~Dec 2007 : LHC starts

pp : $E_{cm} \sim 1$ TeV $\longrightarrow$ 14 TeV 2008

- EW symmetry breaking
- Next layer of structure

compositeness ?
SUSY ?
Grand unif ?
Extra dims ?
Strings / BHs ?
other ?

This course:

- Overview current knowledge
- Importance of TeV scale
- Summarize some scenarios beyond.

... Primer - what LHC could begin to reveal.

$\longrightarrow$ logistics

Theoretical framework: $\boxed{\text{Effective field theory}}$

review:

Practical necessity ($$): organize knowledge by <u>energy</u>.

Basic tenets for low energy physics ($E \ll M_P \sim 10^{19}$ GeV ?)

1. Lorentz invc (SRT)

2. Quantum mechanical
   Hilb. space, superposition, hamiltonian, ...

3. Local

Folk theorem (221; QFT texts):

1+2+3 $\Longrightarrow$ QFT

n.b. include gravity $\Longrightarrow$ <u>problems</u> @ $E \sim M_P$

likely 1, 2, or 3 fail.

guess: ~~locality~~

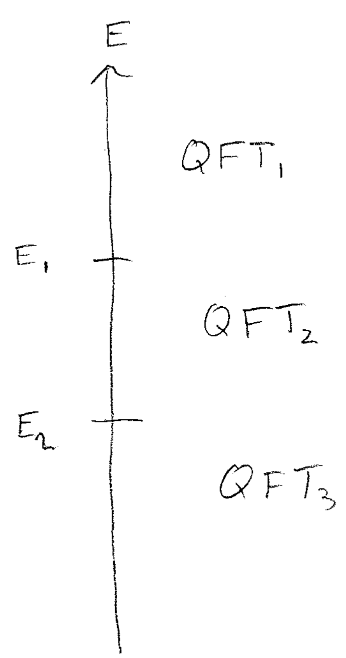
e.g. Strings $\bullet \longrightarrow$

or: grav. effects $\Rightarrow$ more radical nonlocality ?

LHC likely won't probe ... but in theories w/ TeV gravity (large/warped extra dims) <u>could</u> ...

So: assume QFT (for now)

<u>Hierarchies of QFTs</u>



QFT$_3$ $\longrightarrow$

- Summarizes physics $E \ll E_2$
- $\sim$ Insensitive to H.E. physics
  good: don't need to know
  bad: hard to unravel

$\leadsto$ QFT$_3$ is <u>Low-energy effective theory</u> of QFT$_{2,1}$

... a major theme of this course. (Read: Rothstein, p 1–22)

Critical organizing principle: **Symmetry**

(EFTs largely characterized by.)

1. $\Rightarrow$ Poincare invariance:

Lorentz + translations
$SO(3,1)$

Wigner: in QM a sym. must be represented by a unitary or antiunitary operator.

Lorentz reps: $SO(3,1) \sim SO(4) \approx SU(2)\times SU(2)$ ← know reps
c.f. e.g. Srednicki

see from $[M_{\mu\nu}, M_{\rho\sigma}] = i\eta_{\mu\rho} M_{\nu\sigma} \pm$ perms.

Examples:

Rep	Name	spin	notation
$(1,1)$	scalar	0	$\phi(x), \ldots$
$(2,1)$	LH spinor	$1/2$	$\psi_\alpha(x), \ldots$
$(1,2)$	RH spinor	$1/2$	$\chi^{\dot\alpha}(x), \ldots$
$(2,2)$	Vector	$0, 1$	$V^\mu(x), \ldots$
$(3,2)$	LH spin 3/2	$3/2, 1/2$	$\psi^\mu_\alpha(x)$
$(2,3)$	RH spin 3/2	$3/2, 1/2$	$\psi^{\mu\dot\alpha}(x)$
$(3,3)$	rank 2 tensor	$2, 1, 0$	$h_{\mu\nu}(x)$

⋮

Conventions: largely ~ Srednicki (good practice - reconcile)

Particles = irreps of Poincare $M_{\mu\nu}$, P_λ

$$[M_{\mu\nu}, P_\lambda] = i\eta_{\mu\lambda}P_\nu - i\eta_{\nu\lambda}P_\mu$$

$\rightsquigarrow$ extra conditions.

characterize by Casimirs:

P^2 ✓

$W^\mu = \frac{1}{2}\epsilon^{\mu\nu\lambda\sigma}P_\nu M_{\lambda\sigma}$ ... Pauli-Lubanski ~ spin

$\rightsquigarrow$ W^2 (ex.)

Reps: (cf e.g. Ramond)

1) $P^2 = -m^2 \implies W^2 = m^2 s(s+1)$ $\quad s = 0, \frac{1}{2}, 1, \ldots$

states: $|m, s, \vec{P}, s^z\rangle$ $\quad 2s+1$

e.g. $s = \frac{1}{2}$: Dirac ferm.

2) $P^2 = 0$, $W^2 = 0$; $W_\mu P^\mu = 0 \implies W_\mu \propto P_\mu$

indeed $W_\mu = \pm s P_\mu$ $\quad s = 0, \frac{1}{2}, 1, \ldots$

$|0, s, \vec{P}, \pm\rangle$ $\quad 2 \leftarrow$ eg vector w/constraints

3) $P^2 = 0$, $W^2 > 0$ spin continuous

unphysical

4) $P^2 = m^2 > 0$: tachyon

unphysical

... the possible particles

Dynamics: $\mathcal{L}(\varphi^A, \partial_\mu \phi^A, \cdots)$ ... Lorentz scalar.
(e.g.'s to come ...)

$\uparrow$ fields

Other symmetries

Discrete $\quad P, T, C$

$\uparrow$ not spacetime: internal

Internal symmetries:

group $G \ni g$: n-dim rep.

$$\phi \longrightarrow U(g)\, \phi$$

$\uparrow$ n vector $\quad \uparrow$ $n\times n$ rep. matrix

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important implication:

Nöther's theorem:

Suppose $\mathcal{L}$ invt under continuous, global symmetry;

$\uparrow$ x-indep

then EOM $\Rightarrow$ conserved current

$$\partial_\mu j^\mu = 0 .$$

Conserved charge: $\quad Q = \int d^3x\, j^0$

... generates the symmetry.

Global symm: $\phi \to U(g)\phi$ everywhere in Universe

weird?

<u>Gauge symmetry</u> $\phi \to U(g(x))\phi$

local

$\Rightarrow$ gauge bosons (shortly)

Another critical principle:

<u>Scaling & relevance</u>

Another transformation:

$$x^\mu \to s x^\mu$$
$$p_\mu \to s^{-1} p_\mu$$

$$\phi^A(x) \to s^{-d} \phi^A(sx)$$

d = canonical dimension.

- generically not a sym.
- sometimes classical symm
- generically q. effects spoil – anomaly
- preserved: conformal field theories. – special.

E.g $S = -\int d^4x \left[\underbrace{(\partial_\mu\phi)^2}_{\text{dim } 4} + \underbrace{m^2\phi^2}_{\text{dim } 2} + \sum_n \lambda_n \mathcal{O}_n \right]$

dim 4 $\Leftrightarrow [\phi] = 1$

dim of

$s \to \infty$ (IR) : $m^2\phi^2$ dominates

more general ($D=4$):

$[\mathcal{O}] < 4$ Relevant

$[\mathcal{O}] = 4$ Marginal

$[\mathcal{O}] > 4$ Irrelevant

E.g. $\lambda_1 \mathcal{O}_1 = \frac{\phi^2(\partial_\mu\phi)^2}{M^2}$: $[\mathcal{O}_1] = 6$

$M^2 \leftarrow$ dim analysis

small effect as $s \to \infty$

$\sim$ invisible unless $\rightsquigarrow$ qualitatively new physics

Conversely: $s \to 0$ (UV) :

$[\mathcal{O}] < 4 \longrightarrow$ "small"

$[\mathcal{O}] > 4 \longrightarrow$ "large;"

$\sim \mathcal{O}(1)$ effects when $p \sim M$.

Moreover: $[\mathcal{O}] > 4 \longleftrightarrow$ <u>non-renormalizable</u>

Renorm gp: mixes w/ higher dim ops (∞#)

so for $p \sim M$, EFT fails: ~~predictivity~~

replace w/ new EFT

Other RG features

- dims shifted: anomalous dims
- Let cutoff scale $\sim \Lambda$ (typically take $\Lambda \sim M$)

consider $\lambda_n \mathcal{O}_n$ w/ $[\mathcal{O}_n] = d_n < 4$

generically: $\delta\lambda_n \sim \Lambda^{4-d_n}$

e.g. scalar: $\delta m^2 \propto \Lambda^2$

so $m^2 \ll \Lambda^2 \implies$ <u>fine tuning</u>

exception: symmetry prevents.

typically happens if $\lambda_n \to 0$ restores symmetry

(non-anomalous)

then $\lambda_n \ll \Lambda^{4-d_n}$

"technically natural"