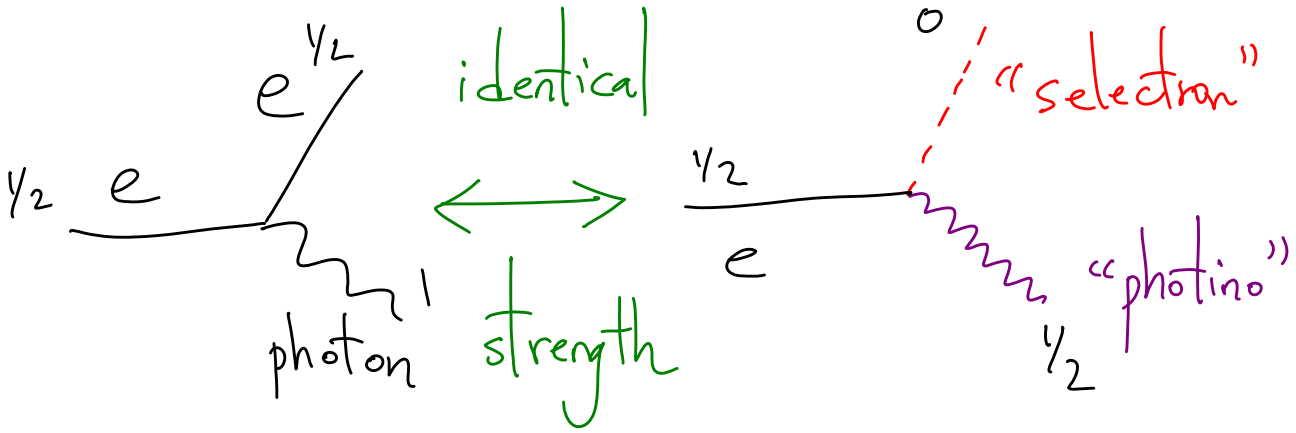
↑ POSSIBLE, VERY SPECIAL!

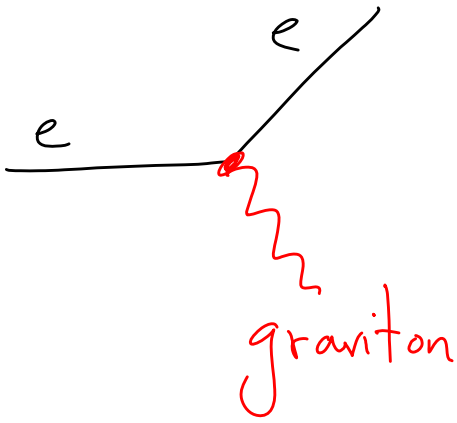
"SUPERSYMMETRY"

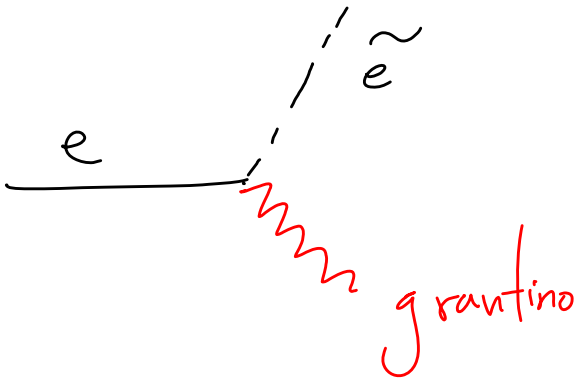


All spin $\frac{1}{2}$ particles have spin 0 "partners"

All spin 1 particles have spin 1/2 "partners"


e
1/2
e
1/2
photon
1
identical
strength
0
"selectron"
1/2
e
"photino"
1/2





"Conserved Quantity"

Energy + Momentum

"Conserved Quantity"

$Q_{1,2,3,4}$

$Q_1 Q_2 = -Q_2 Q_1$ (!)

Supersymmetry

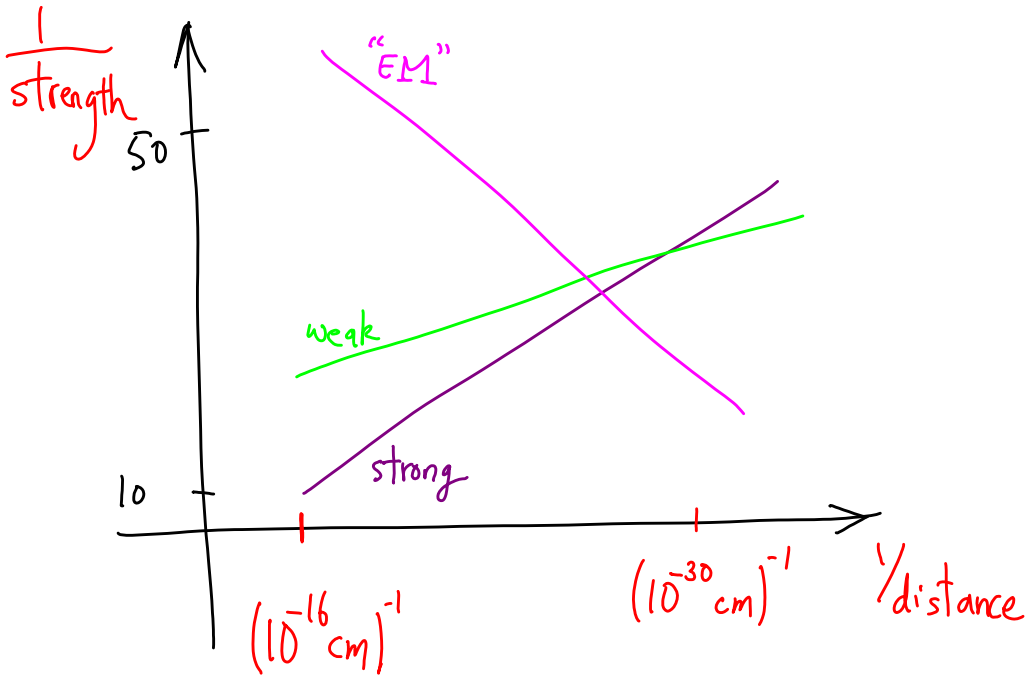
* Last Consistent Possibility
* Dramatic extension of Spacetime → More "Quantum"

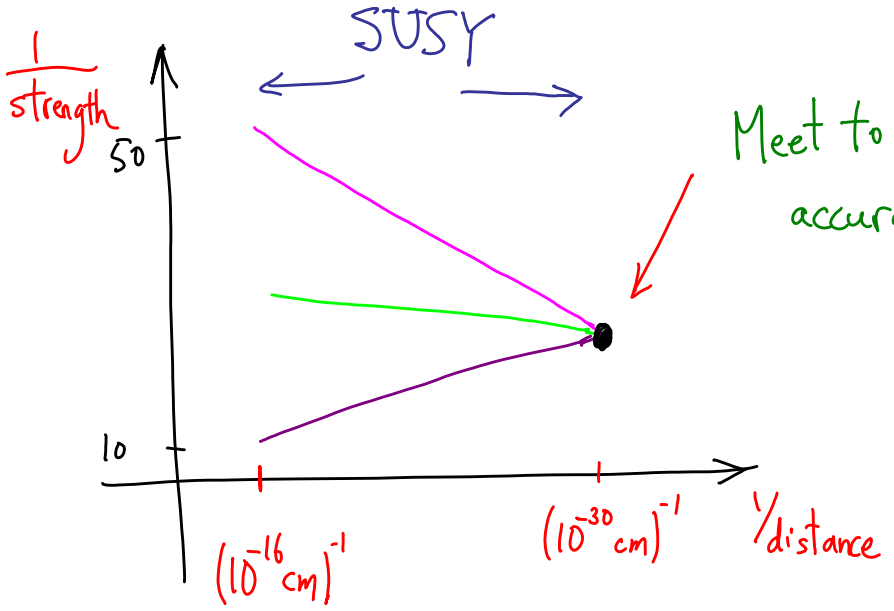
★ Solves Higgs Problem

Higgs: spin 0

↕ SUSY

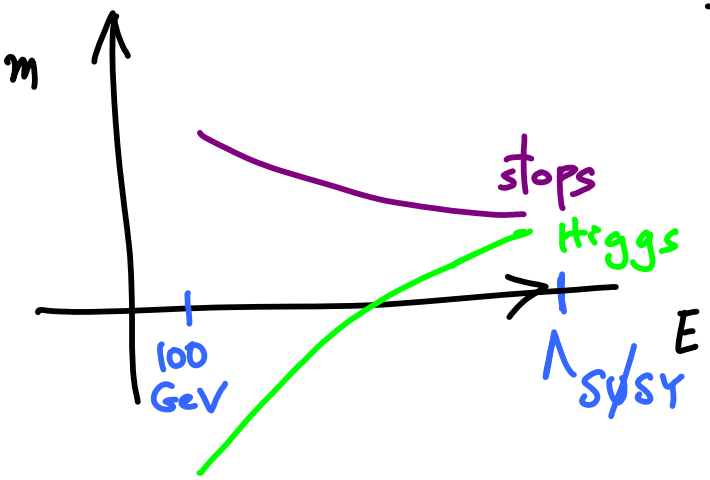
"Higgsino": spin $\frac{1}{2}$ ← Particle with spin, can have tiny mass relative to Planck Scale

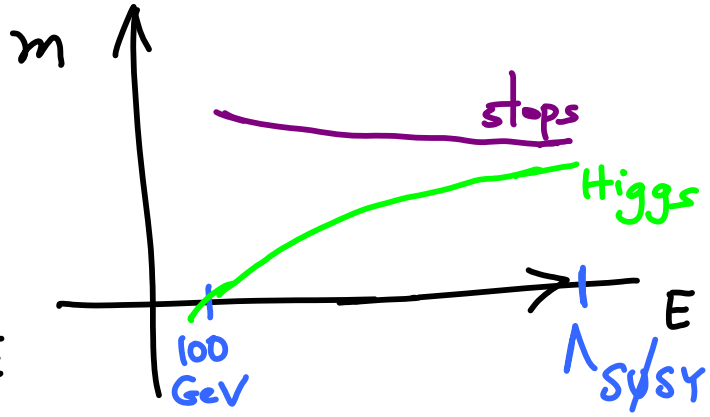

1/strength
50
10
"EM"
weak
strong
$(10^{-16}\,cm)^{-1}$
$(10^{-30}\,cm)^{-1}$
1/distance



Unification of the Forces – Gravity not far behind!

Why No SUSY seen in 1990?





—— $Z, h, \tilde{t}, \tilde{g}$...

—— $\tilde{\ell}$, EW Kinos

"Natural" Spectrum

?

—— Z, h

"Nature-al" spectrum

SUSY + The Higgs

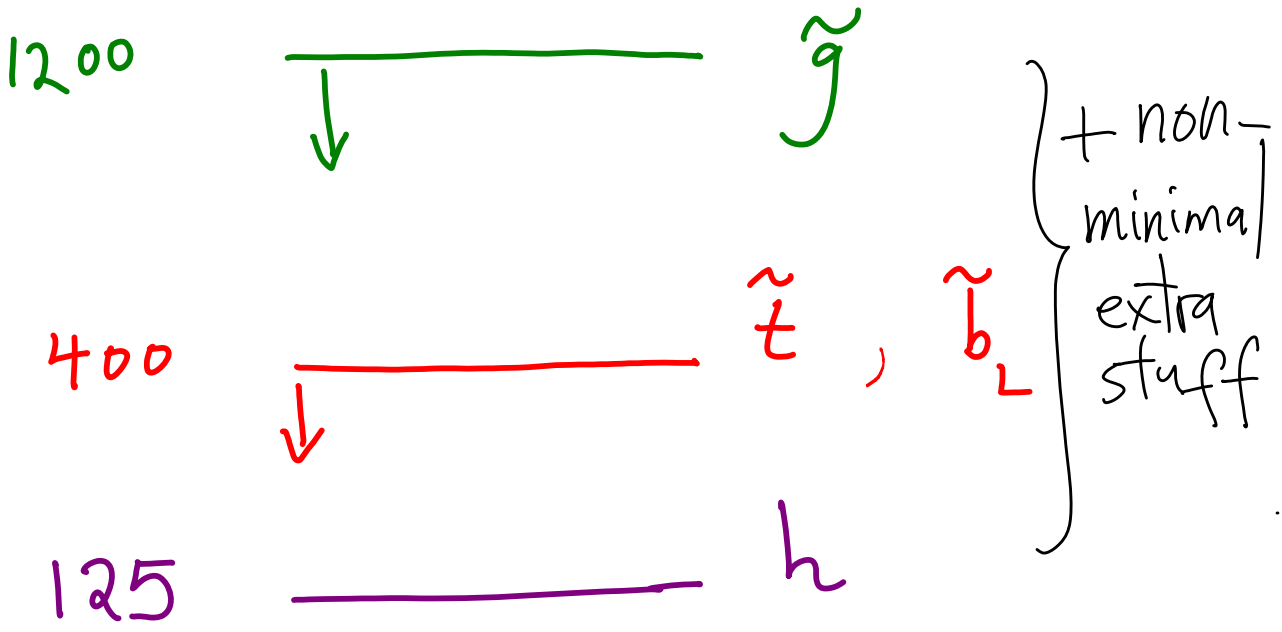
(Z + Higgs) , ("Zino")

3 d.o.f 1 d.o.f. 4 d.o.f

$$M_h \lesssim M_Z + M_h^{\text{syst, stops}}$$

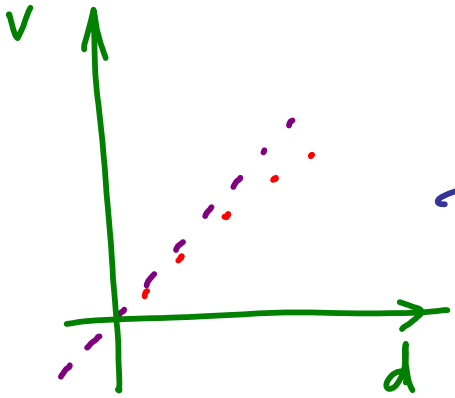
With $m_h \sim 125$, this alone is a few % tuning, in simplest theories

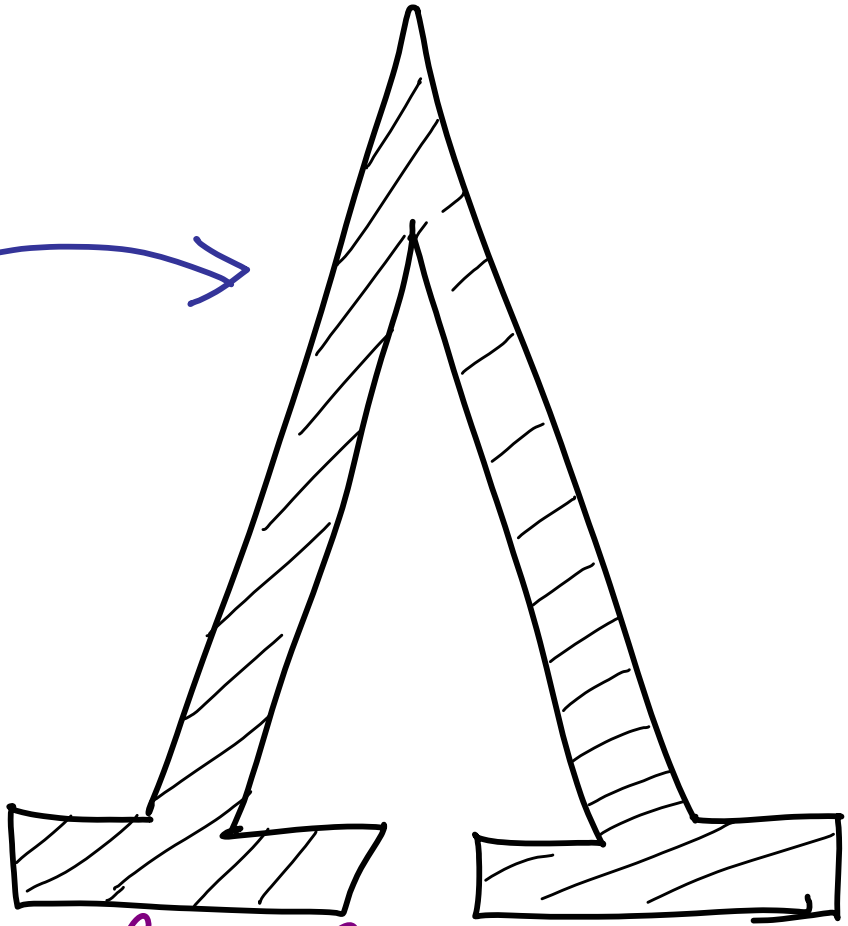
Compulsory Natural SUSY



Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2$, $\left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

It is the broad idea of Naturalness that is being put under (more) pressure by LHC — SUSY is One Example





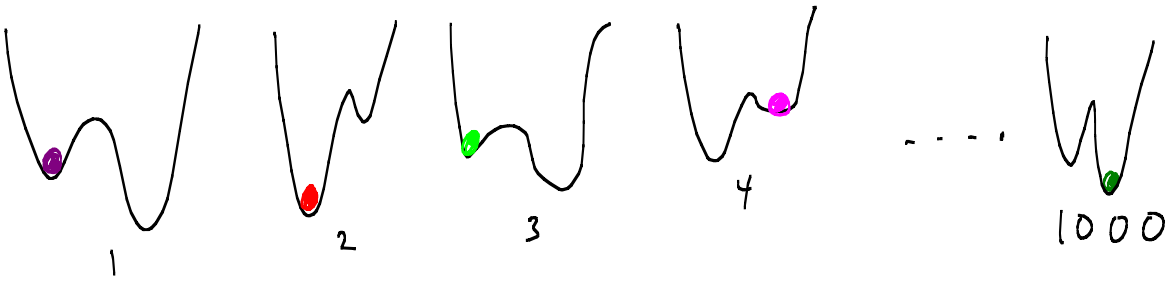
NATURALNESS

String Theory is "unique", BUT, it has zillions of solutions.

pre-95 : zillions ~ millions

post-95 : zillions ~ $10^{1000's}$

"STRING LANDSCAPE" = CONTROVERSIAL SUBJECT

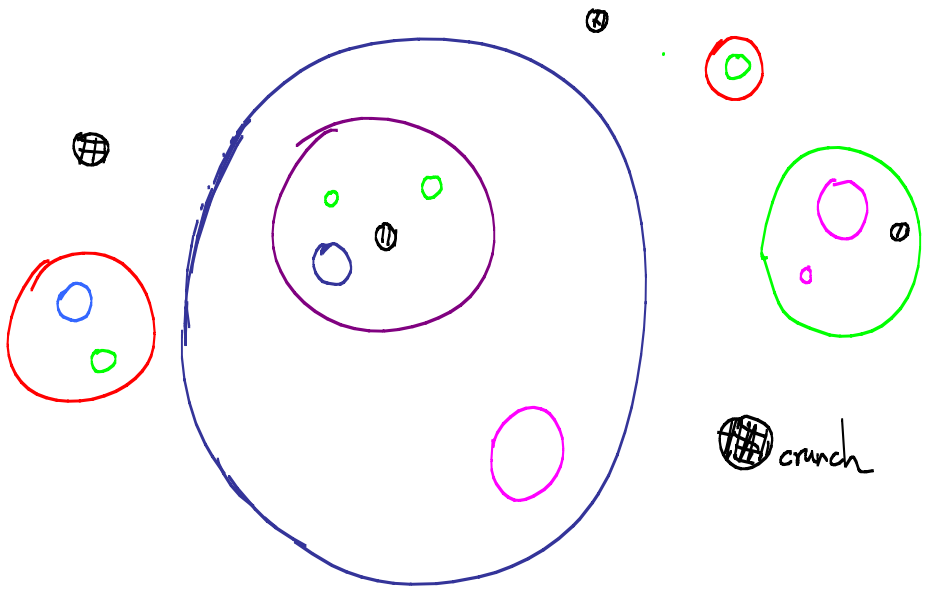


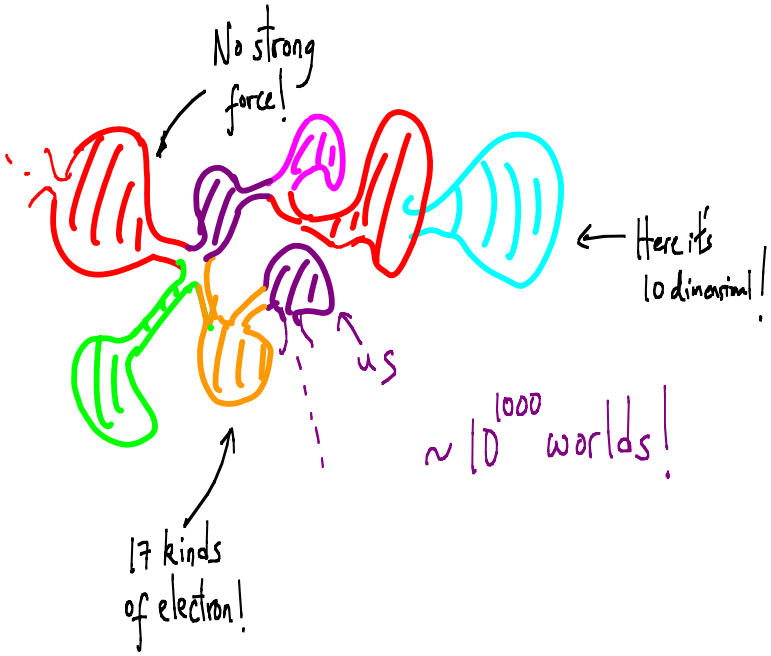
$\Rightarrow 2^{1000}$ different values of energy

$\updownarrow \left(\frac{1}{2}\right)^{1000}$ splittings

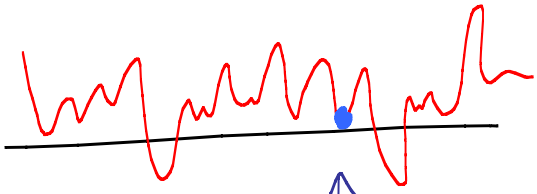
Energy $\sim \left(\frac{1}{2}\right)^{1000}$ — just statistically!

"Eternal Inflation" + The Multiverse





$\sim 10^{1000}$ worlds!



Everywhere Lethal + Empty except ...

Here, accidentally, Universe not empty

Are we tiny part of a Vast Multiverse?!

- Conceptual Problem — how can we "see" other universes — how can we know that they're there?
- Does it make any kind of precise mathematical sense? [Notorious problem of "measures", Prob. are ∞/∞]

Plausible anthropic tuning for weak scale: existence of atoms other than hydrogen

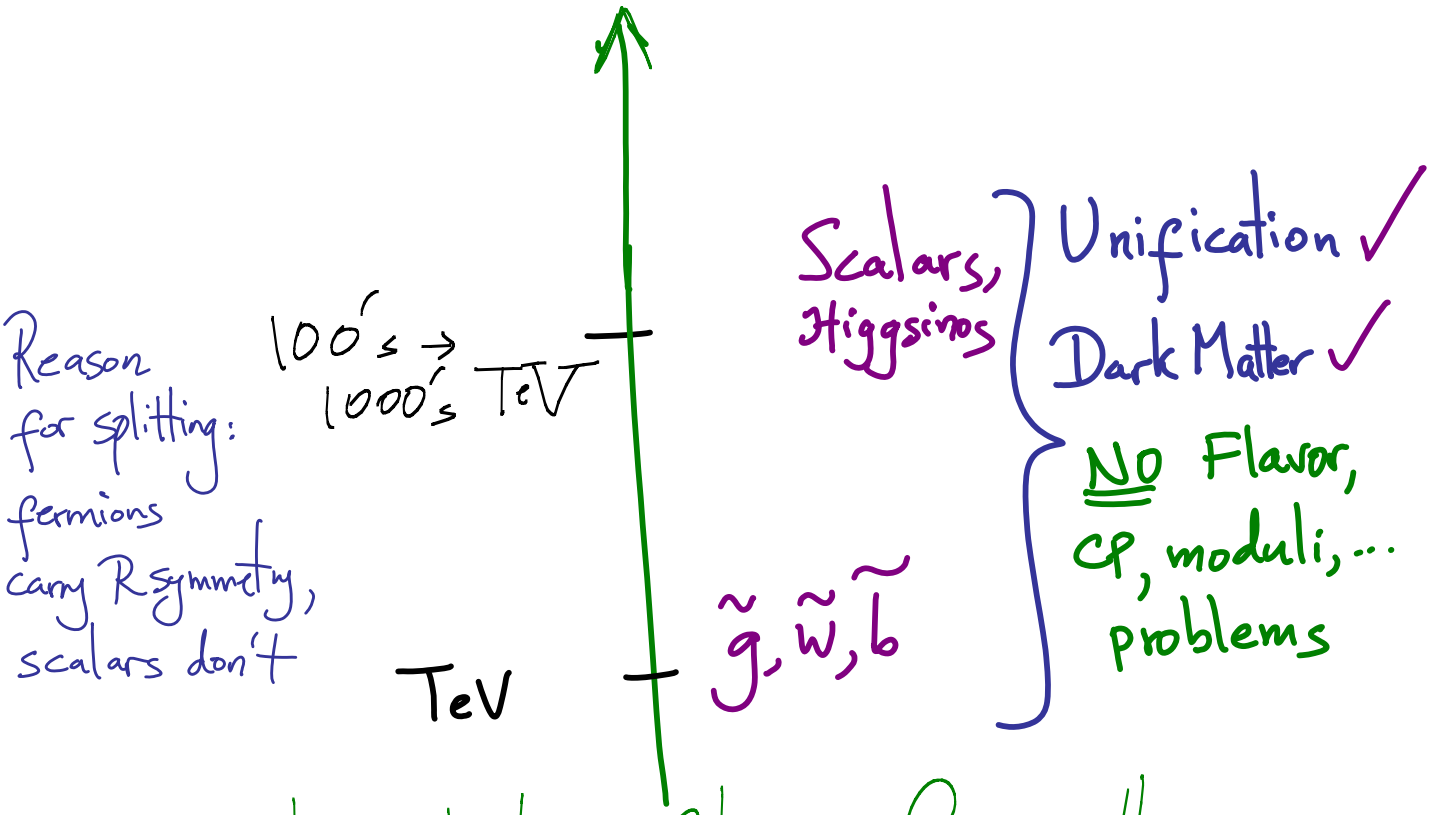
$(m_n - m_p) \gtrsim$ nuclear binding energies

Higgs + Nothing Else?

A Fine-tuning of at least 0.1% for weak scale

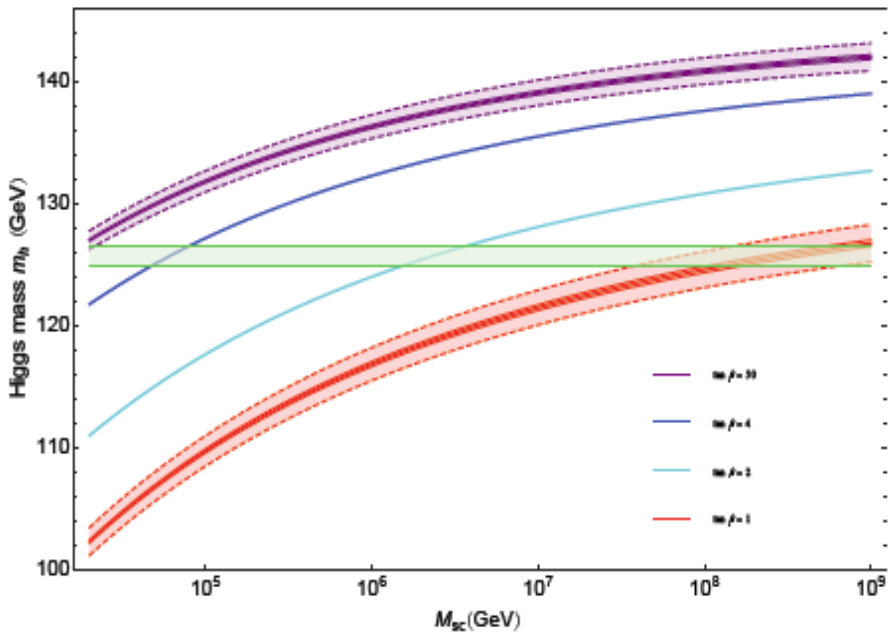
CONVINCING?

Minimally Split SUSY



$\sim \alpha^{-1}$ Splitting Happens Generically

Higgs Mass


140
130
120
110
100
Higgs mass m_h (GeV)
10^5
10^6
10^7
10^8
10^9
M_{SC}(GeV)

Any observed deviation in higgs properties KILLS ALL SUCH THEORIES

$\Rightarrow$ HUGE SUPPORT FOR NATURALNESS

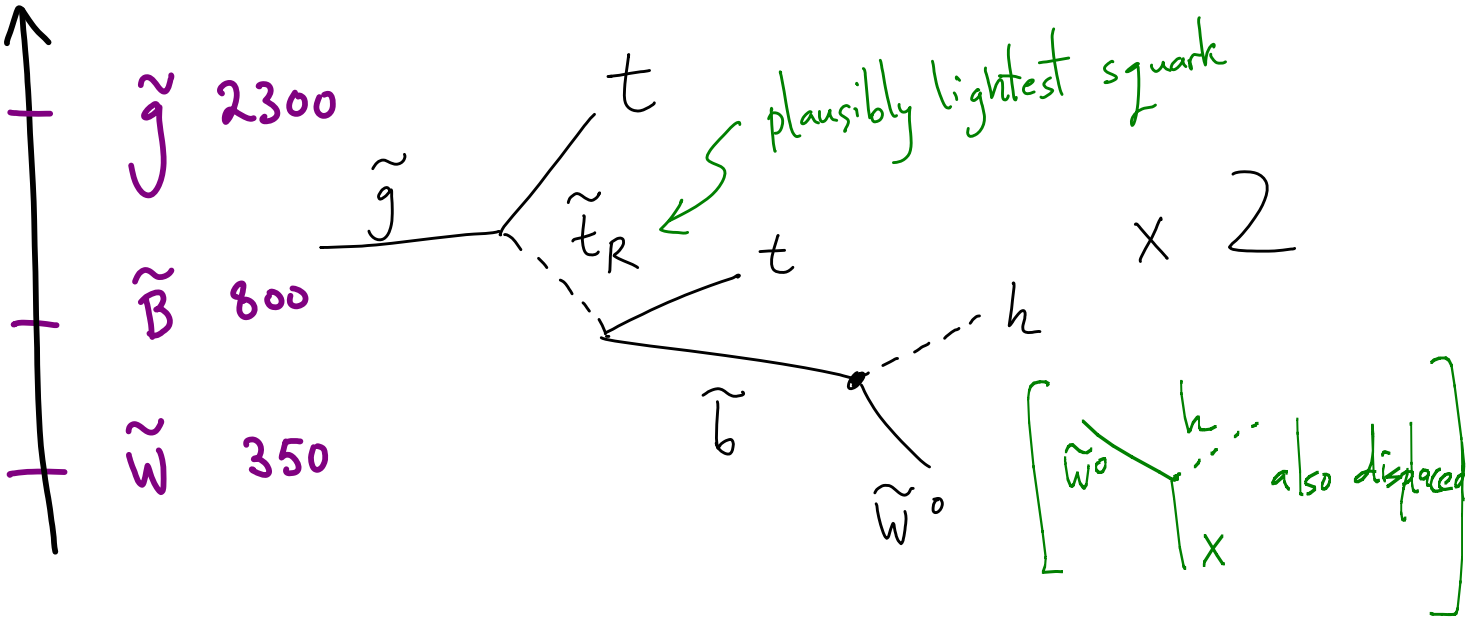
With $\tilde{g}, \tilde{W}, \tilde{b}$ as only new particles – their decays can only proceed through higher-dimension operators!

Inside detector $\longrightarrow$ scale $\gtrsim 10^3$ TeV

LOOK FOR MODERATE DISPLACED DECAYS

If seen: experimental future for HEP on ~50 yr timescale

[WE CAN BUILD 100 TeV COLLIDERS]



$\Rightarrow$ 8 b's, 4 W's [+ perhaps displacement]

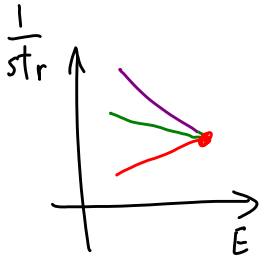
in every event!

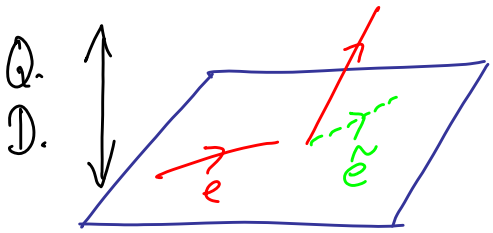
IS HIGGS NATURAL?

DRAMATIC BIFURCATORY

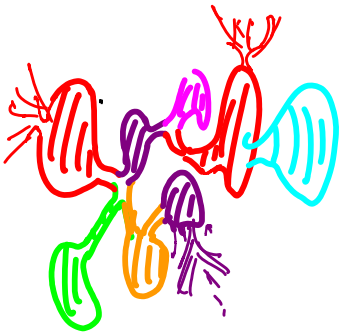
MOMENT IN FUNDAMENTAL PHYSICS

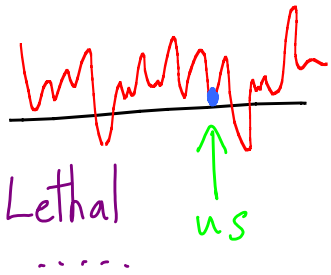
"Order"



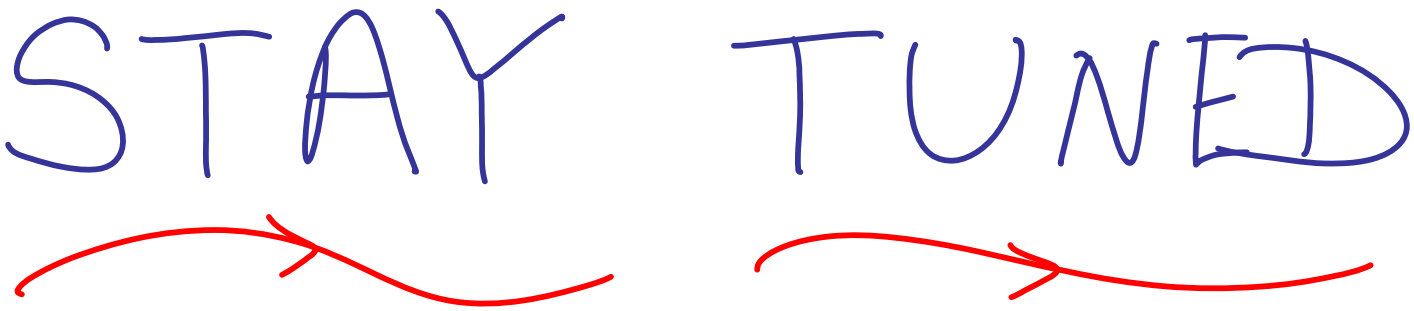


"Chaos"





Λ + weakness of gravity?


STAY TUNED