Fundamental Physics + the LHC: A Progress Report
Matter

- electron
- proton

Quarks:
- up
- down

Protons and neutrons:
4 Basic Interactions

Gravity

Electromagnetism

Weak + Strong
Strong + Weak: Same Structure!
long-range force

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

\[ \frac{1}{2} \times \hbar \]

\[ 1 \times \hbar \]

\[ 2 \times \hbar \]

Allowed:

0,
\[ \frac{1}{2}, \]
\[ 1, \]
\[ \frac{3}{2}, \]
\[ 2, \]
\[ \frac{5}{2}, \]
\[ 3, \]
\[ \ldots \]

\[ x \times \hbar \]
Particles we see extremely simple!

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

Gluons

$SU(3)_c \times SU(2)_L \times U(1)_Y$

\[ \begin{array}{ccc}
Q & \frac{3}{2} & \frac{1}{6} \\
U^c & \frac{3}{2} & -
\end{array} \]

\[ \begin{array}{ccc}
D^c & \frac{3}{2} & -
L & 2 & -
E^c & 2 & +1
\end{array} \]

$e^+ e^- \rightarrow \gamma + W$

$2 \rightarrow \gamma + g$

$e^+ e^- \rightarrow \gamma + Z$
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 $0, \frac{1}{2}, 1, \frac{3}{2}, 2 \leftarrow$ unique, “gravity”
Units!

\[ \text{time} = \frac{\text{distance}}{c} \]

\[ \text{Energy} = \frac{\hbar}{\text{time}} \]

Put \( \hbar = c = 1 \)

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

\[ 10^{16} \text{ GeV}^{-1} \]

\[ \text{Mass} \sim 10^{29} \text{ GeV} \]

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

\[ p \sim 10^{-14} \text{ cm}^{-1} \text{ GeV}^{-1} \]

LHC Energies

7000 GeV
Electric Force $\sim q^2 \frac{1}{r^2}$

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

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

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

$\frac{1}{l_{\text{Pl}}^2} \sim (10^{19} \text{ GeV})$
Quantum Mechanics

Probability = (Amplitude)^2

Amplitude ~ q^2
~ 1%
small

Angle
Amplitude $\sim G_N \times E^2$

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

Graviton interaction with electrons

Planck energy
"Effective" Theories

\[ g^2 \sim \frac{1}{137} \]

\[ g^2 \sim \frac{1}{\text{strong} 10} \]

Only @ low energies!

\[ \text{strength} \sim \text{(length)}^{1,2,3,...} \]

Irrelevant at "long" distances!

Only relevant
At high energies, approximate particles as massless.

Energy = |momentum|
Spin $\rightarrow$ "helicity"
Amplitude depends on (Energy, Angle), Complicated!
NO (Energy, Angle) $\rightarrow$ COMPLETELY FIXED (up to strength) by helicities!
Again, Completely Known
1 yr of Grad School
All Consistent Theories

Spins

\[ \{ 0, \frac{1}{2}, 1, \frac{3}{2}, 2 \} \]  

Unique

+ some #’s for strength of interaction!
What About The Higgs?
Amazing difference between massive + massless particles with spin:

- Massive: $S = 1$
  - 3 spin
- Massless: 2 helicities

One extra guy!
Amp ~ \left( \frac{\text{Energy}}{\text{mass}} \right)

New guy grows!
Amplitude $\sim q^2 \sim 1\%$

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

1% \[\uparrow\]

80 GeV \[\uparrow\]

$>1(!!!)$ if $\text{Energy} > 1200$ GeV.
... Other Problems of this Sort...

Again, Amplitudes become nonsense ($\sim 1$) around 1000 GeV
Energy

Planck Scale
\sim 10^9 \text{ GeV}

Naive Expectation

- W, Z, \ldots \sim 100 \text{ GeV}

Energy

Actual Situation

\sim 1000 \text{ GeV}

- W, Z \sim 100 \text{ GeV}
Assume nothing new till 1000 GeV

$\Rightarrow$ 1\% level corrections
Need Something New Earlier!

Spin of X:

MUST BE SPIN 0

X = Higgs

strengths nailed
At very high energies, $H$ and $W_L, Z_L$ are all united into $H$.

Usual Allowed Interactions
This was a Brave Proposal:
No Fundamental Spin 0 had ever been seen!
Higgs at the LHC

Higgs

gluon

top quark

gluon

p

Higgs

bottom

Very Hard to See!

W

Higgs

bottom

nailed

W

photon

rare, but can see it!
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

# photon photon
WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

massless spin 0

NO DIFFERENCE

$1 = 1$ massive spin 0
“Fine Tuning”

Vertical to accuracy $10^{-30}$ degrees!

CRAZY (?)
Never seen before in "state of nature"

Why are we all pointed in the same direction?

"fine-tuning"
Infinite Energy In Electric Field

\[ \frac{e^2}{4\pi \alpha_{cl}} \sim m_e c^2 \Rightarrow \alpha_{cl} \sim \frac{e^2}{4\pi m_e c^2} \]

\[ a_{compton} \sim \frac{\hbar}{m_e c} \]

\[ \sim \alpha^{-1} \times a_{cl} \]
Tension Driving Field For 30 yrs

"Not Problems - Opportunities"
An Obvious Gap!

\[ \{0, \frac{1}{2}, 1, \frac{3}{2}, 2\} \]

↑ Possible, Very Special!

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

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

Energy + Momentum

"Conserved Quantity"

\[ Q_1, Q_2, Q_3, Q_4 \]

\[ Q_1 Q_2 = -Q_2 Q_1 (\dagger) \]
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
Unification of the Forces - Gravity not far behind!
Why No SUSY seen in 1990?

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- $Z$, $h$, $\tilde{t}$, $\tilde{g}$...
- $\tilde{e}$, EWKinos

“Natural” Spectrum

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“Nature-al” spectrum
SUSY + The Higgs

$$(Z + \text{Higgs}) , \left(\text{"Zino"}\right)$$

3 d.o.f. 1 d.o.f. 4 d.o.f.
\[ M_h \leq M_Z + M_{h^{sys/stop}} \]

With \( m_h \sim 125 \), this alone is a few % tuning, in simplest theories.
Causal Natural SUSY

1200 \rightarrow \tilde{g}

400 \rightarrow \tilde{\tau}, \tilde{b}_L \left\{ \begin{array}{c} \text{non-minimal} \\ \text{extra stuff} \end{array} \right\}

125 \rightarrow h

Unavoidable tunings: \( \left( \frac{400}{m_\tilde{\tau}} \right)^2, \left( \frac{4 m_{\tilde{b}_L}}{M_{\tilde{g}}} \right)^2 \)
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 ~ $10^{1000s}$

“STRING LANDSCAPE” = CONTROVERSIAL SUBJECT
\[ \Rightarrow 2^{1000} \text{ different values of energy} \]

Energy \sim \left(\frac{1}{2}\right)^{1000} - just statistically! \]
“Eternal Inflation” + The Multiverse

(crunch)
No strong force!

17 kinds of electron!

~ 10^6 worlds!

Here it's 10 dinosaurs!

Everywhere lethal + empty except... 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 0/1]
Plausible anthropic tuning for weak scale: existence of atoms other than hydrogen

\[
\nu \nu \nu
\]

\[
3 \nu \nu
\]

\[
\nu \nu
\]

\[
(m_n - m_p) / 2 \text{ nuclear binding energies}
\]
Higgs + Nothing Else?

A Fine-Tuning of at least 0.1% for weak scale CONVINCING?
Minimally Split SUSY

Reason for splitting:
- fermions carry R-symmetry,
- scalars don't

100s $\rightarrow$ 1000s TeV

TeV

$\tilde{g}, \tilde{w}, \tilde{b}$

Scalars, Higgsinos

Unification $\checkmark$

Dark Matter $\checkmark$

NO Flavor, CP, moduli, ...

problems

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

The graph shows the Higgs mass (GeV) as a function of $M_Z$ (GeV). Different lines represent varying $m_{H^+}$ values with the following colors:
- $m_{H^+} = 30$ (purple)
- $m_{H^+} = 4$ (blue)
- $m_{H^+} = 2$ (teal)
- $m_{H^+} = 1$ (red)

The horizontal lines indicate the range of the Higgs mass for different $m_{H^+}$ values.
Any observed deviation in Higgs properties KILLS ALL SUCH THEORIES

⇒ HUGE SUPPORT FOR NATURALNESS
With $\tilde{g}, \tilde{\omega}, \tilde{b}$ as only new particles - their decays can only proceed through higher-dimension operators!

Inside detector $\rightarrow$ scale $\lesssim 10^3$ TeV

Look for moderate displaced decays
If seen: experimental future for HEP on ~ 50 yr timescale

[WE CAN BUILD 100 TeV COLLIDERS]
\[ \tilde{g} \rightarrow 2300 \]
\[ \tilde{B} \rightarrow 800 \]
\[ \tilde{W} \rightarrow 350 \]

\[ \tilde{g} \rightarrow \tilde{t}_R \rightarrow t \rightarrow h \rightarrow \tilde{W}_0 \rightarrow \tilde{W}_0 \text{ also displaced} \times 2 \]

\[ \Rightarrow 8 \ b's, \ 4 \ W's \ [+ \text{perhaps displacement}] \]
\[ \text{in every event!} \]
IS HIGGS NATURAL?

DRAMATIC BIFURCATORY

MOMENT IN FUNDAMENTAL PHYSICS
"Order"

\[ \frac{1}{s_{r}} \rightarrow \varepsilon \]

D. \rightarrow \uparrow \rightarrow \downarrow \\
Q. \rightarrow \uparrow \\
\zeta \rightarrow -\zeta \rightarrow \sim \varepsilon

"Chaos"

Lethal \hspace{1cm} \uparrow \hspace{1cm} \text{us}

\[ \Lambda \rightarrow \text{Weakness of gravity?} \]
STAY TUNED