Standard Model:

Getting There and Beyond

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High Energy Physics has established that all known natural phenomena can be described by a local quantum field theory which is invariant under:

- 3+1 dimensional Lorentz transformations, $SO(3,1)$, and translations.
- $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge transformations

$\Longrightarrow$ *all elementary particles belong to certain representations of the Lorentz and gauge groups:*

Spin-1 bosons

$$\left\{\begin{array}{rl} G^\mu : & (8,1,\ \ 0) \\ W^\mu : & (1,3,\ \ 0) \\ B^\mu : & (1,1,\ \ 0) \end{array}\right.$$

Spin-1/2 fermions

$$3 \times \left\{\begin{array}{rl} q_L : & (3,2,\ \ +1/6) \\ u_R : & (3,1,\ \ +2/3) \\ d_R : & (3,1,\ \ -1/3) \\ l_L : & (1,2,\ \ -1/2) \\ e_R : & (1,1,\ \ -1) \end{array}\right.$$

Parameters of a quantum field theory:

- **masses (dimensionfull)**
- **couplings (dimensionless, $c = \hbar = 1$)**

Experiments measure parameters

or **discover new particles**

or **discover deviations from quantum field theory.**

Examples of measurements:

- $\star$ $\sin^2\theta_W$ **at NuTeV**
- $\star$ **CP asymmetries in B_s decays at BTeV**
- $\star$ θ_{13} **at MINOS**
- $\star$ $Br(K^+ \to \pi^+ \nu\bar{\nu})$ **at CKM**
- $\star$ **...**

Examples of discoveries of new particles:

- $\star$ **Top quark at CDF/D0 (Run I)**
- $\star$ **Tau neutrino at DONUT**
- $\star$ **Next bump in $\sigma(p\bar{p} \to \mu^+\mu^- X)$ in Run II, or in $\sigma(e^+e^- \to \mu^+\mu^-)$ at a future linear collider**
- $\star$ **...**

Complications:

quantum field theory at strong coupling

Example:

BaBar discovery of a narrow resonance at 2.317 GeV in the $D_s^+\pi^0$ final state $\Longrightarrow$ New particle! (April 12, 2003)

Heavy quark effective theory $+$ model of chiral symmetry breaking in QCD (Bardeen, Eichten, Hill, hep-ph/0305049 - May 5):

$c\bar{s}$ **bound state – not a new** *elementary* **particle.**

$\Rightarrow$ **there must also exist an excited D_s^{*+} state of 2.46 GeV**

... discovered by CLEO (May 12, 2003).

Fundamental parameters

Mass scales:

- **Electroweak scale:** $\langle H \rangle \approx 174$ GeV

(Vacuum expectation value which breaks the $SU(2)_W \times U(1)_Y$ symmetry; determines M_W, M_Z up to a gauge coupling)

- **Planck scale:** $M_P \approx 2 \times 10^{19}$ GeV

(determines the strength of the gravitational interactions)

- **Cosmological constant:** $\approx 10^{-3}$ eV

(sets the acceleration of the expansion of the Universe)

Gauge couplings:

- $g_s \longrightarrow \Lambda_{\rm QCD} \approx 100$ MeV
- $g, g' \longrightarrow \alpha_{\rm em}\,,\ \sin^2\theta_W$

Fermion couplings to $\langle H \rangle$:

- $\lambda_u^{ij}, \lambda_d^{ij} \longrightarrow$ quark masses and CKM elements
- $\lambda_e^{ij} \longrightarrow$ charged lepton masses

QCD θ parameter:

- coefficient of $G\tilde{G}$ in the Lagrangian: $\theta < 10^{-9}$

(leads to CP-violating quark masses;
measured by the neutron electric dipole moment)

Neutrino masses and mixings:

- *Either* couplings of new particles (ν_R) to $\langle H \rangle$,

  or a new mass scale, $\frac{C_{ij}}{M_{\mathrm{new}}}(L^i H)(L^j H)$,

  or both?

Higher-Dimensional Operators

Suppressed by some mass scales $\gtrsim 1$ TeV

If non-zero coefficients $\Rightarrow$ "New Physics"

EXAMPLES:

- $\frac{C_1}{M_1^2}\left(\bar{l}_L^2\gamma^\alpha l_L^2\right)\left(\bar{q}_L^1\gamma_\alpha q_L^1\right) = \frac{C_1}{M_1^2}\left(\bar{\nu}_L^\mu\gamma^\alpha\nu_L^\mu\right)\left(\bar{u}_L\gamma_\alpha u_L + \bar{d}_L\gamma_\alpha d_L\right) + \ldots$

  NuTeV measured a combination of $\frac{C_1}{M_1^2}$ and $\sin^2\theta_W$.

- $\frac{C_2}{M_2^2}\left(\bar{q}_L^3\gamma^\alpha q_L^2\right)\left(\bar{q}_L^3\gamma_\alpha q_L^2\right) = \frac{C_2}{M_2^2}\left(\bar{b}_L\gamma^\alpha s_L\right)\left(\bar{b}_L\gamma_\alpha s_L\right) + \ldots$

  induces B_s^0-$\overline{B}_s^0$ mixing; to be measured by D0, CDF.

- $\frac{C_3}{M_3^2}\left(\langle H\rangle\sigma^i W_\alpha^i\langle H\rangle\right)\left(\langle H\rangle\sigma^{i'} W^{\alpha i'}\langle H\rangle\right)$

  shifts M_W/M_Z, changes the electroweak fits.

- ...

Vector-like quarks

$q_L\,,\,q_R$: same gauge charges

Predicted in many models:

- "Top-quark seesaw" model (Dobrescu, Hill, 1997; ...)

  $\longrightarrow$ Higgs doublet is composite

- "Little Higgs" models (Arkani-Hamed et al, 2002)

  $\longrightarrow$ no quadratic divergences at 1-loop

- "Beautiful mirrors" (Choudhury, Tait, Wagner, 2001)

  $\longrightarrow$ explains $A^b_{\rm FB}$;

  $\longrightarrow$ signal in Run II: $b' \rightarrow bZ$ for $m_{b'} < 300$ GeV

New neutral gauge bosons (Z')

Example: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

(Appelquist, Dobrescu, Hopper, hep-ph/0212073)

Z_{B-L} **does not mix at tree level with the** Z

Run I: $M_{Z_{B-L}} > 480$ **GeV (coupling** $\approx e$**)**

Could be discovered in Run II.

$\longrightarrow$ *Gauge anomaly cancellation would then provide information about* $\boldsymbol{\nu}$ *sector.*

More dimensions

4D flat spacetime $\perp$ one dimension of size πR:

$$\text{Boundary conditions}: \quad \frac{\partial}{\partial y}\phi(x,0) = \frac{\partial}{\partial y}\phi(x,\pi R) = 0$$

$$\Longrightarrow \quad \phi(x,y) = \frac{1}{\sqrt{\pi R}}\left[\phi^0(x) + \sqrt{2}\sum_{j\geq 1}\phi^j(x)\cos\left(\frac{jy}{R}\right)\right]$$

Kaluza-Klein modes, $\phi^j(x)$: particles with momentum in extra dimensions

$\Rightarrow$ massive particles in 4D: $m_j^2 = m_0^2 + \frac{j^2}{R^2}$

Fermions in a compact dimension

Lorentz group in 5D ⇒ vector-like fermions:

$$\chi = \chi_L + \chi_R$$

Chiral boundary conditions:

$$\begin{aligned} \chi_L(x^\mu, 0) &= \chi_L(x^\mu, \pi R) = 0 \\ \frac{\partial}{\partial y}\chi_R(x^\mu, 0) &= \frac{\partial}{\partial y}\chi_R(x^\mu, \pi R) = 0 \end{aligned}$$

Kaluza-Klein decomposition:

$$\chi(x, y) = \frac{1}{\sqrt{\pi R}}\left\{\chi_R^0 + \sqrt{2}\sum_{j\geq 1}\left[\chi_R^j \cos\left(\frac{\pi j y}{L}\right) + \chi_L^j \sin\left(\frac{\pi j y}{L}\right)\right]\right\}$$

Universal Extra Dimensions

T. Appelquist, H.-C. Cheng, B. Dobrescu, Phys.Rev.D64 (2001)

All Standard Model particles propagate in $D \geq 5$

Momentum conservation $\Rightarrow$ KK parity is conserved

- **Bounds from one-loop shifts in M_W/M_Z and other observables:** $\frac{1}{R} \gtrsim 300 \text{ GeV}$
- **Pair production of Kaluza-Klein modes at colliders: could be discovered soon!**

(Cheng, Matchev, Schmaltz, hep-ph/0205314)

Six-Dimensional Standard Model

work with T. Appelquist, G. Burdman, E. Ponton, E. Poppitz, H.-U. Yee

$D = 6$ (two universal extra dimensions) is special...

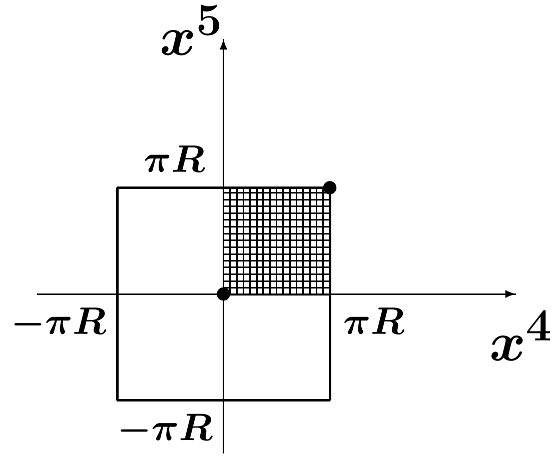
- **Global $SU(2)_W$ anomaly cancellation requires 3 mod 3 generations.**

- **Gravitational anomaly cancellation in 6D requires one right-handed neutrino per generation.**

- **6D Lorentz symmetry allows ν masses only of the Dirac type.**

Compactification of two extra dimensions

Square torus of radius R:



6D Lorentz symmetry broken by compactification:

$$SO(5,1) \longrightarrow SO(3,1) \times Z_8$$

Dominant baryon-number violating processes:
$p \rightarrow e^-\pi^+\pi^+\nu\nu$ and $n \rightarrow e^-\pi^+\nu\nu$

$$\tau_p \approx \frac{10^{35}\mathrm{yr}}{C_{17}^2}\left[\frac{(4\pi)^{-7}10^{-4}}{\Phi_5 F(\pi\pi)}\right]\left[\frac{1/R}{0.5\ \mathrm{TeV}}\right]^{12}\left[\frac{RM_s}{5}\right]^{22}$$

Long-live the proton!

Conclusions