FRONTIERS OF Fundamental Physics

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Elementary Particle Physics

The discovery and understanding of the basic building blocks of all matter and the forces that act on them.
Rutherford’s Discovery of the Nucleus 1911

α Particles

Gold Nucleus

NUCLEUS

David Gross/Madrid/4/13/16
Large Hadron Collider

Switzerland

France
CMS Experiment at the LHC, CERN

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THE STRUCTURE OF MATTER

ELECTROMAGNETISM

STRONG NUCLEAR FORCE

WEAK NUCLEAR FORCE

Structure within the Atom

Quark
Size ≈ 10^{-19} m

Electron
Size ≈ 10^{-18} m

Nucleus
Size ≈ 10^{-14} m

Atom
Size ≈ 10^{-10} m

Neutron and Proton
Size ≈ 10^{-15} m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
\[ \mathcal{L} = - \frac{1}{4g'^4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4g^2} W_{\mu \nu}^a W^{\mu \nu a} - \frac{1}{4g_s^2} G_{\mu \nu}^a G^{\mu \nu a} + \bar{Q}_i i \partial Q_i + \bar{u}_i i \partial u_i + \bar{d}_i i \partial d_i + \bar{L}_i i \partial L_i + \bar{e}_i i \partial e_i + (Y_{ij}^{u} \bar{Q}_i u_j \check{H} + Y_{ij}^{d} \bar{Q}_i d_j H + Y_{ij}^{l} \bar{L}_i e_j H + c.c.) \]

\[ - \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2} \epsilon_{\mu \nu \rho \sigma} G_{\mu \nu}^a G_{\rho \sigma}^a \]
The Standard Model of Elementary Particles

- **Quarks:** u, c, t, d, s, b
- **Leptons:** $\nu_e$, $\nu_\mu$, $\nu_\tau$, e, $\mu$, $\tau$

**Force Carriers:**
- **Electromagnetic (EM) force:** $\gamma$
- **Strong force:** $g$
- **Weak force:** W, Z

**Higgs boson**

It works from the Planck length to the edge of the universe, 60 orders of magnitude.
ELECTROMAGNETISM
FORCE MEDIATED BY THE
ELECTROMAGNETIC FIELD
ONE CHARGE

Energy

distance
$$ER^2 = Q$$

$$dW = QE \cdot dR \rightarrow \text{ENERGY} \sim I - \frac{Q^2}{R}$$
STRAONG FORCE
Classical Oscillator

Quantum Oscillator

GROUND STATE

ZERO POINT OSCILLATION
STRONG FORCE MEDIATED BY
THE CHROMODYNAMIC FIELD

ASYMPTOTIC FREEDOM
\[ \mathbf{E} \mathbf{A} = Q \]

\[ dW = Q \mathbf{E} \cdot d\mathbf{R} \rightarrow \text{ENERGY} \sim \frac{Q^2}{A^2} R \]
ASYMPTOTIC FREEDOM

\[ \downarrow \]

QCD

Quantum Chromodynamics
THE MESON IN QCD

CONFINEMENT

Energy

distance
\( \alpha_s(Q) \)

- \( \triangle \) Deep Inelastic Scattering
- \( \bullet \) \( e^+e^- \) Annihilation
- \( \square \) Heavy Quarkonia

QCD \( \alpha_s(M_Z) = 0.1184 \pm 0.0007 \)

July 2009
Impressive Tests

CMS $L = 34 \text{ pb}^{-1}$
$\sqrt{s} = 7 \text{ TeV}$

- $|y| < 0.5 \times 3125$
- $0.5 \leq |y| < 1 \times 625$
- $1 \leq |y| < 1.5 \times 125$
- $1.5 \leq |y| < 2 \times 25$
- $2 \leq |y| < 2.5 \times 5$
- $2.5 \leq |y| < 3$

$d^2\sigma/dp_T dy$ (pb/GeV)

NLO $\otimes$ NP (PDF4LHC)

Exp. uncertainty

$\text{Anti-}k_T R=0.5$

$p_T$ (GeV)
The Light Hadron Spectrum Of QCD

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$B$ mesons offset by $-4000$ MeV

$D, B, D^*, B^*, D_s, B_s, D_s^*, B_s^*, B_c, B_c^*$
BEYOND THE SM

- Dark Matter
- Neutrino Masses
- Baryon Asymmetry
- Cosmic Acceleration ...
- Unification
- Electroweak scale, “hierarchy”
- Flavor masses, mixings, generations
- Cosmology, inflation, vacuum energy...

SUSY = QUANTUM DIMENSIONS of SPACE TIME
THE SEARCH FOR UNIFICATION
BUT HOW CAN THE FORCES BE THE SAME IF THEY HAVE DIFFERENT STRENGTHS?
WHY ARE THEY DIFFERENT AT LOW ENERGY?

SYMMETRY BREAKING

THE STRENGTH OF THE FORCES COULD BE THE SAME AT HIGH ENERGY.
HOW DO THE FORCES UNIFY?

Asymptotic Freedom

Distance:
- Gravity: $10^{-17}$ cm
- Strong: $10^{13}$ ev
- Weak: $10^{28}$ ev
- E & M: $10^{-33}$ cm

Energy:
- Gravity: $10^{13}$ ev
- Strong: $10^{28}$ ev
- Weak: $10^{-33}$ cm
- E & M: $10^{-33}$ cm

Strength of Forces:
- Strong
- Weak
- E & M

Unification Point at High Energy and Short Distance
An important clue for unification of all the forces with gravity at \(~10^{19}\) TeV, \(10^{-33}\) cm or a coincidence.
HOW DO THE FORCES UNIFY?

Supersymmetry

Present day observation

10^{13}\text{ev}

10^{28}\text{ev}

ENERGY
SUPERSYMMETRY

ROTATIONS IN SUPERSPACE

CLUES:
SCALE
HIERARCHY
UNIFICATION
DARK MATTER

\[ \theta_1 \theta_2 = - \theta_2 \theta_1 \]
SUPERSYMMETRY
Helps unify the forces
An important clue for Susy at \( \sim \) TeV

(and unification)

or

A coincidence
Astrophysicists tell us that, most likely, dark matter = Weakly Interacting Massive Particle

WHAT ARE WIMPS?
SUPERSYMMETRY predicts a candidate for DARK MATTER

IF $M_{\text{SUSY}} \sim 1$ TEV

$\Rightarrow$ DM $\sim 90\%$
AN IMPORTANT CLUE FOR SUSY AT ~ TeV OR A COINCIDENCE
‘TYPICAL’ SUSY EVENT

MISSING ENERGY = ? DARK MATTER
The discovery of SUPERSYMMETRY is the discovery of quantum dimensions of space-time
THE FUTURE

2 EXTREME SCENARIOS

OPTIMISM

PESSIMISM
The Extreme Pessimistic Scenario

Best-fit Higgs mass $m_H$:
$$126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$$

- $M = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$
- $\sigma/\sigma_{SM} = 0.88 \pm 0.21$
The Higgs(-like) boson = SM Higgs.

No direct signal for SUSY (or anything else).

No detection of Dark Matter, in the sky, underground or at the LHC.

No direct indication of the next threshold!

Maybe $10^{10}$--$10^{19}$ GeV

WHAT TO DO?
We Must Fully Explore the 10-100 TeV Energy Range
The Extreme Optimistic Scenario

★ The Higgs(-like) boson ≠ SM Higgs

★ Direct production of SUSY particles

★ Detection of Dark Matter, in the sky, underground and at the LHC

★ Strong guidance for the next steps!

ILC, CLIC, HL-LHC, VHE-LHC, HHC, ...
WE MUST FULLY EXPLORE THE 10-100 TeV ENERGY RANGE
HOW DO THE FORCES UNIFY?

- STRONG
- WEAK
- E & M
- GRAVITY

String Theory

$F_{\text{GRAVITY}} \sim M^2 \sim E^2$
Closed Strings $\sim$ Gravitons

Open Strings $\sim$ SU(N)

Gauge Mesons

$\mathbf{i} = 1 \ldots N$

GAUGE THEORY $=\text{STRING THEORY}$
ARE ALL PARTICLES DIFFERENT VIBRATIONS OF A SUPERSTRING?
Are There More Than 3 Dimensions?

in string theory

6 Dimensions

A Calabi-Yau manifold
The nature of the forces
The form of matter
The values of the masses

are determined by
the shape of the
hidden
dimensions
The Framework of Theoretical Physics

QUANTUM FIELD FRAMEWORK

Standard Theory
The Framework of Theoretical Physics

An incredible FRAMEWORK that includes strings, branes, all consistent field theories and quantum gravity.
SPACETIME

Is all of spacetime emergent?

Is gravity emergent?
WHAT FIXES THE DYNAMICS?

WHAT FIXES THE INITIAL (FINAL) STATE?
HOW DID THE UNIVERSE BEGIN?

Can we determine the initial condition?
WHAT ARE THE RULES?

THE UNIVERSE = SPACETIME HISTORY

THE END

THE BEGINNING

Time

BOUNDARY

Space
WE HAVE A WONDERFUL THEORY OF ELEMENTARY PARTICLES

BUT THE MOST EXCITING QUESTIONS REMAIN TO BE ANSWERED
FANTASTIC INSTRUMENTS AND EXPERIMENTS

FANTASTIC SPECULATIONS
THE BEST IS YET TO COME
Thank You

THE END