Beyond the Standard Model

Lecture 5

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<u>*Outline:*</u>

- *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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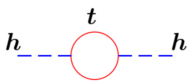
Minimal Supersymmetric Standard Model

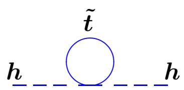
Many new particles, many new parameters
$\rightarrow$ prototype for "New Physics"

Nice theoretical features:

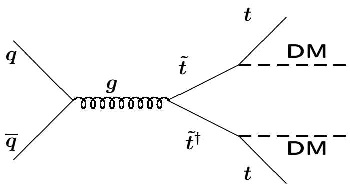
- **No quadratic divergences ($\langle H \rangle \sim M_{\mathrm{SUSY}}\,,\, \mu$)**
- **Gauge couplings unify**
- **Lightest superpartner (LSP) is a dark matter candidate**
- **...**

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.



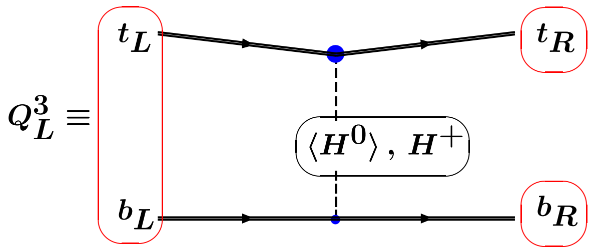


Most powerful test of MSSM: $\tilde{t}\tilde{t}^\dagger$ production.



Fermion masses in the Standard Model

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



Hierarchy of Yukawa couplings: $y_t \approx 1$

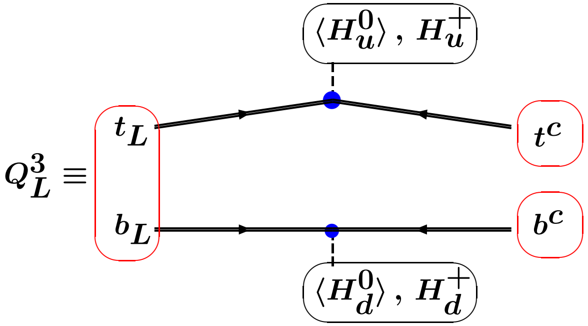
$m_b \approx 2.7$ **GeV at the weak scale** $\Rightarrow y_b \approx 0.016$

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: $\quad W = y_u\,\hat{u}^c\hat{H}_u\hat{Q} - y_d\,\hat{d}^c\hat{H}_d\hat{Q} - y_\ell\,\hat{e}^c\hat{H}_d\hat{L} + \mu\,\hat{H}_u\hat{H}_d$



Lagrangian $\mathcal{L} \supset -y_b\,\bar{b}_R Q_L^3 H_d - y_\tau \bar{\tau}_R L_L^3 H_d$ (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:**

$$\left(|\mu|^2 + m_{H_u}^2\right)|H_u|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d|^2 + b\,H_u H_d$$
$$+\frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u|^2 - |H_d|^2\right)^2$$

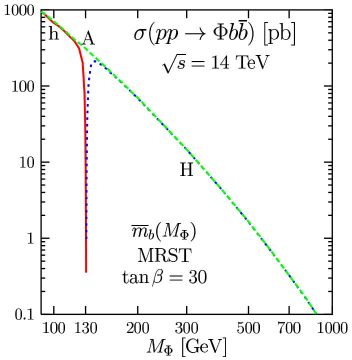
$m_{H_u}^2$, $m_{H_d}^2$ **and** b **(**$\equiv B\mu$**) are soft susy-breaking parameters.**

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

$$\frac{B(A^0 \to \tau^+\tau^-)}{B(A^0 \to b\bar{b})} \approx \frac{y_\tau^2}{3y_b^2} = \frac{m_\tau^2}{3m_b^2} \approx 10\%$$

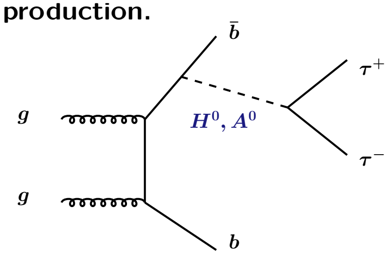
Limits on A^0, H^0 **mass from FCNC (**$b \to s\gamma, ...$**), ...**

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



usual MSSM

A. Djouadi, hep-ph/0503173

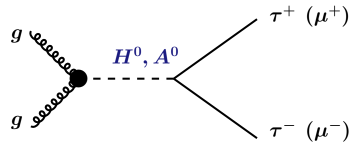


$$\frac{y_b}{\sqrt{2}}\left(A^0\bar{b}\gamma_5 b - H^0\bar{b}b\right)$$

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

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!

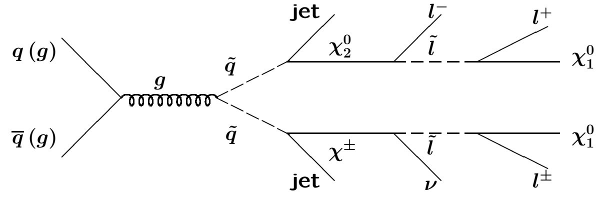
$\Rightarrow$ new particles may be light enough for being discovered soon at colliders!

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.

$\Rightarrow$ Generic signal: missing E_T + jets + leptons

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



Look for: 3 leptons + 2 jets + $\not{E}_T$

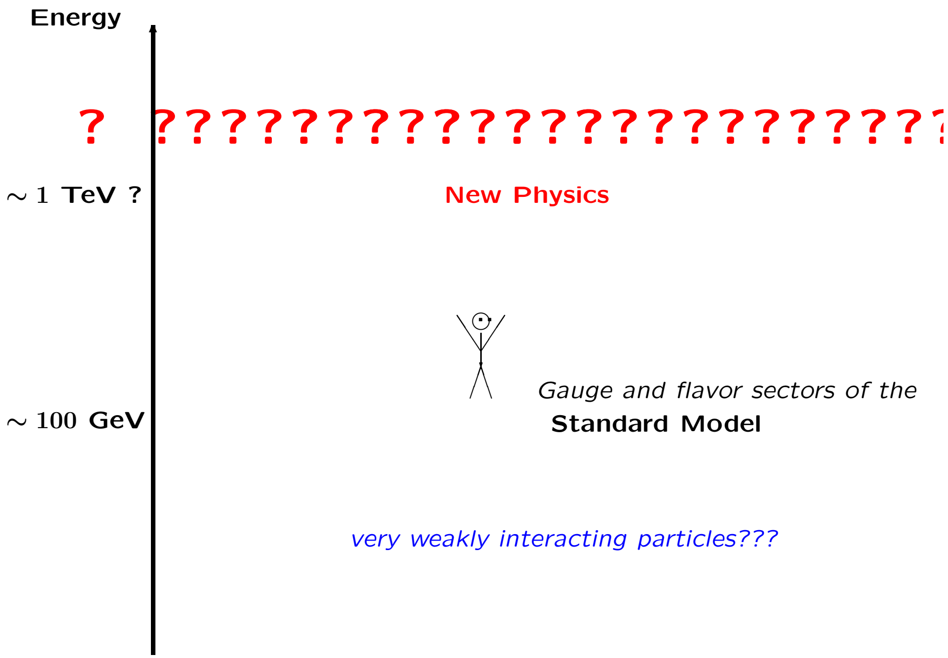
Similarity between supersymmetry, little Higgs with KK parity, and one universal extra dimension is not accidental:

- $N = 1$ 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.



• **Probing the unknown ...**

CMS and ATLAS are exploring physics at distances of $\sim 10^{-19}$*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 $\longrightarrow$ *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".**

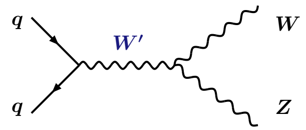
Similar situation for LHCb, Belle, ...

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 ...

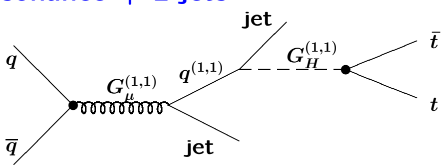
Example – WZ **resonance:**



Search for resonances + X

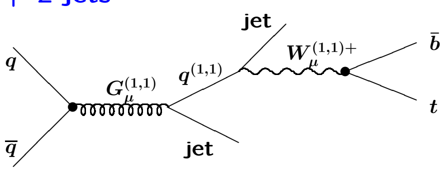
E.g., 2 universal extra dimensions:
s**-channel production of a KK gluon followed by a cascade decay**

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



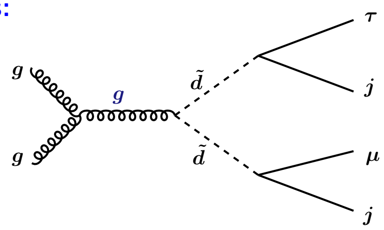
(hep-ph/0601186)

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

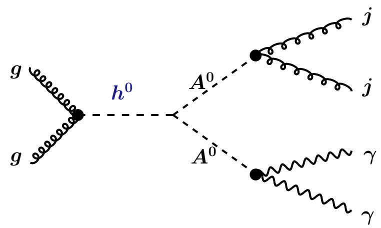


Search for pairs of resonances

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.

Final Exam

Find out what theory describes physics at the TeV scale.