Introduction

- Comments on "Beyond the MSSM" made in panel discussion at OSU workshop on Strings and the Real World

- Perspective of phenomenologist interested in implications of concrete constructions

- Comments apply to all types of constructions, including heterotic and intersecting brane

- Comments based on work with many collaborators, including M. Cvetič, B. Nelson, J. Kang, T. Li, T. Liu, H.S. Lee, V. Barger, $\cdots$

- **Don't be too tied to MSSM paradigm (i.e., don't prejudge the TeV physics to aim for)**
  - **(just) MSSM is not required by experimental data**
  - **Many string constructions involve TeV-scale physics beyond the MSSM. It is usually viewed as a defect of the constructions. However, it may be hinting that the MSSM is not the full story.**

- **I will assume TeV scale supersymmetry. Will focus on "mild" things (i.e., not large dimensions, TeV black holes, time varying couplings, violation of the equivalence principle, Lorentz invariance violation).**

Beyond the MSSM

- Bottom-up studies often assume MSSM with minimal supergravity with R_p (R-parity) conservation
  - However, supersymmetry breaking pattern is likely more complicated
  - R_p may well be violated (there are alternatives to LSP as dark matter candidate)

- Will mention three extensions found in a great many constructions
  - Extended gauge group (especially $U(1)'$)
  - Extended Higgs/neutralino sector
  - Fermion exotics (e.g., heavy, $SU(2)$-singlet D quark)

Extended gauge structures (especially $U(1)'$)

- Extremely common; also in other (non-string) models
- Many consequences for collider physics (Z', associated extended Higgs/neutralino sector, associated exotics); dynamical μ term; FCNC; neutrino mass; cosmology (electroweak baryogenesis (EWBG), cold dark matter (CDM))

Extended Higgs/neutralino sector

- Extra Higgs doublet pairs extremely common
- Higgs singlets also common (can break $U(1)'$)
- Higgs spectrum/limits/decays may be greatly altered (e.g., by doublet-singlet mixing, new F and D terms)
- May be Higgs mediated FCNC, CP effects (EDM, EWGB)
- Singlets may lead to dynamical μ term, and to large cubic term (EWBG)
- Extended neutralino sector modifies cascades and CDM

Fermion exotics (e.g., heavy, $SU(2)$-singlet D quark)

- Often required by anomaly cancellation for extended group
- Should be non-chiral under standard model group because of precision EW (unless confined). May be chiral under extended gauge group.
- Depending on model, decays may be, e.g., by mixing; by leptoquark couplings; by diquark couplings. The latter two still allow a (non-standard) R_p, so that a stable LSP is still possible.
- May also be quasi-stable, i.e., decaying only by higher-dimensional operators. Would appear stable at colliders, but unstable on cosmological scales (BBN constraints important)
- Can also have more exotic "exotics", e.g., color exotics or half-integer electric charge (highly constrained; may be confined)

Minimal Gauge Unification

- One of the most important issues, and one I am most confused about, is the role of the successful gauge unification of the MSSM. Should one insist that string constructions preserve minimal unification or not?

- It is difficult to reconcile with vast majority of existing string constructions
  - Heterotic models usually don't have canonical $U(1)_Y$ normalization; intersecting brane models usually don't have any simple gauge unification conditions (moduli dependent)
  - Exotics (including vectorlike states such as extra Higgs pairs) can destroy unification, even if at intermediate scale
  - String thresholds, KK modes, etc., can be very important

- Scale of MSSM unification is ~ 20 lower than simple heterotic expectation

- Possibilities
  - Insist on canonical MSSM unification (but may miss most interesting constructions)
  - Allow minor modifications, e.g., additional multiplets falling in complete $SU(5)$ representations, as well as additional gauge factors
  - "alternative minimal unification" schemes (i.e., MSSM unification accidental, but some other scheme is minimal)
  - Allow compensations (accidental, fine-tuned, or due to some unknown mechanism) between new matter/thresholds/nonstandard embeddings, etc. This might imply MSSM unification is accidental, but should not be dismissed (cf, the discovery of the "predicted" Pluto, which was a far more unlikely accident)

Strong Dynamics

- Many constructions have a "hidden sector", which may lead to gaugino condensation (but, in fact, in many cases the hidden sector groups are *not* strongly coupled at low energy)

- However, often only "quasi-hidden"
  - May be states charged under non-abelian groups of both ordinary and "hidden" sectors (these may include charge $1/2$ states)
  - $U(1)'$ symmetries may connect sectors

- Many possible effects
  - May play a role in gauge mediated SUSY breaking, e.g., by $U(1)'$ gauginos
  - May lead to confinement of half-integer charges if strong coupling hidden sector

- Could be composite states, such as composite family, or partial family

- More extreme: could be layers of compositeness between string and low energy, e.g., leading to dynamical symmetry breaking, topcolor, little Higgs, $\cdots$

Three Families?

- We know there are at least 3 chiral families. Precision electroweak makes a fourth ordinary or mirror family very unlikely.

- However, it is difficult to achieve 3 families in many string constructions

- Perhaps one should consider constructions which compactify to two (or one) family, with third family arising from the effective field theory
  - Third family could be composite
  - Families could arise from symmetry breaking, e.g., a single $SU(6)$ 6-plet could lead to three $SU(2)$ doublets under $SU(6) \rightarrow SU(2)^3 \rightarrow SU(2)_{\rm diag}$

- **The opposite, i.e., > 3 chiral families reducing to 3 seems difficult to achieve in effective field theory**

- **Related comment: even in 3 family constructions, third family may have a different origin than first two; e.g., could lead to FCNC for additional $U(1)'$**

Neutrino Mass

- Bottom up studies usually assume Majorana masses and minimal seesaw
- Top down: extra symmetries and stringy constraints may constrain possible couplings. In some cases Majorana masses, or the simultaneous Majorana and Dirac masses needed for minimal seesaw, may be forbidden or hard to achieve
- Minimal seesaw is possible, but one should also consider alternatives, such as small Dirac masses (e.g., by high dimensional operators), extended seesaws, or the triplet seesaw (e.g., with $SU(2)$ triplet emerging from diagonal embedding of $SU(2)$ in $SU(2) \times SU(2)$.

Conclusion

- **Keep an open mind about TeV scale physics**

- **Do not overly constrain string vacuum classifications**