Physics beyond the standard model: lecture #1

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Lecture 1:

- **We know very little about physics at the TeV scale.**
- **Discrete symmetries and cascade decays at colliders.**

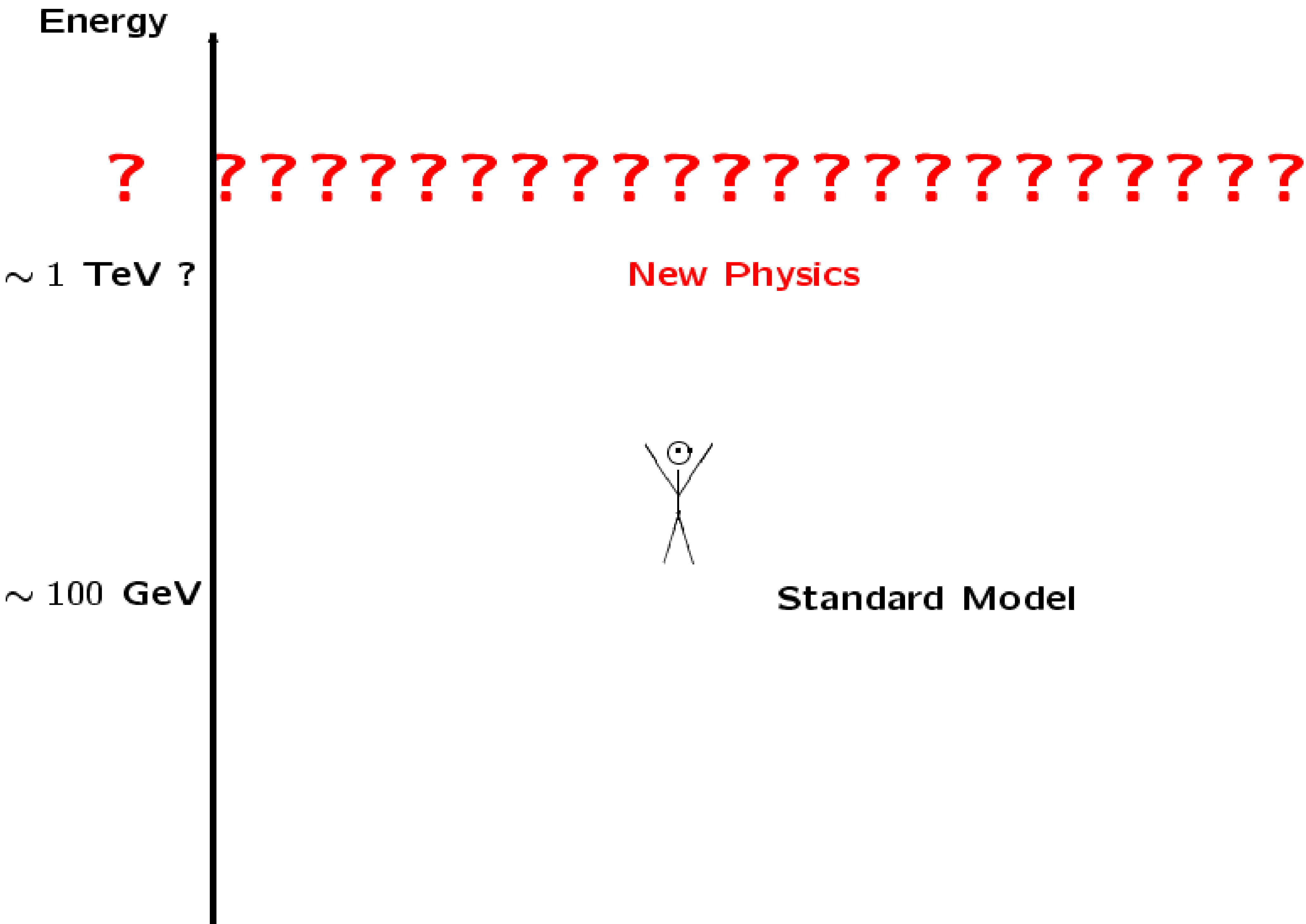
Lecture 2:

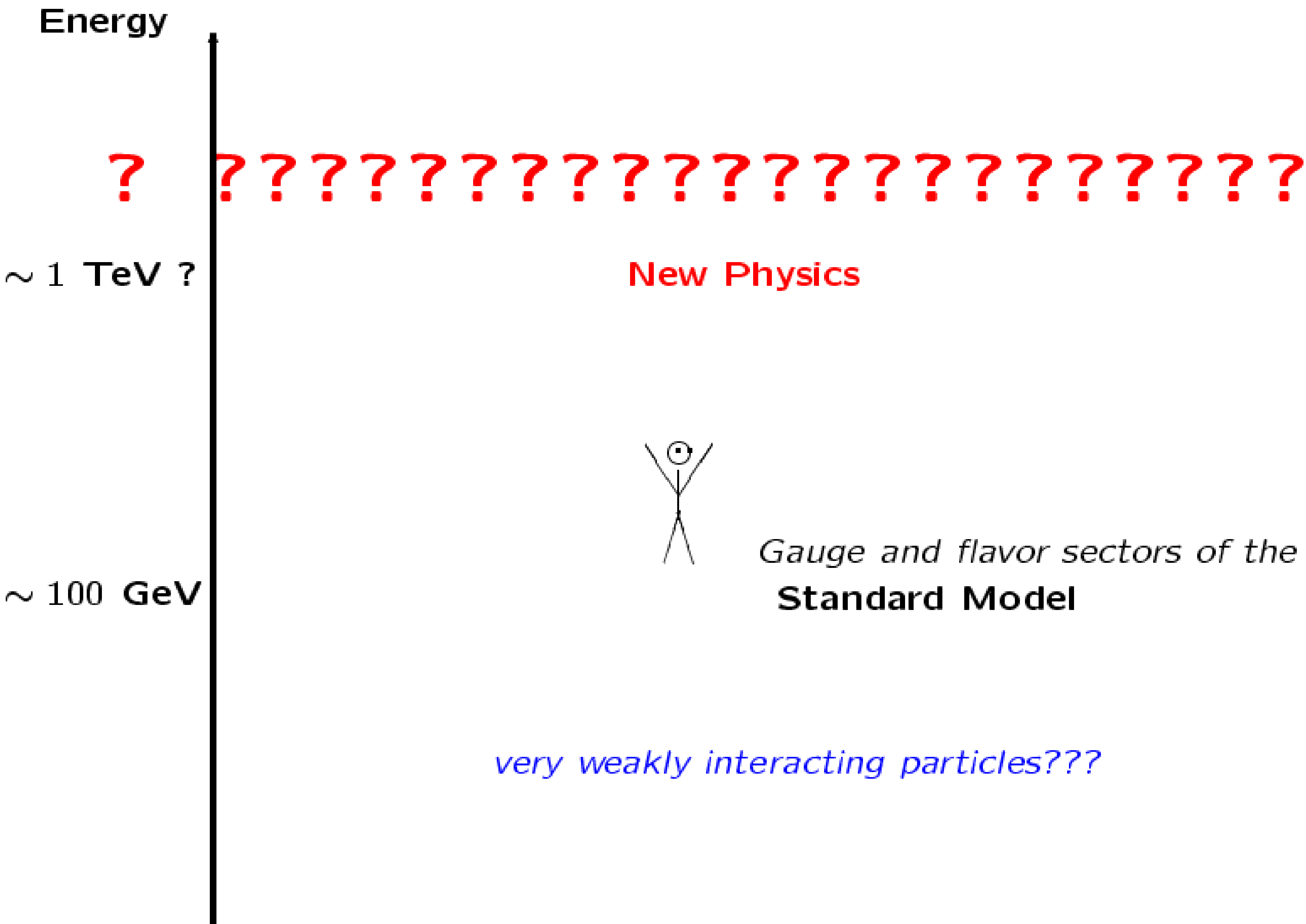
Resonances at the Tevatron and the LHC.

Case study: two universal extra dimensions.

Lecture 3:

Supersymmetry versus Composite Higgs

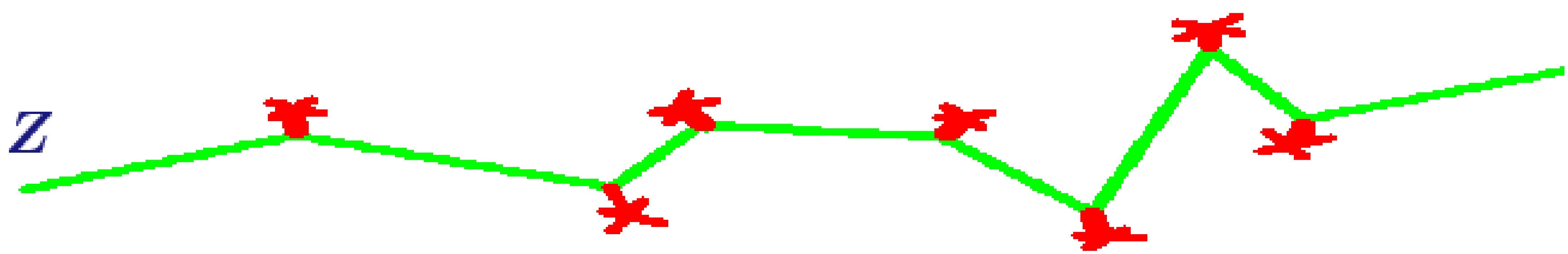

Energy
?
??????????????????????
~ 1 TeV ?
New Physics
~ 100 GeV
Standard Model


Energy
?
??????????????????????
~ 1 TeV ?
New Physics
Gauge and flavor sectors of the
Standard Model
~ 100 GeV
very weakly interacting particles???

We know that $SU(2)_C \times U(1)_Y \rightarrow U(1)_Q$

$\Rightarrow$ $W^{\pm}$ and Z have not only transverse polarizations,

but also longitudinal ones: three spin-0 states have been eaten.

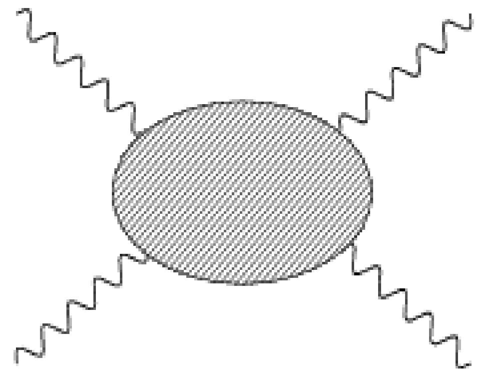


What is the origin of electroweak symmetry breaking?

We do not know:

- what unitarizes $W_L^+ W_L^-$ scattering?
- why is there a VEV that breaks $SU(2) \times U(1)$?
- what has a VEV that breaks $SU(2) \times U(1)$?

$W_L^+ W_L^-$ **scattering:**



Perturbatively:

$$\sigma\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) \approx \frac{G_F^2\, s}{16\pi}$$

This makes sense only up to $\sqrt{s} \sim 1$ **TeV.**

Lee, Quigg, Thacker: 1977

At higher energy scales:

⋆ **A new particle: Higgs boson**

OR

⋆ **New strong interactions (perturbative expansion breaks down)**

OR

⋆ **Quantum field theory description breaks down (?)**

Homework #1.1:
Assume there is a Z' *boson (spin-1) coupled to* $\mathbf{W}^{\pm}$*'s.*
For what value of the trilinear coupling $g_{WWZ'}$
does $\boldsymbol{\sigma}\left(\mathbf{W}_L^+\mathbf{W}_L^- \to \mathbf{W}_L^+\mathbf{W}_L^-\right)$ *become independent of* s*?*

Even in the context of the standard model, we know little about the electroweak breaking sector.

Small perturbations of the standard model field content can affect dramatically the Higgs phenomenology:

• *Higgs branching fractions for* $M_h < 2M_W$ *are set by small couplings*
$\Rightarrow$ *nonstandard Higgs decays expected in the presence of new particles.*

• *electroweak observables depend on* $\ln M_h$, *whereas they typically depend quadratically on the parameters of new particles*
$\Rightarrow$ $M_H \sim 100 - 700$ *GeV ?*

Nonstandard Higgs decays

Standard model + a scalar singlet S: $\quad cH^\dagger H S^\dagger S$

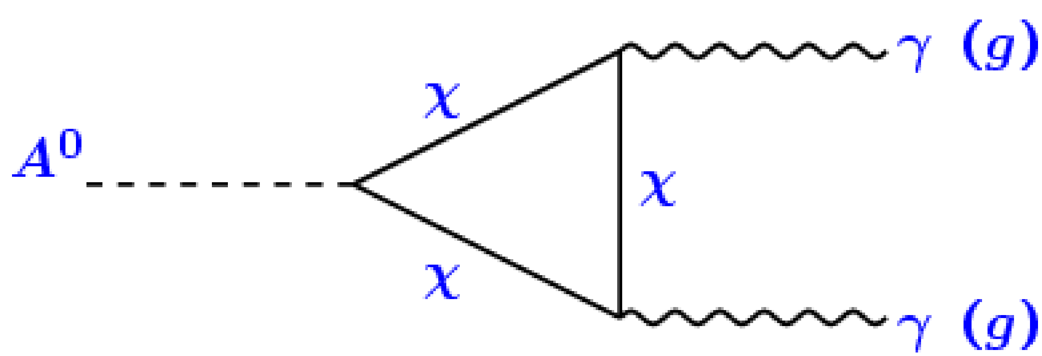
$S = \frac{1}{\sqrt{2}} (\varphi_S + \langle S \rangle) \, e^{iA^0/\langle S \rangle}$, A^0 is a CP-odd spin-0 particle (axion)

$$\frac{c\,v}{2} h^0 A^0 A^0 \text{ coupling } \Rightarrow \Gamma(h^0 \to A^0 A^0) = \frac{c^2 v^2}{32\pi M_h} \left(1 - 4\frac{M_A^2}{M_h^2}\right)^{1/2}$$

Homework #1.2:
What are the Higgs boson branching fractions for $c = 0.1$,
$M_A \ll M_h/2$ and $M_h = 120$ GeV? (also for $M_h = 200$ GeV)

The subsequent decays of A^0 are model dependent.

Example: $\mathcal{L} = \xi S \overline{\chi}_L \chi_R + \text{h.c.} - V(H, S)$, χ is a new fermion



Effective coupling of the axion to pairs of gluons and photons:

$$\frac{-\sqrt{2}}{16\pi\langle S\rangle} A^0 \epsilon^{\mu\nu\rho\sigma} \left[T_2(\chi)\alpha_s \, G_{\mu\nu} G_{\rho\sigma} + N_c e_\chi^2 \alpha \, F_{\mu\nu} F_{\rho\sigma} \right]$$

Case 1) **If the fermion χ is colored and electrically neutral,**

$\Rightarrow$ **Br**$(A^0 \to gg) \approx 100\%$

For $M_h < 2M_W$**, Br**$(h \to A^0 A^0 \to 4\,\mathrm{jets}) \approx 100\%$

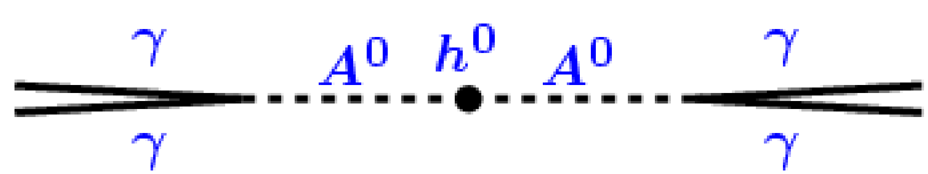
$\Rightarrow$ **huge background at the LHC, Higgs boson will not be observed**

Case 2) **If χ is electrically-charged color singlet**

$\Rightarrow$ **Br**$(A^0 \to \gamma\gamma) \approx 100\%$

Br$(h \to A^0 A^0 \to \gamma\gamma\gamma\gamma) \approx 100\% \Rightarrow$ **tiny background at the LHC, Higgs boson will be discovered early!**

Note: for $M_A \lesssim 1$ GeV the two photons from a Higgs decay overlap: $h \to A^0 A^0 \to 4\gamma$ decay will appear in the detector as a diphoton resonance



Try to predict physics at the TeV scale by addressing some of the “problems” of the standard model.

Fermion and scalar gauge charges in the standard model:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
quark doublet: $q^i_L = (u^i_L, d^i_L)$	3	2	$1/3$
right-handed up-type quark: u^i_R	3	1	$4/3$
right-handed down-type quark: d^i_R	3	1	$-2/3$
lepton doublet: $l^i_L = (\nu^i_L, e^i_L)$	1	2	-1
right-handed charged lepton”: e^i_R	1	1	-2
Higgs doublet: H	1	2	$+1$

$i = 1, 2, 3$ *labels the fermion generations.*

Fermion content looks baroque ...

One compelling explanation: **Grand Unified Theories (GUTs)**

$$SU(5) \rightarrow SU(3)_c \times SU(2)_W \times U(1)_Y$$

$$\begin{aligned} \bar{5} &= (3,1)_{2/3} + (1,2)_{-1} \\ 10 &= (3,2)_{1/3} + (3,1)_{-4/3} + (1,1)_2 \end{aligned}$$

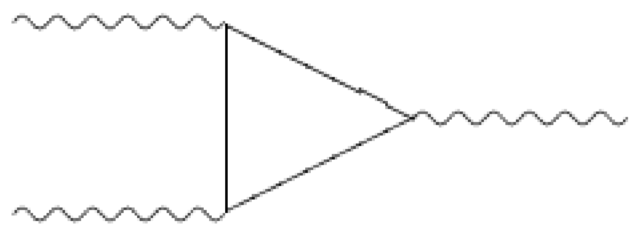
All three gauge couplings are equal to the SU(5) gauge coupling at the GUT scale. Gauge couplings change logaritmically with the scale.

Result of the running between the GUT scale and 100 GeV is consistent with the measured gauge couplings if there are superpartners below the TeV scale.

Alternative explanation for fermion charges: **Anomaly cancellation**

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model: anomalies cancel within each generation

$[SU(3)]^2U(1)$: $\quad 2(1/3) + (-4/3) + (2/3) = 0$

$[SU(2)]^2U(1)$: $\quad 3(1/3) + (-1) = 0$

$[U(1)]^3$: $\quad 3\left[2(1/3)^3 + (-4/3)^3 + (2/3)^3\right] + 2(-1)^3 + (-2)^3 = 0$

$U(1)$-**gravitational:** $\quad 2(1/3) + (-4/3) + (2/3) = 0$

Homework #1.3:
If one generation of fermions transformed as $(3,2)_{x_q}$, $(3,1)_{x_u}$, $(3,1)_{x_d}$, $(1,2)_{x_l}$ *and* $(1,1)_{x_e}$, *under the* $SU(3)_c \times SU(2)_W \times U(1)_x$ *gauge group, then what would the most general values for* x_q, x_u, x_d, x_l *and* x_e *be so that the anomalies cancel?*

The content of each generation of fermions might be due to either GUTs or anomaly cancellation.

Similarly, for most problems of the standard model there are several known solutions with widely different phenomenology.

Fundamental symmetries

gauge	*spacetime*	*global*	*discrete*
$SU(3) \times SU(2) \times U(1)$;	$SO(3,1)$;	$U(1)_B$;	CPT

Fermions:

$$\left.\begin{array}{rl} q_L: & (3,2,\ \ +1/6) \\ u_R: & (3,1,\ \ +2/3) \\ d_R: & (3,1,\ \ -1/3) \\ l_L: & (1,2,\ \ -1/2) \\ e_R: & (1,1,\ \ -1) \end{array}\right\} \times 3$$

Fundamental symmetries

gauge	*spacetime*	*global*	*discrete*
$SU(3) \times SU(2) \times U(1)$;	$SO(3,1)$;	$U(1)_B$;	CPT

$$SU(5) \subset SO(10)$$

Fermions:

$$\left.\begin{array}{rl} q_L: & (3, 2, \;\; +1/6) \\ u_R: & (3, 1, \;\; +2/3) \\ d_R: & (3, 1, \;\; -1/3) \\ l_L: & (1, 2, \;\; -1/2) \\ e_R: & (1, 1, \;\; -1) \end{array}\right\} \times 3 = (10 + \bar{5}) \times 3 \subset 16 \times 3$$

Fundamental symmetries

gauge	*spacetime*	*global*	*discrete*
$SU(3) \times SU(2) \times U(1)$;	$SO(3,1)$;	$U(1)_B$;	CPT

$SO(5,1)$

6D Lorentz symmetry

Fermions:

$$\left.\begin{array}{rl} q_L: & (3,2,\ +1/6) \\ u_R: & (3,1,\ +2/3) \\ d_R: & (3,1,\ -1/3) \\ l_L: & (1,2,\ -1/2) \\ e_R: & (1,1,\ -1) \end{array}\right\} \times 3$$

required by global $SU(2)_W$ anomaly cancellation in 6D

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:

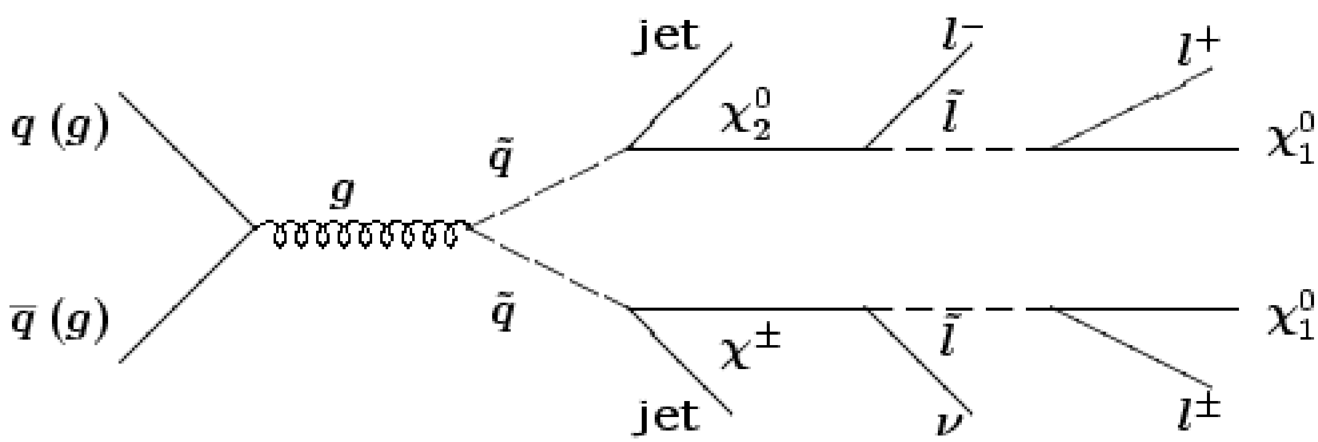
pair production of colored odd particles,

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 + $\not{E}_T$**

Homework 1.4: draw other diagrams which contribute to this signal.

Bosons in compact spatial dimensions

4D flat spacetime $\perp$ one dimension of size πR:

$$\text{Boundary conditions}: \frac{\partial}{\partial y}\phi(x,0) = \frac{\partial}{\partial y}\phi(x,\pi R) = 0$$

$$\text{KK decomposition}: \phi(x,y) = \frac{1}{\sqrt{\pi R}}\left[\phi^0(x) + \sqrt{2}\sum_{j\geq 1}\phi^j(x)\cos\left(\frac{jy}{R}\right)\right]$$

Zero-mode: ϕ^0 - wave function is flat along the extra dimension.

Kaluza-Klein modes, $\phi^j(x)$:

particles with momentum in extra dimensions,

or **4D** point of view: a tower of massive particles:

$$m_j^2 = m_0^2 + \frac{j^2}{R^2}$$

Gauge bosons in 5D:

$A_\mu(x^\nu, y)$, $\mu, \nu = 0, 1, 2, 3$, and

$A_y(x^\nu, y)$ – polarization along the extra dimension.

From the point of view of the 4D theory:

$A_y(x^\nu, y)$ is a tower of spinless KK modes.

$$\text{Dirichlet B.C}: \quad A_y(x, 0) = A_y(x, \pi R) = 0$$

$$\text{KK decomposition}: \quad A_y(x, y) = \sqrt{\frac{2}{L}} \sum_{j \geq 1} A_y^j(x) \sin\left(\frac{jy}{R}\right)$$

$\rightarrow$ $A_y(x^\nu, y)$ does not have a 0-mode! *(Odd field)*

Fermions in a compact dimension

Lorentz group in 5D $\Rightarrow$ vector-like fermions:

$$\chi = \chi_L + \chi_R$$

Chiral boundary conditions:

$$\begin{aligned} \chi_L(x^\mu, 0) &= \chi_L(x^\mu, \pi R) = 0 \\ \frac{\partial}{\partial y}\chi_R(x^\mu, 0) &= \frac{\partial}{\partial y}\chi_R(x^\mu, \pi R) = 0 \end{aligned}$$

Kaluza-Klein decomposition:

$$\chi = \frac{1}{\sqrt{\pi R}}\left\{\chi_R^0(x^\mu) + \sqrt{2}\sum_{j\geq 1}\left[\chi_R^j(x^\mu)\cos\left(\frac{\pi j y}{L}\right) + \chi_L^j(x^\mu)\sin\left(\frac{\pi j y}{L}\right)\right]\right\}$$

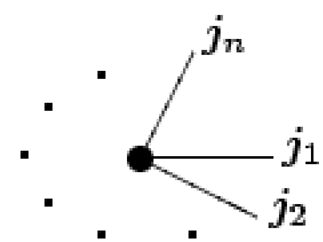
Universal Extra Dimensions

<u>All</u> Standard Model particles propagate in $D \geq 5$ dimensions.

Kaluza-Klein modes are states of definite momentum along the compact dimensions.

Momentum conservation $\longrightarrow$ *KK-number conservation*

$$\mathcal{L}_{4D} = \int dy \, \mathcal{L}_{5D}$$



At each interaction vertex:

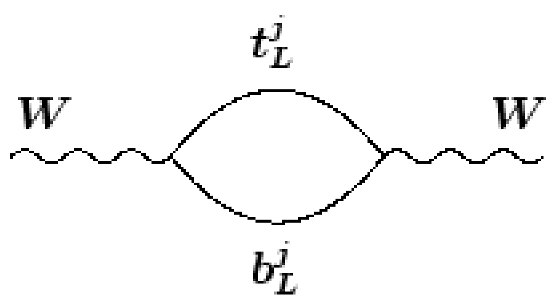
$j_1 \pm j_2 \pm ... \pm j_n = 0$ **for a certain choice of** $\pm$

In particular: $0 \pm \cdots \pm 0 \neq 1$

$\Rightarrow$ tree-level exchange of KK modes does not contribute to currently measurable quantities

$\Rightarrow$ no single KK 1-mode production at colliders

Bounds from one-loop shifts in W and Z masses, and other observables:

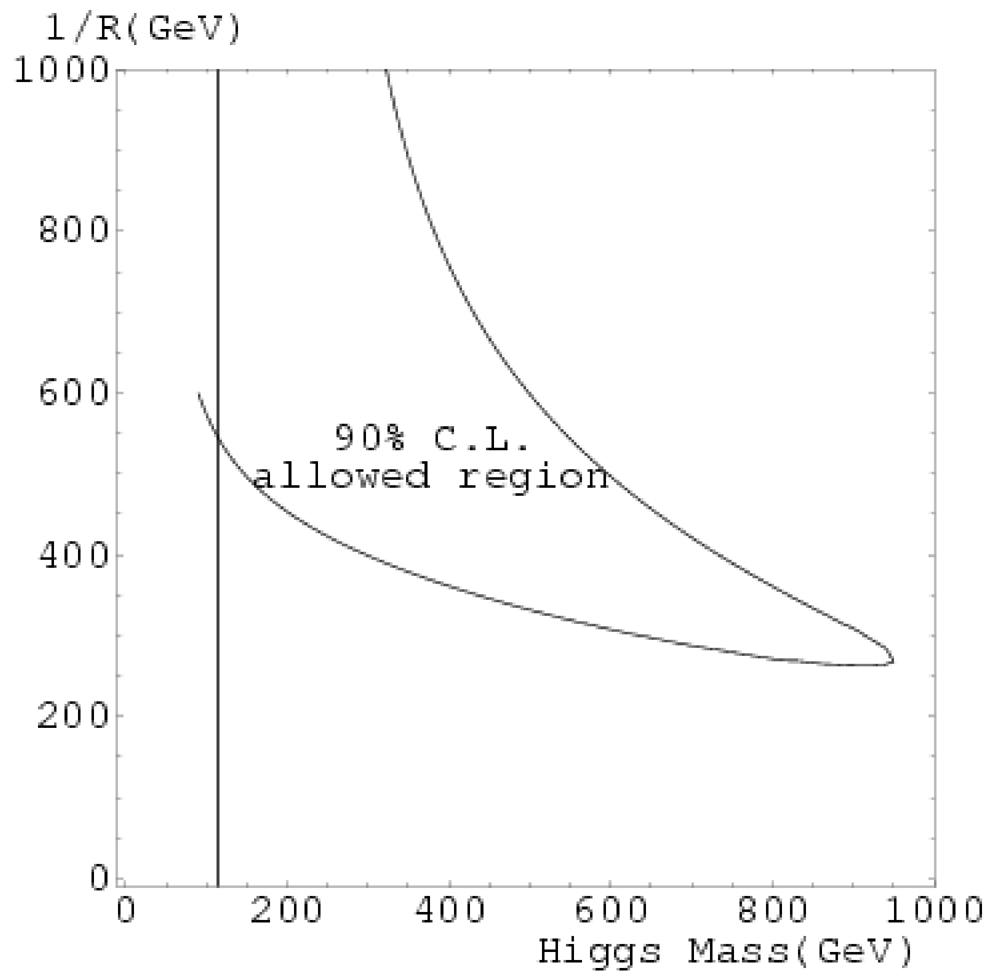


$$\frac{1}{R} \gtrsim 300 \text{ GeV}$$

Is the Higgs boson light?

Contributions to the T parameter from Kaluza-Klein particles may compensate for the effect of a heavy Higgs boson on the electroweak fits.

Appelquist, Yee, hep-ph/0211023



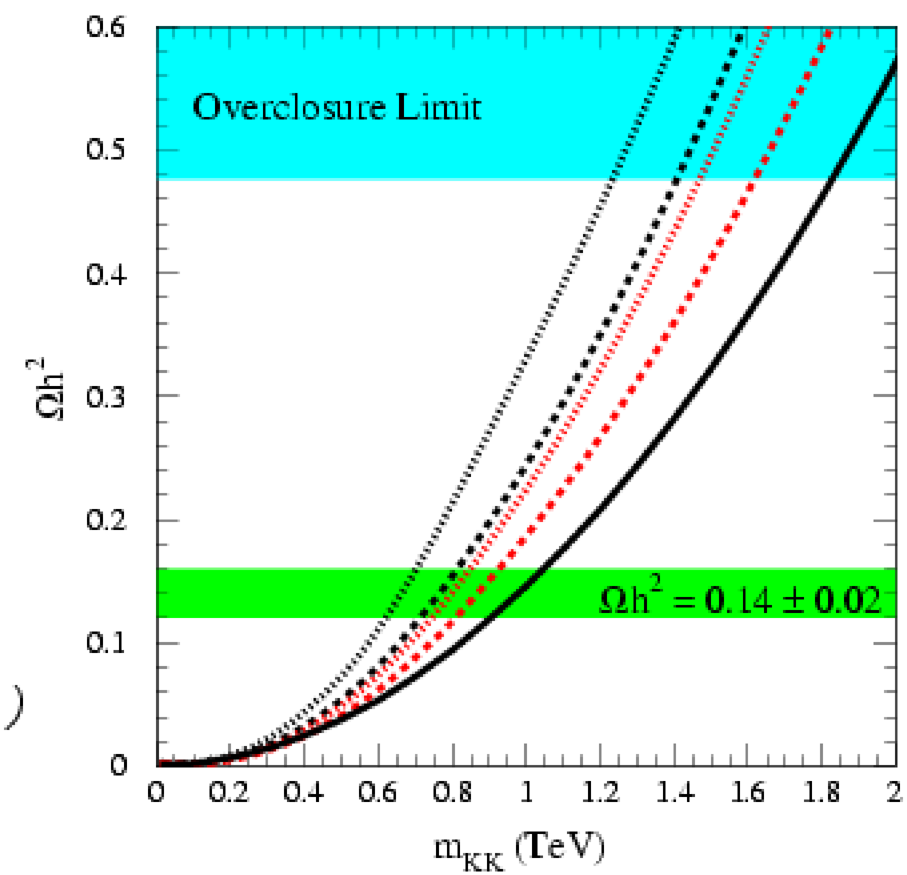
Kaluza-Klein parity: invariance under reflections with respect to the center of the compact dimension.

KK modes with j odd (even) are odd (even) under KK parity.

Lightest KK particle is stable in UED:

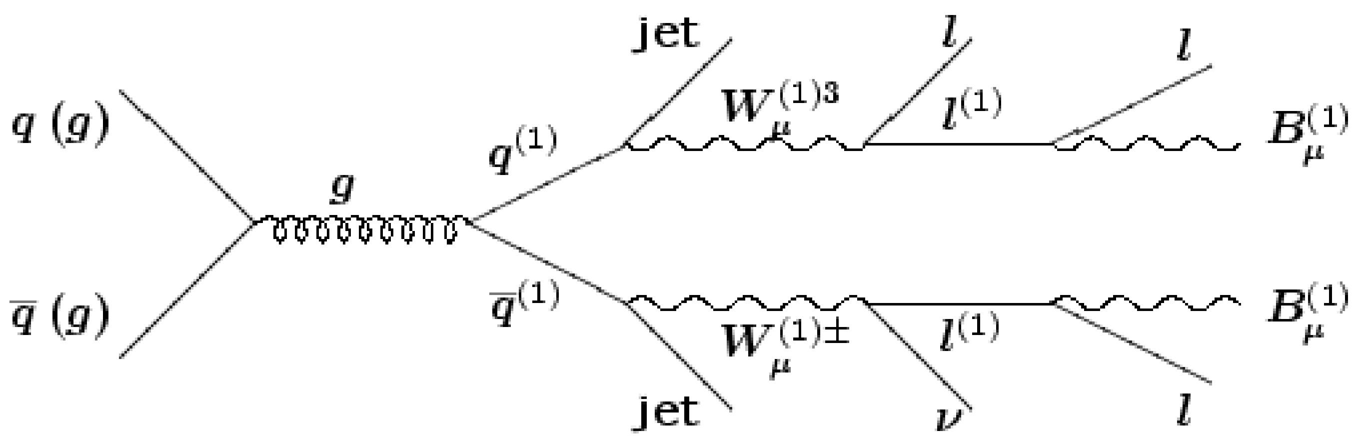
$\gamma^{(1)}$ is a viable dark matter candidate

(from Servant, Tait, hep-ph/0206071)



Signals at hadron colliders

Pair production of (1) modes:



Look for: **2 hard leptons (~ 100 GeV)**

+ 1 soft lepton (~ 10 GeV)

+ 2 jets (~ 50 GeV)

+ $\not{E}_T$

(Cheng, Matchev, Schmaltz, hep-ph/0205314; ...)

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.