

Muon Colliders

and the

Future of Particle Physics

# Why Accelerators?

\*Large Accelerators are the ONLY probe of short-distance frontier in fund. physics — and have given us the most profound structural clues to the laws of Nature.

We Go Because WE MUST and WE CAN!

# Future of Particle Physics

Is There A Future of Particle Physics ?

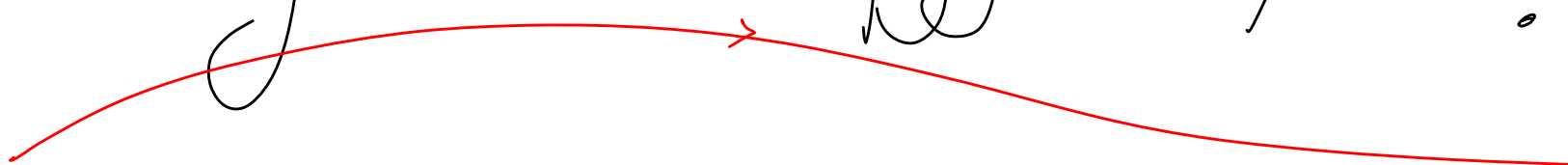
"Only Higgs + nothing else, confirmed.  
50 yr old theory,  $Z_{zzzz} \dots$ , Right?"

WRONG

# Higgs is REALLY New Physics

- \* Simplest elementary particle - very simplicity makes it deeply perplexing
- \* Higgs + nothing else is huge challenge to reductionist paradigm: THEORISTS ARE PROFOUNDLY CONFUSED ABOUT WHAT THE HIGGS MEANS.
- \* EXPT: STUDY HIGGS TO DEATH!

Why is the Higgs Special?



What is Particle Physics!

What

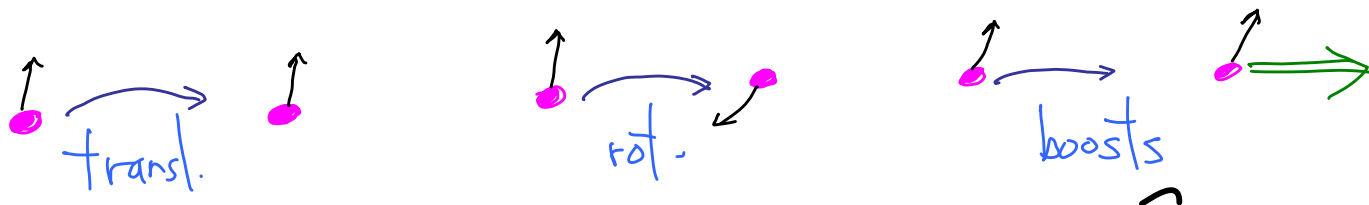
is

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<sup>th</sup> → 20<sup>th</sup> Century Physics



March of REDUCTIONISM

March of SYMMETRIES

# Whatever the Ultimate Theory

Relativity

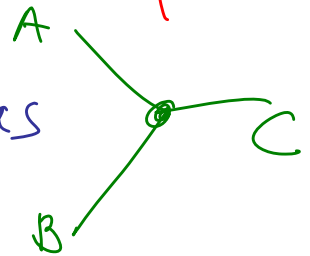
Quantum Mechanics

Symmetries

Reductionism



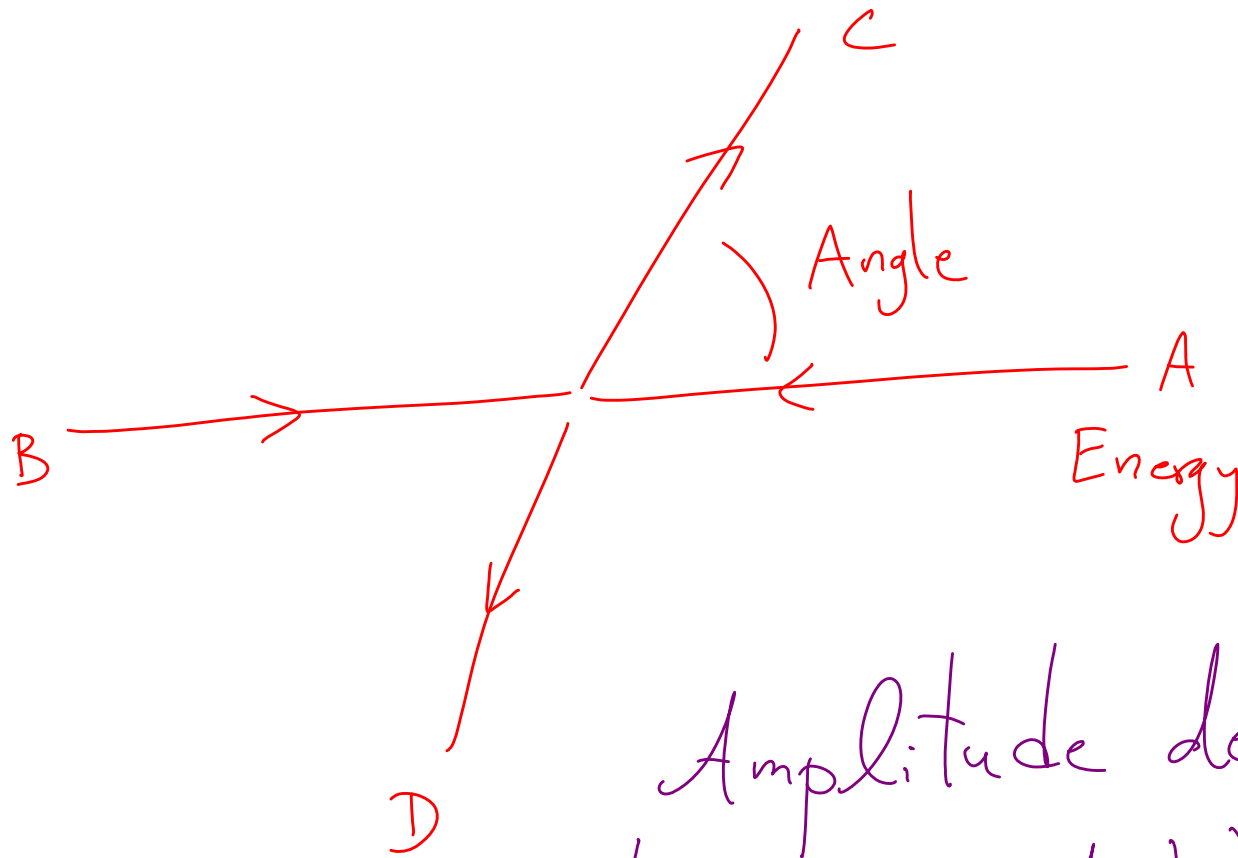
Massless  $p$  particles interacting as



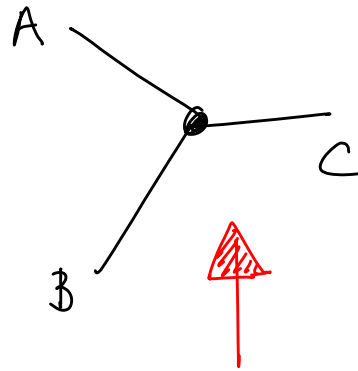
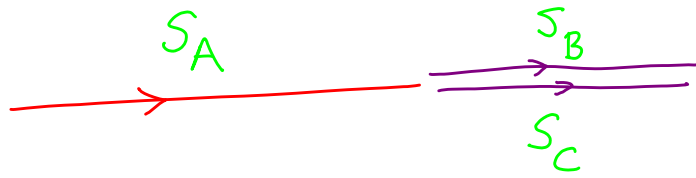
with spins

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

← unique, "gravity"

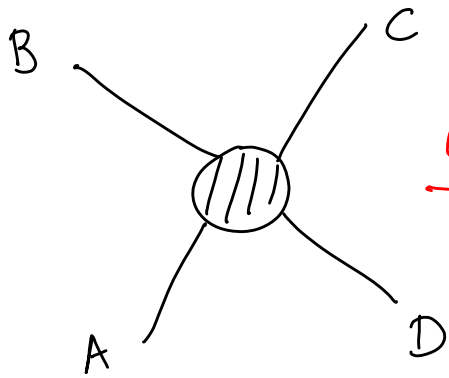


Amplitude depends of  
(Energy, Angle), Complicated!

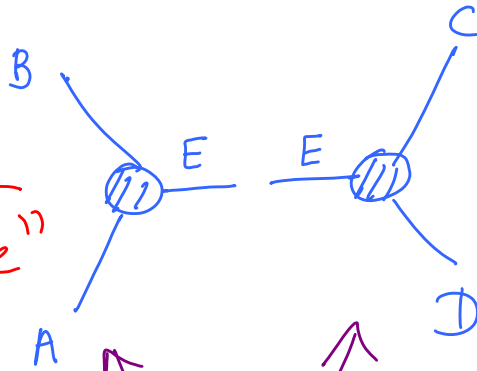


NO (Energy, Angle)  $\rightarrow$  COMPLETELY  
FIXED  
(up to strength)  
by helicities!

Dictated by  
Principles of  
SPACETIME



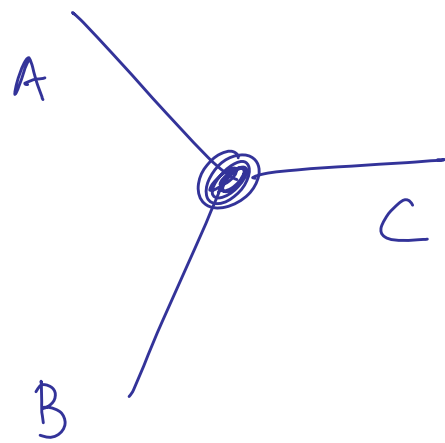
Gets Big  
→  
"Resonance"



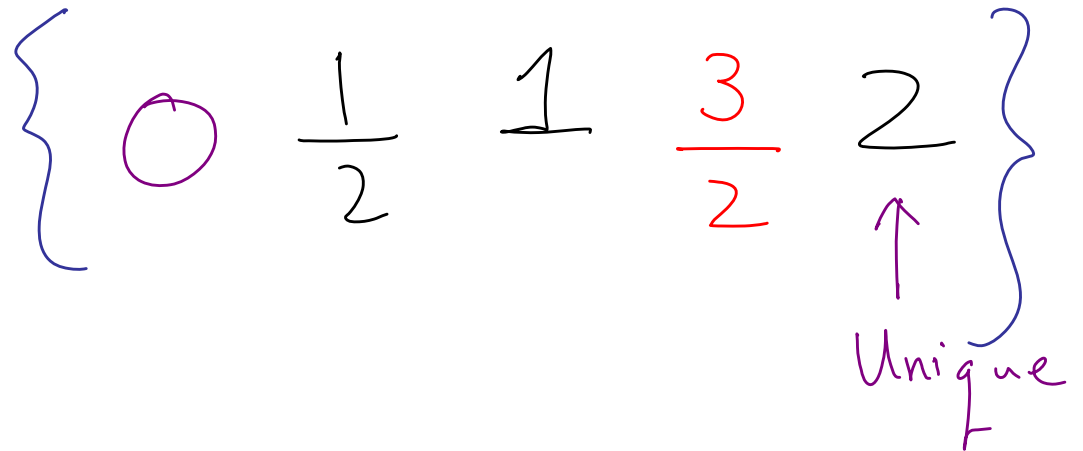
Again, Completely  
Known

Dictated  
By Principles of  
QUANTUM  
MECHANICS

# All Consistent Theories



Spins

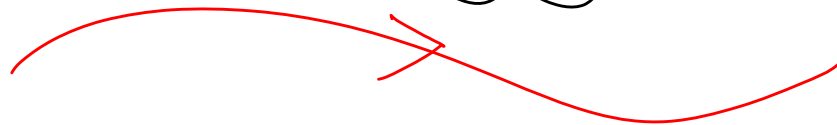


+ some #'s for strength of interaction!



What About The

Higgs ?



Amazing difference between massive +  
massless particles

with spin: } Both SPACETIME  
+ QM matter here

massive  $\uparrow$   $S=1$   


3  
  
spin

massless



2 helicities  


One extra guy!



# Belief in Principles Paid Off

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

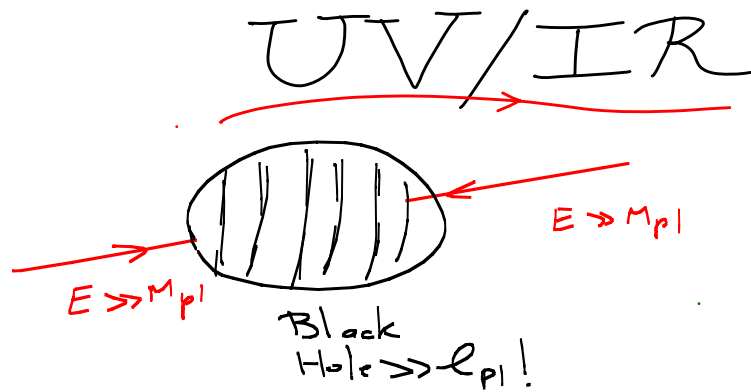


Higgs is first "really new" particle we've seen!

# 21<sup>st</sup> Century Revolutions

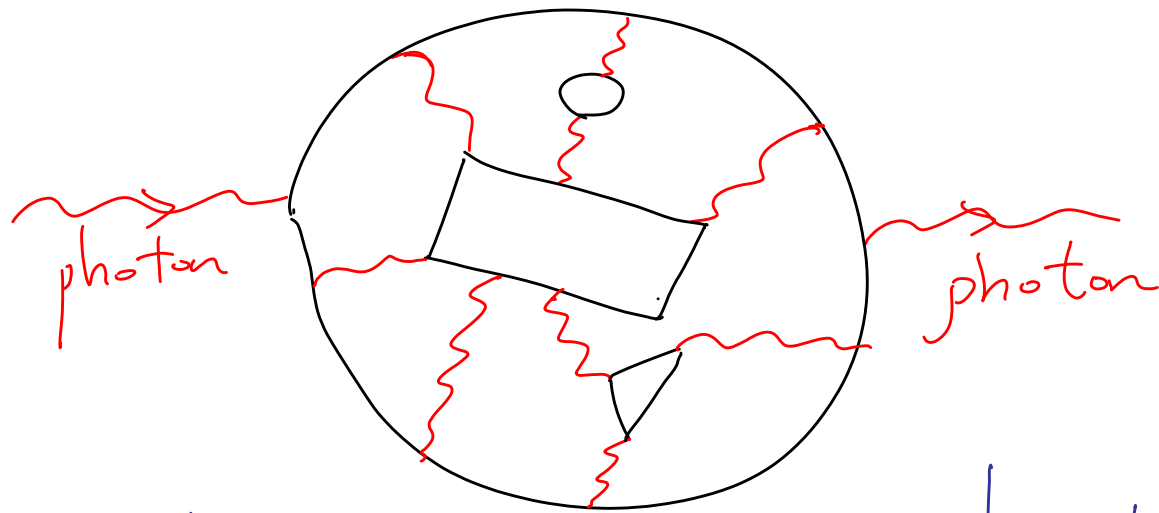
- \* Doom of Spacetime, End of Reductionism
- \* Why is the Universe Big?

REALLY NEW IDEAS NEEDED,  
beyond paradigms of spacetime + internal symmetries



High Energies  
 Long Distances!

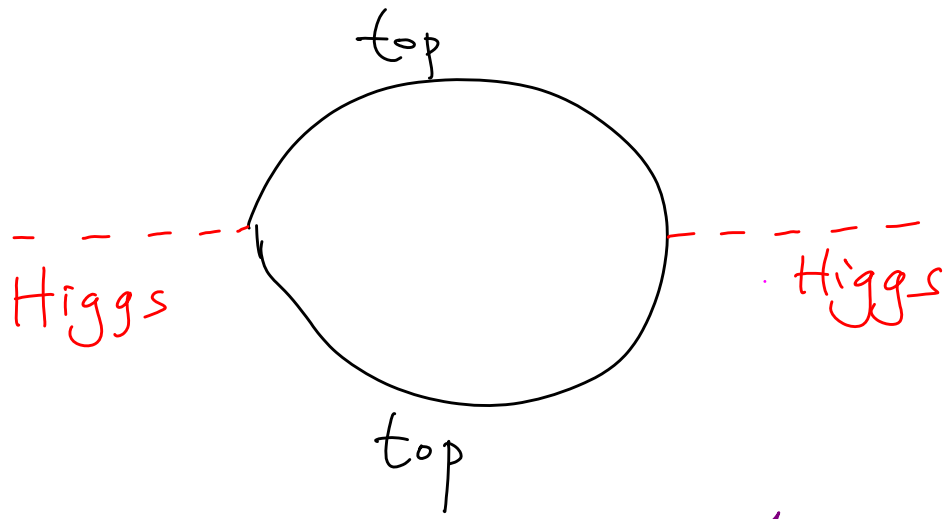
Reductionism + Wilsonian EFT Paradigm is **False**  
 Fundamental Laws Nothing like that of  
 Condensed Matter Physics — **FAR**  
**DEEPER + MORE RADICAL**  
 [ But maybe only at Planck Scale? ]



Photon MUST stay massless, because

$$\begin{array}{ccc} \# \text{ massless} & & \# \text{ massive} \\ \text{helicities} & \rightarrow & \text{spins} \\ & 2 \neq 3 & \end{array}$$

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



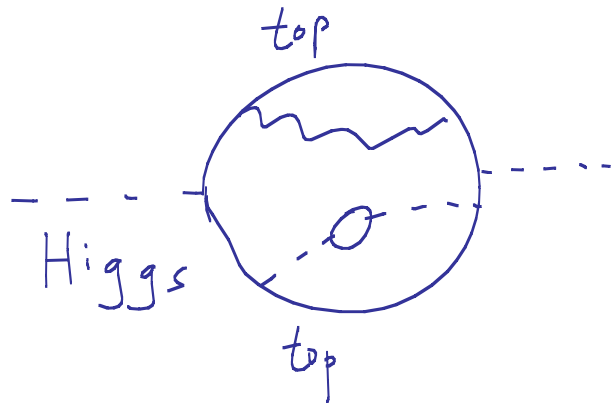
massless spin 0      1      =      1      massive spin 0

NO DIFFERENCE

WHY  
ISN'T  
HIGGS  
ENORMOUSLY  
MASSIVE?  
PLANCKIAN?

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

# $\Lambda$ + Higgs $\rightarrow$ Beyond Symmetries



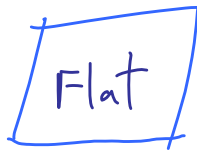
1 d of whether  $m_h^2 > 0, = 0, < 0$

NO DIFFERENCE

Hierarchy Problem



$\Lambda > 0$



$\Lambda = 0$



$\Lambda < 0$

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

Cosmological Constant Problem



Emergent Spacetime?

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

Macroscopic Universe?

# Higgs Discovery Crucial

Our Relativistic Vacuum is Quantitatively

Different than anything we've seen elsewhere in physics

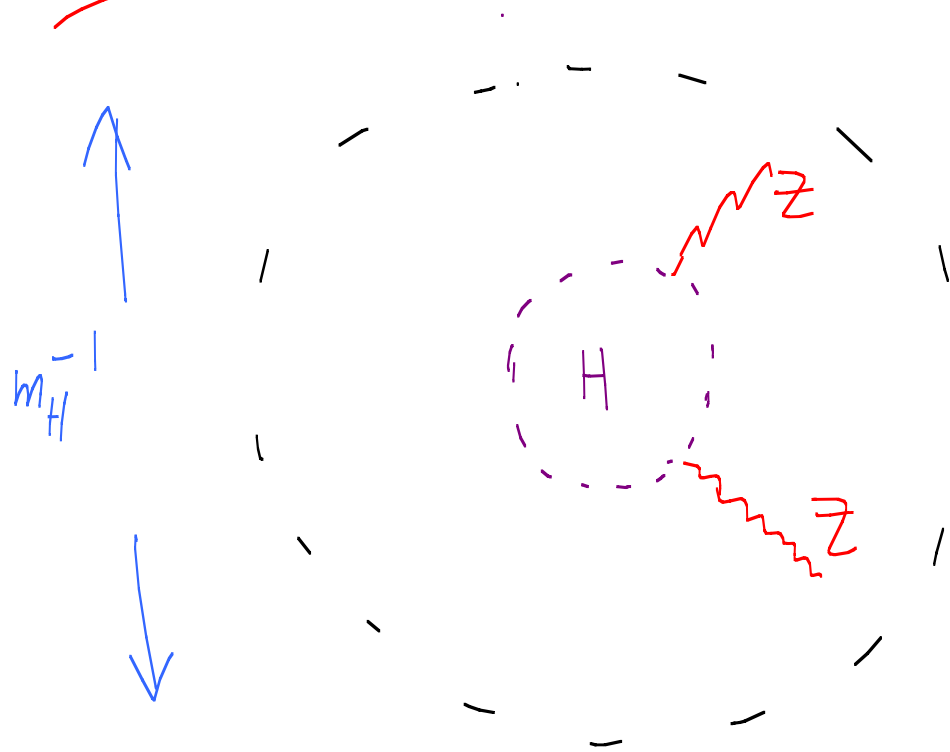
NOT JUST @ Planck scale

ALREADY @ TeV scale

# Higgs is REALLY New Physics

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- \* Higgs + nothing else is huge challenge to reductionist paradigm: THEORISTS ARE PROFOUNDLY CONFUSED ABOUT WHAT THE HIGGS MEANS.
- \* EXPT: STUDY HIGGS TO DEATH!

# Never Seen Point-Like Scalar

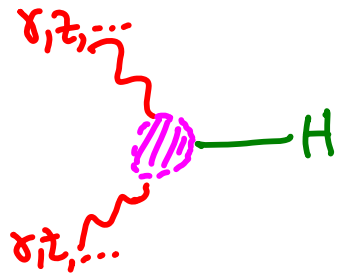


So, how  
pointlike is  
it? <sub>a</sub>

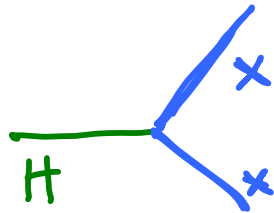


With LHC Resolution, won't  
 know whether Higgs is more  
 point-like than the pion!

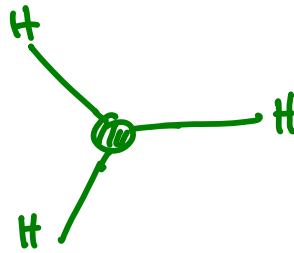
Central Drama: How Pointlike Is It?



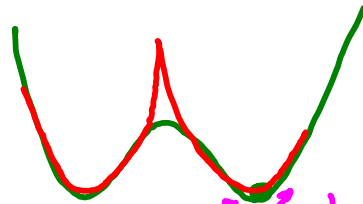
External Probs  $\rightarrow$  LHC



Does it couple to anything else?



Does it look pointlike to itself?



what does potential look like?

Looking at Physics up to

$E_{\max}$

Probes Vacuum Quantum Fluct. up to

$E_{\max}^2$

Why can the Universe have  
BIG THINGS IN IT

||

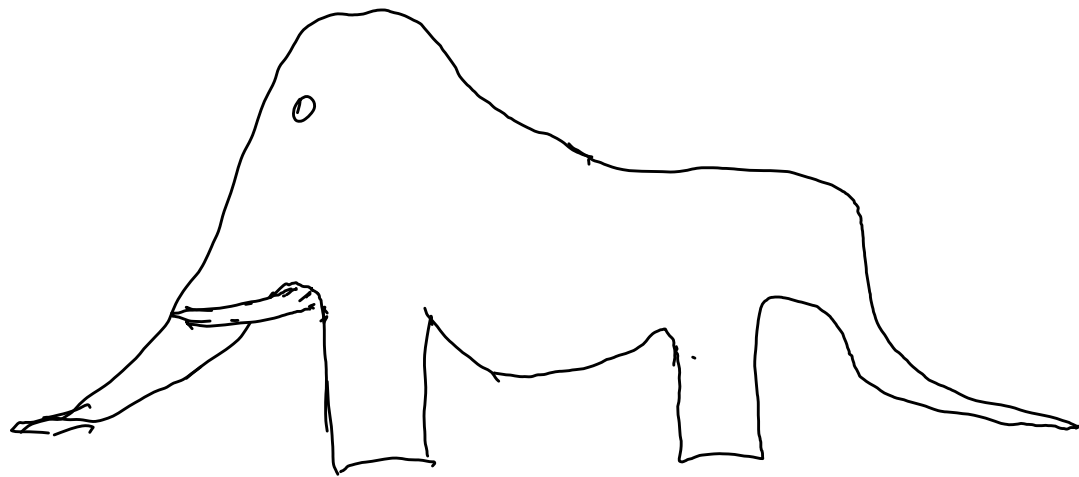
Why is Gravity  
SOOOO WEAK?

||

Why are Particle Masses  
MINISCULE COMPARED TO PLANCK SCALE?







$R_{\text{Elephant}}$

$$R_{\text{Elephant}} \sim \left( \frac{F_{\text{el}}}{F_{\text{Gr}}} \right)^{1/3}$$

$\downarrow$   
 $10^4 \text{ cm}$

$\downarrow$   
 $10^{12}$

$R_{\text{atom}}$

$\downarrow$   
 $10^{-8} \text{ cm}$

What happens if  $m_n^2 < 0$  now?

If  $v > 3 v_{us}$ ,  $(m_n - m_p)$  exceeds.

nuclear binding energy  $\implies$  NO ATOMS

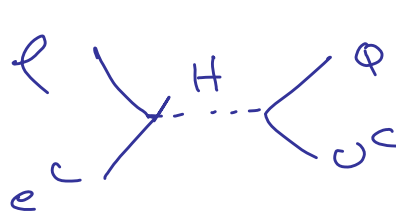
other than hydrogen (eventually  $\Delta^{++} = \text{He!}$ )

What if  $m_h^2 > 0$ ?

\* Still have EWSB from quark condensates  $\langle \bar{Q}Q \rangle$

$$m_{W,Z} \sim g \Lambda_{\text{QCD}} \sim 100 \text{ MeV}$$

\* Still have (much much) lighter fermion masses

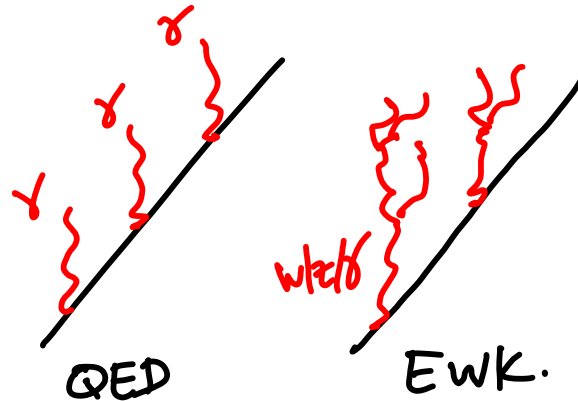
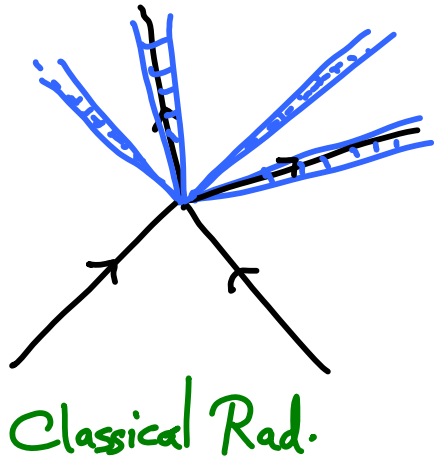


The diagram shows a fermion line (labeled  $f$ ) with a dashed line labeled  $H$  and a solid line labeled  $Q$ . An arrow points from this diagram to the equation  $m_f \sim \Lambda_{\text{QCD}}^3 / m_h^2 \lambda_f$ .

$$m_f \sim \Lambda_{\text{QCD}}^3 / m_h^2 \lambda_f$$

\* But NO BARYONS!! Sphalerons completely unsuppressed, all B converted to  $V$ ...

# Copious Ewk Radiation @ 10TeV



Copious Class. Rad. then  $\propto \log^2 E/m \sim 1$   
 $\propto w \log^2 \left( \frac{10\text{TeV}}{mw} \right) \sim !!$

Finally "see"(!) Ewk symmetry restored @

## Beyond the Higgs?

\* NOT GUARANTEED there  
are new particles... but well-motivated pictures  
(many proposed + actively studied before LHC!)  
where there's a GOOD REASON WHY  
LHC MISSED NEW PARTICLES,  
but 10 TeV [+ not 100 TeV or 10<sup>10</sup> TeV!]  
colliders WOULD SEE THEM

Simplest WIMP DM WEAK!

$$m_{\text{Triplet}} \sim 3\text{TeV}, m_{\text{Doublet}} \sim 1\text{TeV}$$

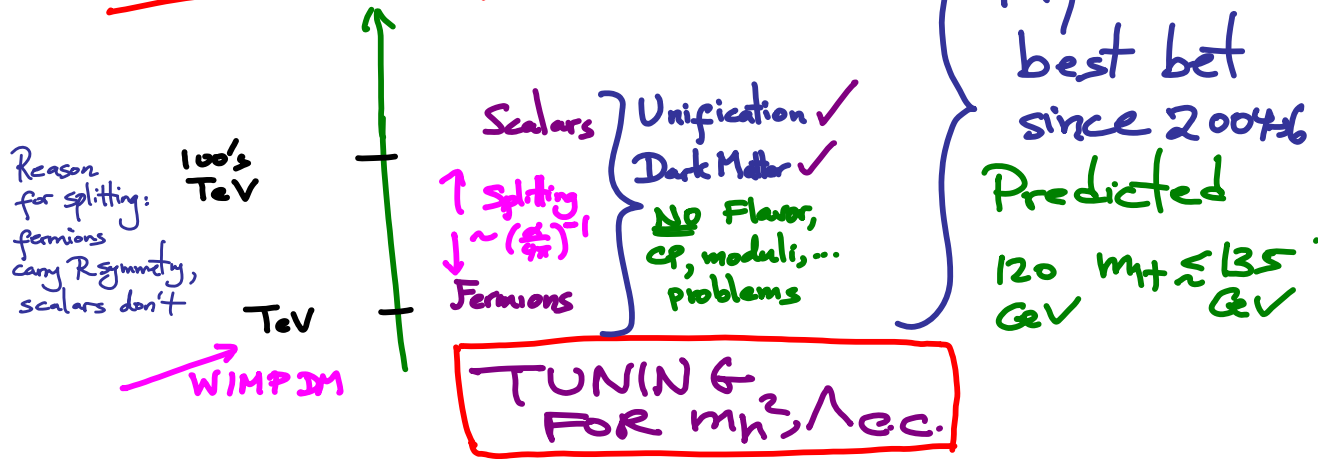


\* TOO HEAVY TO  
MAKE @ LHC.

\* MINISCULE DIRECT DET  
CROSS-SECTION.

10 TeV Scale Collider Will Make Them

# Minimal Split SUSY



- \* Gaugions  $\lesssim 10 \text{ TeV}$  scale.
- \* Higgsinos, "straggler sleptons" possible too
- \* CAN'T MAKE HEAVIER WITHOUT MAKING HIGGS TOO



\* Many other examples!

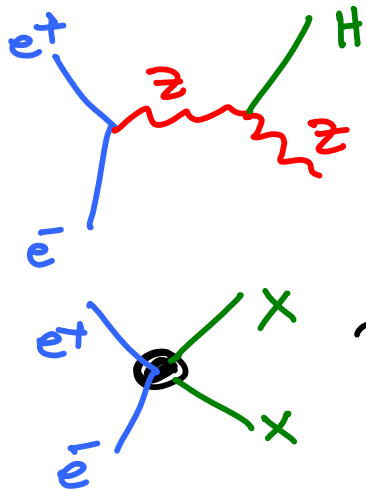
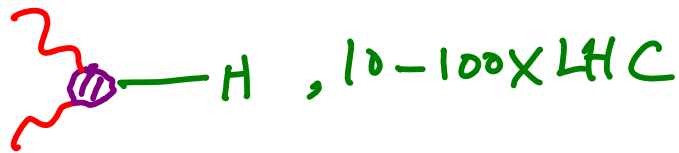
\* GENERAL POINT: IDEAS FROM:  
80's + 90's have been killed/on life support  
from LHC [+ many saw it coming in early 2000's].

\* Others proposed in 2000's - present are alive  
+ well + some gained support from LHC

\* MANY HAVE GOOD REASON FOR NO LHC,  
BUT NEW PARTICLES @ 10 TeV scale.

# An Amazing Vision:

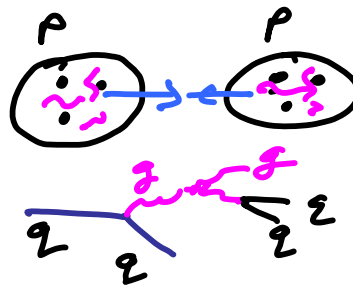
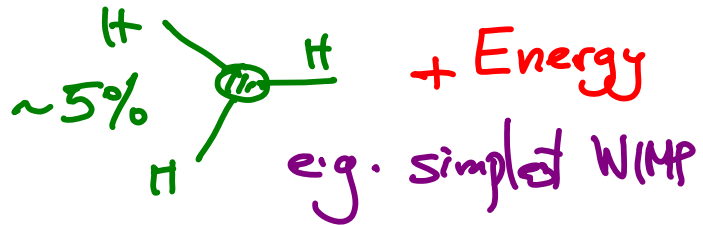
$e^+e^-$  Precision,  
Higgs Factory



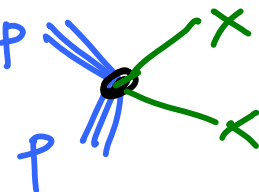
CLEAN

Reach  $M_X \sim E$

100 TeV pp collider




MESSY/  
RICH



Reach  $M_X \sim E/10$

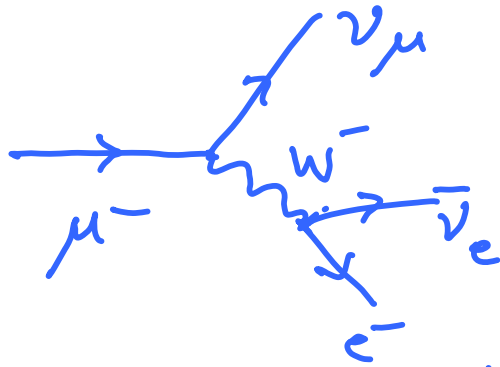
Muon Colliders Rock



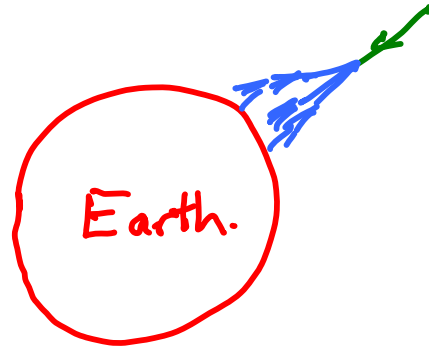
[If they are possible —  
new optimism they are]

$\mu^\pm$   
●

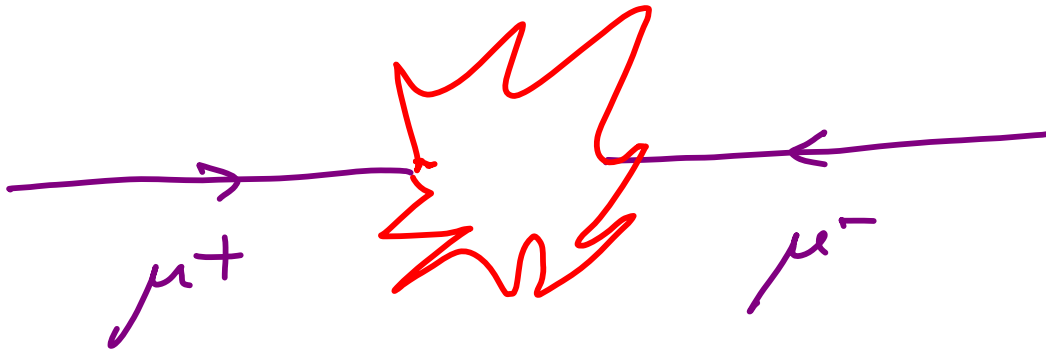
$$m_\mu \sim 105 \text{ MeV} \\ \sim 200 m_e$$



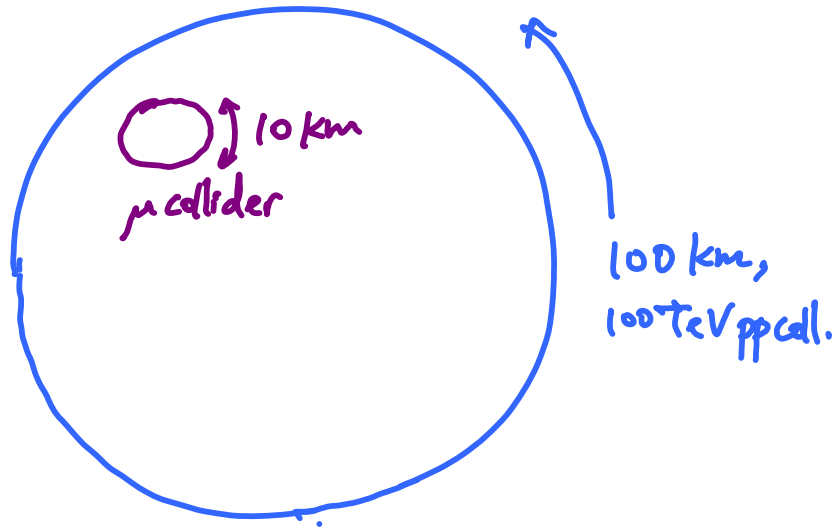
$$\tau_\mu \sim 2.2 \times 10^{-6} \text{ s}$$



200  $\mu/m^2/s$   
from cosmic rays



$$E_{CM} \sim 10 \text{ TeV}, \quad v/c \sim \underbrace{0.9999999999}_{10 \text{ 9's}}$$



Probe  
 $\sim 10 \text{ TeV}$   
 scale physics

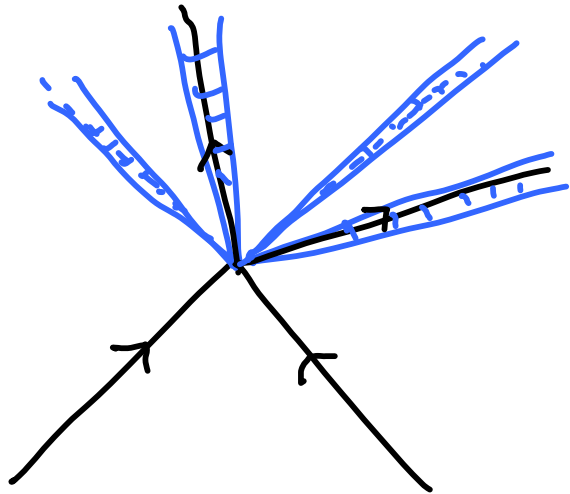
- \*  $P^{\text{synch}} \sim \frac{\alpha}{R^2} \left[ \frac{E}{m} \right]^4$   $\leftarrow 10^9 \times \text{less than electrons!}$
- \*  $\mathcal{L} \sim 10^{34 \rightarrow 35} / \text{cm}^2/\text{s}$  [So  $(10^{-17 \rightarrow 18} \text{ cm})^2$   $\sigma$ 's can be probed on human timescales]
- \* Possible in 25 years? [Not 50!]

# Muon Colliders: 2 Machines in 1

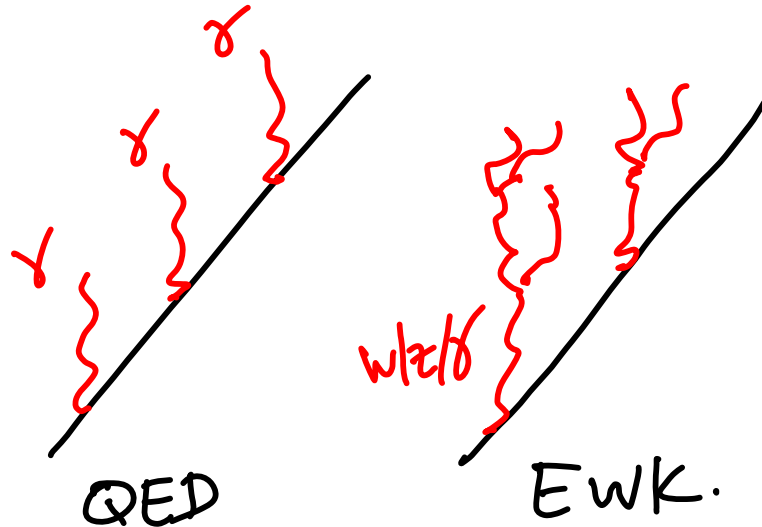
\* Clean env. / high prec. of  $e^+e^-$  [e.g.  $\sim 10^7$  clean Higgses]

High energy of pp (Robust probe of  $10$  TeV)  
+ Rich initial state!

# Copious Ewk Radiation @ 10 TeV



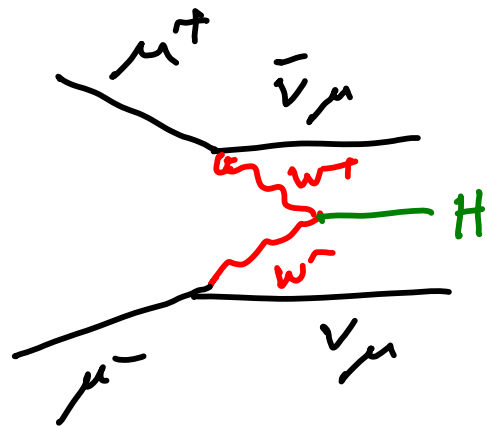
Classical Rad.



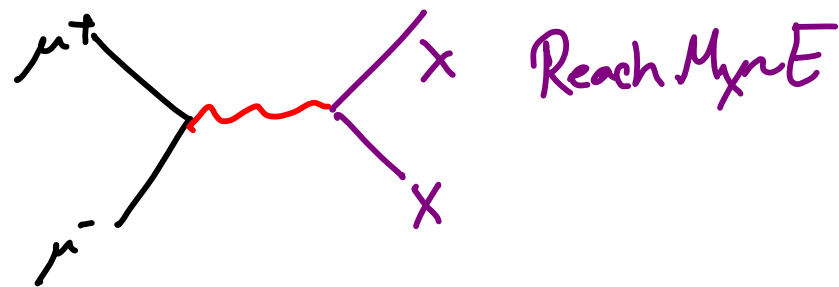
Copious Class. Rad when  $\propto \log^2 E/m \sim 1$   
 $\propto w \log^2 \left( \frac{10 \text{ TeV}}{m_w} \right) \sim !!$

Finally "see"(!) Ewk symmetry restored @ 10 TeV

# Muon Collider = Ewk Vector Boson Collider



Dominates  
Production.  
 $\sim 10^7$  Higgses



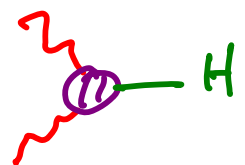
Reach  $M_{\mu} E$

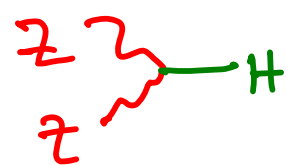
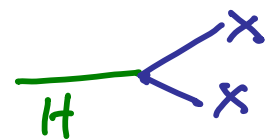
c.f. "LHC = Gluon Collider"

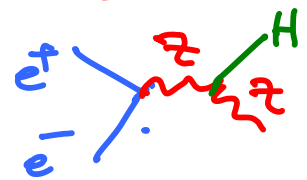
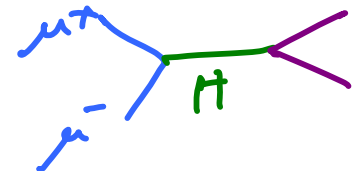
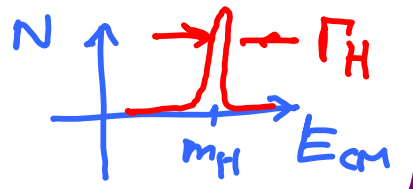
BUT UNLIKE W/ STRONG INT,  
ALL CALCULABLE!



# Two in One

\* Higgs Properties   $H$  comp to  $e^+e^-$

  $H$  better @  $e^+e^-$ ,   $H$  better @  $\mu$  coll

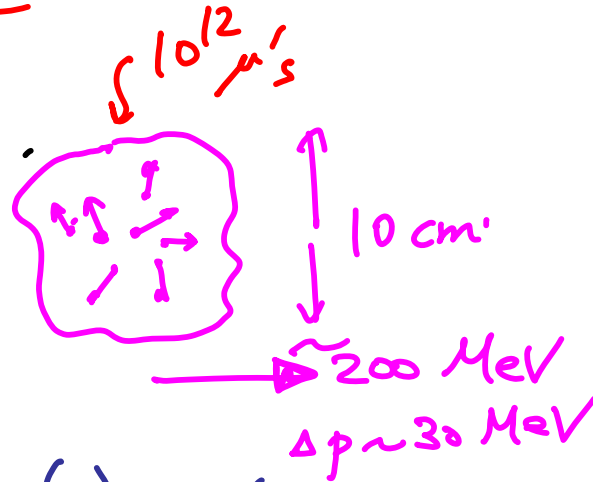
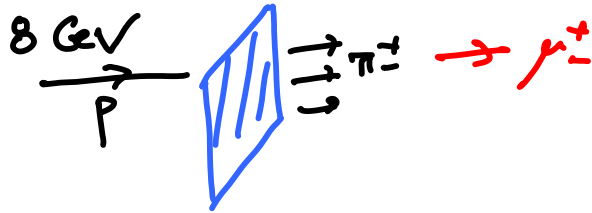
  

\* Robust probe of 10 TeV scale e.g.  
easily covers simplest WIMP DM.

\* Finally see ewk symm. restored in action!

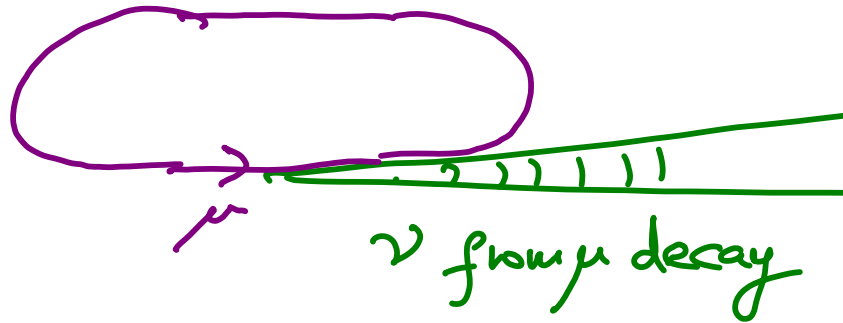
# Challenges

\* "Cooling"



Need compression of  $(10^{-6})$  in  $(\Delta x, \Delta y, \Delta z, \Delta p_x, \Delta p_y, \Delta p_z)$

\*  $\nu$  radiation



$$\Theta \sim \frac{m\mu}{E}$$

$$\text{Dose} \sim E^3 / \text{depth}$$

\* Deeper Underground

\* Wiggle Beam

\* Tilt Machine

On the way to 10 TeV

\* Before  $\sim 10^{-6}$  cooled  $\sim 10$  TeV  
beams we'll have  $\sim 10^{-3}$  cooled  $\sim 10$  GeV  
beams  $\rightarrow$  great  $\gamma$  beam!

\* Higgs resonance

o  
o  
.

MOON COLLIDER IS

INCREDIBLY EXCITING

EXCITEMENT EASY  
TO EXPLAIN TO PROFESSIONALS  
+ LAY PEOPLE...

IT'S TOTALLY NEW!

TIME TO GET

SERIOUS IS

NOW