(very elementary) Introduction to Particle Physics

January 5 (Tue), 2010 at IPMU

“Elliptic Fibration and F-theory”

Taizan Watari (IPMU)

Plan of this talk

- Basic concepts in physics
- Standard Model
- How is string theory related to the Standard Model?

Basic Concepts in Physics

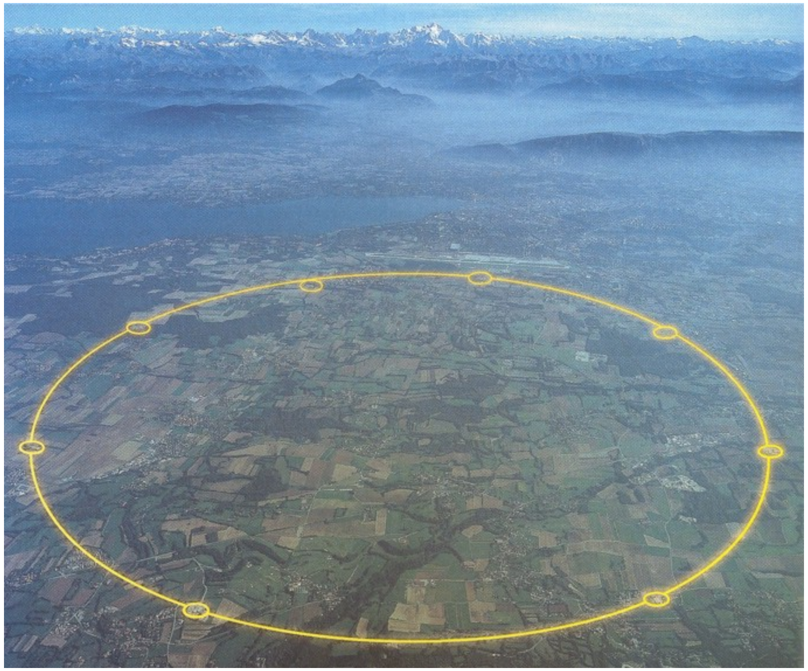
natural unit

mass dimension

scale

Physics and Mathematics

objects in the real world



Large Hadron Collider (LHC) in Geneva

Circumference: 27 km or 17 miles

abstract geometry

$$x^2 + y^2 = 1,$$

$$y^2 = x^3 + fx + g.$$

Coordinates and parameters are just numbers $\in \mathbb{C}, \mathbb{R}$

Everything in the real world has to be measured in appropriate units.

Statistical Mechanics and Relativity

Temperature

$E_{ave} = k_B T.$ Temperature = average energy.

Energy

Momentum

Mass

Time

Length

Electric Field

Magnetic Field

Statistical Mechanics and Relativity

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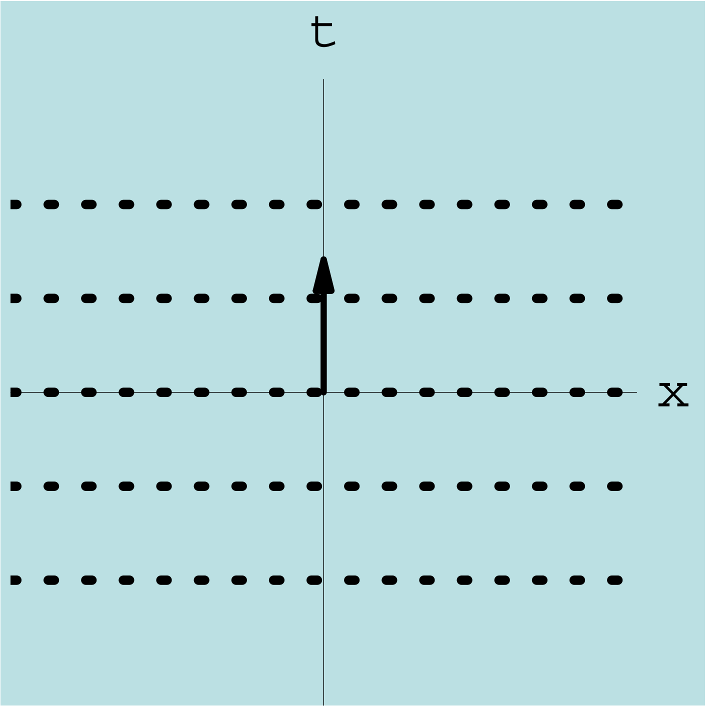

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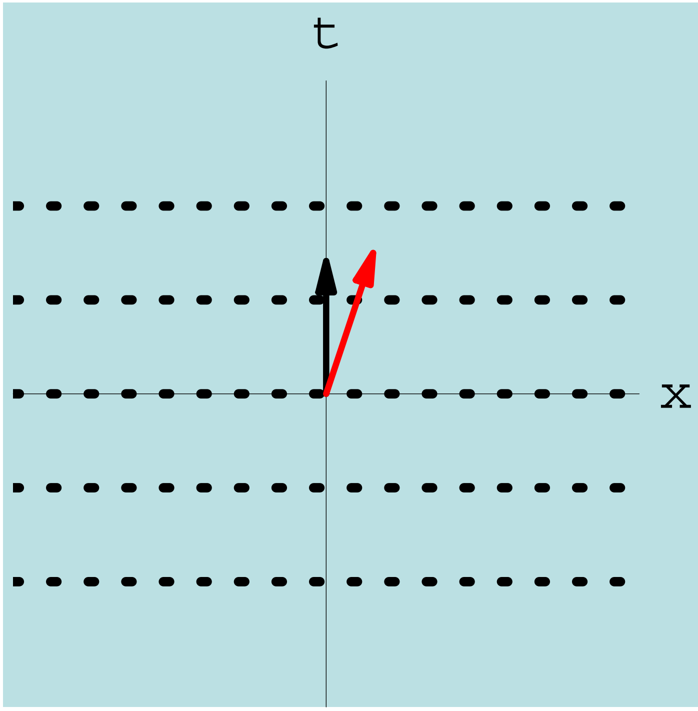

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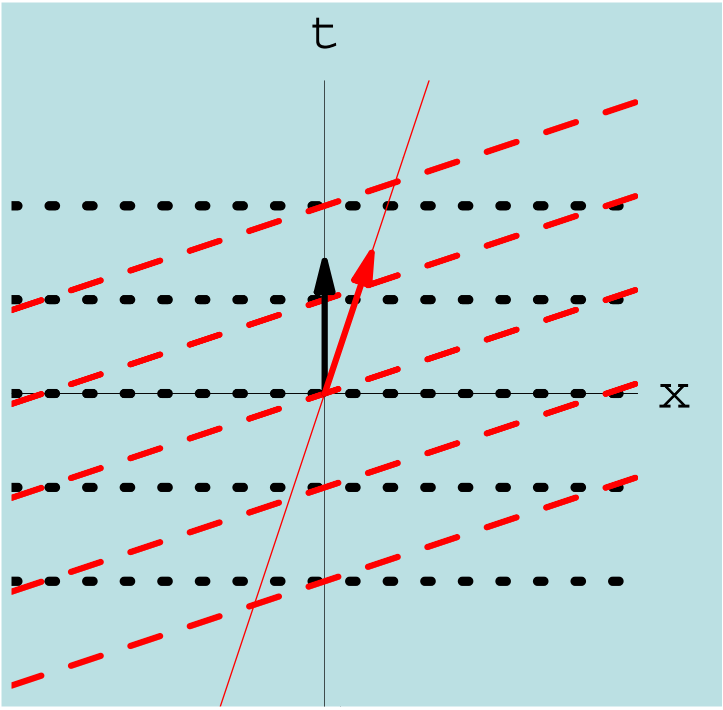


Time and Space directions are mixed up when seen from other observers. essentially the same.

Quantum Mechanics

Particle

with Energy $E = p^0,$
Momentum $c\vec{p} = p^i,$
Mass m

satisfying
$$E^2 - (\vec{p}c)^2 = (mc^2)^2.$$

Wave

with Frequency $\omega = E/\hbar,$
Wavenumber
$$\vec{k} = \vec{p}/\hbar.$$

$$\psi(t,x) \propto e^{i(\omega t - \vec{k}\cdot\vec{x})}$$
$$= e^{i(Et - \vec{p}\cdot\vec{x})/\hbar}.$$

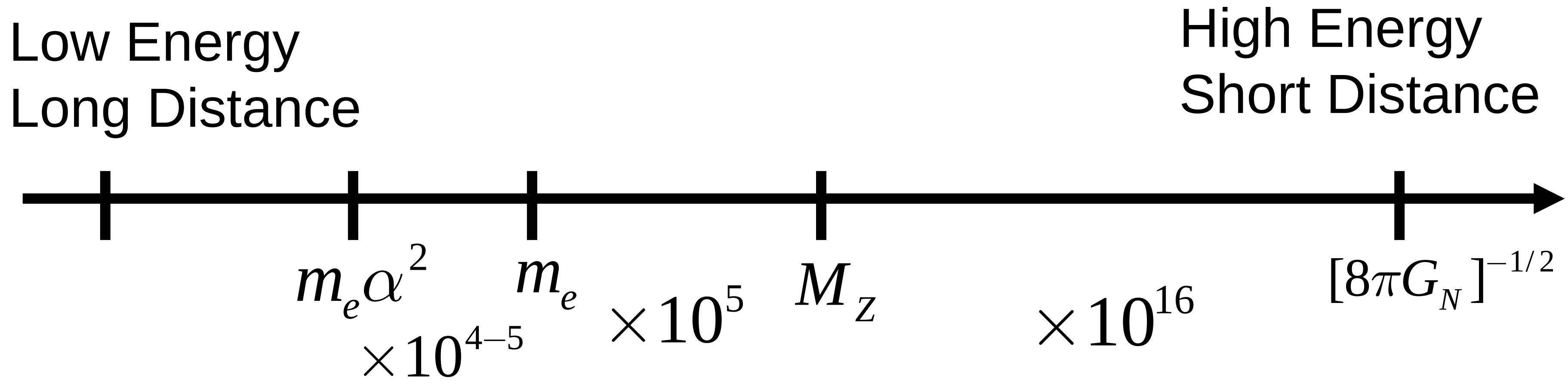
High momentum particle $\Longleftrightarrow$ Short wavelength wave

High energy experiments probe physics at short-distance scale.

After all these discoveries...

- Temperature, Energy, Momentum, Mass: $[\mathrm{mass}]^{+1}$.
- Time, Length: $[\mathrm{mass}]^{-1}$.
- Electric and Magnetic Field Strength: $[\mathrm{mass}]^{+2}$.
- Electric and Magnetic Charge: $[\mathrm{mass}]^{0}$.
- Gravitational coupling G_N: $[\mathrm{mass}]^{-2}$.

Everything is placed on a single axis.



- everything can be measured in a single unit, say [1 eV], $[8\pi G_N]^{-1/2}$ or something else.
- string theory introduces a natural choice of a unit with mass dimension: “string tension”.

⇒ everything can be measured in units of (some power of) “string tension” and made just a number $\in \mathbb{C}, \mathbb{R}$.

Standard Model

Low Energy
Long Distance

High Energy
Short Distance

$m_e \alpha^2$ $\times 10^{4-5}$ m_e $\times 10^5$ M_Z $\times 10^{16}$ $[8\pi G_N]^{-1/2}$

probed experimentally so far

quantum field theory (QFT)

(Schroedinger eq.: L.E. approx of QFT)

Lagrangian [Fields, Interactions, Parameters] $\xrightarrow{\text{QFT calculation}}$ [anything measurable in experiments]

Model

(a.k.a. vector bosons, connections on $\mathbb{R}^{3,1}$)

Gauge Fields of the Standard Model

	$SO(3,1)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
gluon	$A^a_\mu \to \Lambda_\mu{}^\nu A^a_\nu$	$A^a_\mu \to if^{abc} A^b_\mu$		
weak boson	$A^A_\mu \to \Lambda_\mu{}^\nu A^A_\nu$		$A^A_\mu \to if^{ABC} A^B_\mu$	
hyper-charge	$A_\mu \to \Lambda_\mu{}^\nu A_\nu$			

$\mu,\nu = 0,1,2,3.$ $a,b = 1,\cdots,8.$ $A,B = 1,2,3.$

$$\mathcal{L}_{YM} = -\frac{1}{4\boldsymbol{g}_C^2}\boldsymbol{F}^{\boldsymbol{a}}_{\mu\nu}\boldsymbol{F}^{\boldsymbol{a}\mu\nu} - \frac{1}{4\boldsymbol{g}_L^2}\boldsymbol{F}^{\boldsymbol{A}}_{\mu\nu}\boldsymbol{F}^{\boldsymbol{A}\mu\nu} - \frac{3/5}{4\boldsymbol{g}_1^2}\boldsymbol{F}_{\mu\nu}\boldsymbol{F}^{\mu\nu}.$$

3 parameters (gauge couplings): $\boldsymbol{g}_C,\ \boldsymbol{g}_L,\ \boldsymbol{g}_1.$

(Quarks and Leptons)

Matter Fields of the Standard Model

	$SO(3,1)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$ $\times e^{iY\alpha}$
q_L	spinor-+	3	2	$Y=+1/6.$
u^c	spinor-+	$\overline{3}$	1	$Y=-2/3.$
d^c	spinor-+	$\overline{3}$	1	$Y=+1/3.$
ℓ_L	spinor-+	1	2	$Y=-1/2.$
e^c	spinor-+	1	1	$Y=+1.$

q_L : section of $\mathbb{C}^3 \otimes$ [vector bdle above] on $\mathbb{R}^{3,1}$.

$$\mathcal{L}_{\text{Matter-Kin.}} = h^{(q)}_{i\bar{j}}\, q_{Lj}{}^{\dagger}\bar{\sigma}^{\mu} D_{\mu} q_{Li} + h^{(u)}_{i\bar{j}}\, u^{c\dagger}_{j}\bar{\sigma}^{\mu} D_{\mu} u^{c}_{i} + \cdots.$$

$h^{(q)}_{i\bar{j}}$: Hermitian metric of $N_{gen}=3$-dim. vect. sp. $\mathbb{C}^3$.

Higgs boson and Yukawa interactions

	$SO(3,1)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
h	1	1	2	$Y=+1/2.$

$$\mathcal{L}_{Higgs} = (D_\mu h)^\dagger (D^\mu h) - \Lambda^4 + \mu_0^2 |h|^2 - \frac{\lambda}{4} |h|^4 .$$

3 parameters: $\Lambda^4,\ \mu_0^2,\ \lambda \in \mathbb{R}.$

Yukawa interactions: 3-body interactions

$$\mathcal{L}_{\text{Yukawa}} = \lambda_{ij}^{(u)} u_i^c q_{Lj} h + \lambda_{kj}^{(d)} d_k^c q_{Lj} h^* + \lambda_{kj}^{(e)} \ell_{Lk} e_j^c h^* + \text{h.c.}.$$

$\lambda_{ij}^{(u)}, \lambda_{kj}^{(d)}, \lambda_{kj}^{(e)}$: 3 x 3 complex valued matrices

Standard Model Summary

- Fields: vector, matter (q & l), Higgs

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{YM}} + \mathcal{L}_{\text{Matter-Kin.}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}.$$

- Interactions: (other than bilinear (=kinetic) parts)
  - gauge interaction (those from covariant deriv.)
  - Yukawa interactions
  - Higgs potential
- Parameters: 3 ($\boldsymbol{g}_C, \boldsymbol{g}_L, \boldsymbol{g}_1$) + 3 ($\Lambda^4, \mu_0^2, \lambda$)+[$G_N, \vartheta$] and 10 from basis dep. $h^{(q)}_{j\bar{j}}, h^{(u)}_{i\bar{i}}, h^{(d)}_{k\bar{k}},\ \lambda^{(u)}_{ij}, \lambda^{(d)}_{kj}$.

[and 10—12 more from $h^{(l)}_{k\bar{k}}, h^{(e)}_{j\bar{j}}, \lambda^{(e)}_{kj}$ & neutrino masses]

quark masses and mixings

- Yukawa eigenvalues and CKM matrix
  - 3 real and positive eigenvalues of

$$\Lambda^{(u)} \equiv [(h^{(q)})^{-1T}(\lambda^{(u)})^{\dagger}(h^{(u)})^{-1}(\lambda^{(u)})] = (V^{(u)})^{-1} \cdot D_u{}^2 \cdot (V^{(u)}).$$

  - 3 real and positive eigenvalues of

$$\Lambda^{(d)} \equiv [(h^{(q)})^{-1T}(\lambda^{(d)})^{\dagger}(h^{(d)})^{-1}(\lambda^{(d)})] = (V^{(d)})^{-1} \cdot D_d{}^2 \cdot (V^{(d)}).$$

  - A unitary matrix $V_{\mathrm{CKM}} = (V^{(u)})(V^{(d)})^{-1}.$

How is string theory related to the Standard Model?

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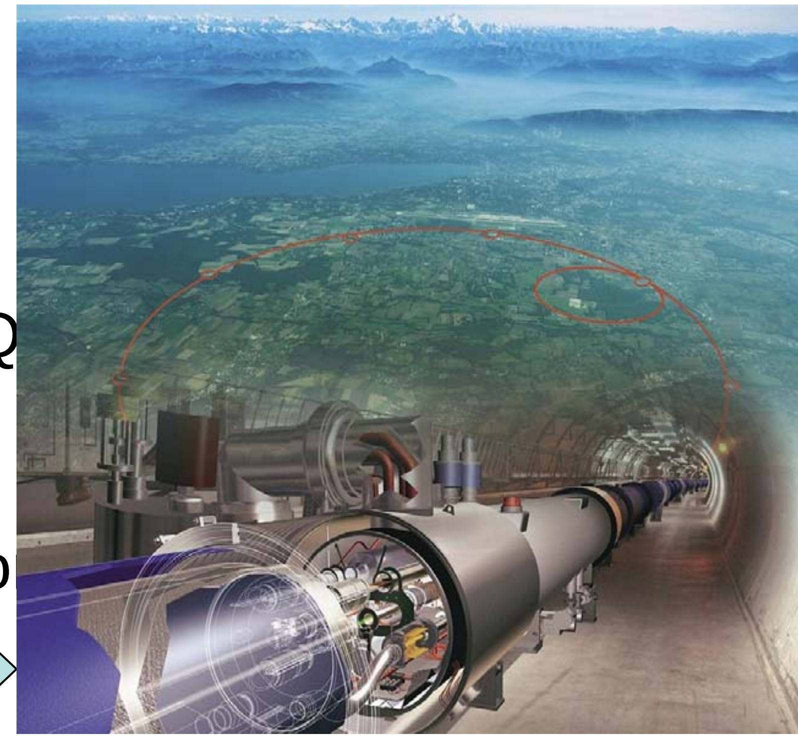


Lagrangian [Fields, Interactions, Parameters]

QFT calculatio

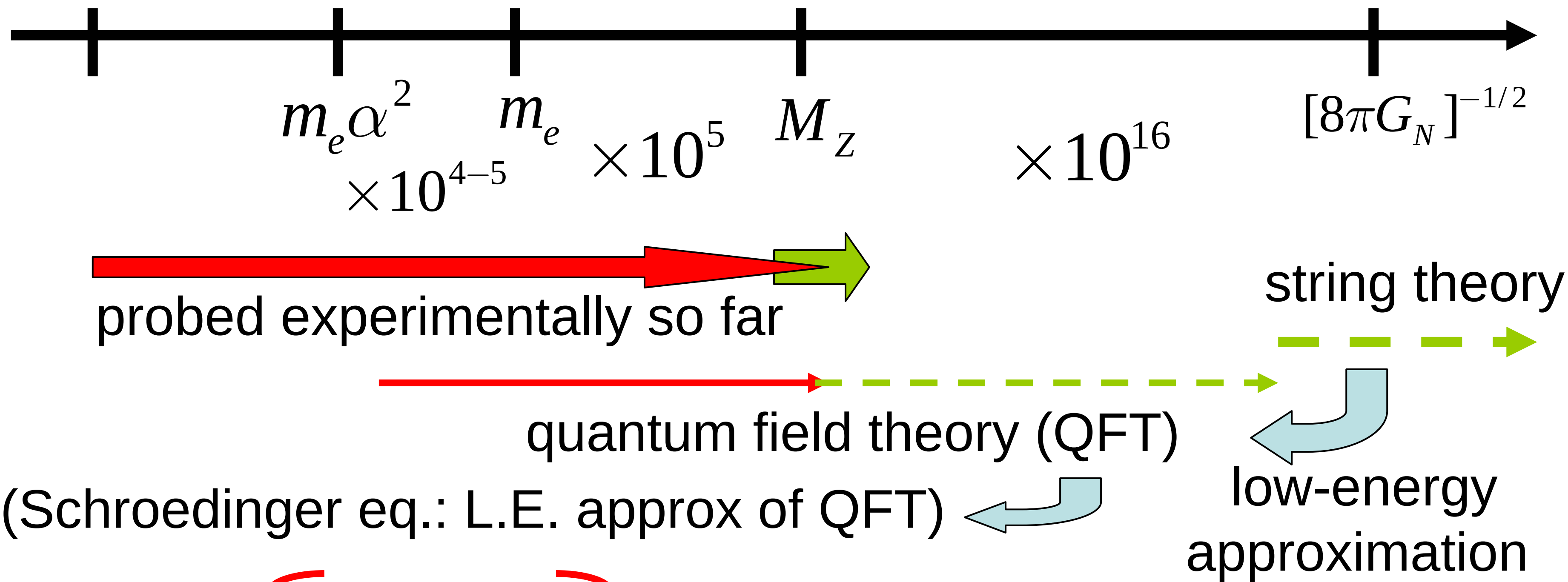
Standard Model

[anything measur-able at the LHC]

[popular scenario]

Low Energy
Long Distance

High Energy
Short Distance



Lagrangian [Fields, Interactions, Parameters]

Standard Model

Q.1
Is the Standard Model available as a low-energy effective theory of string theory?

low-energy (long distance) approximation

String theory → Quantum field theory

geometry for compactification [topology, algebra, moduli] ⇒ model [fields, interactions, parameters]

- understand the dictionary
  - what "we" are, what $\mathbb{C}^3$'s are
  - how $h^{(q)}_{i\bar{i}}$ etc. and $\lambda^{(u)}_{ij}$ etc. are determined
- geometry search

⇕

Q1. Is the Standard Model available as a low-energy effective theory of string theory?

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String theory → Quantum field theory

geometry
for compactification
[topology, algebra,
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model

[fields, interactions,
parameters]

Q2. Is it possible to use string theory to derive predictions?

Q1.

- understand the dictionary
  - what "we" are, what $\mathbb{C}^3$'s are
  - how $h^{(q)}_{i\bar{i}}$ etc. and $\lambda^{(u)}_{ij}$ etc. are determined

- geometry search