Beyond the Standard Model

Lecture #3: Missing Energy Look-alikes

Joseph Lykken
Fermilab

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Outline of Lecture 3

- **General rules for superpartner decays.**
- **Having then completed our very general introduction to SUSY, I now want to concentrate on a few of the more popular realizations.**
- **We can compare their main features and drawbacks.**
- **Then I will introduce two non-SUSY frameworks that provide challenging phenomenological “look-alikes” of SUSY.**
- **These are Universal Extra Dimensions (UED)…**
- **..and Little Higgs with T-Parity (LHTP)**

superpartner decays

spin $\frac{1}{2}$ Majorana fermion gauginos+higgsinos:

- color octet gluino: $\tilde{g}$
- mass eigenstate mixtures of wino and charged higgsino: $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$
- mass eigenstate mixtures of photino, bino, and two neutral higgsinos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$

spin 0 complex scalar squarks:

- squarks that couple to the W boson: $\tilde{u}_L$, $\tilde{d}_L$, $\tilde{c}_L$, $\tilde{s}_L$
- squarks that do not couple to the W boson: $\tilde{u}_R$, $\tilde{d}_R$, $\tilde{c}_R$, $\tilde{s}_R$
- mass eigenstate mixtures of $\tilde{t}_L$ and $\tilde{t}_R$: $\tilde{t}_1$, $\tilde{t}_2$
- mass eigenstate mixtures of $\tilde{b}_L$ and $\tilde{b}_R$: $\tilde{b}_1$, $\tilde{b}_2$

spin 0 complex scalar sleptons:

- sleptons that couple to the W boson: $\tilde{e}_L$, $\tilde{\mu}_L$, $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$
- sleptons that do not couple to the W boson: $\tilde{e}_R$, $\tilde{\mu}_R$
- mass eigenstate mixtures of $\tilde{\tau}_L$ and $\tilde{\tau}_R$: $\tilde{\tau}_1$, $\tilde{\tau}_2$

superpartner decays

There is a lot of model dependence in superpartner decay chains. However there are a number of general rules (I assume R-parity conservation and that the LSP is the lightest neutralino):

- squarks:
  - If the 2-body strong coupling decay $\tilde{\mathrm{q}} \rightarrow \mathrm{q}\,\tilde{\mathrm{g}}$ is kinematically allowed, it will always dominate.
  - Otherwise, $\tilde{\mathrm{q}} \rightarrow \mathrm{q}\,\tilde{\chi}_1^0$ is the most kinematically favored decay, and will dominate for the "right" squarks if the LSP is substantially bino.
  - The "left" squarks may prefer $\tilde{\mathrm{q}} \rightarrow \mathrm{q}\,\tilde{\chi}_1^\pm$ and $\tilde{\mathrm{q}} \rightarrow \mathrm{q}\,\tilde{\chi}_2^0$, because of the large wino component.

superpartner decays

- stops:

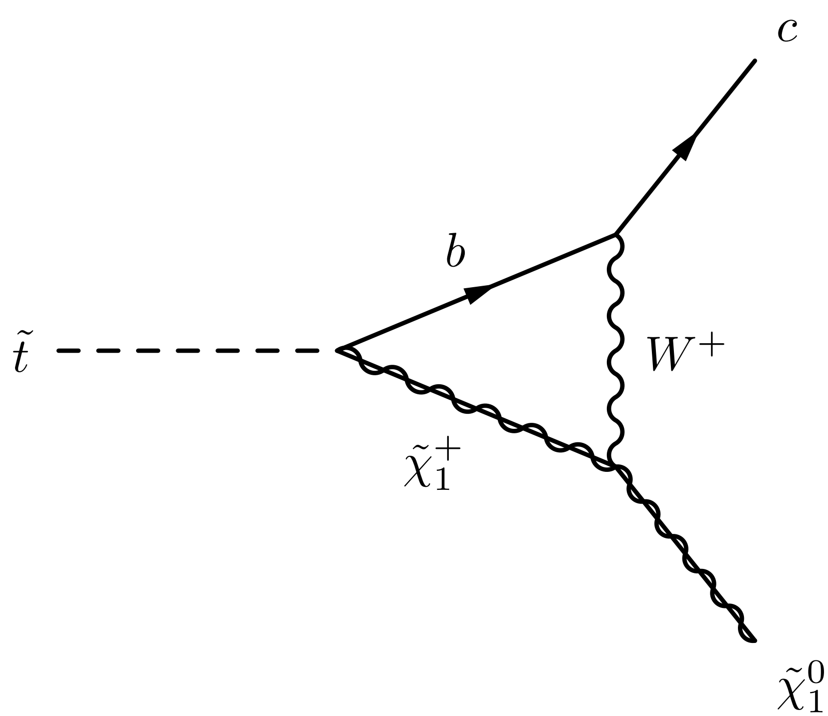
  - The stop quark is a special case. Because the top quark is so heavy, it is possible that $\tilde{t} \to t\,\tilde{g}$ $\quad \tilde{t} \to t\,\tilde{\chi}_1^0$ $\quad \tilde{t} \to t\,\tilde{\chi}_2^0$ are all kinematically forbidden.

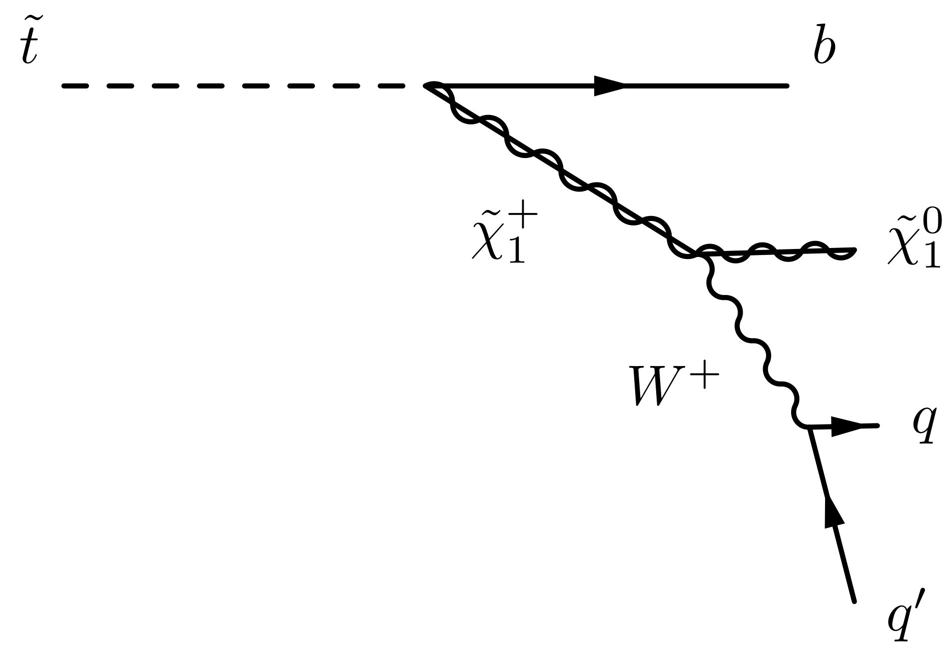
  - Then $\tilde{t} \to b\,\tilde{\chi}_1^+$ will dominate, if allowed. If not, the 3-body decay induced from a 2-body decay of an off-shell chargino may dominate, but the lightest chargino does not necessarily have any 2-body decays.

superpartner decays

- **stops:**

  - **For very light stops, none of the above are allowed, and there can a competition between the loop-suppressed flavor-suppressed 2-body decay $\tilde{\mathrm{t}} \to \mathrm{c}\,\tilde{\chi}_1^0$, and the 4-body decay $\tilde{\mathrm{t}} \to \mathrm{bqq}'\,\tilde{\chi}_1^0$ induced from a 3-body off-shell chargino decay.**





superpartner decays

- **gluinos:**

  - **If the 2-body strong coupling decays** $\tilde{g} \to \bar{q}\tilde{q}$ **and** $\tilde{g} \to q\bar{\tilde{q}}$ **are kinematically allowed, they will always dominate.**

  - **Because e.g. of large mixing, it may be that the lightest stops and/or sbottoms are much lighter than the other squarks. Then the only 2-body gluino decays could be**
    $\tilde{g} \to \bar{t}\,\tilde{t}_1 \qquad \tilde{g} \to t\,\bar{\tilde{t}}_1 \qquad \tilde{g} \to \bar{b}\,\tilde{b}_1 \qquad \tilde{g} \to b\,\bar{\tilde{b}}_1$

  - **Note because the gluino is Majorana,** $\tilde{g}\tilde{g} \to tt\,\bar{\tilde{t}}_1\bar{\tilde{t}}_1$ **is just as likely as** $\tilde{g}\tilde{g} \to t\bar{t}\,\tilde{t}_1\bar{\tilde{t}}_1$

  - **If no 2-body decays are open, the gluino can have 3-body decays via an off-shell squark, to e.g.** $\tilde{g} \to q\bar{q}\tilde{\chi}^0_1,\ \tilde{g} \to q\bar{q}'\tilde{\chi}^\pm_1$

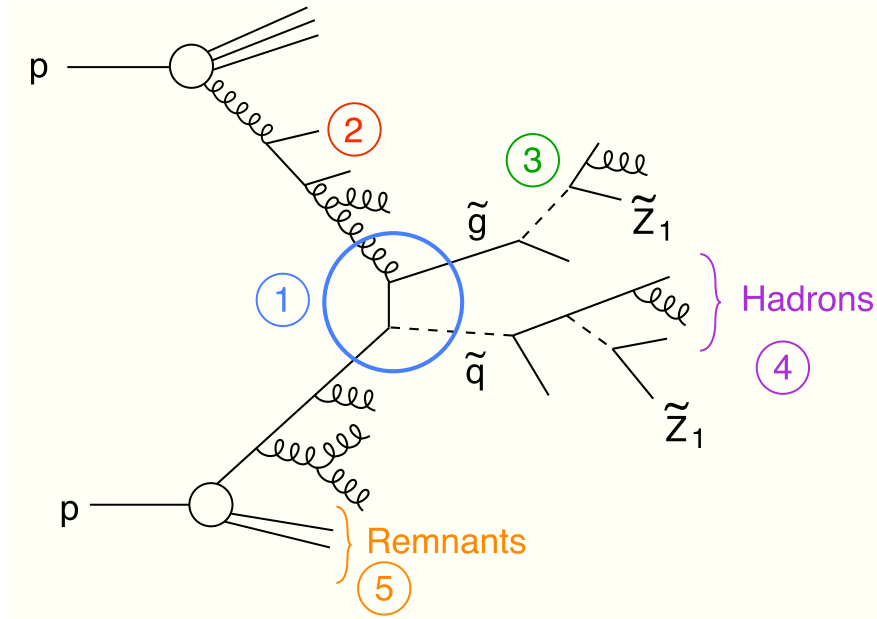
superpartner decays

- charginos and neutralinos:
  - There are many possibilities! But here is a simple rule:
    - Write down all the two body decays of W, Z, and heavy Higgses.
    - In each case, change one final state particle into its superpartner.
    - This now gives the list of possible 2-body decays of the appropriate wino, bino, higgsino-like charginos/neutralinos.
    - Cross out the ones that are kinematically forbidden.
    - If no 2-body decays are left, construct 3-body decays by taking unstable particles from the 2-body final states and decaying them.

superpartner decays

- charginos and neutralinos:
  - Note because of the higgsino components there can be large branching fractions to final states with the light Higgs boson h.
  - For relatively light SUSY, Higgs production from superpartner decays can dominate over direct SM-like Higgs production!
  - If the sleptons are lighter than or approximately degenerate with the lighter neutralinos/chargino, then multi-lepton final states can be greatly enhanced.

SUSY decay chains



- Putting all these decay possibilities together, one finds that most SUSY models predict a fairly complicated list of fairly complicated decay chains.

- This is further complicated by the fact that we pair-produce the superpartners, and the final state particles do not carry a label saying which parent particle they came from.

- This is further complicated by the fact that each SUSY event contains two unseen particles, the LSPs (assumed so far to be the lightest neutralino).

SUSY breaking

- Any explicit SUSY model (as opposed to effective theories like the MSSM) has to posit an explicit mechanism for soft SUSY breaking.

- Since we want SUSY to be related to electroweak symmetry breaking, the obvious thing to do is to expand the SM Higgs sector, supersymmetrize, and try to get a simultaneous tree level spontaneous breaking of both SUSY and $\mathbf{SU(2)_L \times U(1)_Y}$

- Such models exist, but obey a deadly sum rule:

$$\sum m^2_{J=0} - 2\sum m^2_{J=\frac{1}{2}} + 3\sum m^2_{J=1} = 0$$

Hidden sector SUSY breaking

- The next best idea is that SUSY is broken dynamically in a "hidden sector", by some QCD-like force that gets strong at some energy scale $\Lambda_{\rm hidden}$, inducing a condensate of its gauginos. Thus the condensate is of order $\Lambda^{\bf 3}_{\rm hidden}$.
  The condensate by itself does not break SUSY, but its interactions with other fields can.

- Then some "messenger" interaction "mediates" the SUSY breaking to the supersymmetrized SM (SSM).

- The messenger couplings have to be either loop suppressed or higher dimension operators, to escape the sum rule problem.

Hidden sector SUSY breaking

- Modern SUSY models almost all share this basic picture, and differ only by their assumptions about the messengers, i.e. the "mediation" mechanism.

- There are three major families of models:

  - gravity mediation

  - gauge mediation

  - bulk mediation

Gravity mediated SUSY breaking

- Planck-suppressed couplings related to supergravity (and perhaps superstrings) will be there whether we want them or not.

- Scalar fields from this Planckian sector can have Planck-suppressed couplings to a gaugino condensate in the hidden sector, and to the SSM.

- The result is that the SSM sees SUSY breaking of order

$$\frac{\mathbf{\Lambda^3_{\mathrm{hidden}}}}{\mathbf{M^2_{\mathrm{Planck}}}} \sim \mathbf{100}\ \mathrm{GeV}\ \mathrm{for}\ \mathbf{\Lambda_{\mathrm{hidden}}} \sim \mathbf{2} \times \mathbf{10^{13}}\ \mathrm{GeV}$$

Gravity mediated SUSY breaking

- For the Planckian scalar field that is the superpartner of the graviton, we can actually compute these couplings in terms of a couple of unknown functions that parametrize our ignorance of Planckian physics.

- If we take the simplest form for these functions (which may not be what Planckian physics does), we get a very simple pattern of soft-breaking called “minimal supergravity” or mSUGRA.

- Instead of the the 105 new parameters of the MSSM, there are only 4 parameters plus a sign choice.

mSUGRA

$$\mathbf{m_0},\ \mathbf{m_{1/2}},\ \mathbf{A_0},\ \tan\beta,\ \mathbf{sign}(\mu)$$

- **mSUGRA models were the first realistic SUSY models, and are still wildly popular because of their simplicity.**
- **It has become fashionable to criticize the theoretical assumptions behind this model, but in fact it is as well-motivated as anything else on the market.**
- **However the origin of flavor is certainly a mystery in this model, since the whole flavor structure in hidden in the "Planck slop".**

mSUGRA

$$\mathbf{m_0},\ \mathbf{m_{1/2}},\ \mathbf{A_0},\ \tan\beta,\ \mathbf{sign}(\mu)$$

- **I should also warn you that some people mistakenly use "mSUGRA" to refer to a special *subset* of models where the gravitino is the LSP, rather than the lightest neutralino.**

- **This subset of models is perfectly OK, just the nomenclature is flawed.**

- **Also the name "CMSSM" is often used for the low energy effective theory resulting from mSUGRA, i.e. the mSUGRA-like subset of the MSSM.**

Anomaly Mediation

- **An interesting variation of gravity-mediated SUSY breaking is "anomaly mediation".**
- **Supergravity has a hidden "superconformal" structure, extending the usual spacetime symmetry by *both* SUSY and conformal symmetry.**
- **The running of the SM gauge couplings break scale invariance, and thus conformal symmetry.**
- **In supergravity this is related to the SUSY breaking scalar, resulting in soft-breaking terms proportional to the SM beta functions.**
- **This mechanism is simple and predictive, but not realistic on its own (tachyonic sleptons).**

Gauge Mediation

- Here we assume there are some messenger fields whose couplings to the hidden sector SUSY breaking are suppressed by some scale $\mathrm{M_s} << \mathrm{M_{Planck}}$.

- And we assume that the messengers carry SM charges.

- Then for the SSM we generate soft gaugino masses at 1-loop, and soft scalar masses at 2-loops, both of comparable size.

$$M_a \sim \frac{g_a^2}{(4\pi)^2}\frac{F_S}{M_S} \qquad\qquad m_{\tilde{f}}^2 \sim \frac{g^4}{(16\pi^2)^2}\frac{F_S^2}{M_S^2}$$

Gauge Mediation

- **Gauged mediated models are naturally free of FCNCs.**
- **They have gravitino LSP instead of the lightest neutralino.**
- **They have radiative electroweak breaking, like mSUGRA.**
- **There is a minimal model, MGM, with only 4 new parameters plus a sign choice:**

$$\mathbf{M_s},\ \mathbf{\Lambda = F_s/M_s},\ \mathbf{N_5},\ \tan\beta,\ \mathbf{sign}(\mu).$$

Bulk Mediation

- Here the idea is that the hidden sector and the SSM sector are trapped on different "branes" at opposite ends of a fifth dimension.

- The SUSY-breaking messengers must then be fields that propagate in the "bulk" 5d space in between the branes.

- Some choices for the bulk messenger fields:

  - Gravity: then this is a "sequestered" supergravity model.
  - Gauginos: then this is "gaugino mediation".
  - Radions: then this is "radion mediation".

what percentage of these CMS benchmark models for SUSY are actually mSUGRA models?

CMS Collaboration

Table 13.2. Cross sections for the test points in pb at NLO (LO) from PROSPINO1.

Point	$M(\tilde{q})$	$M(\tilde{g})$	$\tilde{g}\tilde{g}$	$\tilde{g}\tilde{q}$	$\tilde{q}\bar{\tilde{q}}$	$\tilde{q}\tilde{q}$	Total
LM1	558.61	611.32	10.55	28.56	8.851	6.901	54.86
			(6.489)	(24.18)	(6.369)	(6.238)	(43.28)
LM2	778.86	833.87	1.443	4.950	1.405	1.608	9.41
			(0.829)	(3.980)	(1.013)	(1.447)	(7.27)
LM3	625.65	602.15	12.12	23.99	4.811	4.554	45.47
			(7.098)	(19.42)	(3.583)	(4.098)	(34.20)
LM4	660.54	695.05	4.756	13.26	3.631	3.459	25.11
			(2.839)	(10.91)	(2.598)	(3.082)	(19.43)
LM5	809.66	858.37	1.185	4.089	1.123	1.352	7.75
			(0.675)	(3.264)	(0.809)	(1.213)	(5.96)
LM6	859.93	939.79	0.629	2.560	0.768	0.986	4.94
			(0.352)	(2.031)	(0.559)	(0.896)	(3.84)
LM7	3004.3	677.65	6.749	0.042	0.000	0.000	6.79
			(3.796)	(0.028)	(0.000)	(0.000)	(3.82)
LM8	820.46	745.14	3.241	6.530	1.030	1.385	12.19
			(1.780)	(5.021)	(0.778)	(1.230)	(8.81)
LM9	1480.6	506.92	36.97	2.729	0.018	0.074	39.79
			(21.44)	(1.762)	(0.015)	(0.063)	(23.28)
LM10	3132.8	1294.8	0.071	0.005	0.000	0.000	0.076
			(0.037)	(0.004)	(0.000)	(0.000)	(0.041)
HM1	1721.4	1885.9	0.002	0.018	0.005	0.020	0.045
			(0.001)	(0.016)	(0.005)	(0.021)	(0.043)
HM2	1655.8	1785.4	0.003	0.027	0.008	0.027	0.065
			(0.002)	(0.024)	(0.007)	(0.028)	(0.061)
HM3	1762.1	1804.4	0.003	0.021	0.005	0.018	0.047
			(0.002)	(0.018)	(0.004)	(0.019)	(0.043)
HM4	1815.8	1433.9	0.026	0.056	0.003	0.017	0.102
			(0.014)	(0.043)	(0.003)	(0.017)	(0.077)

Are CMS and ATLAS stupid and/or lazy?

- No (or at least not for this reason).

- In the experiments mSUGRA is used for SUSY model templates, similar to the dijet resonance case I discussed.

- As templates these benchmark models cover most of the relevant kinematic range, parton initial states, and lepton multiplicities in the SUSY cascade final states.

- However they do have limitations that we need to keep in mind:

Limitations of mSUGRA for templates

- Considered as a subset of the MSSM, mSUGRA enforces special relations, e.g. between the gaugino masses.

- Doesn't include SUSY models that have much less missing energy.

- Doesn't include models with very light stops.

- Other special cases also not covered.

Who is the LSP?

- Even within mSUGRA there are many possibilities for a neutral weakly-interacting LSP:
  - spin 1/2 Majorana bino-like neutralino.
  - wino-like neutralino.
  - higgsino-like neutralino
  - spin 3/2 gravitino
  - spin 0 sneutrino
  - spin 1/2 singlino, etc.

Who is the missing energy?

- For an LHC experimenter, the more relevant question is what is the source of large MET in events with energetic jets and leptons?

- I will now start from a completely different theoretical perspective, and quickly derive a non-SUSY framework, Universal Extra Dimensions (UED), that gives a very similar missing energy signature.

what is the physics that hides extra dimensions?

If extra spatial dimensions exist, they must be (for some reason) difficult to probe

There are several possible explanations:

e.g. the extra spatial dimensions are compact and small

T. Kaluza, and O. Klein, circa 1920

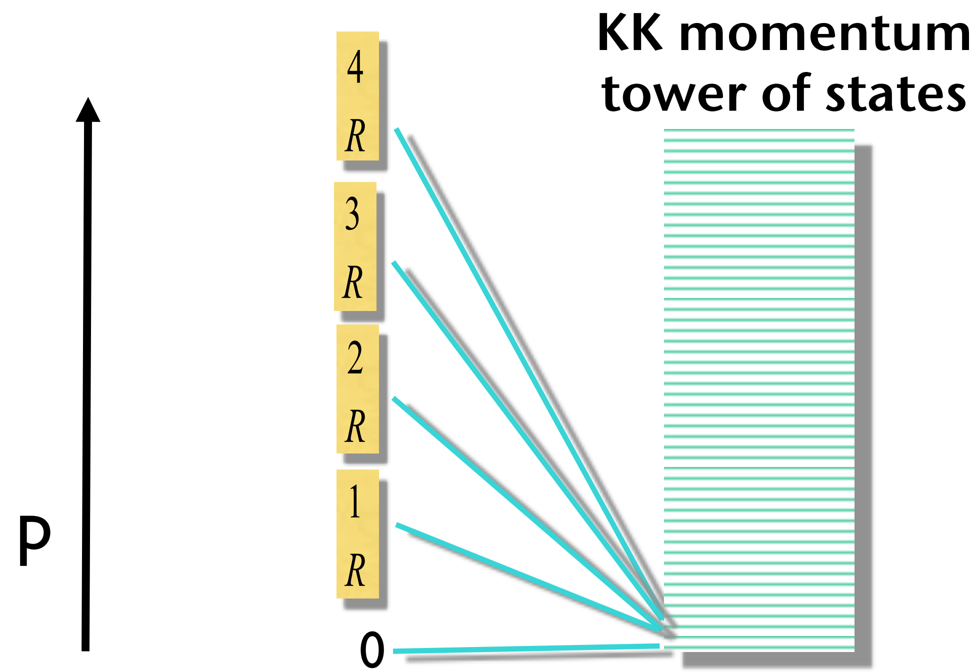
Kaluza-Klein modes

If spatial dimension is compact then momentum in that dimension is quantized:

$$p = \frac{n}{R}$$

From our point of view we see new massive particles

$$m^2 = m_0^2 + \frac{n^2}{R^2}$$



Kaluza-Klein modes on a circle

scalar field in 5d with the 5th dimension compactified on a circle of radius $\frac{\mathbf{L}}{\pi}$

$$\phi(\mathbf{x}^{\mu}, \mathbf{x}^{\mathbf{5}}) = \phi(\mathbf{x}^{\mu}, \mathbf{x}^{\mathbf{5}} + \mathbf{2L})$$

$$\phi(\mathbf{x}^{\mu}, \mathbf{x}^{\mathbf{5}}) = \sum_{\mathbf{n}=\mathbf{0}}^{\infty} \phi_{\mathbf{n}}^{(\mathbf{e})}(\mathbf{x}^{\mu})\cos\left(\frac{\mathbf{n}\pi\mathbf{x}^{\mathbf{5}}}{\mathbf{L}}\right) + \phi_{\mathbf{n}}^{(\mathbf{o})}(\mathbf{x}^{\mu})\sin\left(\frac{\mathbf{n}\pi\mathbf{x}^{\mathbf{5}}}{\mathbf{L}}\right)$$

The zero mode $\phi_{\mathbf{0}}^{(\mathbf{e})}(\mathbf{x}^{\mu})$ **is a massless 4d field**

5d gauge theory

$$\mathbf{A_M}(\mathbf{x}^\mu, \mathbf{x}^5) = (\mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x}^5), \mathbf{A_5}(\mathbf{x}^\mu, \mathbf{x}^5))$$

$$\mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x}^5) = \sum_{\mathbf{n}=0}^{\infty} \mathbf{A}^{(\mathbf{e})}_{\mu\mathbf{n}}(\mathbf{x}^\mu)\cos\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right) + \mathbf{A}^{(\mathbf{o})}_{\mu\mathbf{n}}(\mathbf{x}^\mu)\sin\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right)$$

$$\mathbf{A_5}(\mathbf{x}^\mu, \mathbf{x}^5) = \sum_{\mathbf{n}=0}^{\infty} \mathbf{A}^{(\mathbf{e})}_{\mathbf{5n}}(\mathbf{x}^\mu)\cos\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right) + \mathbf{A}^{(\mathbf{o})}_{\mathbf{5n}}(\mathbf{x}^\mu)\sin\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right)$$

The zero mode $\mathrm{A}^{(\mathbf{e})}_{\mu\mathbf{0}}(\mathrm{x}^\mu)$ is a massless 4d gauge field

The zero mode $\mathrm{A}^{(\mathbf{e})}_{\mathbf{50}}(\mathrm{x}^\mu)$ is a massless 4d scalar

5d gauge theory

5d gauge transformation:

$$\begin{aligned} \mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x^5}) &\rightarrow \mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x^5}) + \partial_\mu \mathbf{\Lambda}(\mathbf{x}^\mu, \mathbf{x^5}) \\ \mathbf{A_5}(\mathbf{x}^\mu, \mathbf{x^5}) &\rightarrow \mathbf{A_5}(\mathbf{x}^\mu, \mathbf{x^5}) + \partial_\mathbf{5} \mathbf{\Lambda}(\mathbf{x}^\mu, \mathbf{x^5}) \end{aligned}$$

$$\mathbf{A_5}(\mathbf{x}^\mu, \mathbf{x^5}) = \sum_{\mathbf{n=0}}^{\infty} \mathbf{A_{5n}^{(e)}}(\mathbf{x}^\mu)\cos\left(\frac{\mathbf{n}\pi\mathbf{x^5}}{\mathbf{L}}\right) + \mathbf{A_{5n}^{(o)}}(\mathbf{x}^\mu)\sin\left(\frac{\mathbf{n}\pi\mathbf{x^5}}{\mathbf{L}}\right)$$

$$\mathbf{\Lambda}(\mathbf{x}^\mu, \mathbf{x^5}) = \sum_{\mathbf{n=0}}^{\infty} \mathbf{\Lambda_n^{(e)}}(\mathbf{x}^\mu)\cos\left(\frac{\mathbf{n}\pi\mathbf{x^5}}{\mathbf{L}}\right) + \mathbf{\Lambda_n^{(o)}}(\mathbf{x}^\mu)\sin\left(\frac{\mathbf{n}\pi\mathbf{x^5}}{\mathbf{L}}\right)$$

We can gauge away all the KK modes of A5 except $\mathbf{A_{50}^{(e)}}(\mathbf{x}^\mu)$

The remaining gauge freedom generated by $\mathbf{\Lambda_0^{(e)}}(\mathbf{x}^\mu)$
is just the usual 4d gauge transf on the zero mode $\mathbf{A_{\mu 0}^{(e)}}(\mathbf{x}^\mu)$

5d gauge theory

So the 5d gauge fixed theory on a circle has:

a 4d photon

a massless scalar

a tower of massive vectors

5d gauge theory with branes

- Almost as simple as compactifying on a circle is to compactify on a line segment of length L.
- Now there are boundaries at x5=0 and x5=L.
- We call these boundaries “branes”, because in a much more sophisticated string context they are related to D-branes, M-branes, etc.

5d gauge theory with branes

- Now we have to specify boundary conditions
- The simplest choice is Neumann, i.e. the x5 derivative of the field vanishes at x5=0 or L
- With this choice, $\mathrm{A}_\mu(\mathrm{x}^\mu, \mathrm{x}^5)$ has only even, i.e. cosine, KK modes:

$$\mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x}^5) = \sum_{\mathbf{n}=0}^{\infty} \mathbf{A}_{\mu\mathbf{n}}(\mathbf{x}^\mu) \cos\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right)$$

5d gauge theory with branes

$$\begin{aligned}\mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x}^5) &\to \mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x}^5) + \partial_\mu \mathbf{\Lambda}(\mathbf{x}^\mu, \mathbf{x}^5) \\ \mathbf{A}_5(\mathbf{x}^\mu, \mathbf{x}^5) &\to \mathbf{A}_5(\mathbf{x}^\mu, \mathbf{x}^5) + \partial_5 \mathbf{\Lambda}(\mathbf{x}^\mu, \mathbf{x}^5)\end{aligned}$$

- **So, unless we want to break the gauge symmetry with boundary conditions, we had better pick Neumann bc for $\Lambda(\mathrm{x}^\mu, \mathrm{x}^5)$, but Dirichlet bc for $\mathrm{A}_5(\mathrm{x}^\mu, \mathrm{x}^5)$**

- **Then $\mathrm{A}_5(\mathrm{x}^\mu, \mathrm{x}^5)$ only has odd KK modes:**

$$\mathbf{A}_\mu(\mathbf{x}^\mu, \mathbf{x}^5) = \sum_{\mathbf{n}=\mathbf{0}}^{\infty} \mathbf{A}_{\mu\mathbf{n}}(\mathbf{x}^\mu) \cos\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right)$$

$$\mathbf{A}_5(\mathbf{x}^\mu, \mathbf{x}^5) = \sum_{\mathbf{n}=\mathbf{0}}^{\infty} \mathbf{A}_{5\mathbf{n}}(\mathbf{x}^\mu) \sin\left(\frac{\mathbf{n}\pi\mathbf{x}^5}{\mathbf{L}}\right)$$

orbifolds

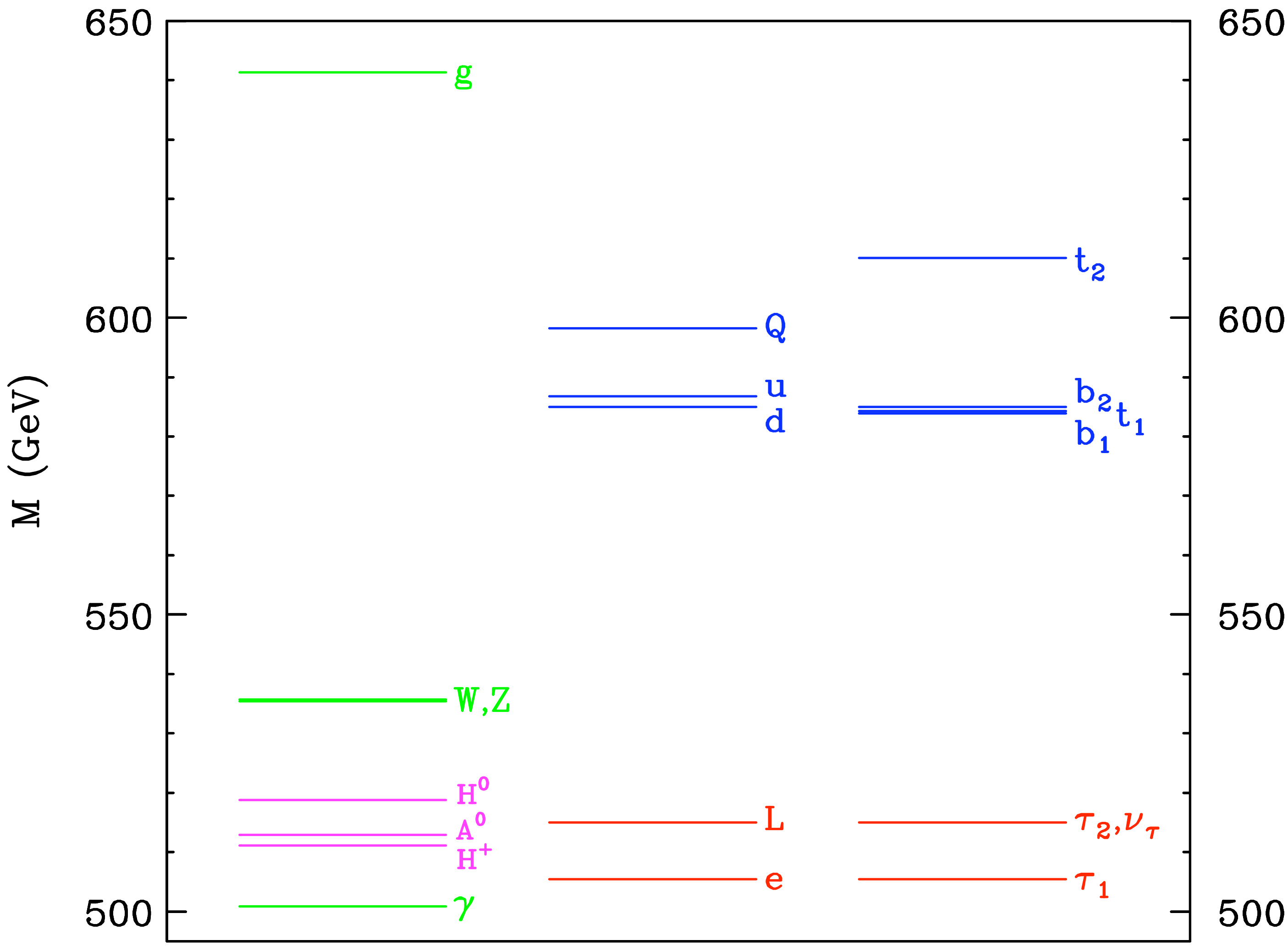
- What we just did is the same thing as 5d gauge theory on a “Z2 orbifold of a circle”.
- Note this theory does not have any massless scalar.
- If you *wanted* a massless scalar you could chose the other set of boundary conditions that break the gauge symmetry.
- This leads to another framework called gauge-Higgs unification.

5d gauge theory with branes

- If I introduced a 5d fermion field, the 5d Dirac structure would tell me that its 4d KK modes were in left-right symmetric pairs.
- So, compactified on a circle, the massless 4d fermions are vector-like.
- In the orbifold theory, however, I can choose bc such that the left-handed KK tower has a zero mode, but the right-handed one doesn't.
- So the orbifolding the 5th dimension allows massless 4d chiral fermions, like we have in the SM.

UED

- **This 5d orbifold theory is a simple example of a Universal Extra Dimensions model (UED).**
- **Obviously I can make a UED model whose zero modes are *exactly* the Standard Model.**
- **Then I *predict* massive KK copies of the SM model particles with masses starting at 1/L.**



After radiative corrections (and perhaps other splittings from brane effects), the spectrum of the first set of massive UED KK modes look a lot like superpartners, but with different spins.

dark matter from UED

- The UED orbifold (unlike a circle) is not translation invariant, so $\mathrm{p_5}$ is not conserved.
- But since $\mathrm{x_5 \to x_5 + L}$ is still a symmetry, there is a conserved "Kaluza-Klein parity".
- So the lightest massive KK particle (LKP) is stable.
- In 5d UED this dark matter candidate is naturally the first heavy KK mode of the photon or hypercharge gauge boson.
- So in this case the dark matter particle has spin 1.

A light Higgs from symmetries

- The Little Higgs models come from stepping back to ask the question: What are all possible symmetries that could solve the Higgs naturalness problem?

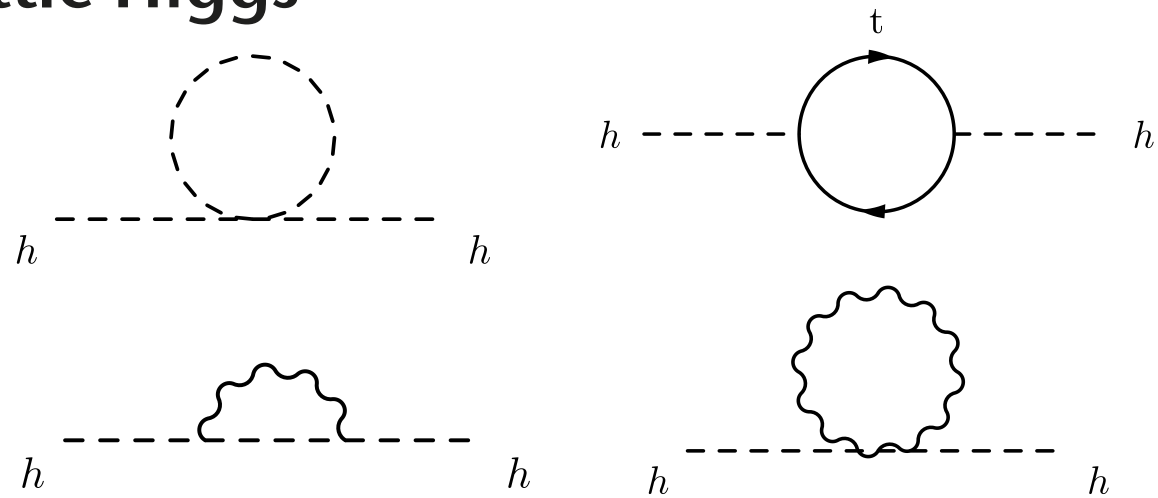
  - SUSY is a space-time symmetry that does this.

  - In gauge-Higgs unification, the Higgs is light because it is secretly an extra-dimensional component of a gauge boson.

  - A third possibility is that the Higgs, like the pion, is a pseudo-Nambu-Goldstone boson (PNGB) of some broken global symmetry.

Little Higgs

$$\frac{3G_F}{8\sqrt{2}\pi^2}\left(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)\Lambda^2$$



- **Suppose SUSY is softly broken at ~ 10 TeV.**
- **Then you will have to explain a "little hierarchy", i.e. why the Higgs mass and electroweak scales are << 10 TeV.**
- **For this I just need to cancel the *most important* SM 1-loop corrections (shown above) via heavy partners for the top, W, Z, and Higgs:** $\mathbf{T},\ \mathbf{W_H^\pm},\ \mathbf{Z_H},\ \mathbf{\Phi}$
- **Little Higgs is a way of implementing this (almost) automatically with broken global and gauge symmetries.**

The Littlest Higgs

- For example, suppose at 10 TeV we have two copies of the electroweak gauge group:

$$\mathbf{SU(2)_1 \times U(1)_1 \times SU(2)_2 \times U(1)_2}$$

- Suppose these are subgroups of an even bigger global symmetry, an SU(5).

- At some scale ~ 1 TeV, the SU(5) is dynamically broken (somehow) to SO(5), producing 14 massless Goldstone bosons, 4 of which have the quantum numbers of to make a complex Higgs doublet.

The Littlest Higgs

- But the partial gauging of the SU(5) also *explicitly* broke the global SU(5) symmetry.

- This would reintroduce the 1-loop Higgs quadratic divergences...

- ...except we have been clever and done a "collective" breaking:
  - When $g_{SU(2)_1} \to 0$, the Higgs is an exact massless Goldstone.
  - When $g_{SU(2)_2} \to 0$, the Higgs is an exact massless Goldstone.

- The net result is that Higgs quadratic divergences only appear at 2-loops.

Littlest Higgs with T parity

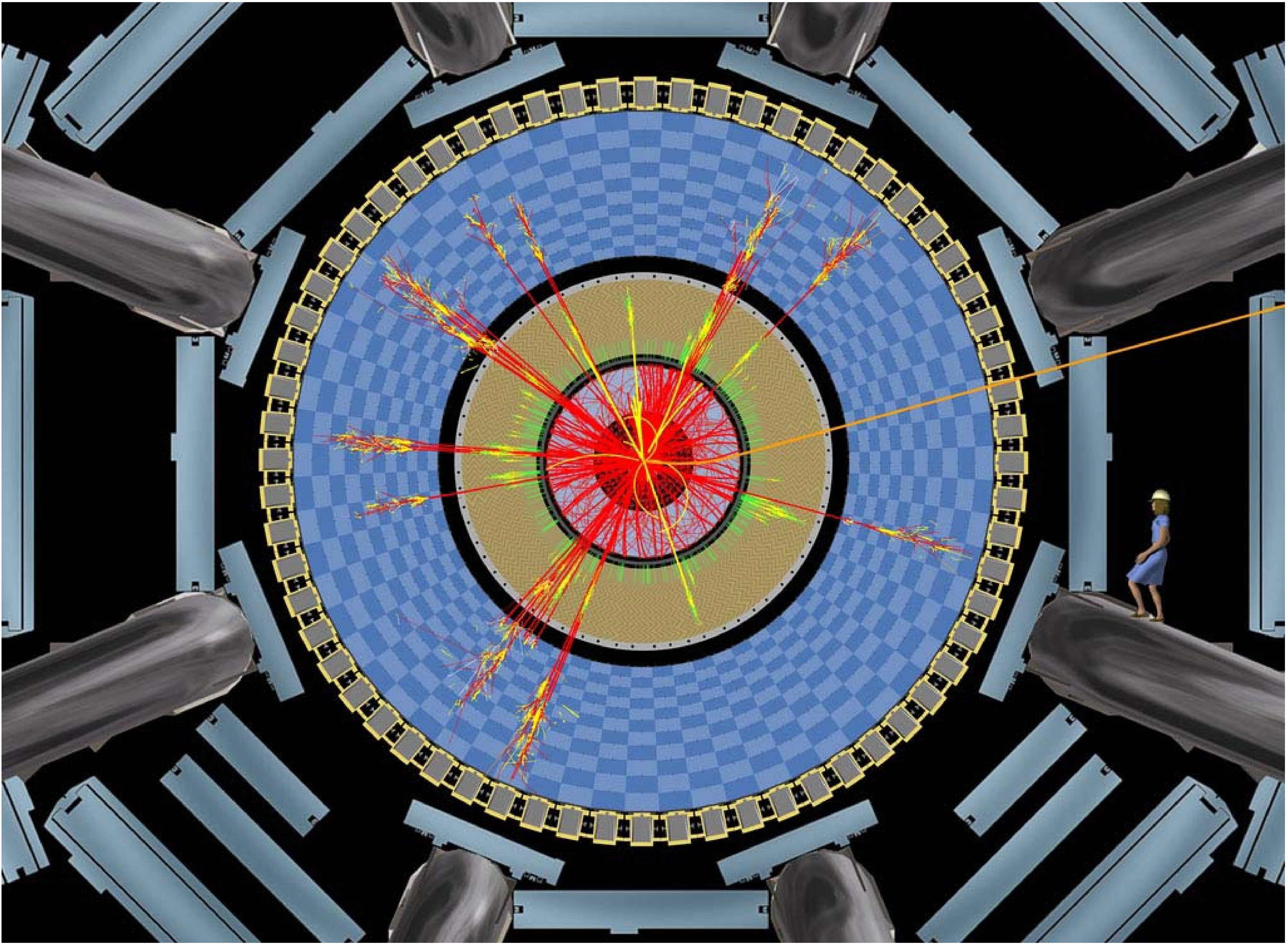
- These fancy symmetry arguments are just enforcing coupling relations for the heavy partner particles that guarantee certain cancellations in 1-loop diagrams, as in SUSY.

- To avoid constraints from EWPT, we would like these heavy partners to be produced only in pairs.

- We can guarantee this by making them odd under “T-parity”, a discrete symmetry that interchanges the two copies of the electroweak group.

Littlest Higgs with T parity

- So e.g. the W is T parity even, while the W_H is T-parity odd.
- But this means every SM particle has a heavier T-odd partner.
- These partners look very much like KK modes.
- And the lightest one is a dark matter candidate.



First questions for a missing energy signal

- How many invisible particles per event?
- Are they massive or nearly massless?
- Are they associated with top, W, or Z decays?
- How many kinds of parent particles?
- How many kinds of decay chains?

Missing energy from SUSY

- SUSY models already provide too many possibilities.

- Many choices for the WIMP LSP.

- At the LHC, an invisibly decaying or long-lived NLSP can be mistaken for an LSP.

- With R-parity breaking, can still get a missing energy signal from neutrinos.

Missing energy from not-SUSY

- Little Higgs: the dark matter candidate is a spin 1 vector boson partner stabilized by T parity.

- 5-dimensional UED: the dark matter candidate is a spin 1 vector boson partner stabilized by KK parity.

- 6-dimensional UED: the dark matter candidate is a spin 0 vector boson partner stabilized by KK parity.

More missing energy from not-SUSY

- Models with large extra dimensions produce missing energy from single emission of a massive graviton.

- Hidden valley or unparticle models can produce missing energy from multiple hidden sector particles.

- Models with new heavy particles decaying to neutrinos, either directly or via top quarks, W's or Z's.

Missing energy look-alikes

- A discovery plan for the LHC should include strategies to begin discriminating missing energy look-alikes.

- Here “look-alike” is defined by a particular experimental analysis, not by comparing lagrangians or mass spectra.

- Direct measurements of spins, charges, and couplings at the LHC can definitively resolve most look-alike questions, but these could come roughly a decade later, as they did e.g. for top quarks.

- Can we sort this out more quickly at LHC?

results: SUSY versus not-SUSY

Take not-SUSY model LH2 as the "data", compare to the SUSY look-alike NM4:

LH2 vs. NM4 [100 pb^{-1}]			
Variable	LH2	NM4	Separation
MET			
r(mT2-500)	0.16	0.05	4.87
r(mT2-400)	0.44	0.21	4.84
r(mT2-300)	0.75	0.54	3.49
r(Meff1400)	0.11	0.25	2.99
r(mT2-500/300)	0.21	0.09	2.98
r(M1400)	0.07	0.19	2.69
r(mT2-400/300)	0.58	0.40	2.48
r(HT900)	0.13	0.24	2.34
r(MET420)	0.48	0.37	2.00
r(mT2-500/400)	0.36	0.22	1.47

Table 21. Best discriminating ratios in the MET box, with separations in units of σ, for the comparison of LH2 vs.NM4, taking LH2 as the "data", assuming an integrated luminosity of 100 pb^{-1}.

LH2 vs. NM4 [1000 pb^{-1}]			
Variable	LH2	NM4	Separation
MET			
r(mT2-500)	0.16	0.05	14.11
r(mT2-400)	0.44	0.21	11.13
r(mT2-500/300)	0.21	0.09	8.52
r(Meff1400)	0.11	0.25	7.24
r(M1400)	0.07	0.19	6.57
r(mT2-300)	0.75	0.54	6.26
r(mT2-400/300)	0.58	0.40	5.77
r(HT900)	0.13	0.24	5.67
r(M1800)	0.02	0.07	4.82
r(MET420)	0.48	0.37	4.32

Table 36. Best discriminating ratios in the MET box, with separations in units of σ, for the comparison of LH2 vs.NM4, taking LH2 as the "data", assuming an integrated luminosity of 1000 pb^{-1}.

Summary of third lecture - I

- SUSY superpartner decays lead to complicated final states with jets, leptons, and MET from two invisible LSPs.
- Realistic SUSY models break SUSY in a hidden sector.
- SUSY models are classified according to the "mediator" of the breaking from the hidden sector to the SSM.
- Gravity mediation, Gauge mediation, and Bulk mediation are the highest level categories.
- The simplest gravity-mediation scenario is mSUGRA, which is also used extensively for LHC SUSY benchmarks.
- This is OK as a start, but we need also to consider broader possibilities.

Summary of third lecture - II

- **The smoking gun experimental signature of SUSY at the LHC is an excess of energetic events with large MET from the LSPs.**

- **There are many possible LSPs in SUSY: 3 kinds of neutralinos, gravitinos, sneutrinos, singlinos, etc.**

- **SUSY, UED and Little Higgs models, starting from completely different theory motivations, all produce weakly-interacting dark matter candidates.**

- **It will be a challenge to tell these models apart in data.**