Physics beyond the standard model: lecture #2

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.

Case study: two universal extra dimensions.

Lecture 3:

Supersymmetry versus Composite Higgs

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

$[SU(3)_C]^2 U(1)_z$, $[SU(2)_W]^2 U(1)_z$, $U(1)_Y [U(1)_z]^2$ and $[U(1)_Y]^2 U(1)_z$ 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 $\theta' \lesssim 10^{-3} \Rightarrow M_{Z'} \gtrsim 2$ TeV

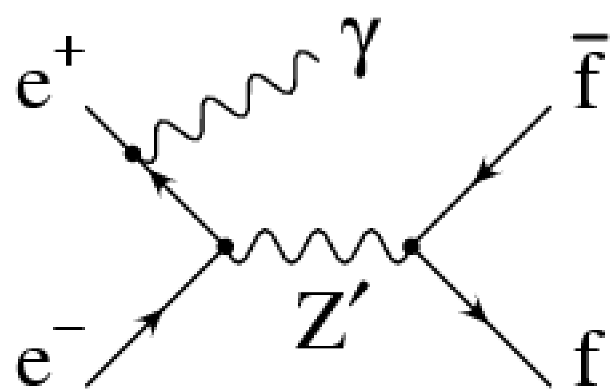
Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

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

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}:

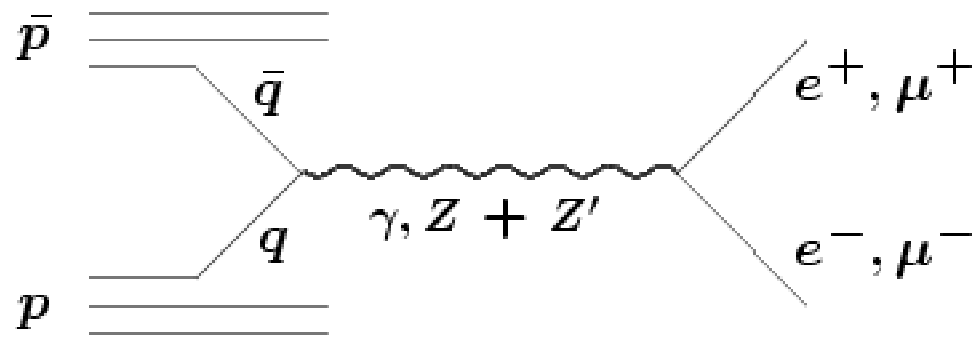
$$N(Z_{B-L}) \approx 3 \times 10^4 \, (z_l g_z)^2$$

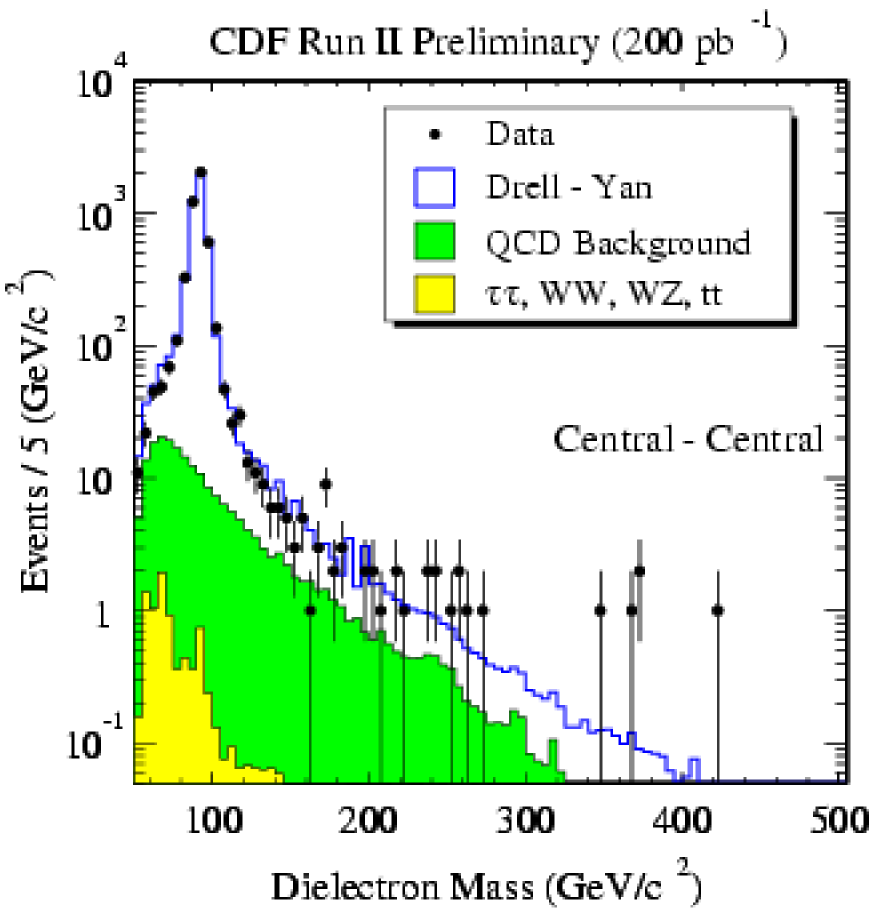
Main background: $e^+e^- \to \gamma^*\gamma, Z^*\gamma \to \mu^+\mu^-\gamma$
(~ 6.4 events in an energy bin of 5 GeV)

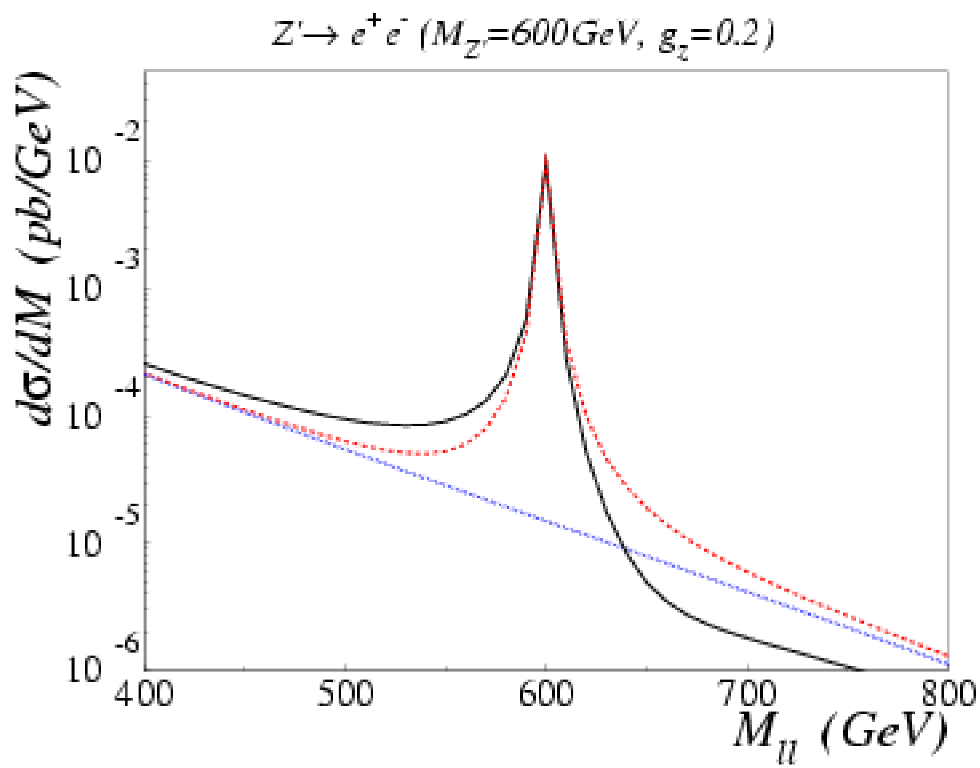
At the 95% confidence-level: $z_l g_z \lesssim 10^{-2}$

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

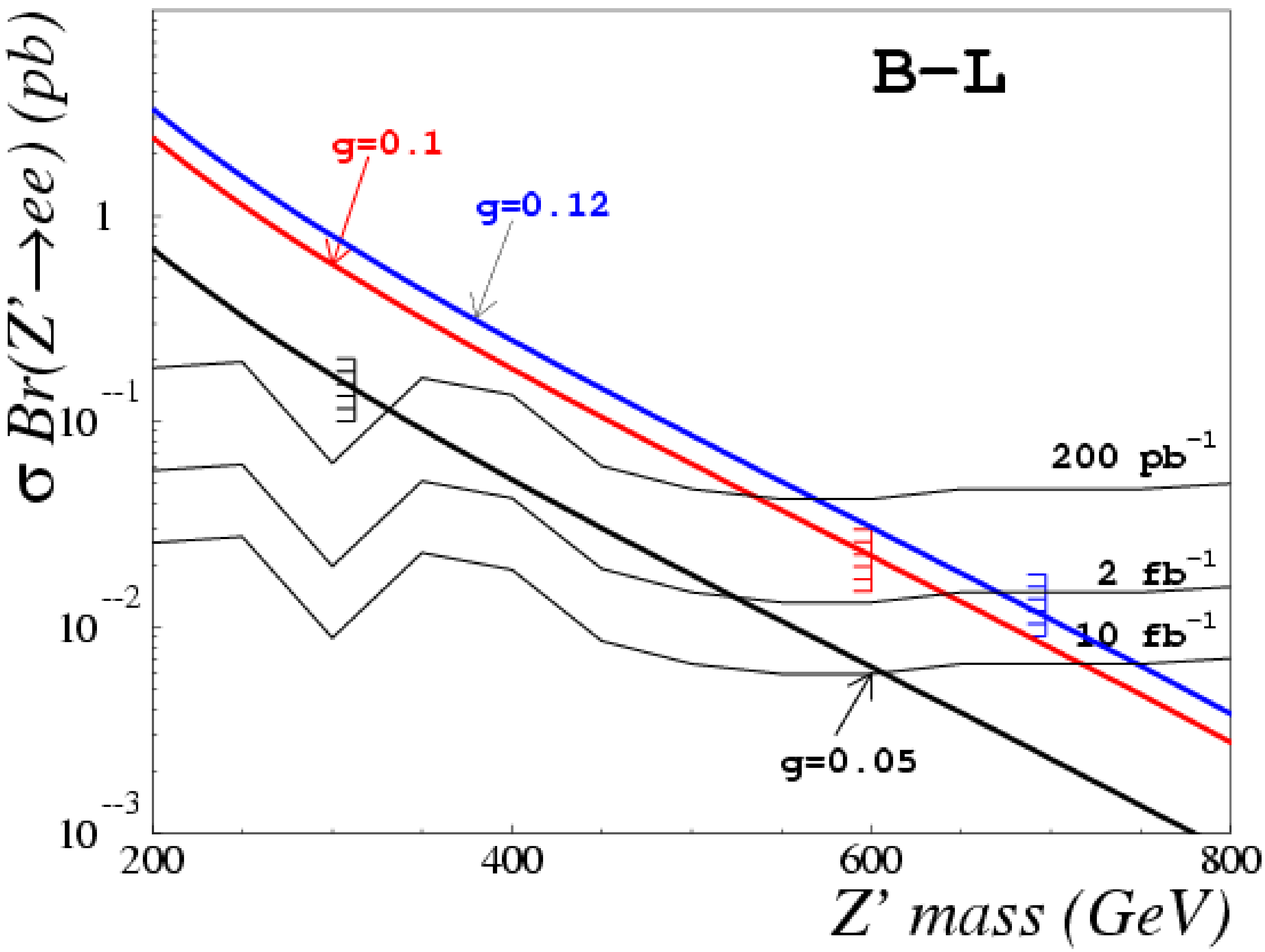
Z' searches at the Tevatron







Limits on Z': Tevatron versus LEPII



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

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
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				·	·	$(1+x)/3$	$x/15$

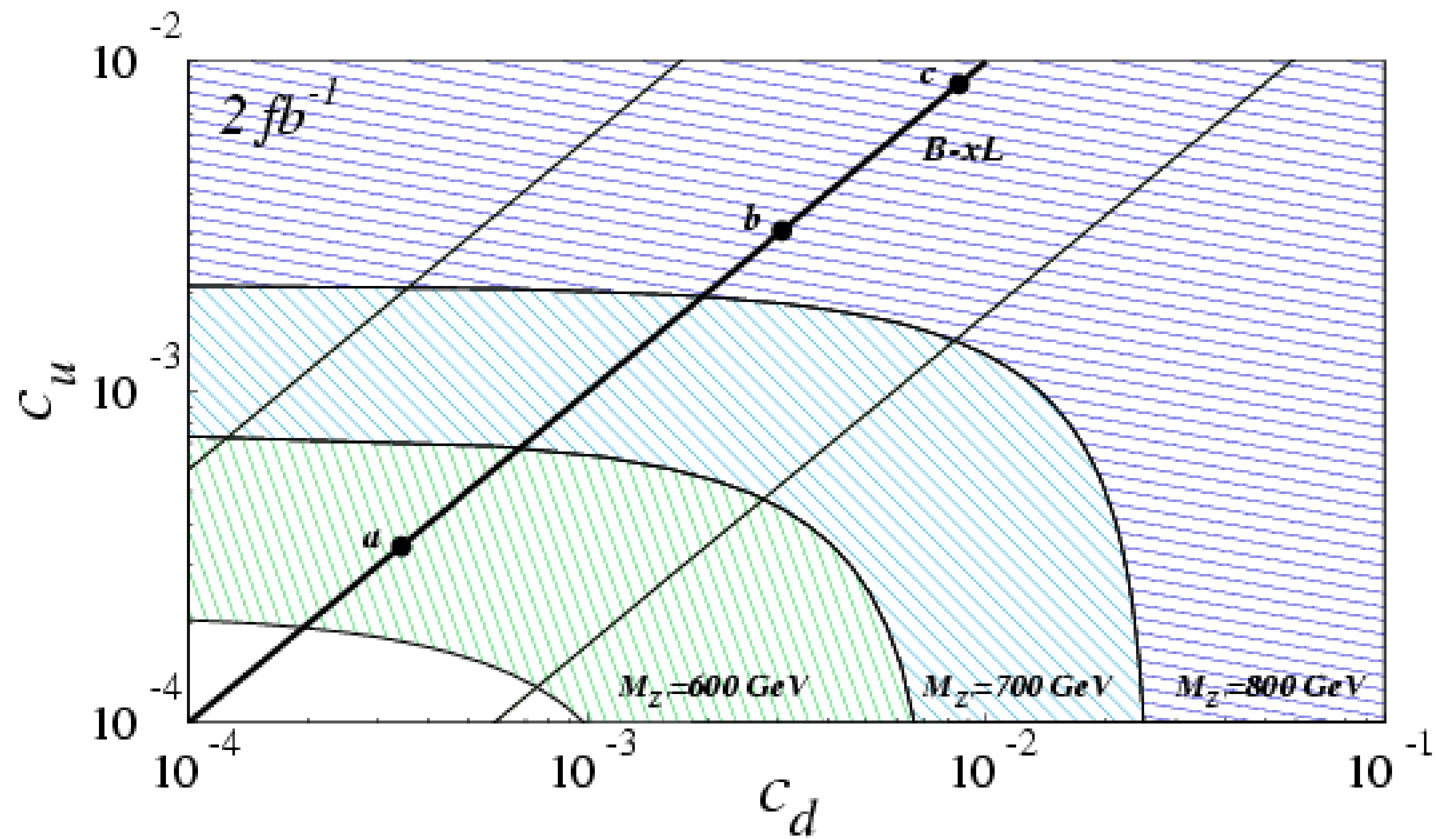
Homework # 2.1:
Identify the couplings of the Z' arising from the $SO(10) \to SU(5)$ GUT breaking.

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:

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



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

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.

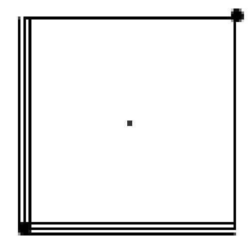
Homework # 2.2:
What are the analytical formulas for $w'_{u,d}$ at NLO in α_s?

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 $j + k$

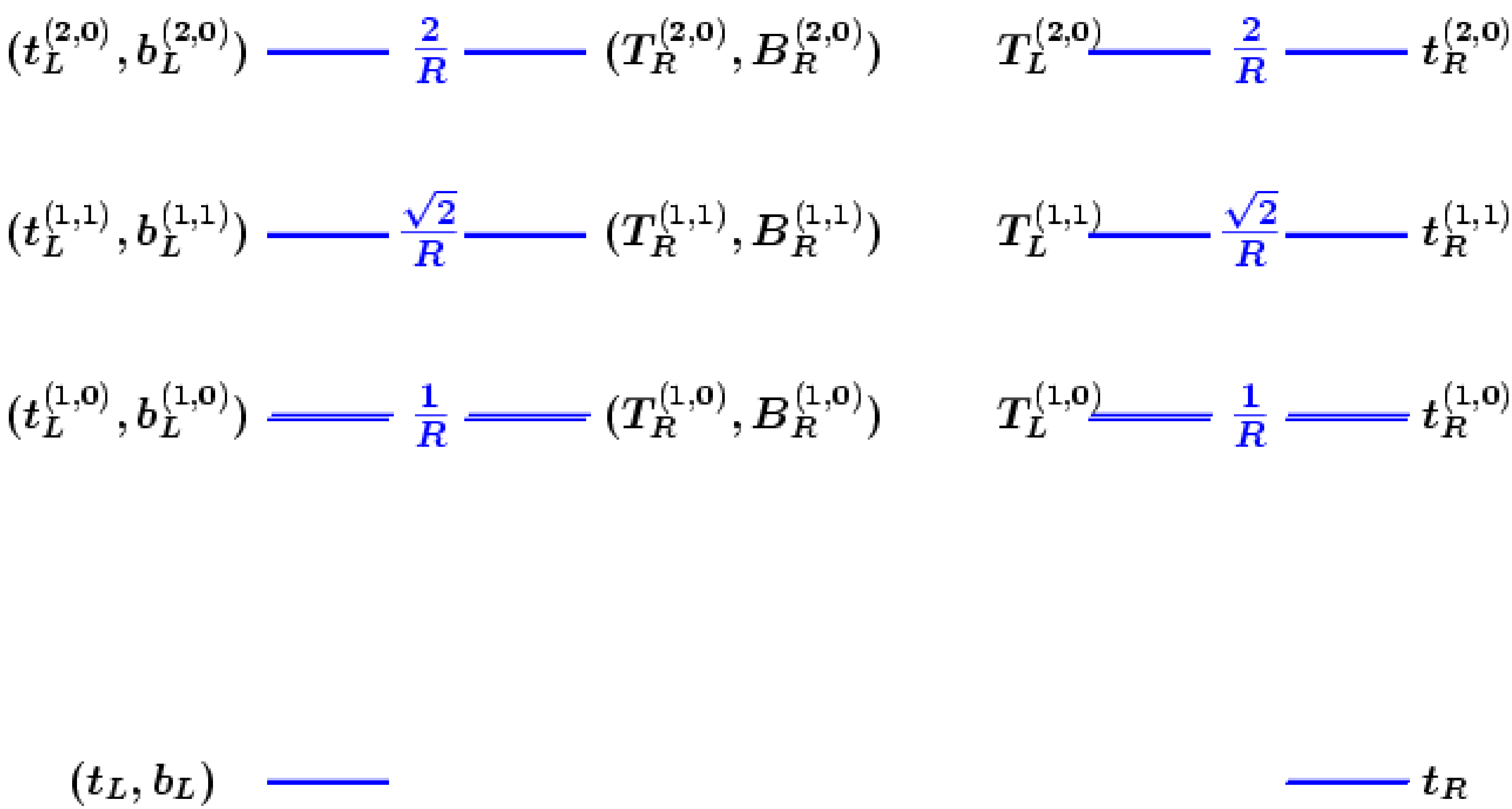
$\Rightarrow$ **(1,0) particles are produced only in pairs at colliders**

Kaluza-Klein spectrum of gauge bosons

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

⋮	⋮		⋮
$A_\mu^{(2,0)}$	$\frac{2}{R}$	$A_G^{(2,0)}$	$A_H^{(2,0)}$
$A_\mu^{(1,1)}$	$\frac{\sqrt{2}}{R}$	$A_G^{(1,1)}$	$A_H^{(1,1)}$
$A_\mu^{(1,0)}$	$\frac{1}{R}$	$A_G^{(1,0)}$	$A_H^{(1,0)}$
$A_\mu^{(0,0)}$			

Kaluza-Klein spectrum of quarks and leptons

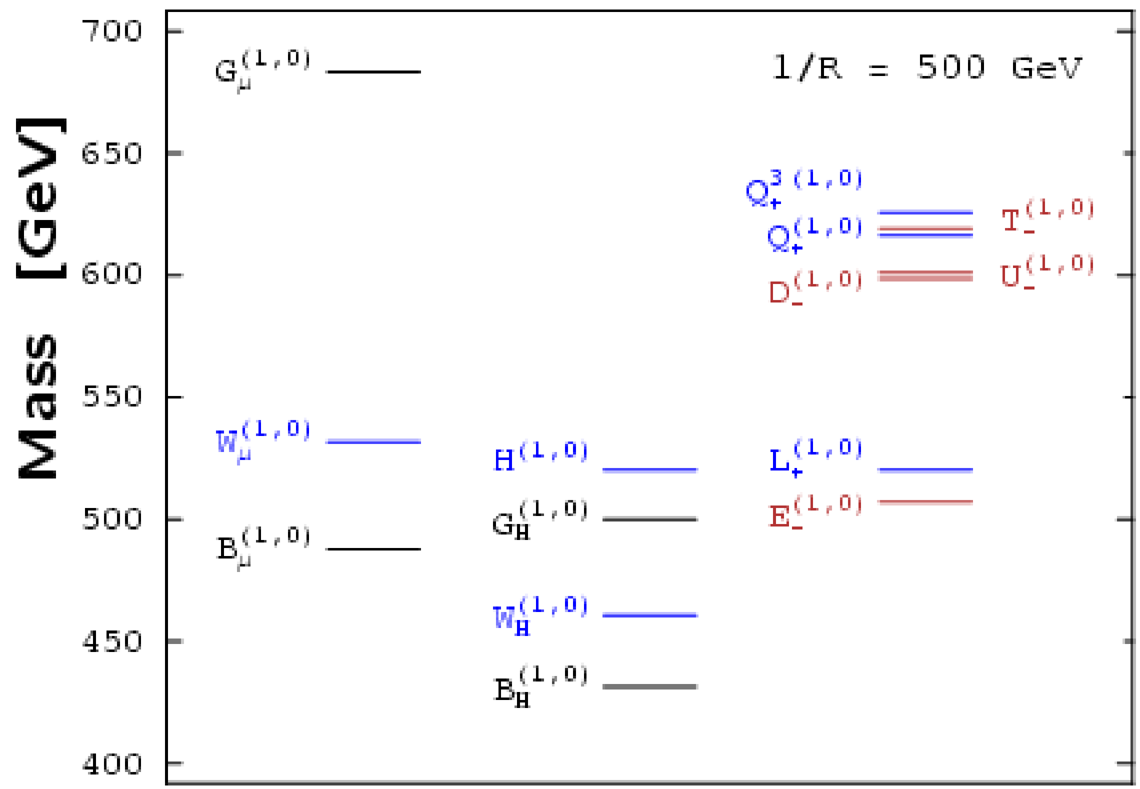


(1,0) modes have a tree-level mass of $1/R$, and KK parity $-$.

One-loop contributions and EWSB split the spectrum

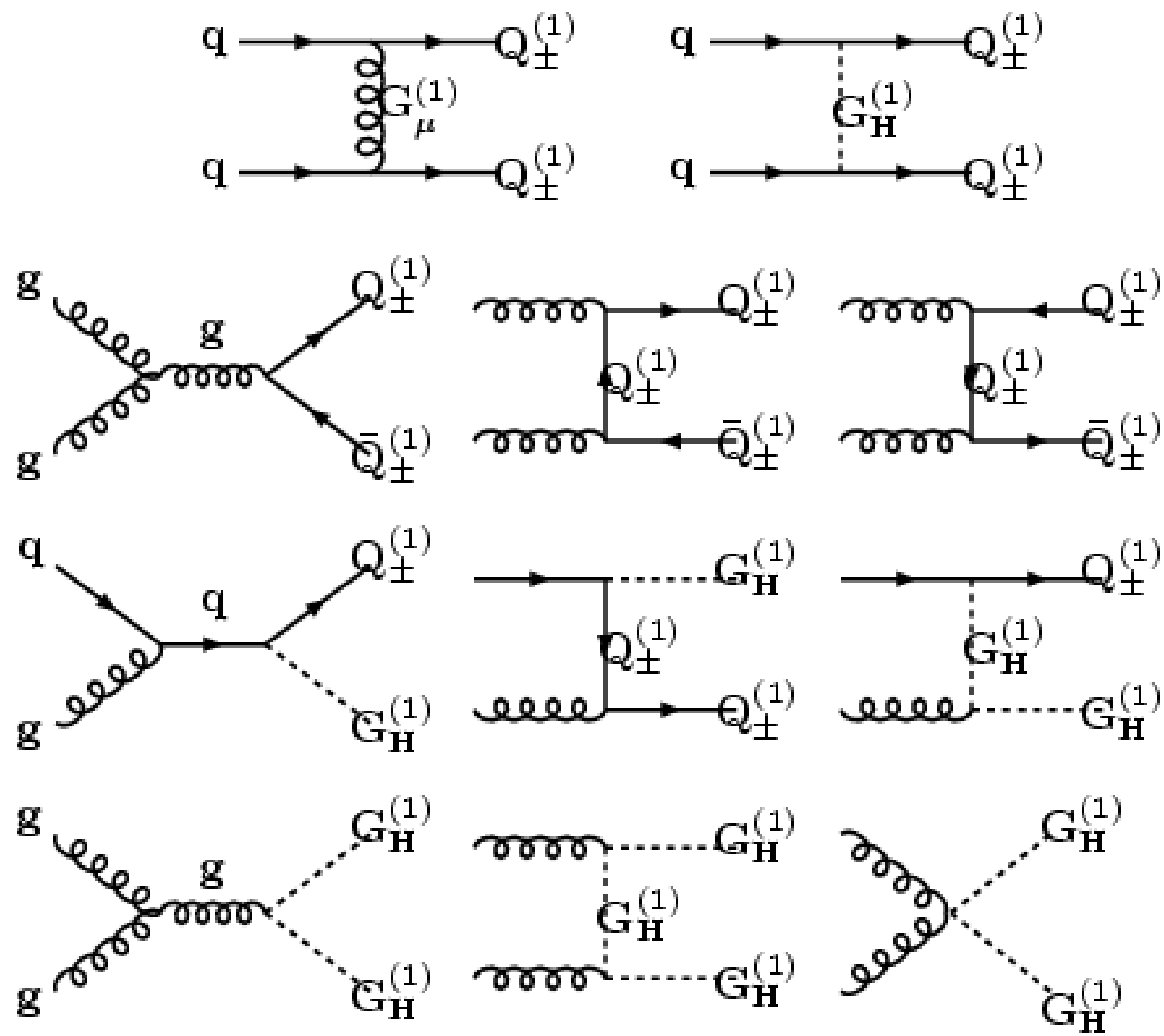
(Cheng, Matchev, Schmaltz, hep-ph/0204342 ; Ponton, Wang, hep-ph/0512304)

Mass spectrum of the (1,0) level:



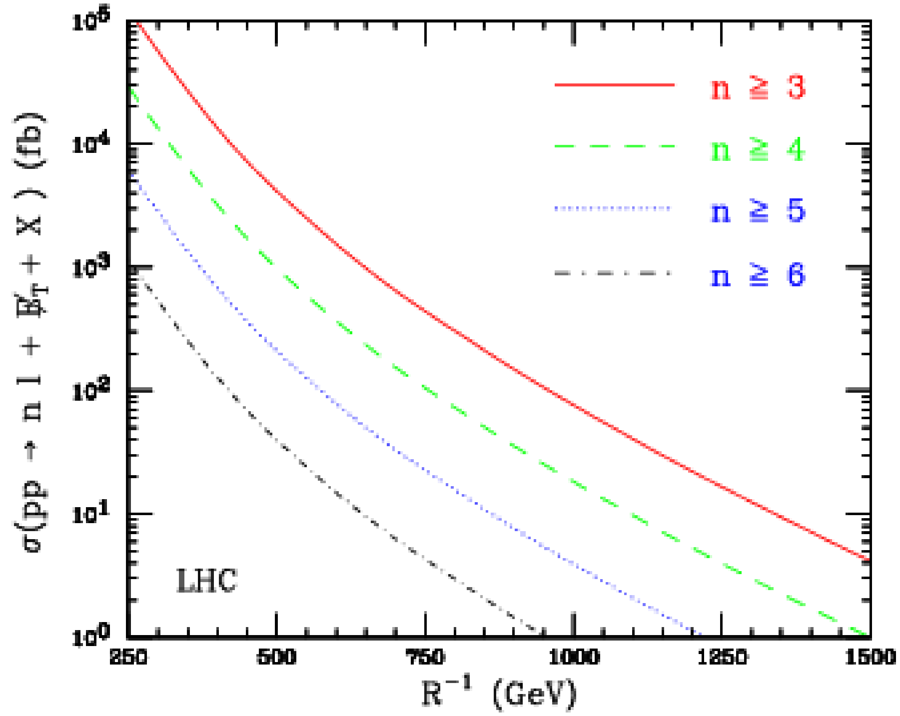
Homework 2.3: compute the branching fractions of the (1,0) particles.

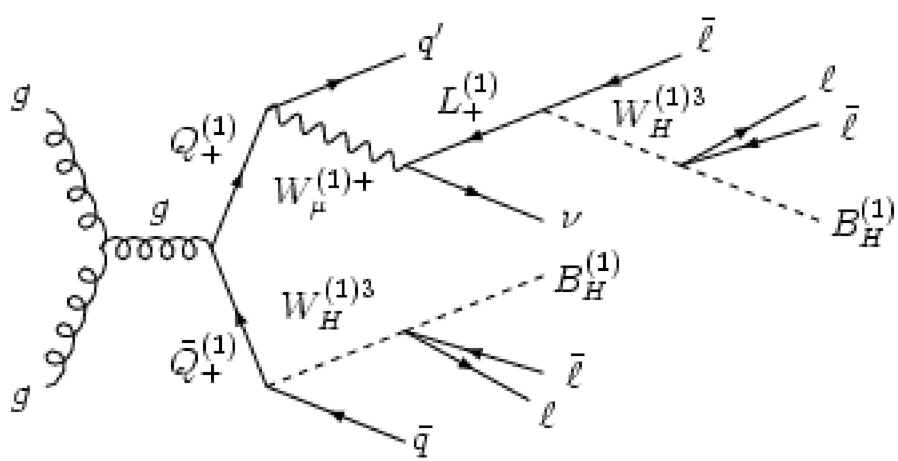
Production of (1,0) particles at the LHC



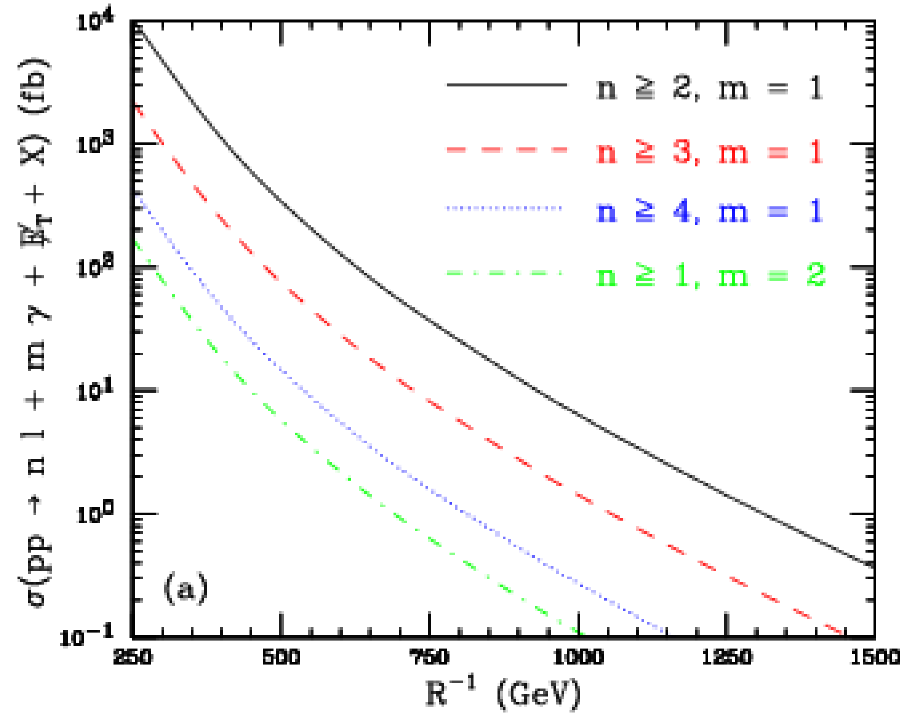
Use CalcHEP to compute cross section for (1,0) pair production.

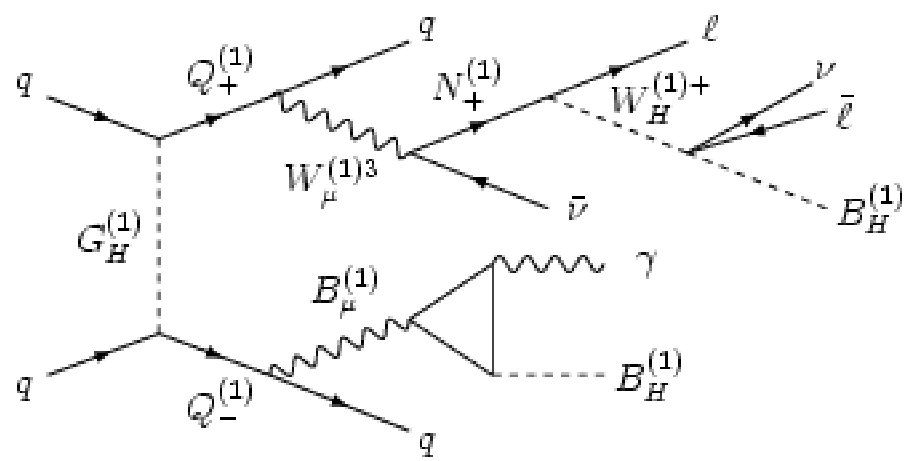
Multi-lepton signal at the LHC:





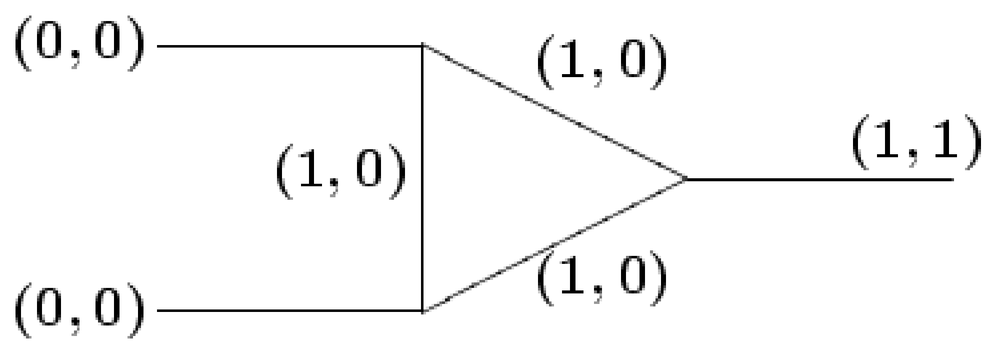
Leptons + photons at the LHC:





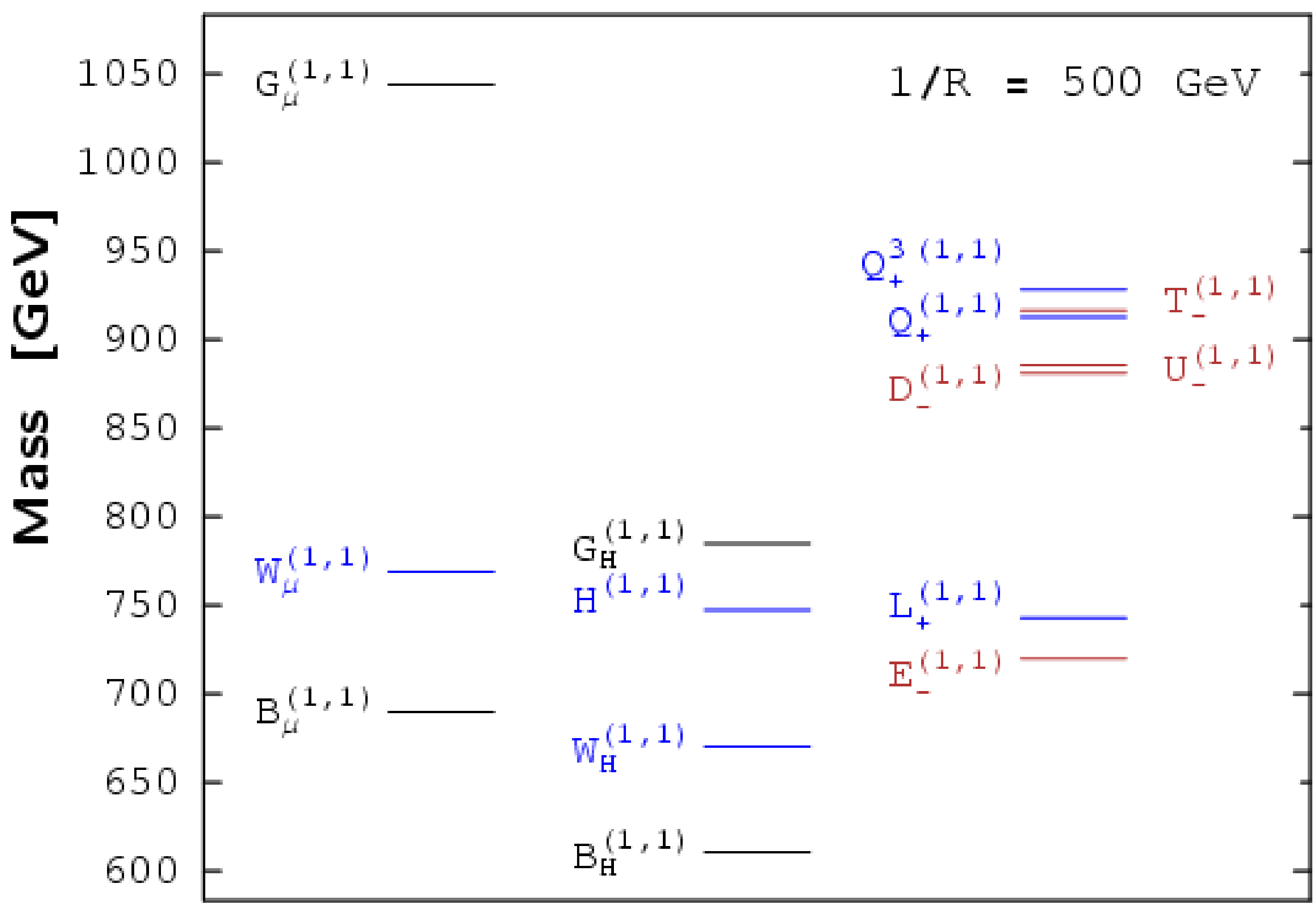
KK parity is conserved: $(-1)^{j+k}$

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:

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

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

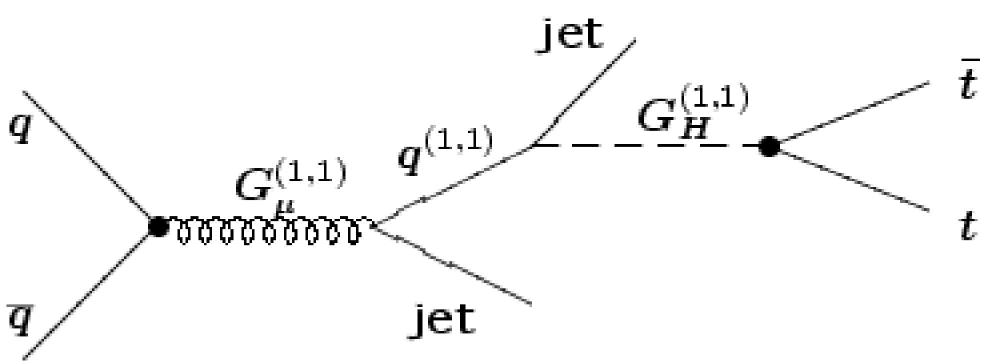
$\Rightarrow$ G_H, W_H and B_H couple to usual quarks and leptons proportional to the fermion mass!

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

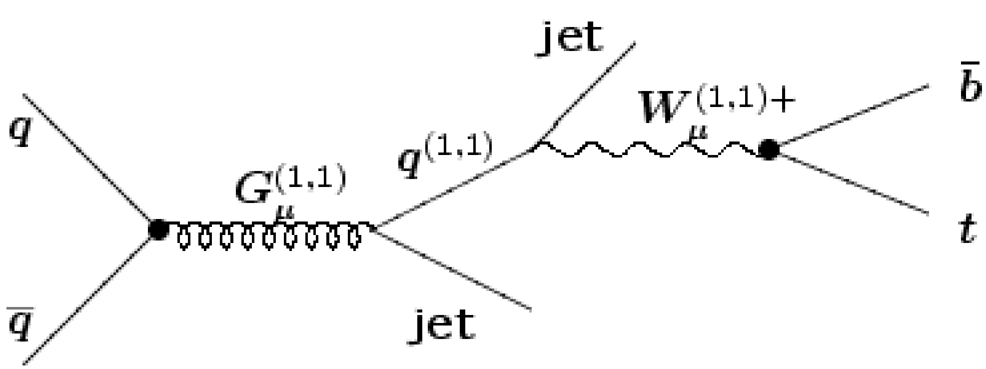
Signals of (1,1) particles at the LHC:

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):



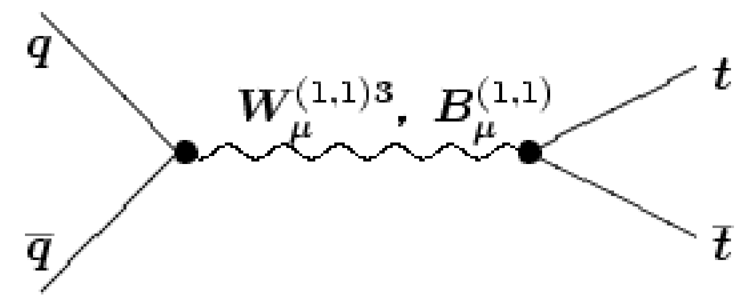
$\rightarrow$ $t\bar{b}$ resonance + 2 jets ($\sim 50-100$ GeV):



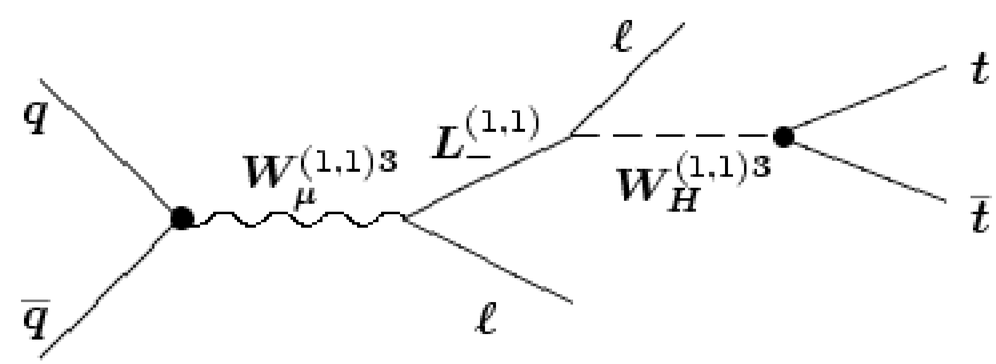
More signals at the LHC:

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

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

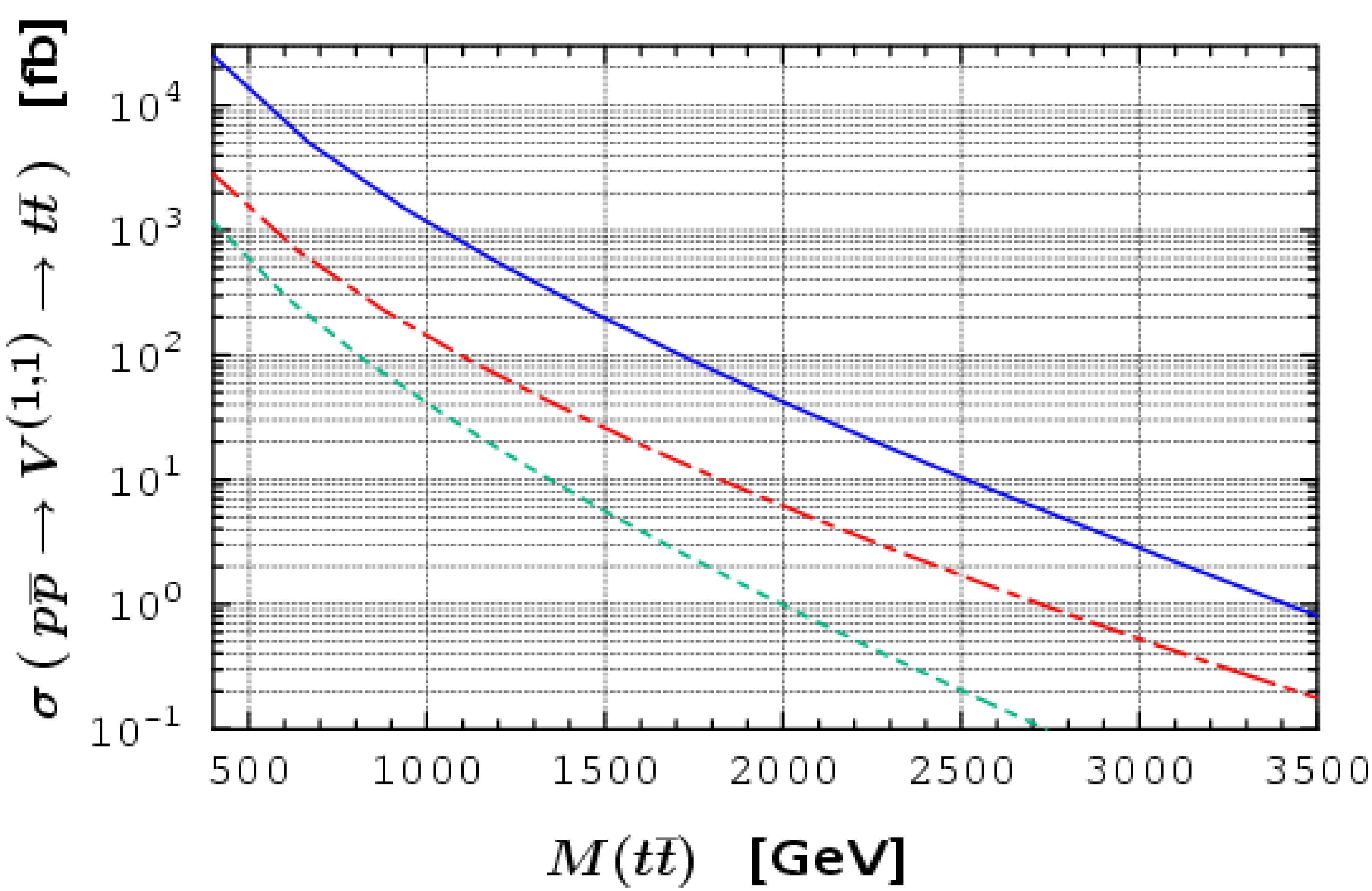


$\rightarrow$ $t\bar{t}$ resonance + 1 lepton ~ 70 GeV + 1 lepton ~ 20 GeV:



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

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



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