Outline:
- Electroweak symmetry breaking (Lecture 1)
- Quark and lepton masses; vectorlike quarks (Lecture 2)
- New gauge bosons (Lecture 3)
- Extra dimensions (Lecture 4)
- Supersymmetry; how to search for new phenomena (Lecture 5)

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Minimal Supersymmetric Standard Model

Many new particles, many new parameters
→ prototype for "New Physics"

Nice theoretical features:
- No quadratic divergences ($(H) \sim M_{SUSY}, \mu$)
- Gauge couplings unify
- Lightest superpartner (LSP) is a dark matter candidate
- ...

Fermion masses in the Standard Model

All Standard Model fermions are chiral ⇒ they get masses from interactions with the vacuum:

$$Q_L^3 = \langle H^0 \rangle, H^+$$

Hierarchy of Yukawa couplings: $y_t \approx 1$

$m_b \approx 2.7$ GeV at the weak scale ⇒ $y_b \approx 0.016$
Fermion masses in the MSSM

The supersymmetric Higgs sector is a Two-Higgs-Doublet model of type-II (only up-type quarks get masses from $H_u$).
This is imposed by holomorphy, i.e., the superpotential is a function of fields and not their Hermitian conjugates.

Superpotential: \[ W = y_u \bar{u}^c H_u \bar{Q} - y_d \bar{d}^c H_d \bar{Q} - y_t \bar{t}^c H_t \bar{L} + \mu H_u H_d^\dagger \]

Limits on $A^0, H^0$ mass from FCNC ($b \to s\gamma,...$, ...)

At the LHC: $b \bar{b} H^0$ associated production.

Background to $b \bar{b} \tau^+ \tau^-$ from $t \bar{t}$ production.

There is also $s$-channel production via gluon fusion:

Cross section depends on the masses and mixing of $\tilde{b}$ squarks.

Lagrangian \[ \mathcal{L} \supset -y_b \bar{b} R Q_L^3 H_d^\dagger - y_t \bar{r} R H_L^3 H_d \] (due to the superpotential)

The MSSM allows $y_b = O(1)$ if $\tan \beta \equiv v_u / v_d \approx 50$. 

$\tan \beta$ is determined by the minimization of the potential:
\[ \left( |\mu|^2 + m_{H_u}^2 \right) |H_u|^2 + \left( |\mu|^2 + m_{H_d}^2 \right) |H_d|^2 + b H_u H_d + \frac{1}{8} \left( g_2^2 + g_2^2 \right) \left( |H_u|^2 - |H_d|^2 \right)^2 \]

$m_{H_u}^2$, $m_{H_d}^2$ and $b \equiv B \mu$ are soft susy-breaking parameters.

Note: $y_b / y_\tau = m_\tau / m_b$ in the MSSM is independent of $\tan \beta$, so that
\[ \frac{B(A^0 \to \tau^+ \tau^-)}{B(A^0 \to bb)} \approx \frac{y_b^2}{3 y_\tau^2} = \frac{m_\tau^2}{3 m_b^2} \approx 10\% \]
**Importance of discrete symmetries:**

Standard model must be extended in order to include dark matter: a new electrically-neutral stable particle.

Stability of dark matter must be ensured by some symmetry. Simplest possibility: a new discrete symmetry.

Examples:

- Supersymmetry with \( R \) parity
- Universal extra dimensions (KK parity)
- Little Higgs models with \( T \) parity

**Bonus:**

If new particles couple only in pairs to standard model ones, then the contributions to electroweak observables are loop-suppressed! ⇒ new particles may be light enough for being discovered soon at colliders!

**At the Tevatron and the LHC:**

pair production of colored odd particles, followed by cascade decays through lighter odd particles, until a pair of dark matter candidates escapes the detector.

⇒ Generic signal: missing \( E_T \) + jets + leptons

E.g., squark production and cascade decays to neutralinos:

\[
\begin{align*}
q (g) & \rightarrow \tilde{q} \quad \text{jet}^0 \quad t^- \quad t^+ \\
\tau (g) & \rightarrow \tilde{\tau} \quad \text{jet}^\pm \quad \chi^0_2 \quad \chi^0_1
\end{align*}
\]

Look for: 3 leptons + 2 jets + \( E_T \)

Similarity between supersymmetry, little Higgs with KK parity, and one universal extra dimension is not accidental:

- \( N = 1 \) supersymmetry is an extra dimension with anticommuting coordinate
- Little Higgs with \( T \) parity is a deconstructed extra dimension.

An important distinction: spins of partners are different (squarks have spin 0, KK quarks have spin 1, etc.)

Measuring spins at the LHC is challenging but not impossible.

Energy

\[
\begin{align*}
? & \quad \text{New Physics} \\
\sim 1 \text{ TeV} & \quad \text{Gauge and flavor sectors of the Standard Model} \\
\sim 100 \text{ GeV} & \quad \text{very weakly interacting particles?}
\end{align*}
\]
Probing the unknown ...

CMS and ATLAS are exploring physics at distances of $\sim 10^{-19} \text{m}$.
This may be qualitatively different than the physics at larger distances, probed by CDF and D0.

It is hard to make predictions!

There are many theories for physics beyond the SM.
No theory is sufficiently successful so far in explaining the puzzles of the SM $\rightarrow$ we should consider a wide range of theories.
Even within well defined models, a small change in parameters may lead to widely different collider signatures.

Best attitude: search as many final states as possible, try to be "model independent".

Similar situation for LHCb, Belle, ...

Search for resonances $+ X$

E.g., 2 universal extra dimensions:
s-channel production of a KK gluon followed by a cascade decay

$\rightarrow t\bar{t}$ resonance + 2 jets

$G_{1,1}^{(1)} q^{(1,1)} \rightarrow t\bar{t}$ resonance + 2 jets

Search for two-body resonances

Try all combinations of two objects: $jj, \mu\mu, ee, \gamma\gamma, t\bar{t}, tb, \tau\mu, ...$

Don't make simplifying assumptions such as lepton universality or gauge coupling unification ...

E.g. $WZ$ resonance:

Search for pairs of resonances

E.g., leptoquarks:

E.g., nonstandard Higgs decays:
Conclusions

Many possibilities for what you could discover:
- Vectorlike fermions
- New gauge bosons ($Z', W', G', ...$)
- Extended Higgs sectors
- UED, little Higgs, susy, warped ED, ...

Unitarity of longitudinal $WW$ scattering requires a Higgs boson (may have non-SM production/decays) or a new strong interaction.

Final Exam

Find out what theory describes physics at the TeV scale.

\begin{align*}
\text{Energy} & \quad ? \quad ?????????????????????????????????????
\end{align*}

$\sim 1 \text{ TeV}$ ?

New Physics

\begin{align*}
\text{Energy} & \quad \sim 100 \text{ GeV}
\end{align*}

Standard Model

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