Beyond the Standard Model

Lecture 5

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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 ($\langle H \rangle \sim M_{\text{SUSY}}, \mu$)
• Gauge couplings unify
• Lightest superpartner (LSP) is a dark matter candidate
• …
Quadratic divergences in the Higgs self-energy due loops with SM particles are exactly cancelled by those due loops with superpartners: requires mass of $\tilde{t}$ (and probably of $\tilde{g}$) to be near the electroweak scale.

Most powerful test of MSSM: $\tilde{t}\tilde{t}^\dagger$ production.
Fermion masses in the Standard Model

All Standard Model fermions are chiral $\Rightarrow$ they get masses from interactions with the vacuum:

$$Q^3_L \equiv \langle H^0 \rangle, H^+$$

Hierarchy of Yukawa couplings: $y_t \approx 1$

$$m_b \approx 2.7 \text{ GeV at the weak scale} \Rightarrow y_b \approx 0.016$$
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: \[ W = y_u \hat{u}^c \hat{H}_u \hat{Q} - y_d \hat{d}^c \hat{H}_d \hat{Q} - y_\ell \hat{\ell}^c \hat{H}_d \hat{L} + \mu \hat{H}_u \hat{H}_d \]
Lagrangian \( \mathcal{L} \supset -y_b \bar{b}_R Q^3_L H_d - y_\tau \bar{\tau}_R L^3_L H_d \) (due to the superpotential)

The MSSM allows \( y_b = O(1) \) if \( \tan \beta \equiv \frac{v_u}{v_d} \approx 50 \).

\( \tan \beta \) is determined by the minimization of the potential:

\[
\left( |\mu|^2 + m^2_{H_u} \right) |H_u|^2 + \left( |\mu|^2 + m^2_{H_d} \right) |H_d|^2 + b H_u H_d
+ \frac{1}{8} \left( g^2 + g'^2 \right) \left( |H_u|^2 - |H_d|^2 \right)^2
\]

\( m^2_{H_u}, m^2_{H_d} \) and \( b \) (\( \equiv B\mu \)) are soft susy-breaking parameters.

Note: \( y_\tau/y_b = m_\tau/m_b \) in the MSSM is independent of \( \tan \beta \), so that

\[
\frac{B(A^0 \rightarrow \tau^+\tau^-)}{B(A^0 \rightarrow b\bar{b})} \approx \frac{y_\tau^2}{3y_b^2} = \frac{m_\tau^2}{3m_b^2} \approx 10\%
\]
Limits on $A^0, H^0$ mass from FCNC ($b \to s\gamma,...$), ...

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

\[
\frac{y_b}{\sqrt{2}} \left( A^0 \bar{b} \gamma_5 b - H^0 \bar{b} b \right)
\]

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

usual MSSM

A. Djouadi, hep-ph/0503173
There is also $s$-channel production via gluon fusion:

$b$ and $\tilde{b}$ loops $\Rightarrow$

Cross section depends on the masses and mixing of $\tilde{b}$ squarks.
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 $E_T + \text{jets} + \text{leptons}$

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

Look for: $3 \text{ leptons} + 2 \text{jets} + E_T$
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

$\sim 1 \text{ TeV}$

$\sim 100 \text{ GeV}$

New Physics

Gauge and flavor sectors of the Standard Model

very weakly interacting particles???
• 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 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 ...

Example – $WZ$ resonance:

\begin{center}
\begin{tikzpicture}[baseline=(current bounding box.center)]
  \node (q1) at (0,0) [crossed dot] {$q$};
  \node (W) at (1.5,0) [crossed dot] {$W$};
  \node (Z) at (2,0) [crossed dot] {$Z$};
  \node (Wp) at (1,1) [crossed dot] {$W'$};
  \draw (q1) -- (Wp);
  \draw (Wp) -- (W);
  \draw (Wp) -- (Z);
\end{tikzpicture}
\end{center}
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

$\rightarrow t\bar{b}$ resonance $+ 2$ jets
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.
Find out what theory describes physics at the TeV scale.

Energy

? ??????????????????????????????????????????????????

∼ 1 TeV ?

New Physics

∼ 100 GeV

Standard Model

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