FUNDAMENTAL PHYSICS & THE FIFTH DIMENSION

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THE LHC IS A MULTI-TEV PROTON-PROTON COLLIDER

THE HAIL OF EMERGING PARTICLES SCRUTINIZED BY...
BIG, BIG EYES

CMS DETECTOR

ATLAS DETECTOR

LHCb DETECTOR
BUT

WHY?
OUTLINE

Nothing is Something too!

Unification & the Geometric Universe

The Origin of the Masses —
  LHC, Higgs boson, other matters

Incarnations of Spacetime —
  Multiverse, 5th dimension, Supersymmetry, curved spacetime, emergent dimensions

Extra-dimensional Perception —
  Collider strategies
NON-RELATIVISTIC SPACE & TIME
RELATIVISTIC SPACETIME
ALCHEMY
in RELATIVISTIC SPACETIME

New particle species created!

particle

anti-particle
ALCHEMY
in RELATIVISTIC SPACETIME

New particle species created!
PRICE:
\[ E = mc^2 \]

particle

anti-particle
VACUUM \ (n = 0)
(QUANTUM) NATURE ABHORS A VACUUM

$\Delta E \Delta t > \hbar$

$\Rightarrow$ vacuum = Relativistic Quantum Aether
Example: Polarizability of the Vacuum

⇒ detectable violations of Coulomb's Law at short distances
Electro Weak UNIFICATION of PARTICLE INTERACTIONS

Electromagnetism + Weak Nuclear Force

\[ \gamma \text{ photon} \]

\[ W^\pm \]

Radioactive decay

Neutral current

\[ Z^0 \]
Electroweak Unification of Particle Interactions

Electromagnetism + Weak Nuclear Force

$\gamma$ photon

$|W^+\rangle + |W^-\rangle \over \sqrt{2}$

$|W^\pm\rangle \rightarrow Z^\circ$

Radioactive decay

Neutral current

$|\phi\rangle \sin \theta$

$+ |Z^\circ\rangle \cos \theta$

"Weak Isospin" Symmetry
Rich in mathematical beauty & subtlety!!

Yang-Mills Gauge Theory to physicists

~ (Quantized) Differential Geometry of Fiber Bundles to mathematicians

Möbius Strip ... ... as cartoon of Fiber Bundle
Rich in Mathematical Beauty & Subtlety!!

Yang-Mills Gauge Theory to physicists

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... as cartoon of Fiber Bundle

Mobius Strip
Electroweak Unification predicts mass spectrum of all known elementary particles!
Electro Weak Unification

PREDICTS MASS SPECTRUM
of all known elementary particles

\[ \text{mass} \]

\[ 0 \quad \gamma \quad W^\pm \\ Z^0 \quad \text{gluon} \quad \text{quarks} \quad \text{electron} \quad \text{muon} \quad \text{neutrinos} \]
Electroweak Unification

PREDICTION: DATA

- top
- Z
- W
- bottom
- charm
- strange
- down
- up
- e
- ??

m

$\frac{\text{TeV}}{c^2}$

$\frac{\text{GeV}}{c^2}$

$\frac{\text{MeV}}{c^2}$

$10^3 \text{eV}/c^2$

0

- gluon
- neutrinos

??
ANALOGY: Rotational symmetry by gravitational force field

Long distance propagation asymmetrized by gravity
ANALOGY: Rotational symmetry by gravitational force field

Collisions at close quarters ≈ rotationally symmetric

Long distance propagation asymmetrized by gravity
IN RELATIVITY,

\[ E^2 = p^2 c^2 + (mc^2)^2 \]

Mass governs propagation

Interactions point like in space-time
suggests space filled by invisible, uniform scalar field "pointing" in "isospace"

≡ Higgs field, made of Higgs boson particles, as EM fields are made of photons.
To test this structure we must create & detect such quantum "ripples".
LHC has blasted Higgs bosons out of hiding!

proton → BLAM! Invisible Higgs Field → proton

Disturbed Higgs boson de-excites back into Higgs field by emitting UV photons

"Seen" by LHC detectors, carefully sifted out from large background "noise" of other photons, nuclear jets, ...
Candidate Higgs $\rightarrow 2 \text{ photon event in CMS detector}$
$m_{\text{Higgs}} = 125\text{ GeV}$

Early LHC DATA
STANDARD MODEL NOW COMPLETE

Higgs boson discovery wins Nobel prize for theorists.

Standard Model brilliant culmination of decades of theory & experiment, deep insights into Nature.

It can be extrapolated theoretically to extremely high energies, BUT...
HIERARCHY PROBLEM

of quantum vacuum

$M_{\text{Planck}} \equiv \sqrt{\frac{c^7}{G_{\text{Newton}}}} \sim 10^{18} \text{GeV/c}^2$

boundary between particles & black holes!

Why are we here?

$M_{\text{W}}^\text{theory}$

$M_{\text{W}}^\text{expt.}$

$100 \text{ GeV/c}^2$

1

couplings

in $\mathcal{H}_{\text{standard model}}$
HIERARCHY PROBLEM
of quantum-corrected vacuum

\[ m_{\text{theory}} \]

\[ M_{\text{Planck}} \equiv \sqrt{\frac{\text{ch}}{G_{\text{Newton}}}} \sim 10^{18} \text{GeV/c}^2 \]

boundary between particles & black holes!

"UNNATURAL!"

Why are we here?

in \( H_{\text{standard model}} \)

\[ m_{\text{ext. W}} = 100 \text{ GeV/c}^2 \]

\[ m_{W} \]
A DIFFERENT VACUUM?

$m_{\text{theory}}^W$

$M_{\text{Plank}} \equiv \sqrt{\frac{c^7}{G_{\text{Newton}}}} \sim 10^{18} \text{GeV}/c^2$

small $m_W$ over large range in $H$ standard model

couplings $g$
A DIFFERENT VACUUM?

\[ M_{\text{Planck}} \equiv \sqrt{\frac{c^3}{G_{\text{Newton}}} \sim 10^{18} \text{ GeV/c}^2} \]

"NATURAL"

- small \( m_W \) over large range
- couplings in H in standard model
OR A MULTI-VERSE?
with Anthropic Selection
(Goldilocks)

Universe 1
theory

eq

Universe 2

Universe 3

exp

eq

no EWSB, e- not bound to atoms

just right for a good life

Universe \(10^{42}

\)

ours

elementary particles nearly black holes
OR A MULTI-VERSE?
with Anthropic Selection

The end of Science?
OR A MULTI-VERSE?
with Anthropic Selection

The end of Science?

Most famous prediction
(rough order of magnitude)
when applied to UNNATURAL
COSMOLOGICAL CONSTANT
& ACCELERATION OF UNIVERSE

Weinberg '87
Flavor Puzzle

elementary particle masses

- $\text{TeV} \frac{c^2}{c^2}$
- $\text{GeV} \frac{c^2}{c^2}$
- $\text{MeV} \frac{c^2}{c^2}$
- $\pm 10^3 \text{eV} \frac{c^2}{c^2}$

Pattern?

- $\text{top}$
- $\text{Z}$
- $\text{W}$
- $\text{bottom}$
- $\text{charm}$

- $\mu$ (strange)
- $\text{up}$
- $\text{down}$

- $e$

- $\delta$ (gluon)
- neutrinos
Flavor Puzzle

Pattern?

elementary particle mass-matrices

GeV/c^2

TeV/c^2

MeV/c^2

\( \pm 10^{-3}\text{eV}/c^2 \)

\( \pm \text{gluon} \)

\( \text{neutrinos} \)

\( \pm \text{couplings to Higgs Boson} \)

\( \top \)

\( \downarrow \)

\( \text{top} \)

\( \text{bottom} \)

\( \text{charm} \)

\( \text{strange} \)

\( \text{down} \)

\( \text{up} \)

\( \text{e} \)
WHAT IS DARK MATTER?

Galaxies distorted by gravitational lensing due to (otherwise) invisible Dark Matter.

Hubble Space Telescope Abell Cluster
"WIMP" DARK MATTER

~ stable Higgs cousin?

~ observed dark matter density

Standard Model particles

Weak-lish interactions

Expanding, cooling UNIVERSE

HOT BIG BANG ~ thermal equilibrium
THE MATTER/ANTIMATTER ASYMMETRY FOR WIMPS

Matter "parent" ~ long-lived Higgs cousin?
decaying asymmetrically to
standard matter & antimatter

~ observed standard
matter (~ antimatter)

Standard
Model
particles

Weak-ish
interactions

TeV WIMPS
annihilate till
"anti-WIMPs"

can't find

Expanding
UNIVERSE

HOT BIG BANG ~ thermal equilibrium

Cui, Sundrum '13
THE ANSWERS TO THESE PUZZLES MAY BE HIDDEN...
IN NEW DIMENSIONS!

SPACE
A NEW DIMENSION COULD HIDE if it's so small that seeing it requires far-UV light.

Boundaries of Space

Microscopic 5th dimension

IS THERE A FIFTH DIMENSION?

(In Relativity, TIME is the "4th dimension")
5D CHAOS $\rightarrow$ 4D COSMOS
Different species have different wavefunction solutions to their wave equations.
Warped Compactification solves the Hierarchy Problem...

$M \ll M_{pl}$

via Higgs mechanism

by small grav.-Higgs overlap

$= \text{mini black hole}$

Robust solution to 5D Einstein Equations:

high curvature (hidden)

$X_5$
Some of the physics inspiration behind "Interstellar"
\[ M_{\text{Planck}} = \sqrt{\frac{c^4}{G_{\text{Newton}}}} \sim 10^{18} \text{GeV/}c^2 \]

Goldberger, Wise '99
stabilization of
5th dimension

small \( m_W \) over
large range

SD couplings
Satisfying answer to FLAVOR PUZZLE

Overlap with Higgs via Higgs mechanism

Boundary of 5th dimension

Neutrino
W^+
Electron
γ
Top quark
Higgs boson

\( \propto m \) matrix

3D
Work of many hands to discover this story:

Goldberger, Wise '00
Arkani-Hamed, Schmaltz '00
Davoudiasl, Hewett, Rizzo '00
Grossman, Neubert '00
Chang, Hisano, Nakano, Okada, Yamaguchi '00
Gherghetta, Pomarol '00
Agashe, Delgado, May, Sundrum '03
Contino, Namura, Pomarol '03
Agashe, Contino, Pomarol '05
Agashe, Okui, Sundrum '08
& test & constrain it by high-precision pre-LHC data

Davoudiasl, Hewett, Rizzo '00
Gherghetta, Pomarol '00
Huber, Shafi '01
Huber, Lee, Shafi '02
Csaki, Erlich, Terning '02
Burdman '02
Hewett, Petriello, Rizzo '02
Agashe, Delgado, May, Sundrum '03
Agashe, Perez, Soni '04 '05 '06
Fitzpatrick, Perez, Randall '07
Csaki, Falkowski, Weiler '08
Agashe, Azatov, Zhu '08 ...

EXTRA-DIMENSIONAL PERCEPTION requires shorter wavelengths. Cost: "E = \frac{hc}{\lambda}" warped version \sim few TeV

- Boundary of 5th dimension
- warped sine wave
- top quark
- Higgs boson
- discrete, set by boundary conditions
EXTRA-DIMENSIONAL PERCEPTION

Agashe, Belyaev, Krupovnickas, Perez, Virzi '06
Lillie, Randall, Wang '07

fast top quark → Decay products

5th Dimension
anti-top

KK gluon excitation

anti-quark wave function

quark wave function

$E_{KK} = E_{tops}$

also KK gravitons, top quarks, W etc.
COMPETES WITH STANDARD MODEL BACKGROUND
EMERGENT DIMENSIONS

Warped extra dimension is an emergent phenomenon!
Not put into fundamental Hamiltonian "by hand," created by strong quantum interactions

"AdS/CFT duality"
Maldacena ’97; Gubser, Klebanov, Polyakov ’98
Witten ’98

related to compositeness of Higgs degrees of freedom
Weinberg ’79; Susskind ’79;
Georgi, Kaplan ’84
Supersymmetry (SUSY) = \( \sqrt{-1} \)

of Quantum Spacetime

Gervais, Sakita '71;
Golfand, Likhtman '71;
Volkov, Akulov '72;
Ramond, Schwartz, Neveu '71; Wess, Zumino '74
SUSY CARTOON

\[ i \mathcal{D}_{t} \equiv H = \mathcal{Q}^{2} \]

\[ Q | \text{boson} \rangle = | \text{fermion} \rangle \]
\[ Q | \text{fermion} \rangle = | \text{boson} \rangle \]
\[ Q | \text{vacuum} \rangle = 0 \]

Many quantum corrections to vacuum (related to Hierarchy Problem) MUST cancel by SUSY algebra. E.g. \( H | \text{vacuum} \rangle = 0 \) clearly.
Rich in mathematical beauty & subtlety

From Seiberg-Witten '94 theory
**Boson-Fermion Superpartners**

- Electron (spin-$\frac{1}{2}$)
- Selectron (spin-0)
- Photon (spin-1)
- Photino (spin-$\frac{1}{2}$)
- Top squark (spin-$\frac{1}{2}$)
- "Stop" (spin-0)
- Higgs (spin-0)
- Higgsino (spin-$\frac{1}{2}$)

A “Mirror” in Quantum Statistics

\[ \equiv \text{Minimal Supersymmetric Standard Model} \]

Georgi, Dimopoulos ’81

But a Mirror cracked...
What LHC sought but hasn't found (so far)
HUNTING THE INVISIBLE

Energy imbalance perpendicular to beams due to “Higgsino” ("neutralino", generally) readily escaping detectors.

But there are backgrounds, famously neutrinos.

Several variants of SUSY & their large parameter spaces are being pursued.
MINIMAL CONSEQUENCES

Top down:
SUSY (breaking) + Gravity
(supergravity)

⇒ "Anomaly-Mediation"

Equivalence Principle

subtle

⇒ Wino phenomenology

Bottom up: Flexible "agnostic" Framework for LHC searches for SUSY

Randall, Sundrum '99
Giudice, Luty, Murayama, Rattazzi '99
Luty, Sundrum '00

Brust, Katz, Lawrence, Sundrum '11
MATTER "PARENT" produced at LHC must live long enough to decay out of equilibrium in early Universe

\[ \rightarrow \text{DISPLACED VERTEX DECAYS (v. low backgrounds)} \]
PRECISION HIGGS PHYSICS is underway

- Photons
- Virtual $W^+$
- Decaying Higgs boson
- Higgs decay: Standard

- Photons
- New particles hiding from direct searches
- Exotic "displaced vertex"

- Quarks

Non-standard

CAN PROBE OTHERWISE HIDDEN NATURALNESS

- Chacko, Goh, Harnik '06
- Burdman, Chacko, Goh, Harnik '07
New Displaced Vertex Detector Proposal

MAssive Timing Hodoscope for Ultra-Stable Neutral PAarticles

displaced vertex from LLP decay is so spectacular...
... that near-perfect background rejection is possible!

On schedule for
- prototype mid 2017
- letter of intent end 2017
- theory white paper mid 2017

Figure Credit: Curtin, Sundrum, submitted to Physics Today
LHC is very powerful & may make dramatic discoveries, perhaps requiring considerable ingenuity. But unable to VERY DEFINITELY & strongly test Naturalness or very precisely test Higgs.

To do this, & to fully understand LHC findings, New colliders, more powerful/precise, will be needed.
On Theory side, all roads seem to lead to Extensions of Relativistic Spacetime in some form or another & connects to a host of experiments in Cosmology, Astrophysics, Cosmic Rays, Emergent Relativity in Condensed Matter, ..
My sense is our journey into Spacetime is just at The Beginning ...