Physics beyond the standard model: lecture #1

Bogdan Dobrescu (*Fermilab*)

Lecture 1:

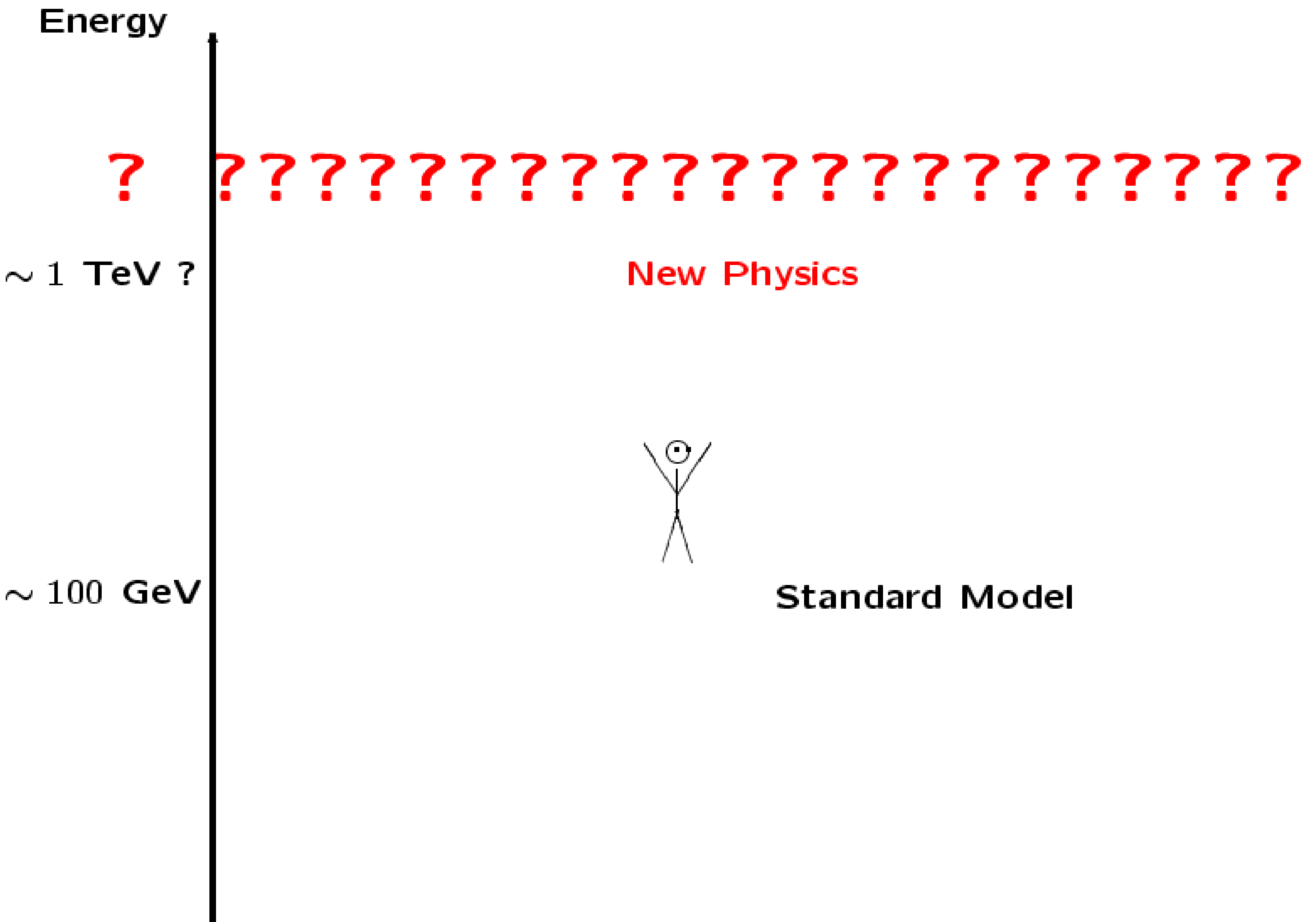
- **We know very little about physics at the TeV scale.**
- **Discrete symmetries and cascade decays at colliders.**

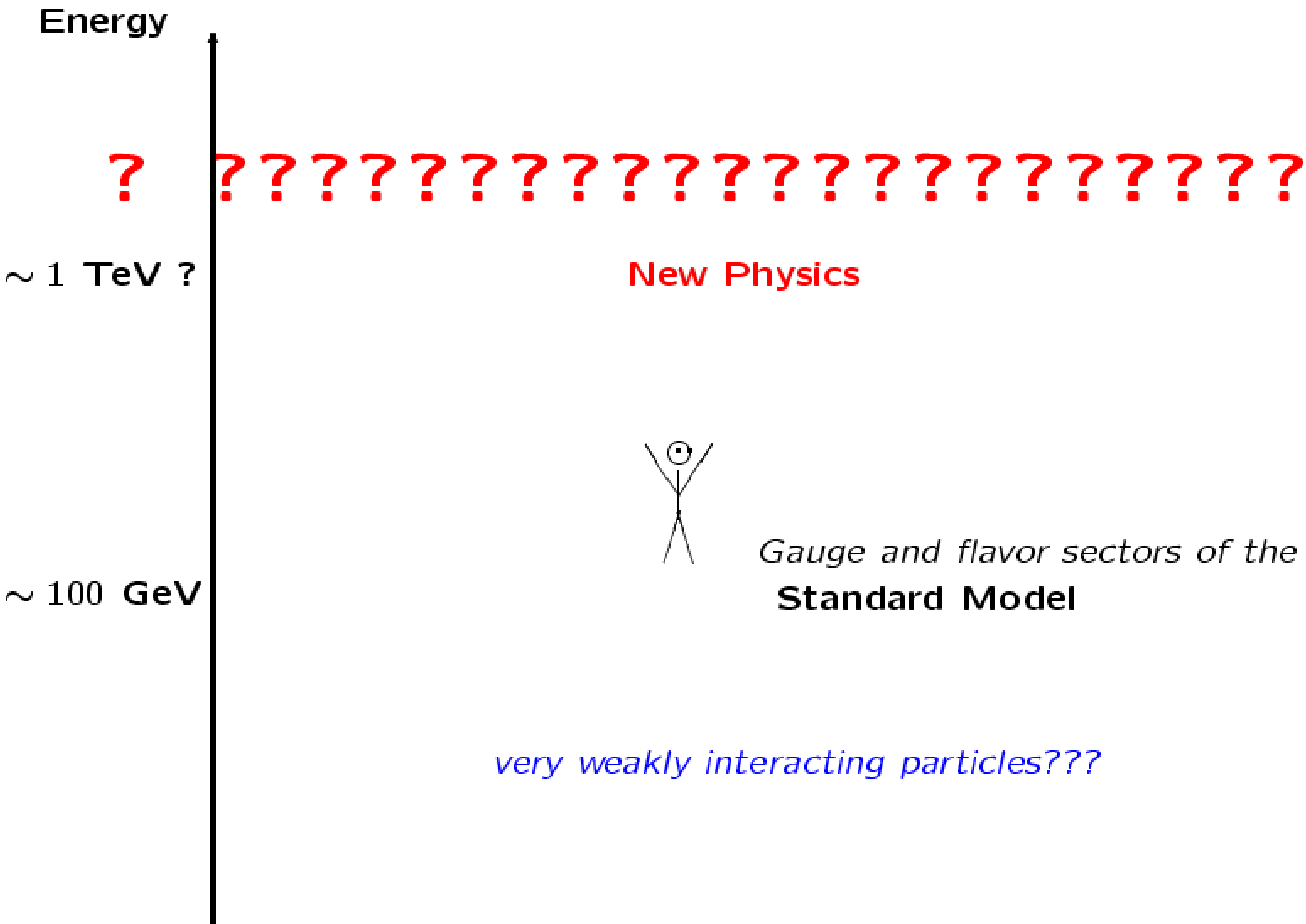
Lecture 2:

Resonances at the Tevatron and the LHC.

Lecture 3:

Case study: two universal extra dimensions.


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

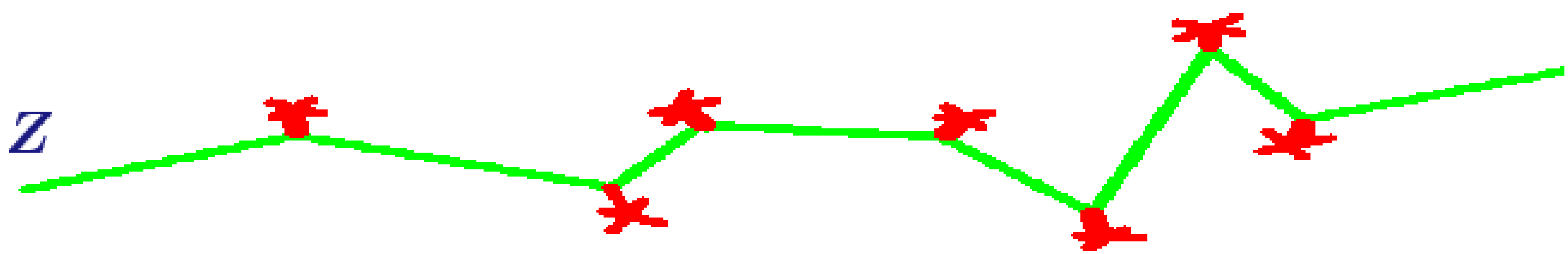


Energy
? ??????????????????????
~ 1 TeV ?
New Physics
Gauge and flavor sectors of the
Standard Model
~ 100 GeV
very weakly interacting particles???

We know that $SU(2)_W \times U(1)_Y \to U(1)_Q$

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

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

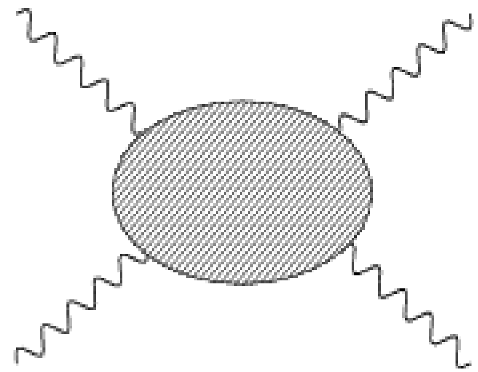


What is the origin of electroweak symmetry breaking?

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 $\boldsymbol{Z'}$ *boson (spin-1) coupled to* $\boldsymbol{W^{\pm}}$*'s.*

For what value of the trilinear coupling $g_{WWZ'}$

does $\boldsymbol{\sigma}\left(\boldsymbol{W_L^+ W_L^-} \rightarrow \boldsymbol{W_L^+ W_L^-}\right)$ *become independent of* $\boldsymbol{s}$*?*

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: $\quad cH^\dagger H S^\dagger S$

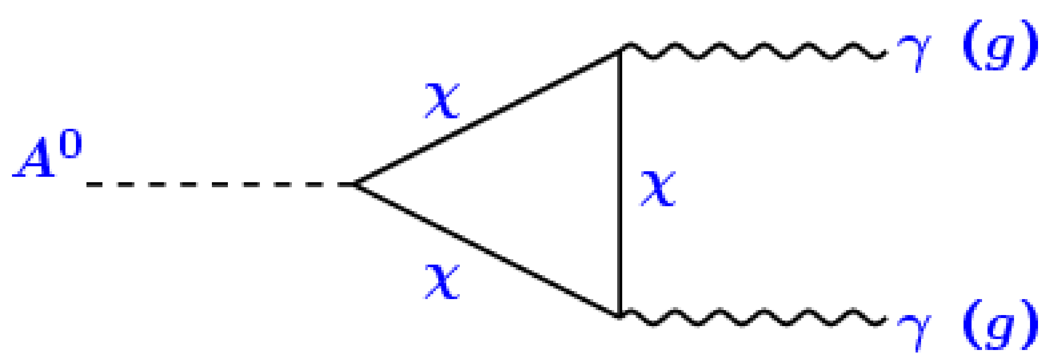
$S = \frac{1}{\sqrt{2}} (\varphi_S + \langle S \rangle)\, e^{iA^0/\langle S \rangle}$, A^0 is a CP-odd spin-0 particle (axion)

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

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:

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

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**$(h \to A^0A^0 \to 4\,\text{jets}) \approx 100\%$

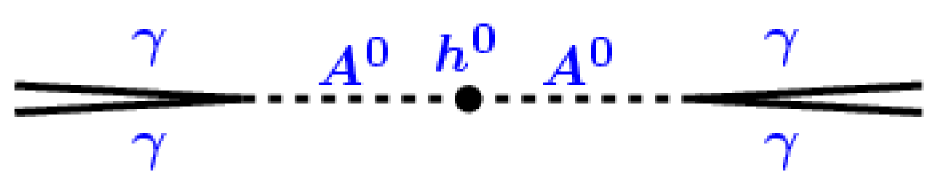
$\Rightarrow$ **huge background at the LHC, Higgs boson will not be observed**

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

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

Br$(h \to A^0A^0 \to \gamma\gamma\gamma\gamma) \approx 100\% \Rightarrow$ **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: $h \to A^0A^0 \to 4\gamma$ 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: $q_L^i = (u_L^i, d_L^i)$	3	2	$1/3$
right-handed up-type quark: u_R^i	3	1	$4/3$
right-handed down-type quark: d_R^i	3	1	$-2/3$
lepton doublet: $l_L^i = (\nu_L^i, e_L^i)$	1	2	-1
right-handed charged lepton": e_R^i	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)**

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

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

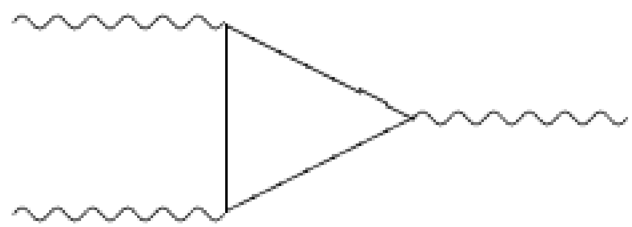
All three gauge couplings are equal to the SU(5) gauge coupling at the GUT scale. Gauge couplings change logaritmically with the scale.

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

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

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

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

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

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*

$$SU(3) \times SU(2) \times U(1) \; ; \; SO(3,1) \; ; \; U(1)_B \; ; \; \text{CPT}$$

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:

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

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!

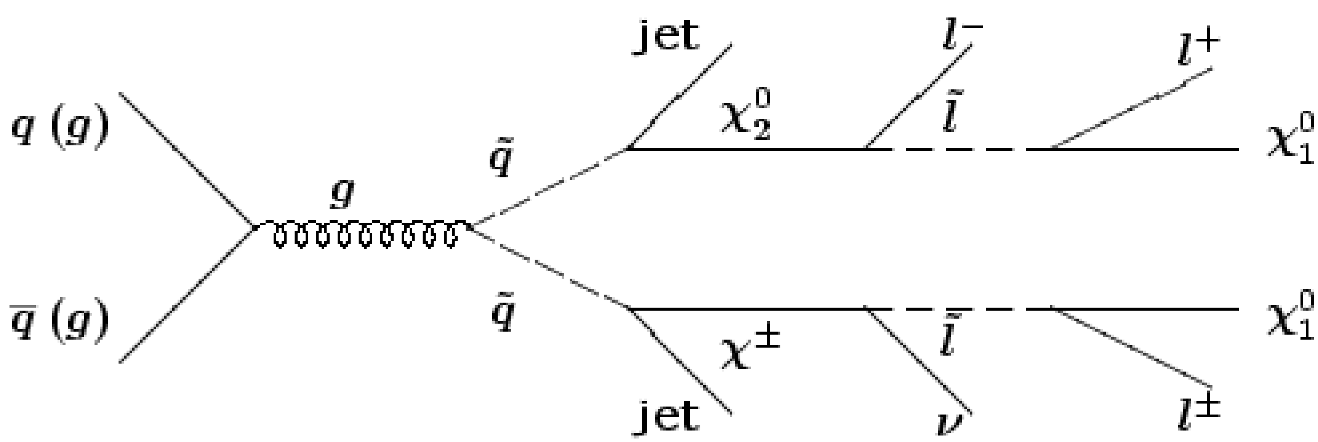
$\Rightarrow$ new particles may be light enough for being discovered soon at colliders!

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.

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.

Physics beyond the standard model: lecture #2

Bogdan Dobrescu (*Fermilab*)

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Z' bosons

Z' = any new electrically-neutral gauge boson (spin 1).

Consider an $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_z$ gauge symmetry spontaneously broken down to $SU(3)_C \times U(1)_{\rm em}$ by the VEVs of a doublet H and an $SU(2)_W$-singlet scalar, φ.

The mass terms for the three electrically-neutral gauge bosons, $W^{3\mu}$, B_Y^μ and B_z^μ, arise from the kinetic terms for the scalars:

$$\frac{v_H^2}{8}\left(gW^{3\mu} - g_Y B_Y^\mu - z_H g_z B_z^\mu\right)\left(gW_\mu^3 - g_Y B_{Y\mu} - z_H g_z B_{z\mu}\right) + \frac{v_\varphi^2}{8} g_z^2 B_z^\mu B_{z\mu}$$

Mass-square matrix for B_Y^μ, $W^{3\mu}$ and B_z^μ:

$$\mathcal{M}^2 = \frac{g^2 v_H^2}{4\cos^2\theta_w}\, U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -z_H t_z \cos\theta_w \\ 0 & -z_H t_z \cos\theta_w & \left(r + z_H^2\right) t_z^2 \cos^2\theta_w \end{pmatrix} U$$

where $t_z \equiv g_z/g$, $\tan\theta_w = g_Y/g$, $r = v_\varphi^2/v_H^2$

$$U = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w & \cos\theta_w & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

relates the neutral gauge bosons to the physical states in the case $z_H = 0$.

The relation between the neutral gauge bosons and the corresponding mass eigenstates can be found by diagonalizing $\mathcal{M}^2$:

$$\begin{pmatrix} B_Y^\mu \\ W^{3\mu} \\ B_z^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & -\sin\theta_w\cos\theta' & \sin\theta_w\sin\theta' \\ \sin\theta_w & \cos\theta_w\cos\theta' & -\cos\theta_w\sin\theta' \\ 0 & \sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{pmatrix}$$

A^μ is the photon field

Z^μ is the field associated with the observed Z boson

Z'^μ is a neutral gauge boson, not discovered yet.

The mixing angle $-\pi/4 \leq \theta' \leq \pi/4$ satisfies

$$\tan 2\theta' = \frac{2 z_H t_z \cos\theta_w}{(r + z_H^2) t_z^2 \cos^2\theta_w - 1}$$

The Z and Z' masses are given by

$$M_{Z,Z'} = \frac{g v_H}{2\cos\theta_w}\left[\frac{1}{2}\left((r + z_H^2) t_z^2 \cos^2\theta_w + 1\right) \mp \frac{z_H t_z \cos\theta_w}{\sin 2\theta'}\right]^{1/2}$$

Z' is heavier than Z when $(r + z_H^2) t_z^2 \cos^2\theta_w > 1$.

The mass and couplings of the Z' boson are described by the following parameters:

- gauge coupling g_z
- VEV v_φ
- $U(1)_z$ charge of the Higgs doublet, z_H
- fermion charges under $U(1)_z$ – constrained by anomaly cancellation conditions and requirement of fermion mass generation

Nonexotic Z'

Nonanomalous $U(1)_z$ gauge symmetry *without* new fermions charged under $SU(3)_C \times SU(2)_W \times U(1)_Y$

Allow an arbitrary number of ν_R's

Assume:
- generation-independent charges,
- quark and lepton masses from standard model Yukawa couplings

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
q_L^i	3	2	$1/3$	z_q
u_R^i	3	1	$4/3$	z_u
d_R^i	3	1	$-2/3$	$2z_q - z_u$
l_L^i	1	2	-1	$-3z_q$
e_R^i	1	1	-2	$-2z_q - z_u$
ν_R^k , $k = 1, ..., n$	1	1	0	z_k
H	1	2	$+1$	$-z_q + z_u$
φ	1	1	0	1

$[SU(3)_C]^2U(1)_z$, $[SU(2)_W]^2U(1)_z$, $U(1)_Y[U(1)_z]^2$ and $[U(1)_Y]^2U(1)_z$ anomalies cancel

Gravitational-$U(1)_z$ and $[U(1)_z]^3$ anomaly cancellation conditions:

$$\frac{1}{3}\sum_{k=1}^{n} z_k = -4z_q + z_u$$

$$\left(\sum_{k=1}^{n} z_k\right)^3 = 9\sum_{k=1}^{n} z_k^3$$

- **For $n \leq 2$:**

$z_1 = -z_2 \Rightarrow z_u = 4z_q \;\; \Rightarrow$ **trivial or Y-sequential $U(1)_z$-charges**

- **For $n \geq 3$:**

$U(1)_{B-L}$ **charges:** $z_1 = z_2 = z_3 = -4z_q + z_u$

or $z_1 = z_2 = -(4/5)z_3 = -16z_q + 4z_u = -4$

ν masses: three LH Majorana,
two dimension-7 and one dimension-12 Dirac operators,
RH Majorana ops. of dimension ranging from 4 to 13

or ...

LEP I requires $\theta' \lesssim 10^{-3} \Rightarrow M_{Z'} \gtrsim 2\ \mathrm{TeV}$

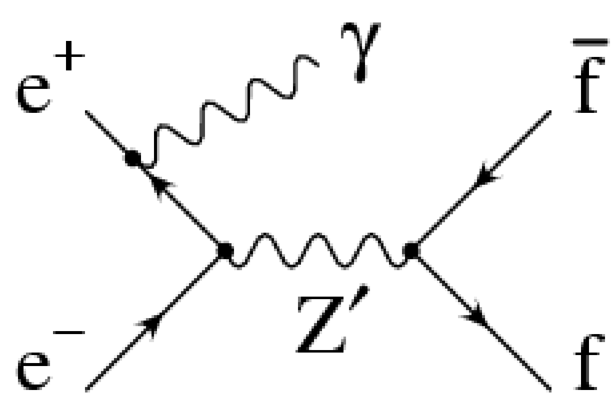
Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} \implies z_H = 0$$

No Z_{B-L}-Z mixing at tree level ($\theta' = 0$)!

Best bounds on $z_l g_z$ come from limits on direct production at the Tevatron and LEP II.

Initial state radiation at LEP for a narrow Z_{B-L} resonance at $M_{Z'} < \sqrt{s}$:



$$\sigma\left(e^+e^-\to\gamma Z_{B-L}\right)\mathrm{Br}\left(Z_{B-L}\to\mu^+\mu^-\right)\approx\frac{3\alpha}{74}(z_l g_z)^2\frac{s^2+M_{Z'}^4}{s^2\left(s-M_{Z'}^2\right)}\ln\left(\frac{s}{m_e^2}\right)$$

LEPII has run at $\sqrt{s} \approx 130, 136, 161, 172, 183, 189, 192 - 209$ GeV

For a Z_{B-L} with $M_{Z'} \sim 140$ GeV:

Number of $\mu^+\mu^-$ events at $\sqrt{s} \approx 161$ GeV due to Z_{B-L}:

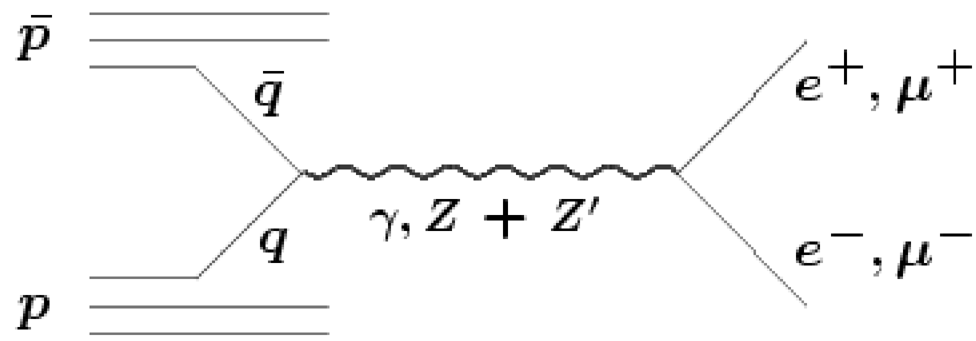
$$N(Z_{B-L}) \approx 3 \times 10^4 \,(z_l g_z)^2$$

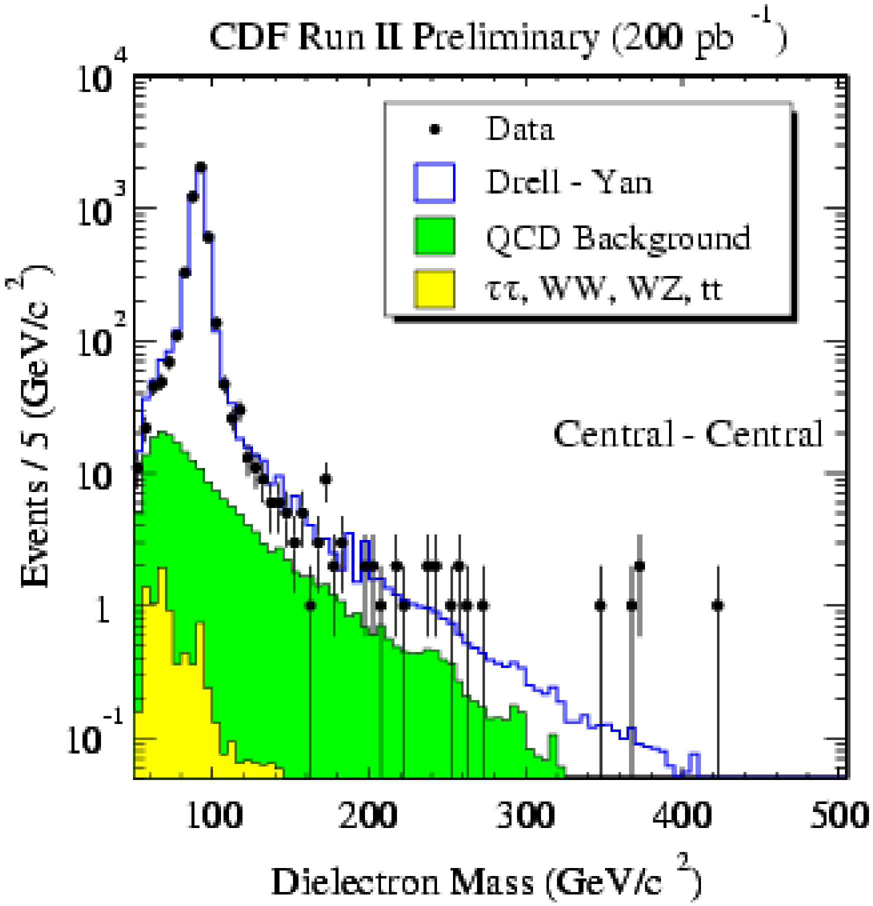
Main background: $e^+e^- \to \gamma^*\gamma, Z^*\gamma \to \mu^+\mu^-\gamma$
(~ 6.4 events in an energy bin of 5 GeV)

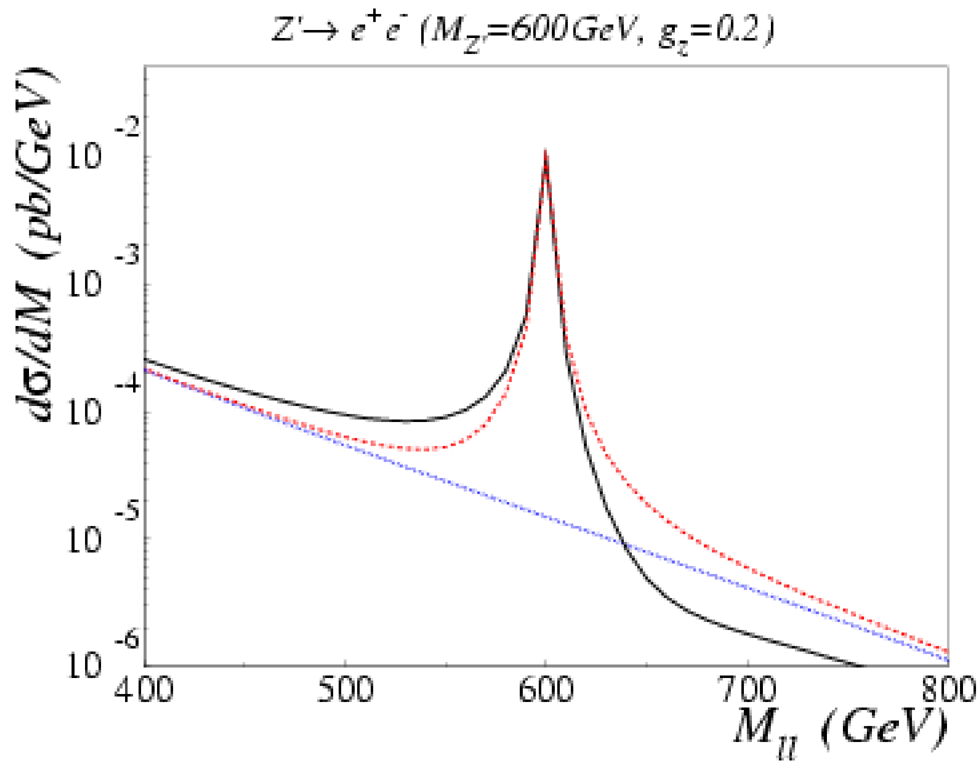
At the 95% confidence-level: $z_l g_z \lesssim 10^{-2}$

If $\sqrt{s} = M_{Z'}$: no need for initial state radiation.
Strongest bound for $M_{Z'} \sim 189$ GeV: $z_l g_z < 10^{-3}$

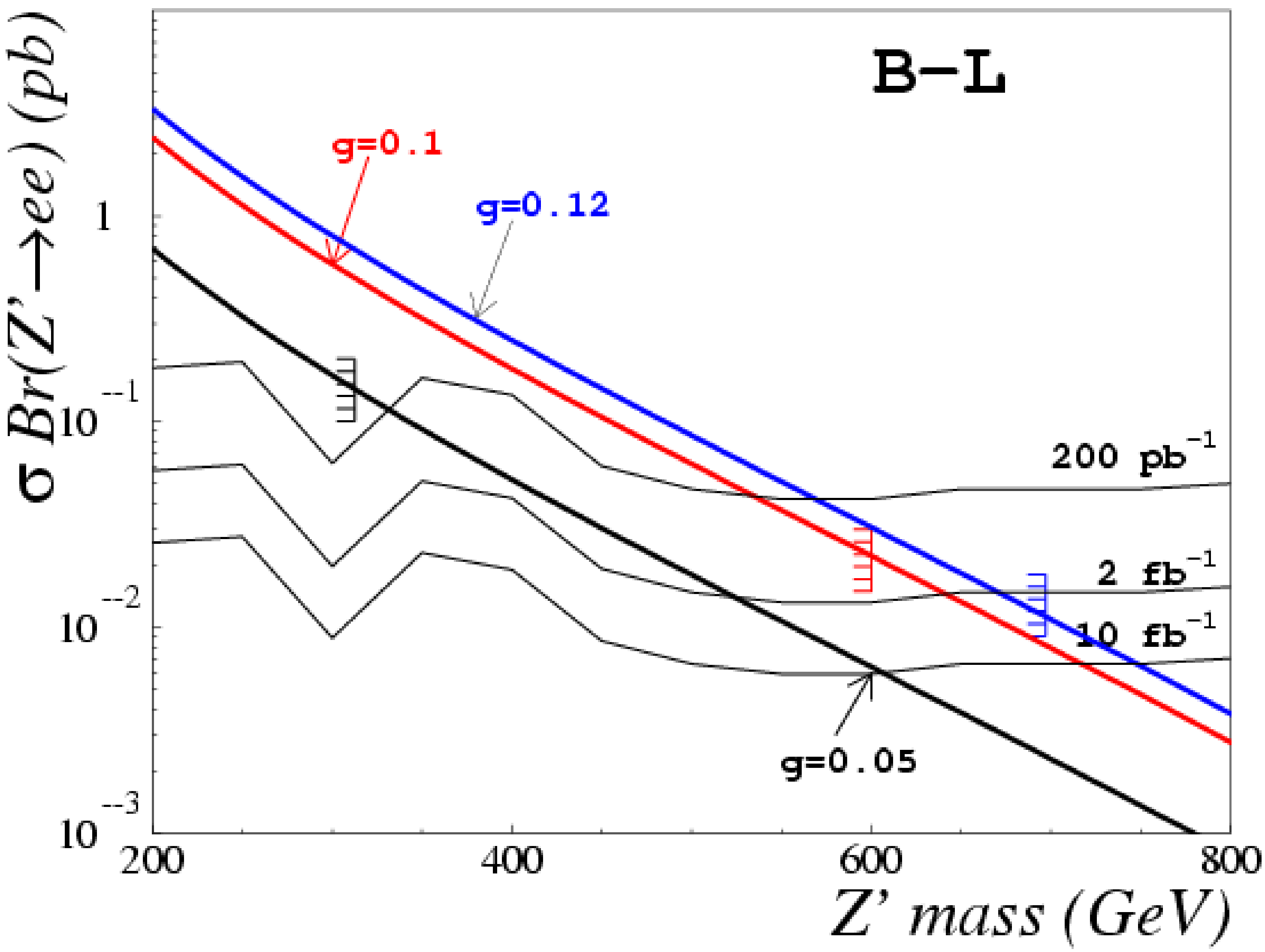
Z' searches at the Tevatron







Limits on Z': Tevatron versus LEPII



More general charges are allowed in the presence of new fermions:

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x5}$	$U(1)_{d-xu}$
q_L	3	2	$1/3$	$1/3$	$1/3$	$1/3$	0
u_R	3	1	$4/3$	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	3	1	$-2/3$	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν'_R				·	·	$-1-x/3$	·
ψ^l_L	1	2	-1	-1	·	$-(1+x)/3$	$-2x/5$
ψ^l_R				$-x$	·	$2/3$	$(-1+x/5)/3$
ψ^e_L	1	1	-2	-1	·	·	·
ψ^e_R				$-x$	·	·	·
ψ^d_L	3	1	$-2/3$	·	·	$-2/3$	$(1-4x/5)/3$
ψ^d_R				·	·	$(1+x)/3$	$x/15$

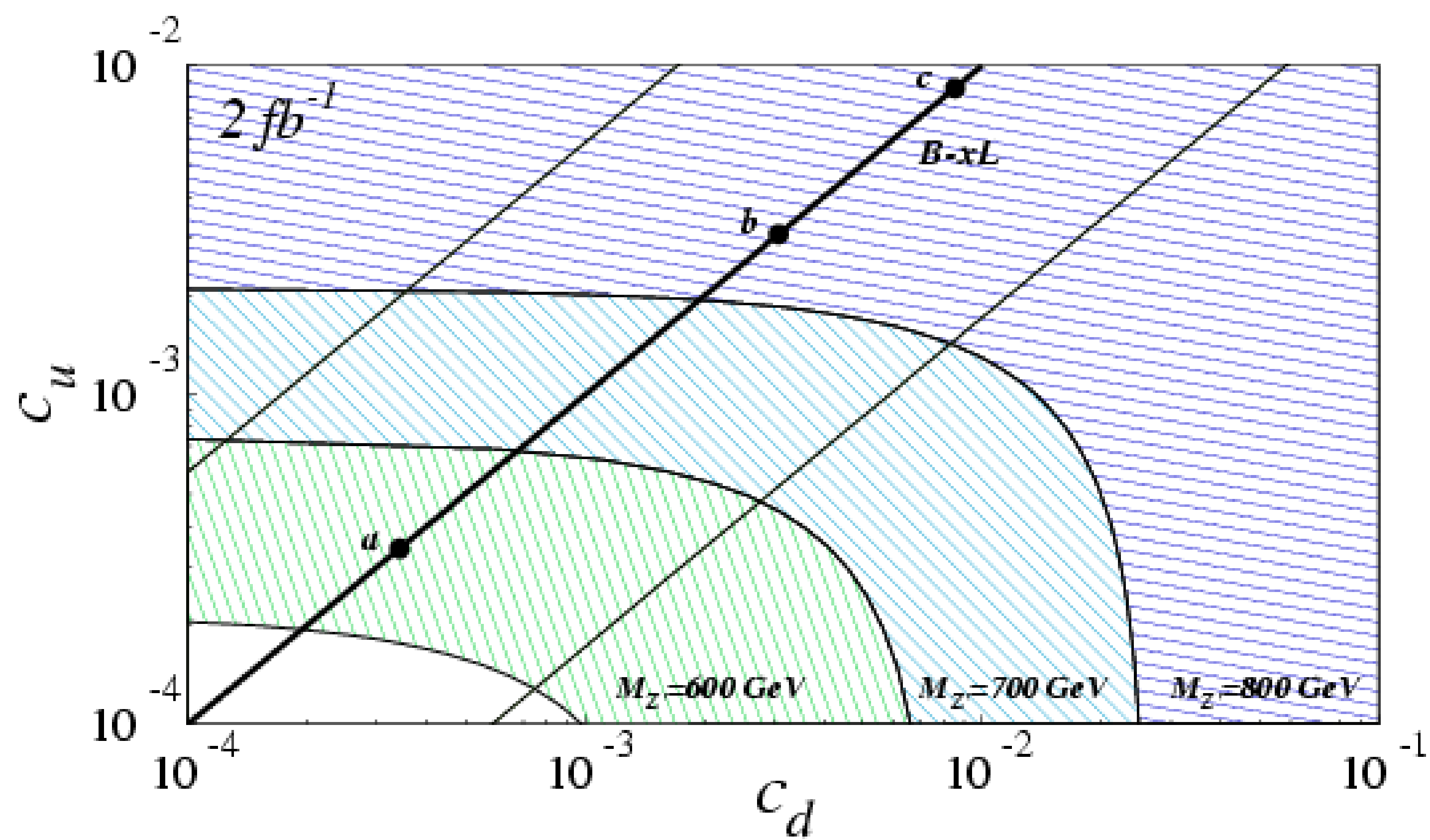
Homework # 2.1:
Identify the couplings of the Z' arising from the $SO(10) \to SU(5)$ GUT breaking.

A user-friendly parametrization (hep-ph/0408098):

$$\sigma\left(p\bar{p} \to Z' X \to l^+ l^- X\right) = \frac{\pi}{48\, s}\left[c_u\, w_u\left(\frac{M_{Z'}^2}{s}, M_{Z'}\right) + c_d\, w_d\left(\frac{M_{Z'}^2}{s}, M_{Z'}\right)\right]$$

All the information about charges is contained in:

$$c_{u,d} = g_z^2\,(z_q^2 + z_{u,d}^2)\,\mathrm{Br}(Z' \to l^+ l^-)$$



$$\sigma\left(pp \to Z' X \to l^+ l^- X\right) = \frac{\pi}{48\, s}\left[c_u\, w'_u\left(\frac{M^2_{Z'}}{s}, M_{Z'}\right) + c_d\, w'_d\left(\frac{M^2_{Z'}}{s}, M_{Z'}\right)\right]$$

w'_u and w'_d contain all the information about QCD:

values at the LHC are different than at the Tevatron

$\Rightarrow$ c_u and c_d can be determined independently if a Z' is observed at both the Tevatron and the LHC.

More information about Z' couplings ($U(1)_z$ charges) can be extracted from angular distributions, etc.

Homework # 2.2:
What are the analytical formulas for $w'_{u,d}$ at NLO in α_s?

Physics beyond the standard model: lecture #3

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Case study: two universal extra dimensions.

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:

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

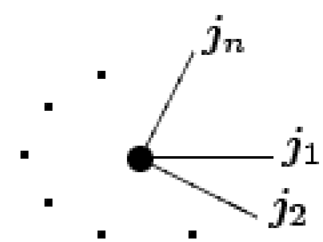
Universal Extra Dimensions

All 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:

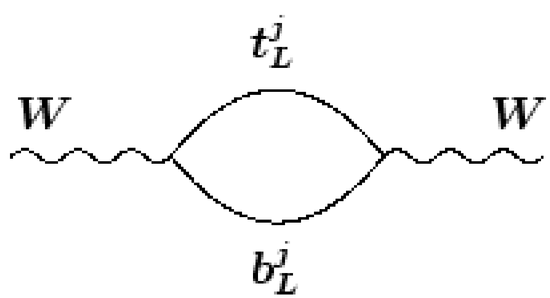
$j_1 \pm j_2 \pm ... \pm j_n = 0$ **for a certain choice of** $\pm$

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:

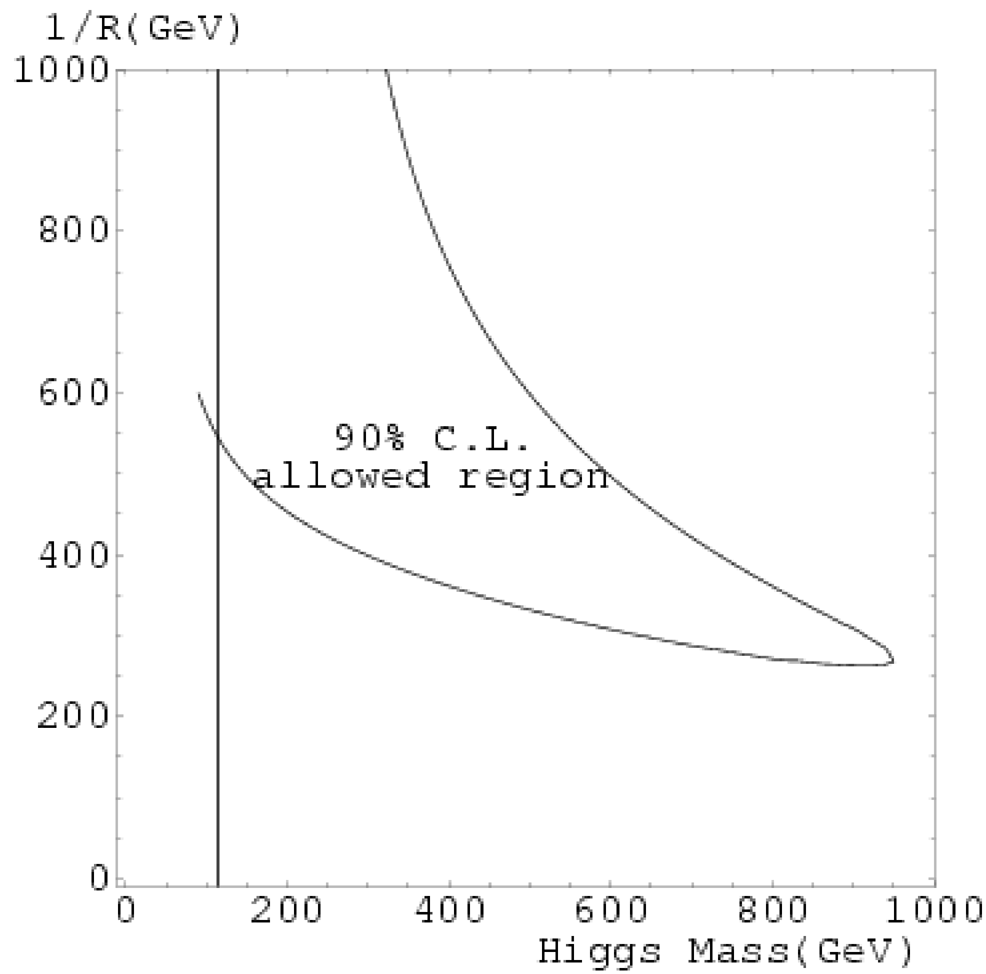


$$\frac{1}{R} \gtrsim 300 \text{ GeV}$$

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



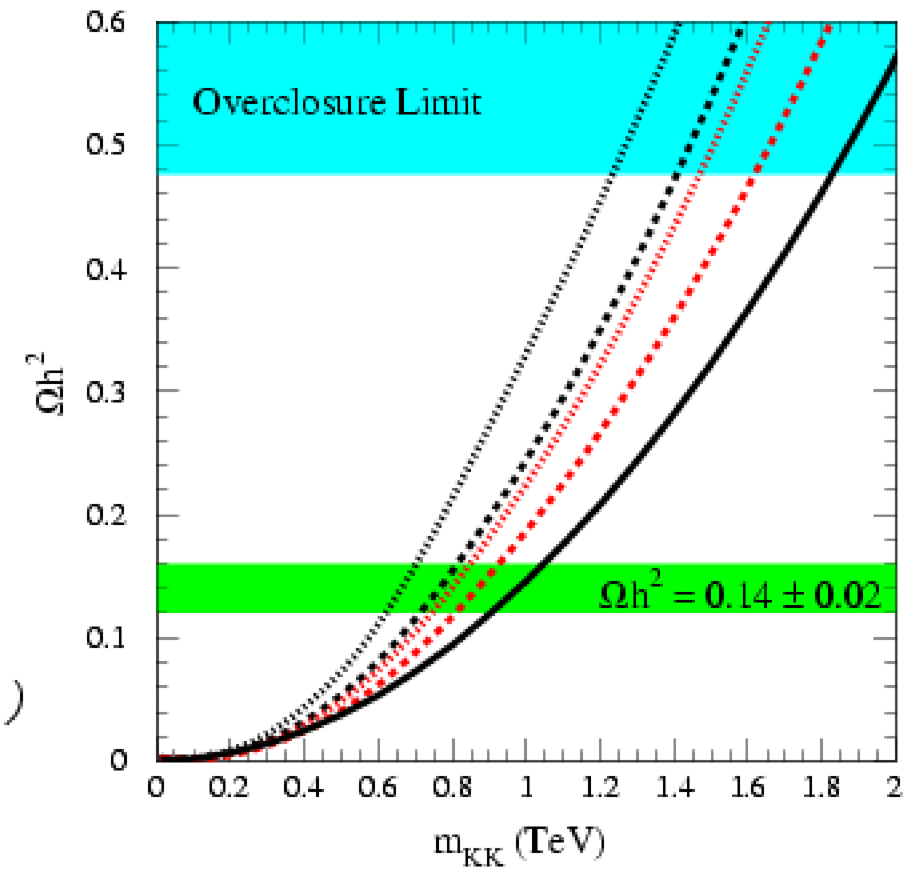
Kaluza-Klein parity: invariance under reflections with respect to the center of the compact dimension.

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

Lightest KK particle is stable in UED:

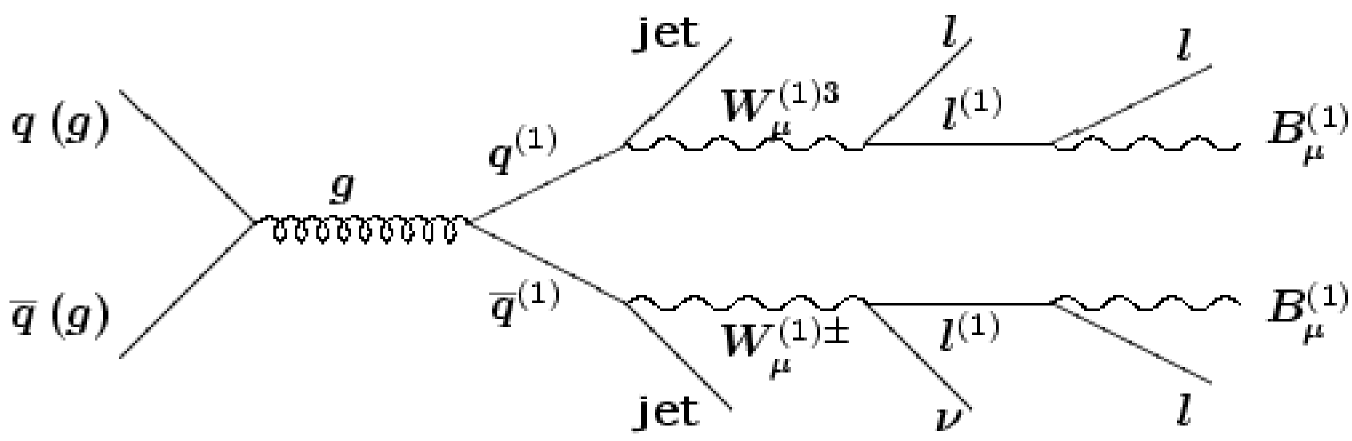
$\gamma^{(1)}$ is a viable dark matter candidate

(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)

+ $\not{E}_T$

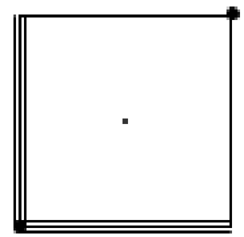
(Cheng, Matchev, Schmaltz, hep-ph/0205314; ...)

Two Universal Extra Dimensions

hep-ph/0601186, hep-ph/0703231

All Standard Model particles propagate in $D = 6$ dimensions.

Two dimensions are compactified on a square.



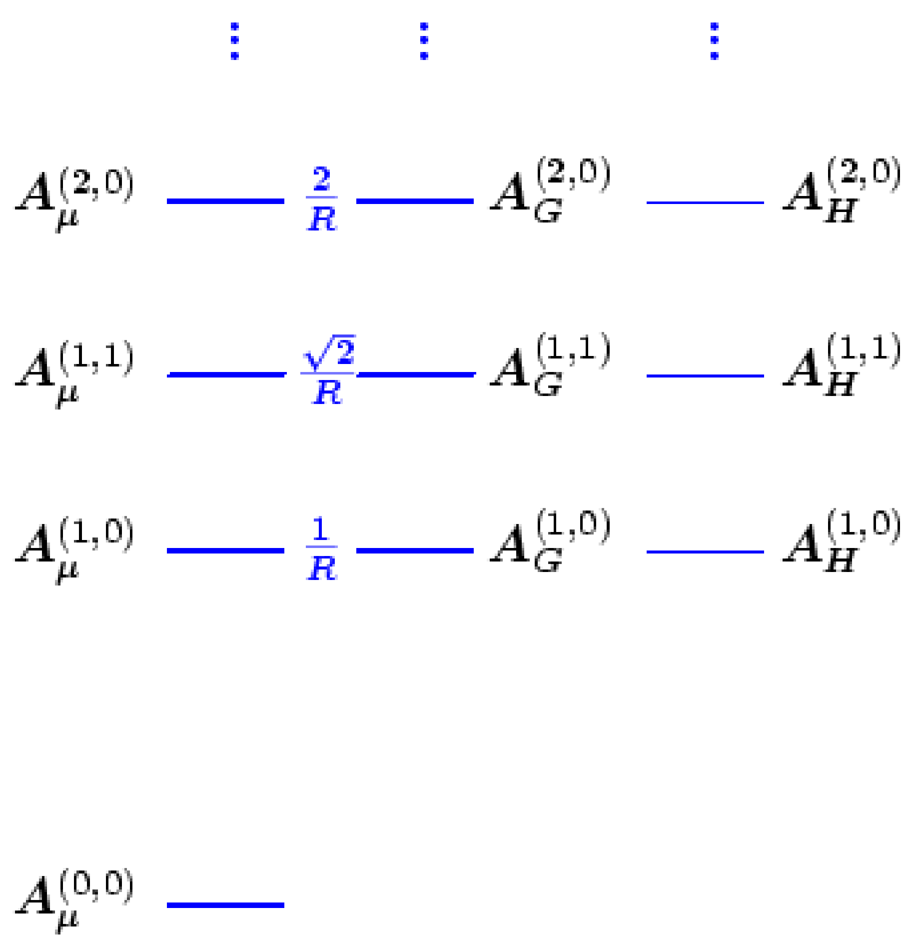
Kaluza-Klein particles are states of definite momenta along the two compact dimensions, labelled by two integers (j, k).
Tree-level masses: $\sqrt{j^2 + k^2}/R$

Momentum conservation $\rightarrow$ *KK-parity given by* $j + k$

$\Rightarrow$ **(1,0) particles are produced only in pairs at colliders**

Kaluza-Klein spectrum of gauge bosons

$A_G^{(j,k)}(x^\nu)$ becomes the longitudinal degree of freedom of the spin-1 KK mode $A_\mu^{(j,k)}(x^\nu)$.



Kaluza-Klein spectrum of quarks and leptons

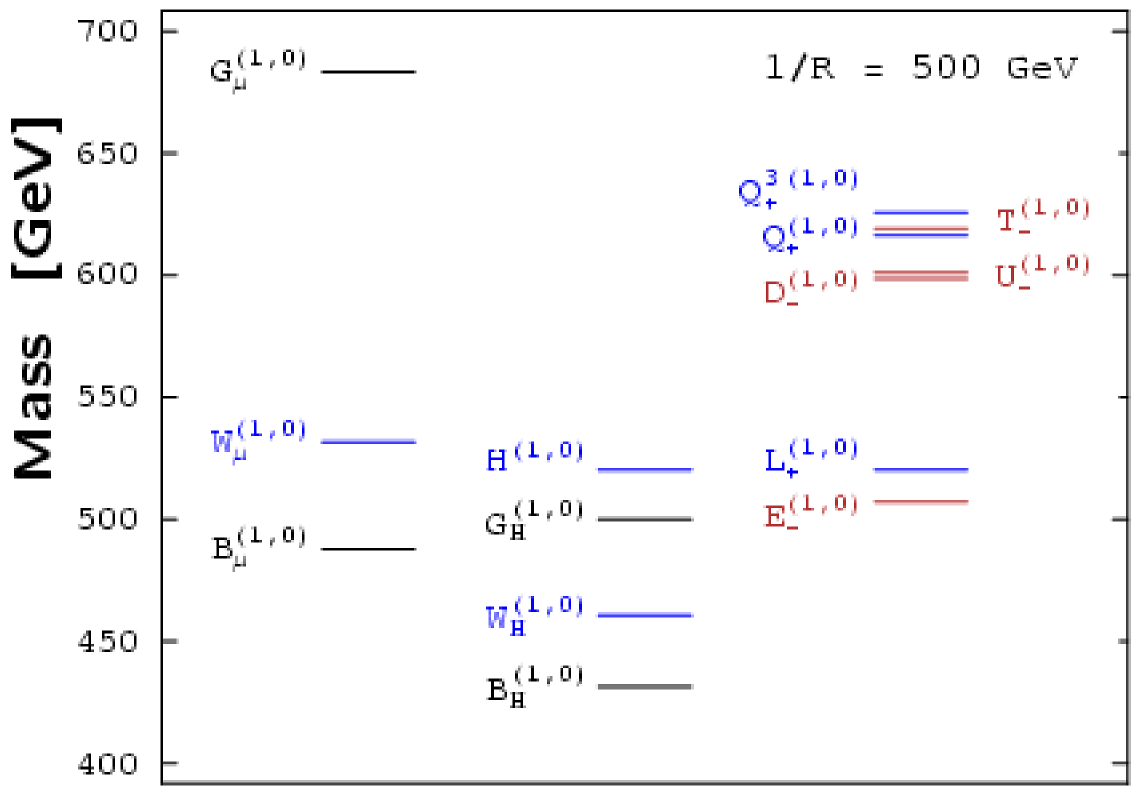
$(t_L^{(2,0)}, b_L^{(2,0)})$	$\frac{2}{R}$	$(T_R^{(2,0)}, B_R^{(2,0)})$	$T_L^{(2,0)}$	$\frac{2}{R}$	$t_R^{(2,0)}$
$(t_L^{(1,1)}, b_L^{(1,1)})$	$\frac{\sqrt{2}}{R}$	$(T_R^{(1,1)}, B_R^{(1,1)})$	$T_L^{(1,1)}$	$\frac{\sqrt{2}}{R}$	$t_R^{(1,1)}$
$(t_L^{(1,0)}, b_L^{(1,0)})$	$\frac{1}{R}$	$(T_R^{(1,0)}, B_R^{(1,0)})$	$T_L^{(1,0)}$	$\frac{1}{R}$	$t_R^{(1,0)}$
(t_L, b_L)					t_R

(1,0) modes have a tree-level mass of $1/R$, and KK parity $-$.

One-loop contributions and EWSB split the spectrum

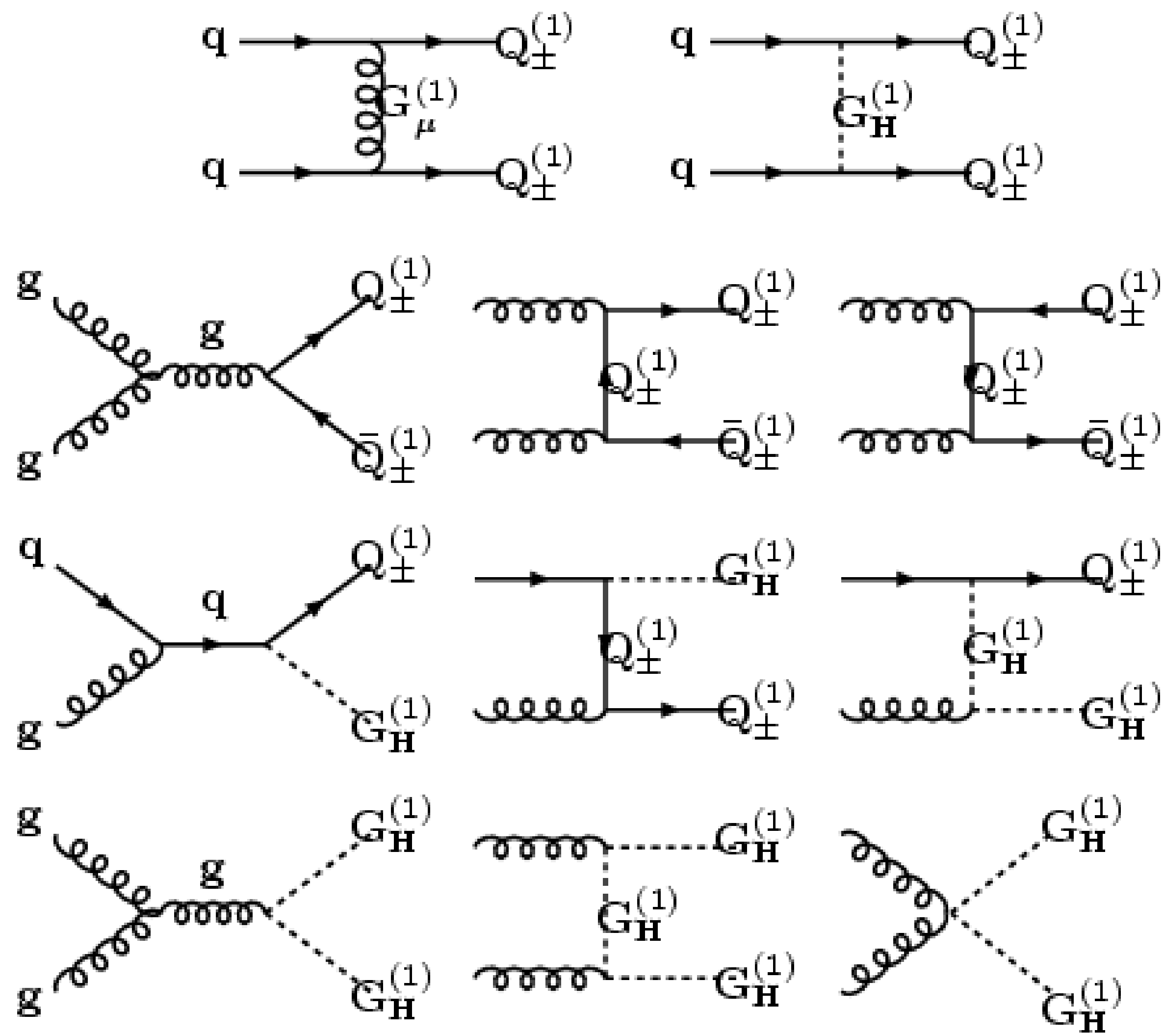
(Cheng, Matchev, Schmaltz, hep-ph/0204342 ; Ponton, Wang, hep-ph/0512304)

Mass spectrum of the (1,0) level:



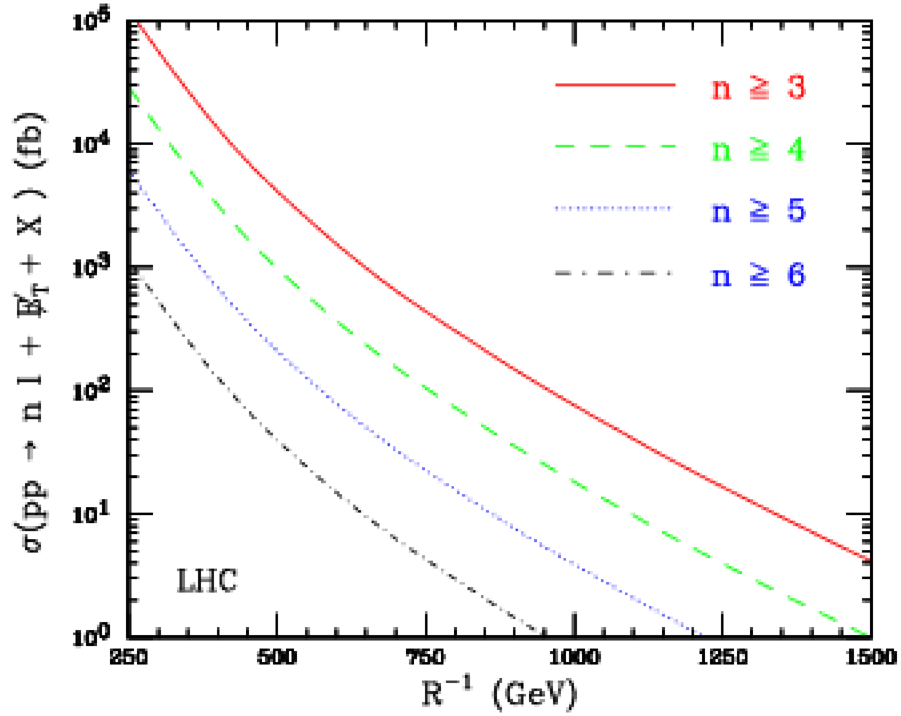
Homework 3.1: compute the branching fractions of the (1,0) particles.

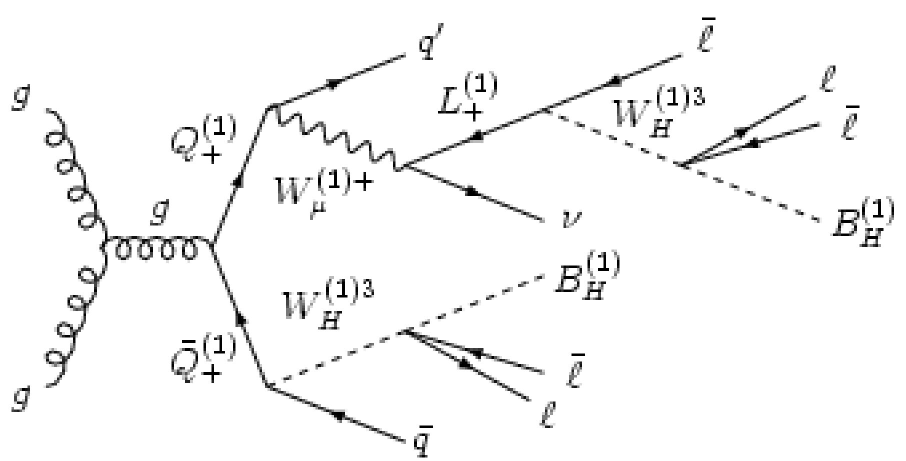
Production of (1,0) particles at the LHC



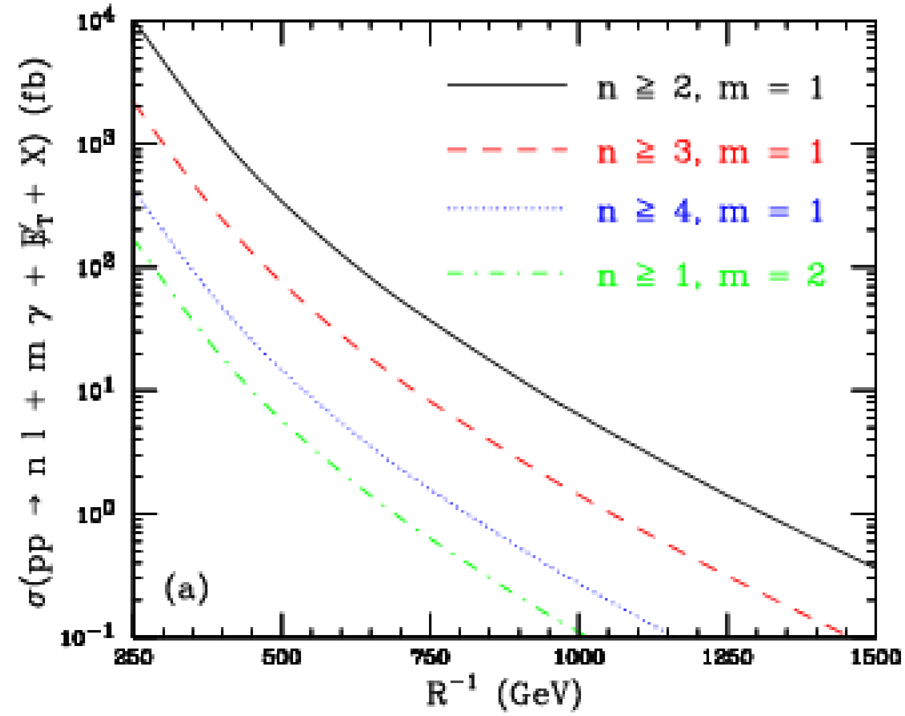
Use CalcHEP to compute cross section for (1,0) pair production.

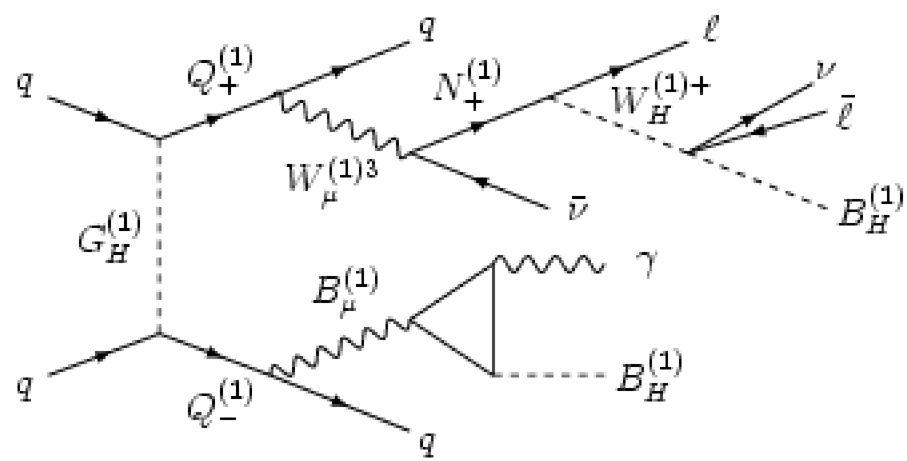
Multi-lepton signal at the LHC:





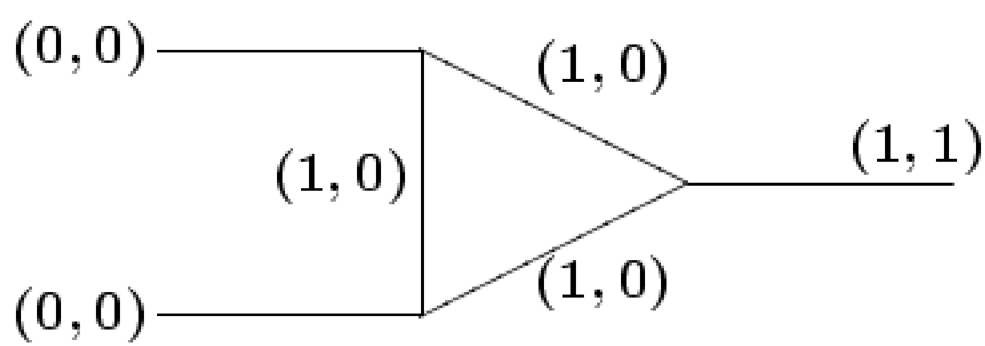
Leptons + photons at the LHC:





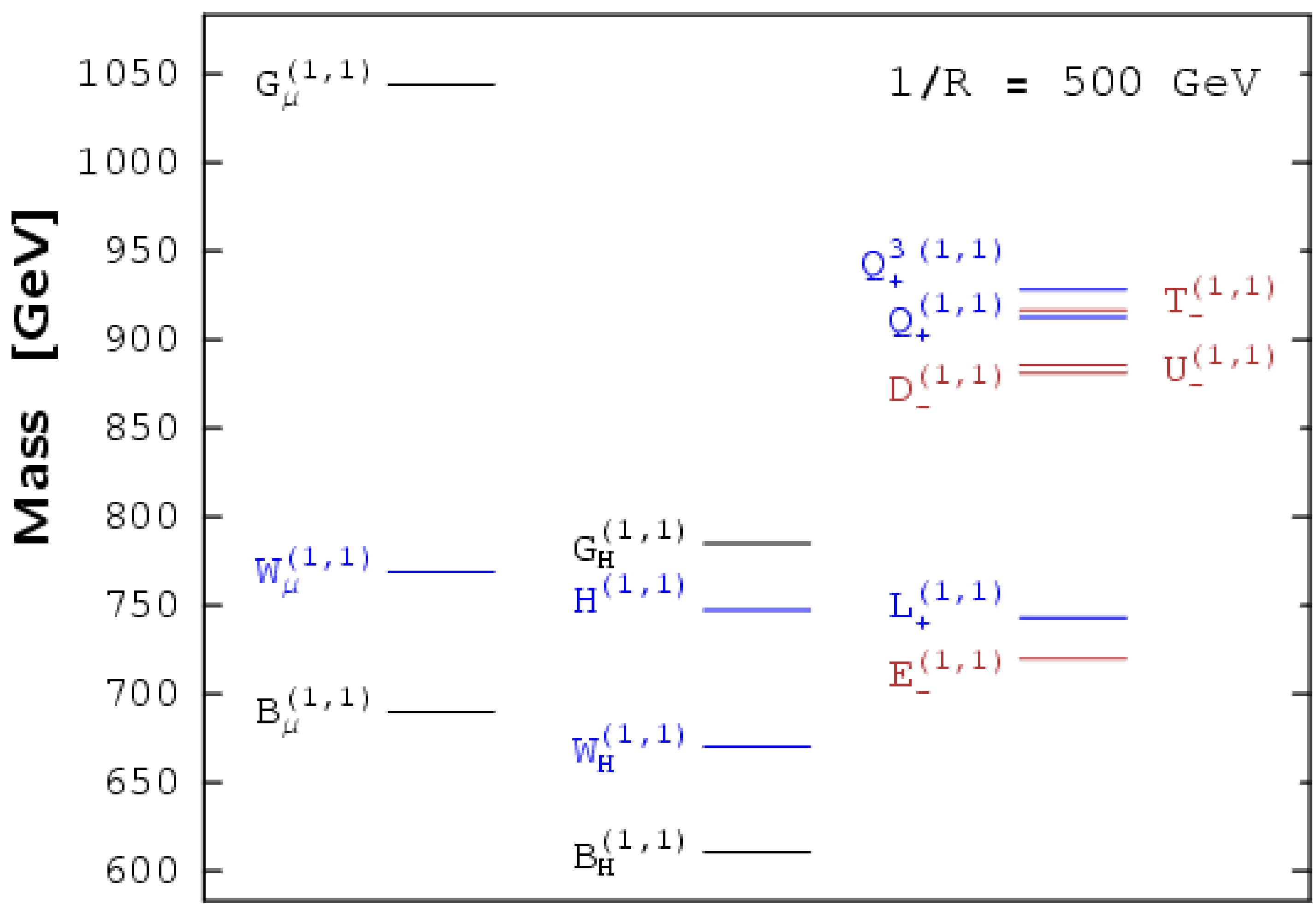
KK parity is conserved: $(-1)^{j+k}$

At colliders: s**-channel production of the even-modes at 1-loop**



(1,1) modes have a tree-level mass of $\sqrt{2}/R$*, and KK parity* $+$.

Mass spectrum of the (1,1) level for $1/R = 500$ GeV:



Spinless adjoints interact with the zero-mode fermions only via dimension-5 or higher operators:

$$\frac{g_s \tilde{C}^{qG}_{j,k}}{M_{j,k}} \left(\overline{q}\gamma^{\mu} T^a q\right) \partial_{\mu} G_H^{(j,k)a}$$

$\tilde{C}^{qG}_{j,k}$ are real dimensionless parameters.

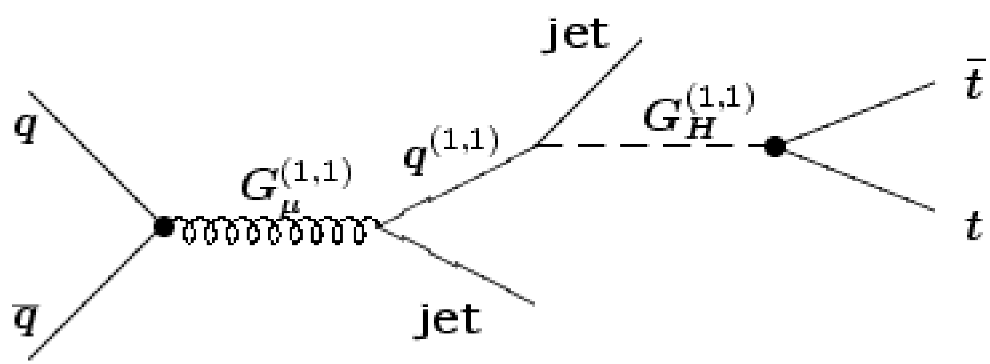
$\Rightarrow$ G_H, W_H and B_H couple to usual quarks and leptons proportional to the fermion mass!

$\Rightarrow$ KK-number violating couplings of the spinless adjoints are large only in the case of the top quark.

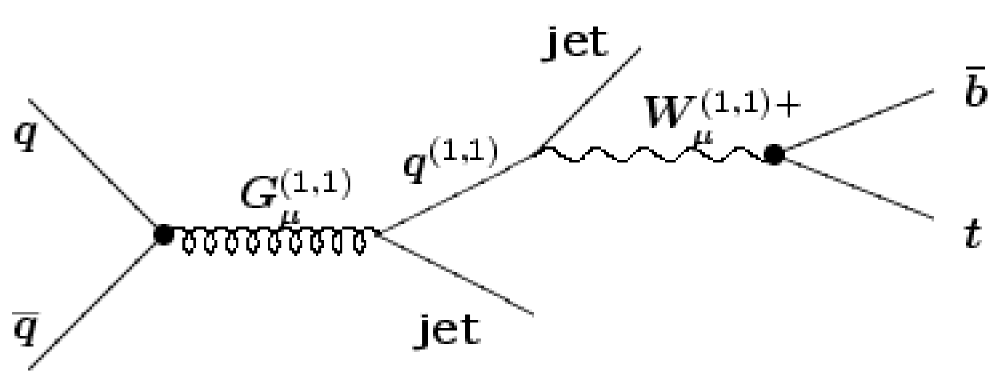
Signals of (1,1) particles at the LHC:

1. s-channel production of a (1,1) gluon of mass $\sim \sqrt{2}/R\,(1+\alpha_s)$

$\rightarrow$ $t\bar{t}$ resonance + 2 jets ($\sim 50-100$ GeV):



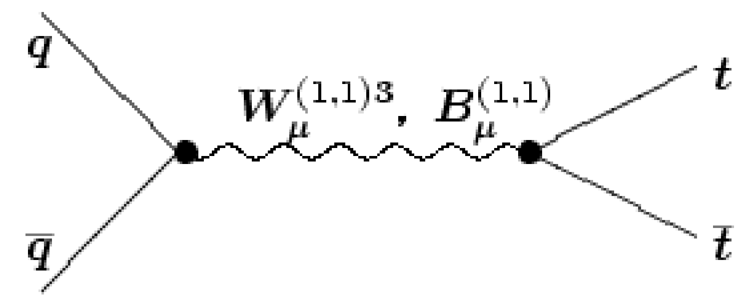
$\rightarrow$ $t\bar{b}$ resonance + 2 jets ($\sim 50-100$ GeV):



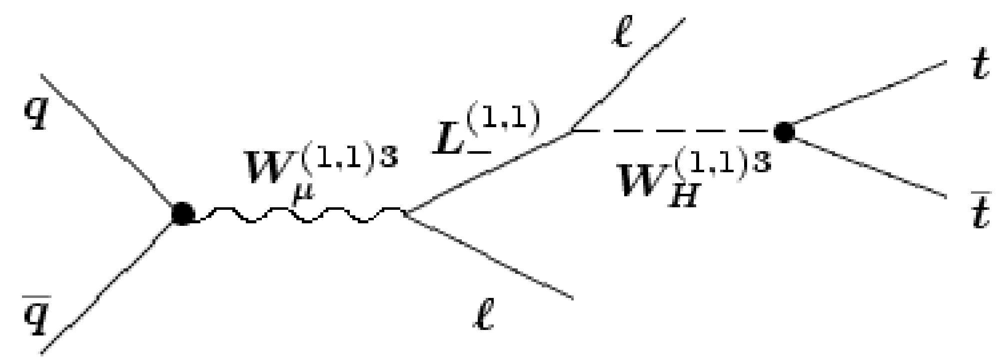
More signals at the LHC:

2. s-channel production of a (1,1) electroweak gauge boson

$\rightarrow$ $t\bar{t}$ resonance:

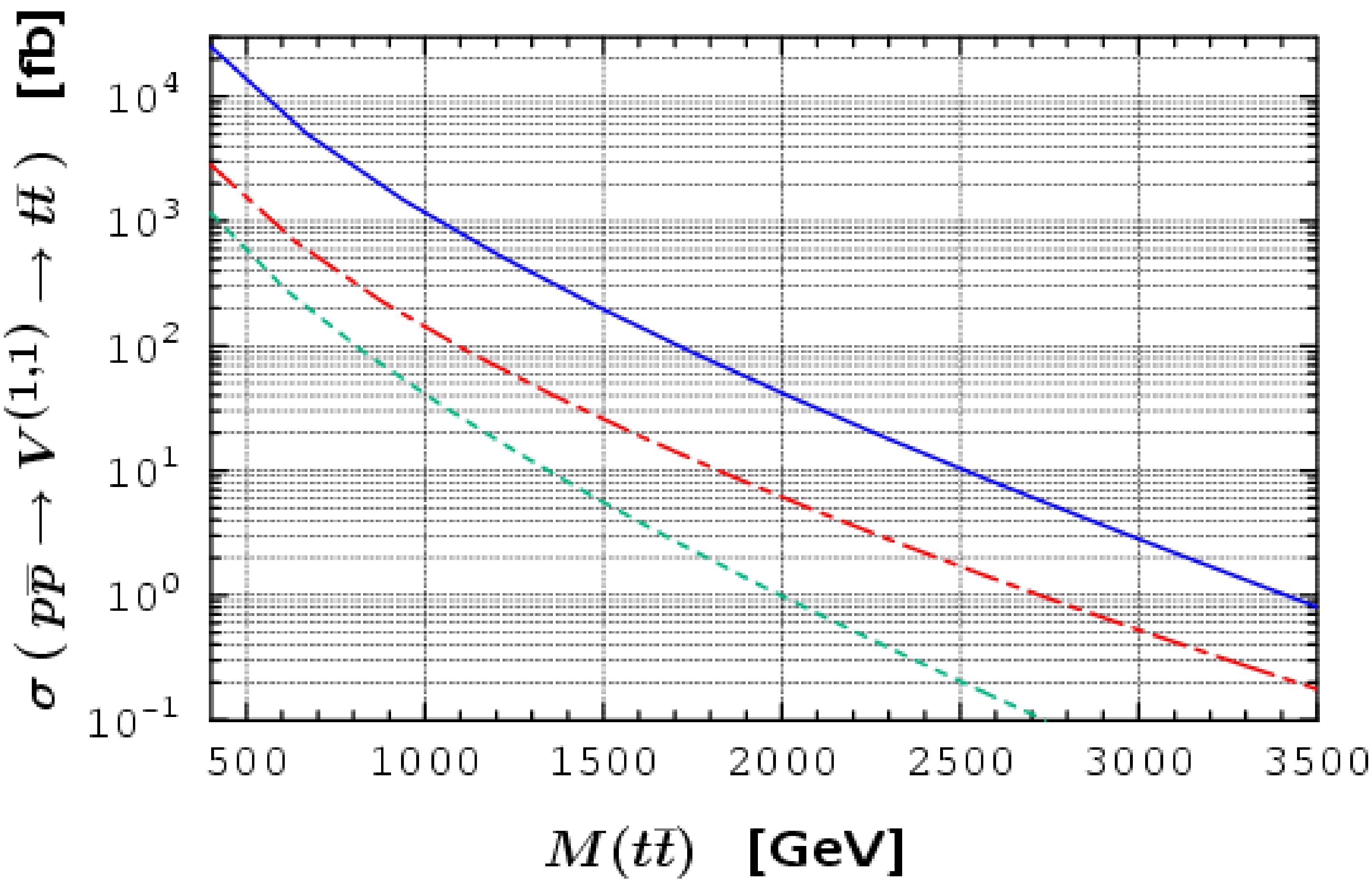


$\rightarrow$ $t\bar{t}$ resonance + 1 lepton ~ 70 GeV + 1 lepton ~ 20 GeV:



Production of $t\bar{t}$ pairs at the LHC from mass peaks at:

- $G_H^{(1,1)} + W_\mu^{(1,1)3}$ (solid blue) $\quad M_{t\bar{t}} \simeq 1.10\,\sqrt{2}/R$
- $W_H^{(1,1)3} + B_\mu^{(1,1)}$ (dashed red) $\quad M_{t\bar{t}} \simeq 0.96\,\sqrt{2}/R$
- $B_H^{(1,1)}$ (dashed green) $\quad M_{t\bar{t}} \simeq 0.87\,\sqrt{2}/R$



Conclusions

- 6-Dimensional Standard Model
  - 3 generations of quarks and leptons are required for global $SU(2)_W$ anomaly cancellation
  - proton is long-lived due to 6D Lorentz invariance
  - neutrinos are special
- *At colliders, look for:*
  - $t\bar{t}$ and $t\bar{b}$ resonances
  - many leptons + jets + missing E_T
  - leptons + photons + jets + missing E_T
  - other signatures of Kaluza-Klein modes

More conclusions

The Tevatron and the LHC will probe the TeV scale. There are many possibilities for what may be discovered:

- Vector-like fermions
- New gauge bosons (Z', W', ...)
- extended Higgs sectors
- ...

Many other interesting theories for physics beyond the SM:

- warped extra dimension
- technicolor
- little Higgs models
- Twin Higgs
- composite Higgs models (top seesaw)
- NMSSM
- ...