Beyond the Standard Model

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High Energy Physics has established that all known natural phenomena can be described by a local quantum field theory which is invariant under:

- 3+1 dimensional Lorentz transformations $SO(3,1)$ and translations
- $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge transformations

High Energy Physics has established that all known natural phenomena can be described by a local quantum field theory which is invariant under:

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$\Longrightarrow$ *all elementary particles belong to certain representations of the Lorentz and gauge groups:*

Spin-1 bosons **Spin-1/2 fermions**

$$\left\{ \begin{array}{rl} G^\mu : & (8, 1, \ \ 0) \\ W^\mu : & (1, 3, \ \ 0) \\ B^\mu : & (1, 1, \ \ 0) \end{array} \right.$$

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

Spin-2: graviton **Dark matter particle (spin =?)**

Electroweak symmetry

The laws of physics are invariant under $SU(2)_W \times U(1)_Y$ gauge transformations $\longrightarrow$ there are 4 gauge bosons: γ, $W^\pm$, Z^0

Photon mass term, $A_\mu A^\mu$, is not gauge invariant $\Rightarrow$ γ is massless!

Where are the $W^\pm$ and Z^0 masses coming from?

Electroweak symmetry is spontaneously broken

(Similar to superconductivity!)

Lagrangian has an $SU(2)_W \times U(1)_Y$ gauge symmetry

Vacuum has only a $U(1)_{\mathrm{em}}$ gauge symmetry.

$\Rightarrow$ **Some spin-0 field has a Vacuum Expectation Value ($v_h \simeq 174$ GeV, "electroweak scale")**

For the W and Z, the vacuum is partially opaque.

We know that $SU(2)_W \times U(1)_Y \to U(1)_{\rm em}$
$\Rightarrow$ $W^\pm$ and Z have not only transverse polarizations, but also longitudinal ones: 3 spin-0 states have been 'eaten'.

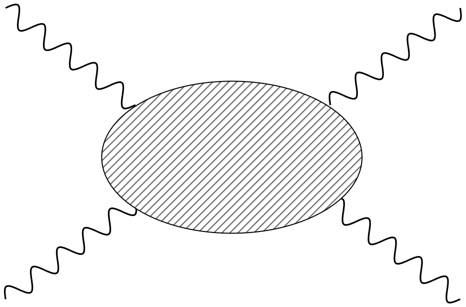
(Higgs mechanism)

What is the origin of electroweak symmetry breaking?

We do not know:

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

$W_L^+ W_L^-$ 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

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 ?*

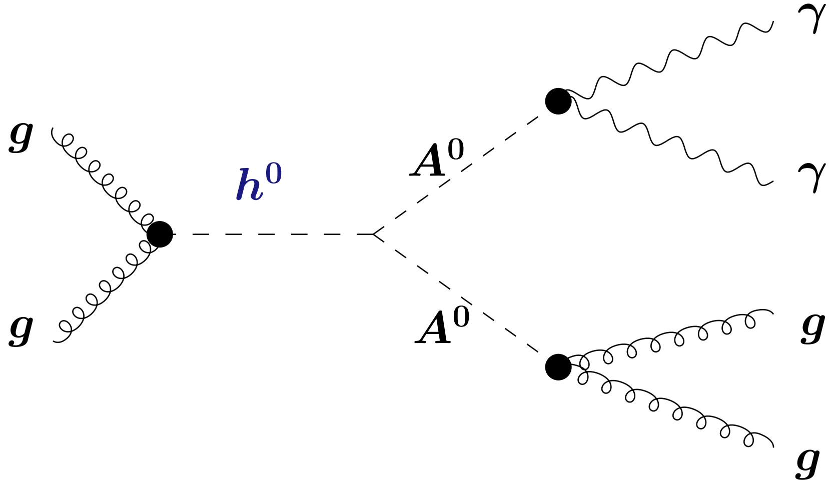
Nonstandard Higgs decays

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

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

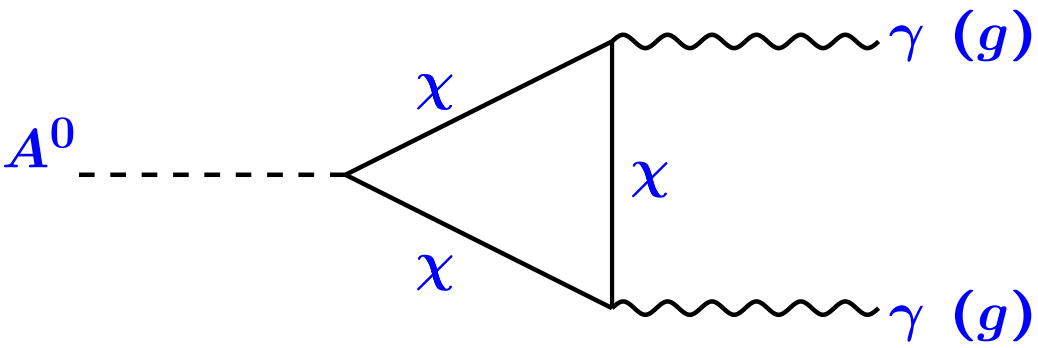
$$\frac{c\,v}{2} h^0 A^0 A^0 \text{ coupling } \Rightarrow \Gamma(h^0 \to A^0 A^0) = \frac{c^2\,v^2}{32\pi M_h}\left(1 - 4\frac{M_A^2}{M_h^2}\right)^{1/2}$$

At the LHC, h^0 would be produced as in the standard model, but its dominant decay mode would be unusual:



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

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

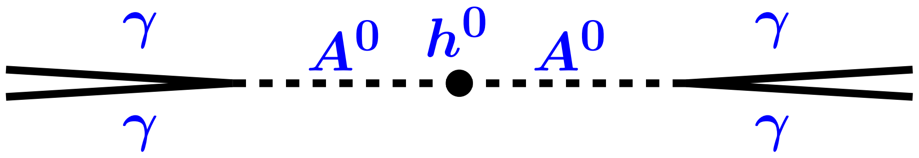
Case 2) **If χ is electrically-charged color singlet**

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

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

(Dobrescu, Landsberg, Matchev, hep-ph/0005308, Chang, Fox, Weiner, hep-ph/0608310, ...)

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



What is the role of the top quark in electroweak symmetry breaking?

Is the Higgs boson an elementary particle, or a composite one?

The two top quarks:

- **"left-handed" top** *(feels the weak interaction)*
- **"right-handed" top** *(no interaction with* $\boldsymbol{W^{\pm}}$*)*

$t_{\boldsymbol{L}}$

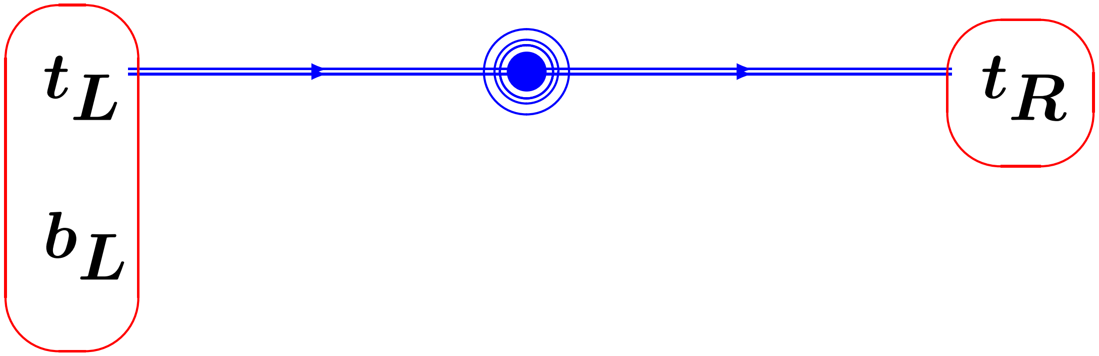
$b_{\boldsymbol{L}}$

$t_{\boldsymbol{R}}$

The two top quarks:

- **“left-handed” top** *(feels the weak interaction)*
- **“right-handed” top** *(no interaction with* $W^{\pm}$*)*

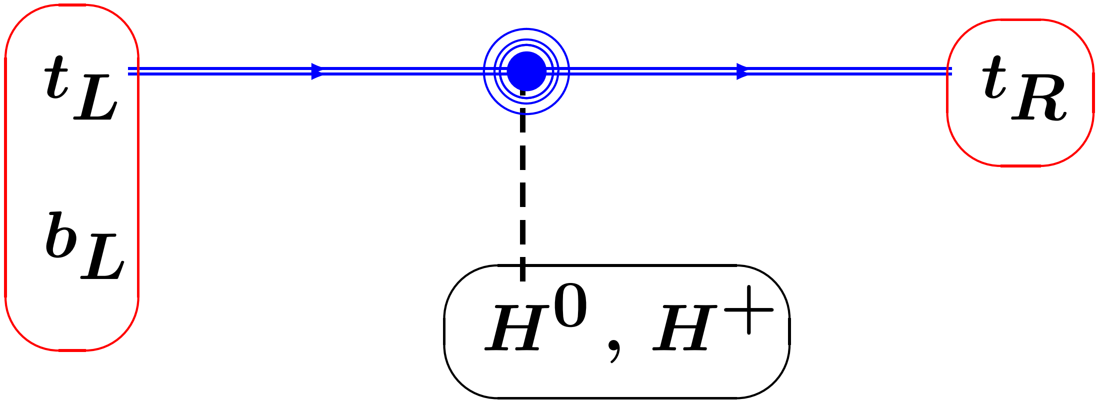
Top mass: t_L **turns into** t_R **and vice-versa**



Top quark gets a mass from its interaction with the vacuum:

$\lambda_t \, \bar{t}_R \langle H^0 \rangle t_L$, $\langle H^0 \rangle \approx 174$ **GeV**

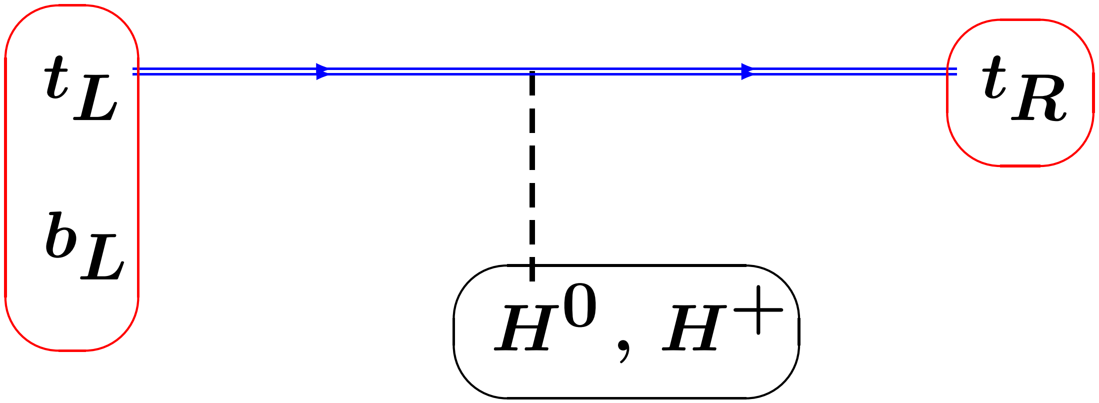
Measured top mass $\Rightarrow$ **coupling constant is** $\lambda_t \approx 1$.



The coupling of the top quark to the Higgs field changes with the distance (similar to vacuum polarization in electrodynamics).

In a world of only top and Higgs:

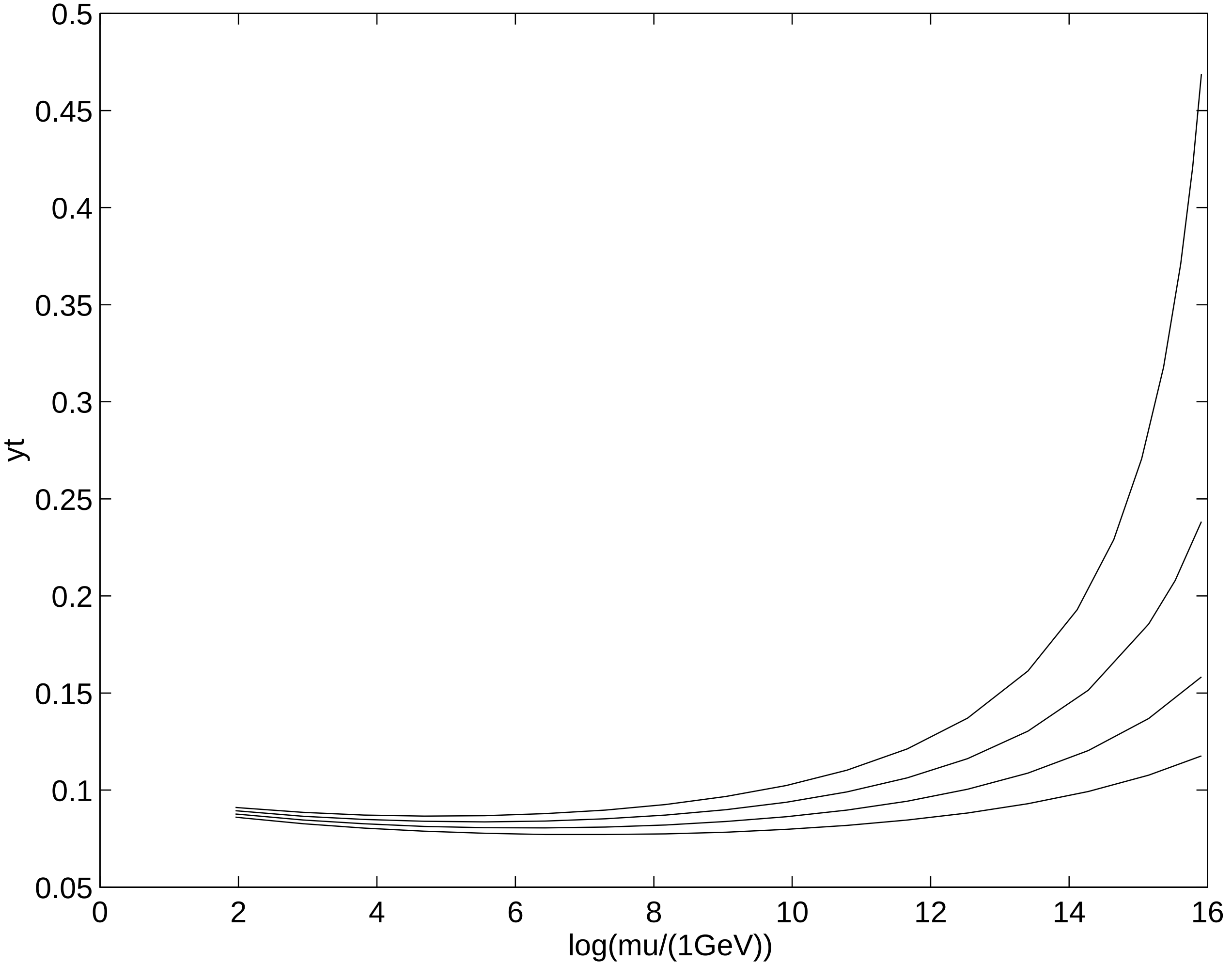
$$\lambda_t\,(\mu) = \frac{\lambda_t(m_t)}{\sqrt{1 - \frac{9\lambda_t^2(m_t)}{64\pi^2}\ln\frac{\mu}{m_t}}}$$



Infrared Fixed Point for λ_t

(C. Hill, 1981, ...)

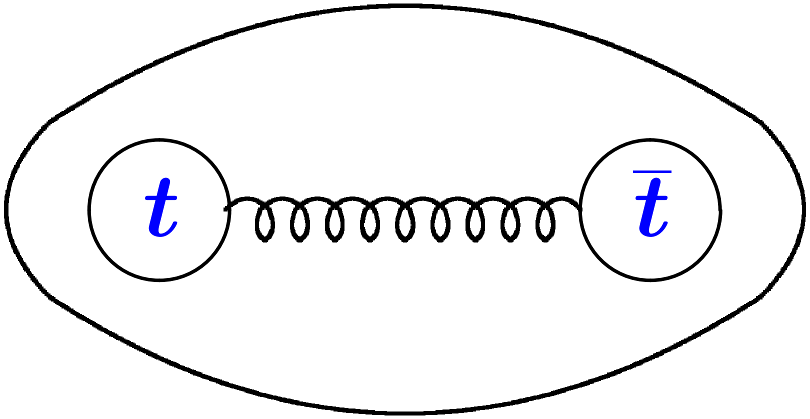
$$\frac{\lambda_t^2}{4\pi}$$



$$\log\left(\frac{\mu}{1\ \mathrm{GeV}}\right)$$

Top condensation $\Rightarrow$ Higgs boson is a $\bar{t}t$ bound state!
(Bardeen, Hill, Lindner, 1990, ...)

Binding may be due to some strongly-interacting heavy gauge bosons



New heavy quarks (vectorlike) could accelerate the λ_t running:
scale of Higgs compositeness may be as low as a few TeV.

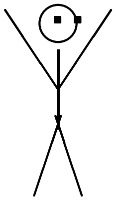
Explicit models: top seesaw, QCD in extra dimensions, ...

Energy

? ??????????????????????

~ 1 **TeV ?**

New Physics



~ 100 **GeV**

Standard Model

very weakly interacting particles???

- **Probing the unknown ...**

CMS and ATLAS will explore physics at distances of $\sim \mathbf{10^{-19}}$*m.*

This may be qualitatively different than the physics at larger distances, probed by CDF and D0.

- **It is hard to make predictions!**

There are many theories for physics beyond the SM.

No theory is sufficiently successful so far in explaining the puzzles of the SM $\longrightarrow$ *we should consider a wide range of theories.*

Even within well defined models, a small change in parameters may lead to widely different collider signatures.

- **Best attitude: search as many final states as possible, try to be “model independent”.**

Z' gauge boson

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.

Three electrically-neutral gauge bosons: γ, Z, Z'.

"Nonexotic" Z' (*T. Appelquist, B. Dobrescu, A. Hopper: hep-ph/0212073*)

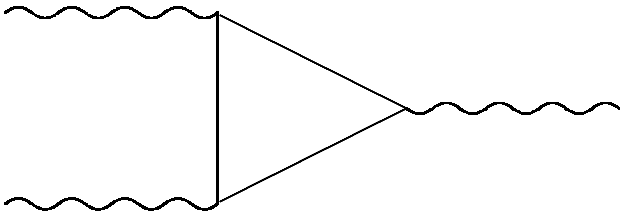
Assume:

- generation-independent charges,
- quark and lepton masses as in the standard model,
- no new fermions other than an arbitrary number of ν_R's

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

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
quark doublet: $q_L^i = (u_L^i, d_L^i)$	3	2	$1/3$	z_q
right-handed up-type quark: u_R^i	3	1	$4/3$	z_u
right-handed down-type quark: d_R^i	3	1	$-2/3$	$2z_q - z_u$
lepton doublet: l_L^i	1	2	-1	$-3z_q$
right-handed charged lepton: 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

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

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

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

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

Diophantine equation!

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

Nontrivial solutions only if the number of ν_R is $n \geq 3$.

(*e.g.* $z_1 = z_2 = z_3 = -4z_q + z_u$)

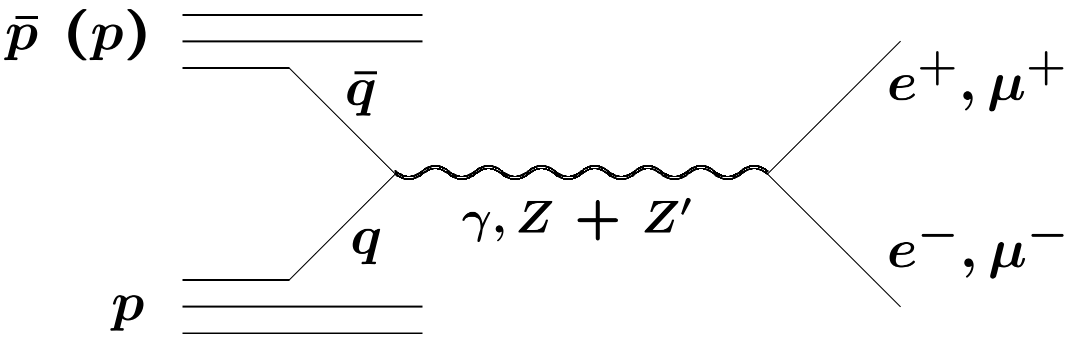
Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

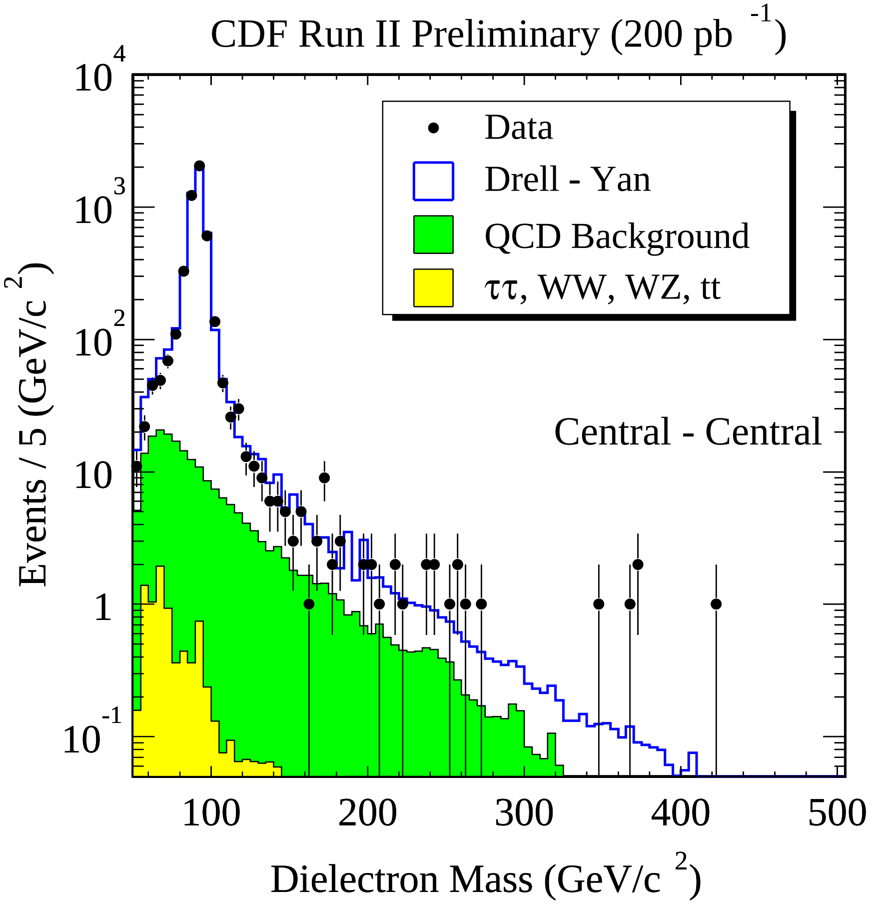
Charges given by the baryon minus lepton number:

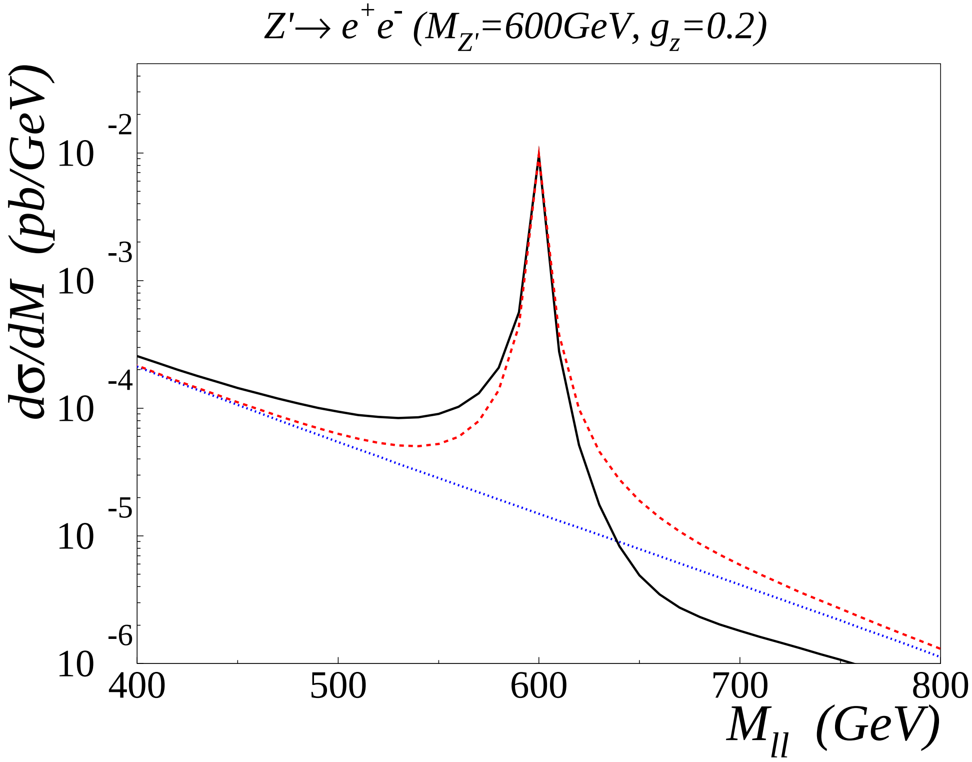
$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} \ , \quad z_H = 0$$

no Z'-Z mixing (tree level) $\Rightarrow$ no constraints from electroweak measurements

Z' searches at the Tevatron and the LHC:







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:

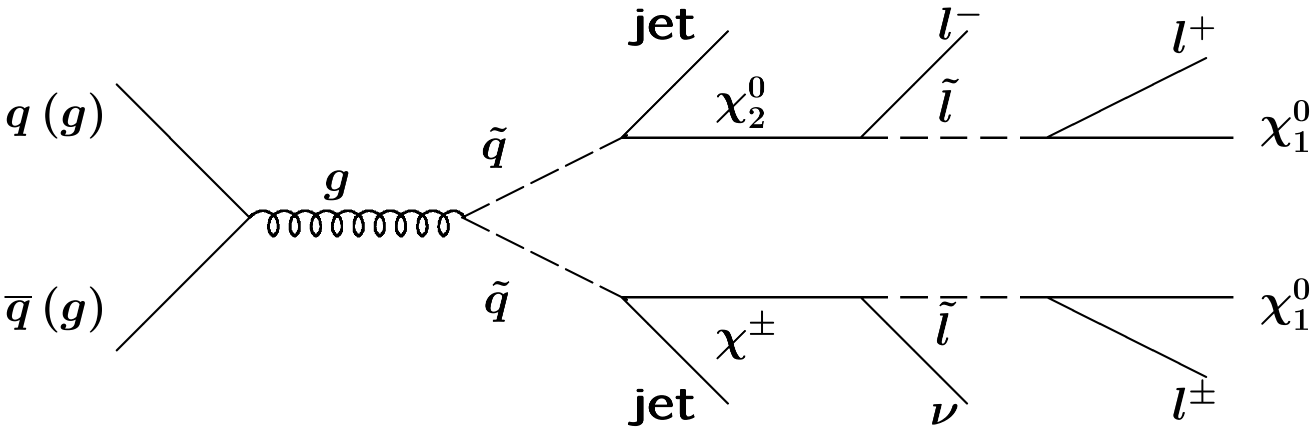
pair production of colored odd particles,

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 + $\not\!\!E_T$**

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

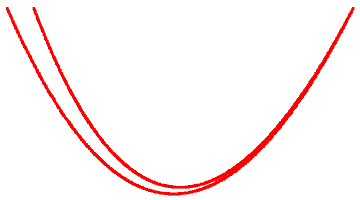
$$\begin{array}{cccc} \textit{gauge} & \textit{spacetime} & \textit{global} & \textit{discrete} \\ \underbrace{SU(3)\times SU(2)\times U(1)}_{SU(5)\,\subset\, SO(10)}\ ; & SO(3,1)\ ; & U(1)_B\ ; & \mathrm{CPT} \end{array}$$

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

$$\begin{array}{ccccccc} \textit{gauge} & & \textit{spacetime} & & \textit{global} & & \textit{discrete} \\ SU(3)\times SU(2)\times U(1) & ; & SO(3,1) & ; & U(1)_B & ; & \text{CPT} \end{array}$$

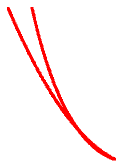


$$SO(5,1)$$

6D Lorentz symmetry

Fermions:

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



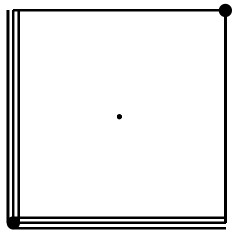
required by global $SU(2)_W$ anomaly cancellation in 6D

Two Universal Extra Dimensions

G. Burdman, B. Dobrescu, E. Ponton, hep-ph/0601186

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: $\sqrt{j^2 + k^2}/R$

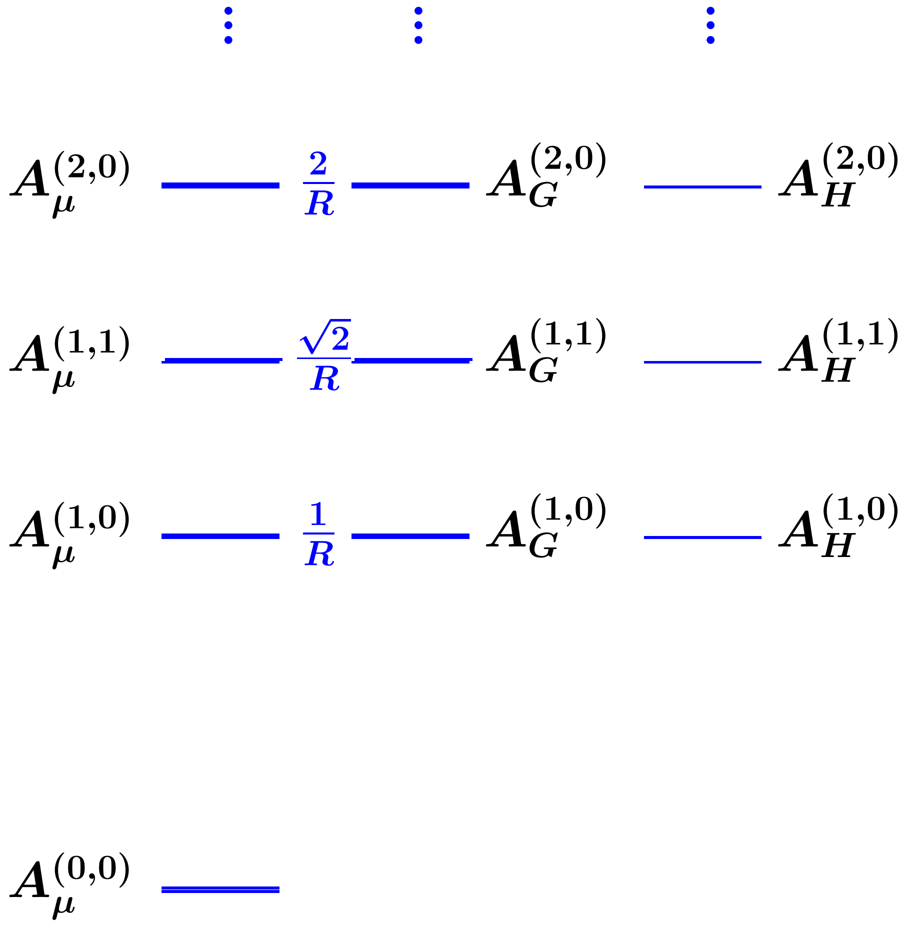
Momentum conservation ⟶ KK-parity given by $j + k$

⇒ tree-level exchange of KK particles does not contribute to currently measurable quantities

⇒ (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 $A_\mu^{(j,k)}(x^\nu)$.



$\vdots$ $\vdots$ $\vdots$

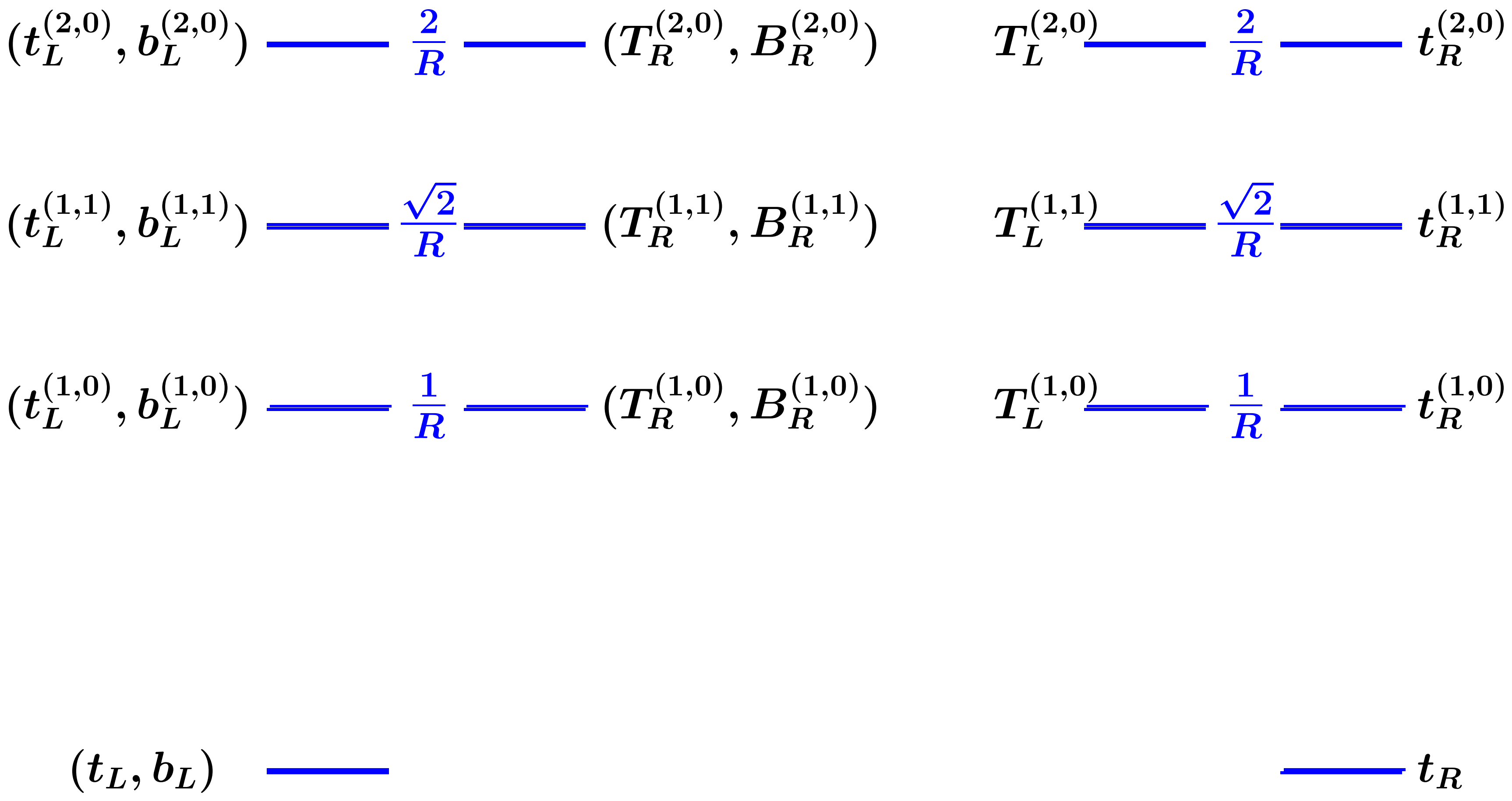
$A_\mu^{(2,0)}$ $\frac{2}{R}$ $A_G^{(2,0)}$ $A_H^{(2,0)}$

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

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

$A_\mu^{(0,0)}$

Kaluza-Klein spectrum of quarks and leptons



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

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

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

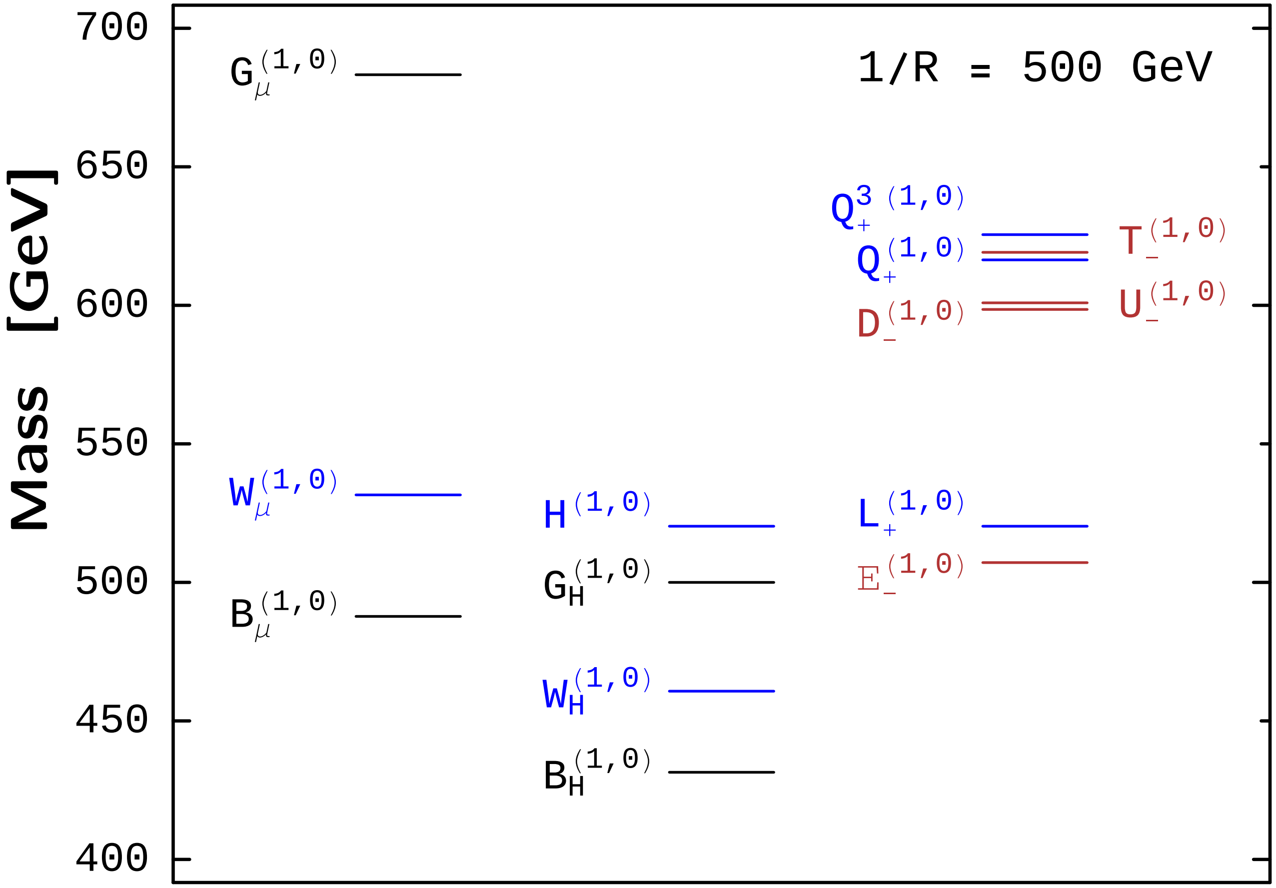
(t_L, b_L) t_R

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

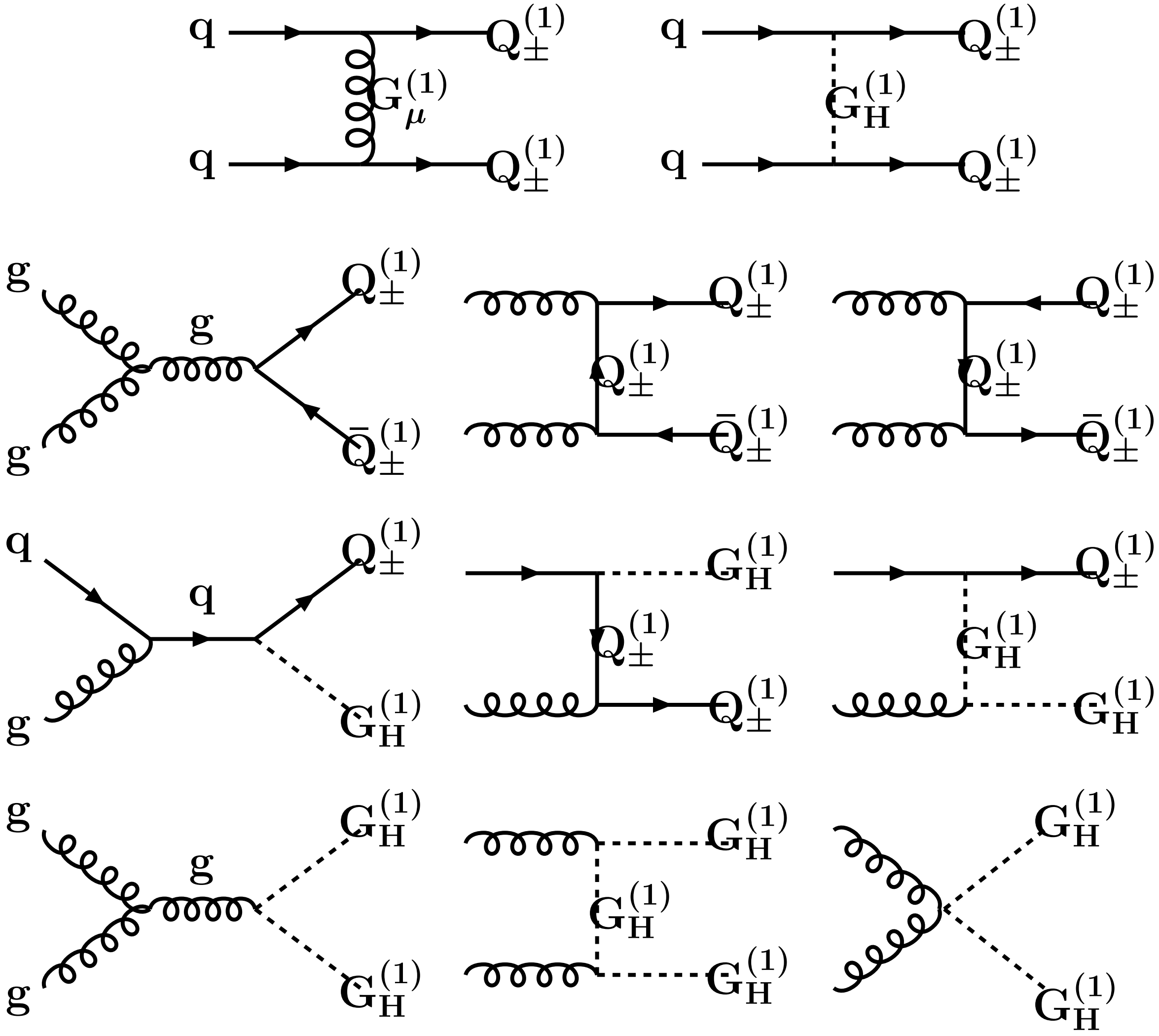
One-loop contributions and EWSB split the spectrum

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

Mass spectrum of the (1,0) level:



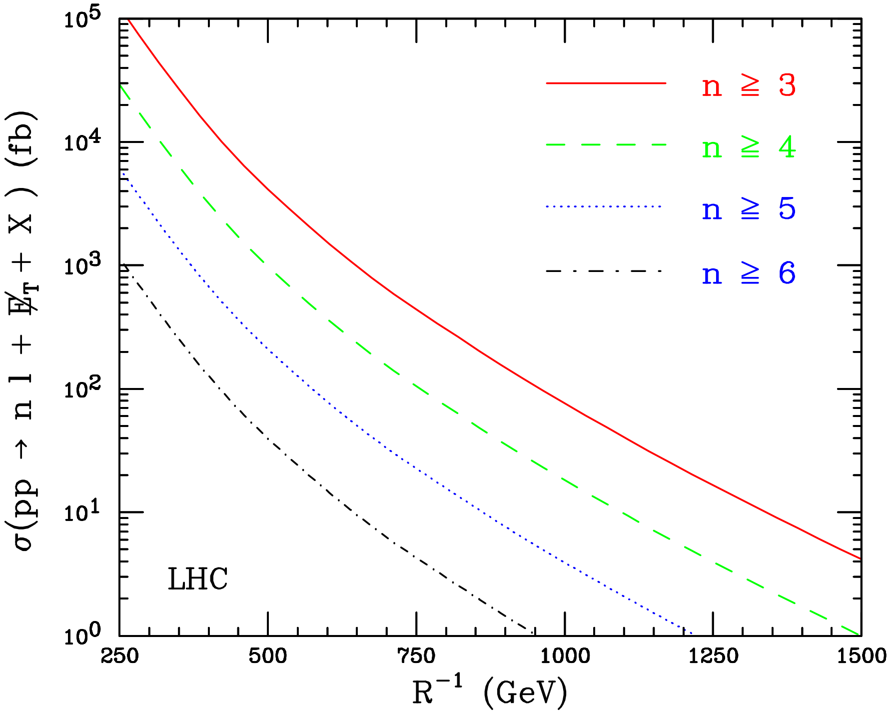
Production of (1,0) particles at the LHC

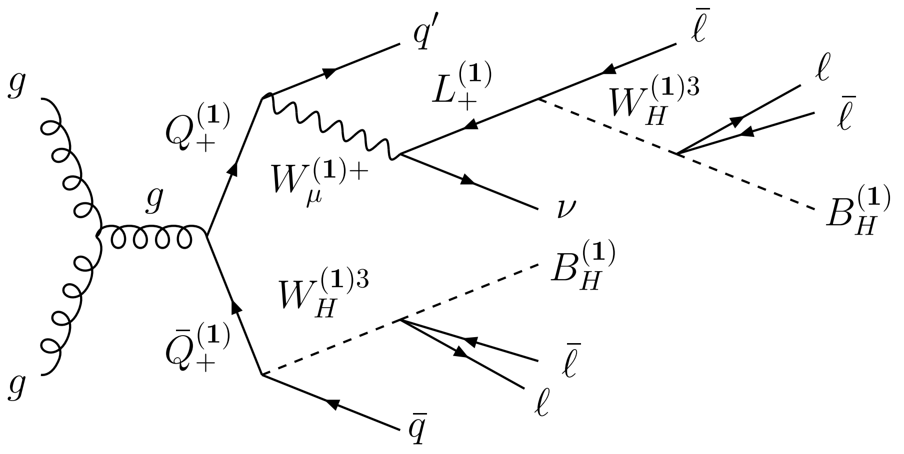


Use CalcHEP to compute cross section for (1,0) pair production.

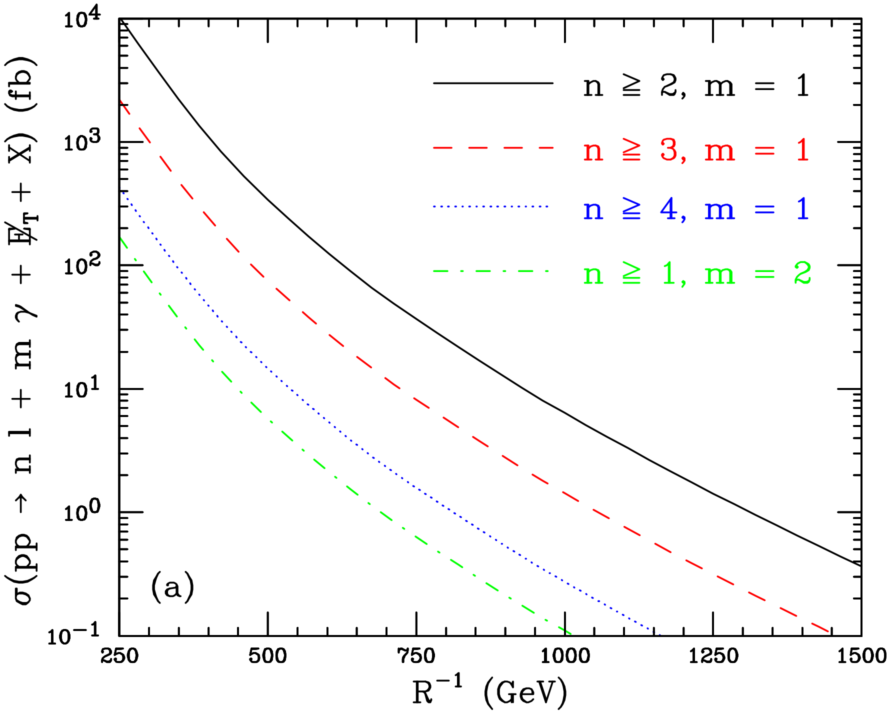
Work with K.C. Kong and Rakhi Mahbubani (hep-ph/0703231).

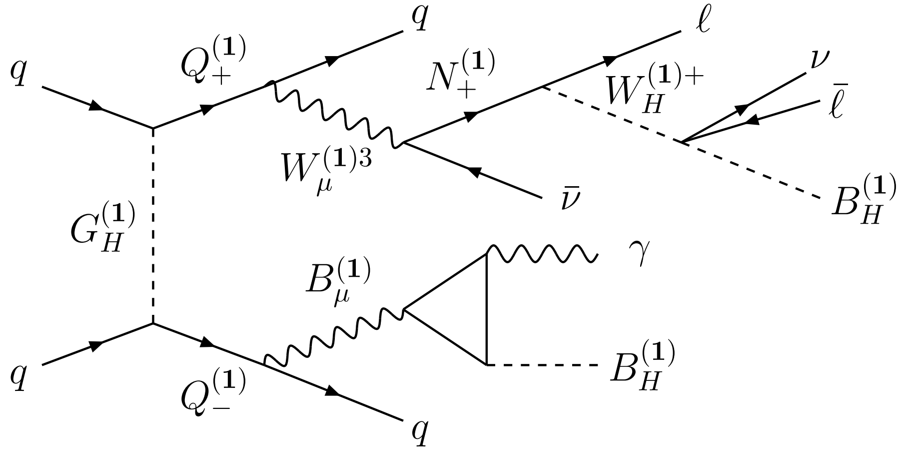
Multi-lepton signal at the LHC:





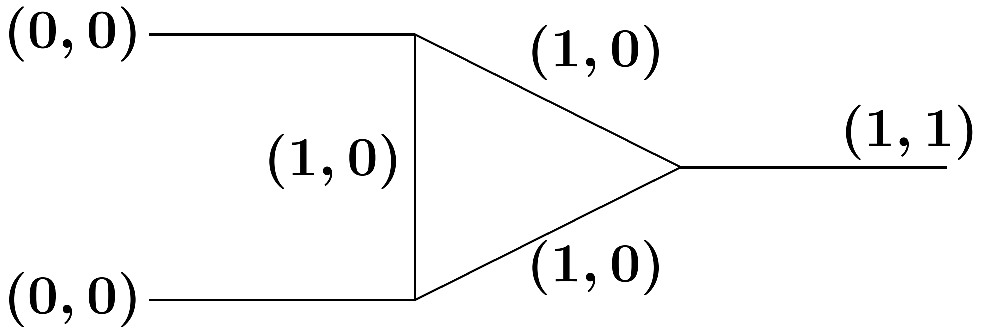
Leptons + photons at the LHC:





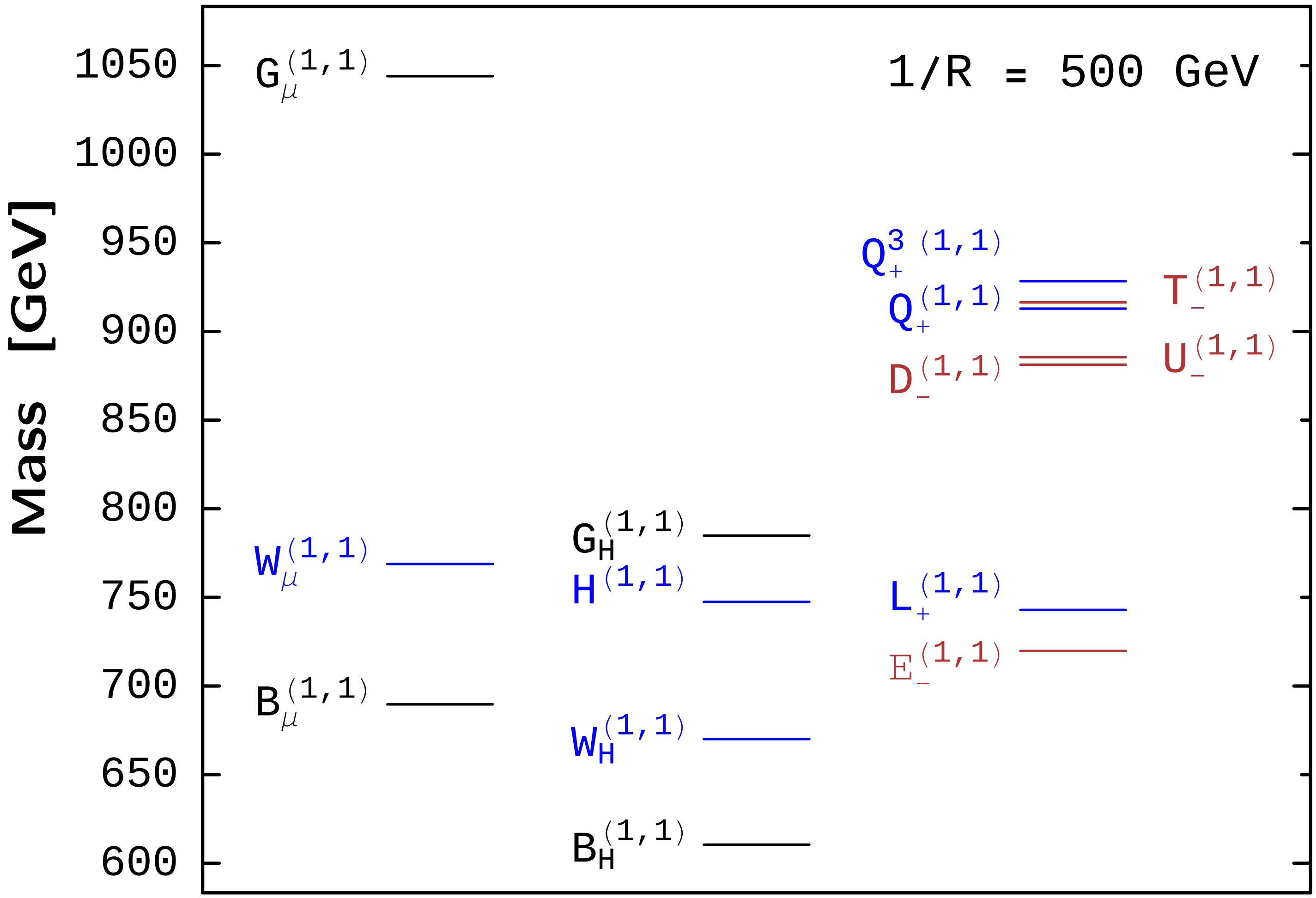
KK parity is conserved: $(-1)^{j+k}$

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.

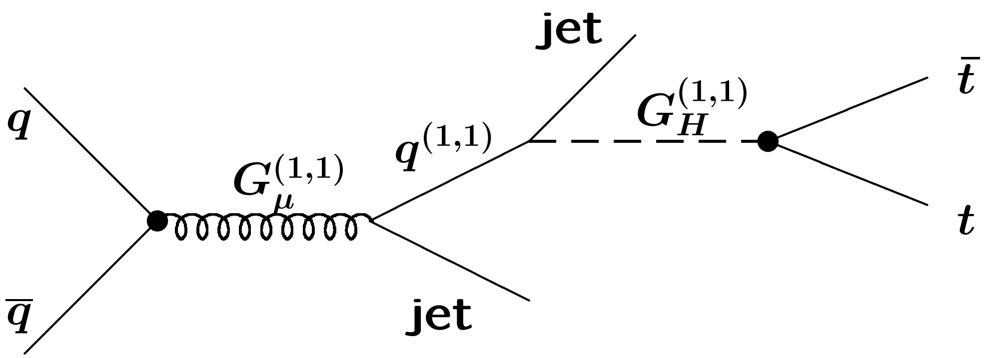
$\Rightarrow$ G_H, W_H and B_H couple to usual quarks and leptons proportional to the fermion mass!

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

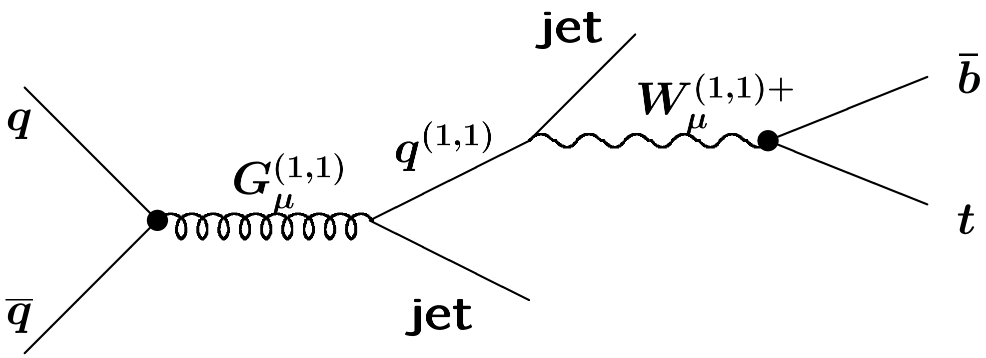
Signals of (1,1) particles at the LHC:

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):



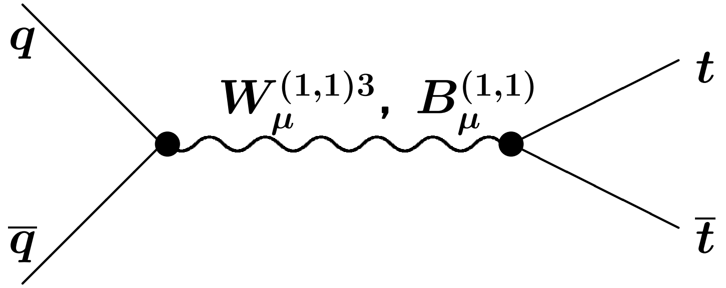
$\rightarrow$ $t\bar{b}$ resonance + 2 jets ($\sim 50 - 100$ GeV):



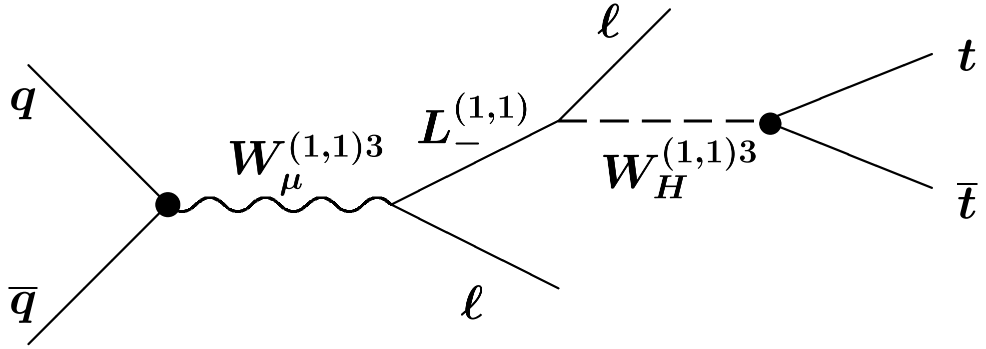
More signals at the LHC:

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

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

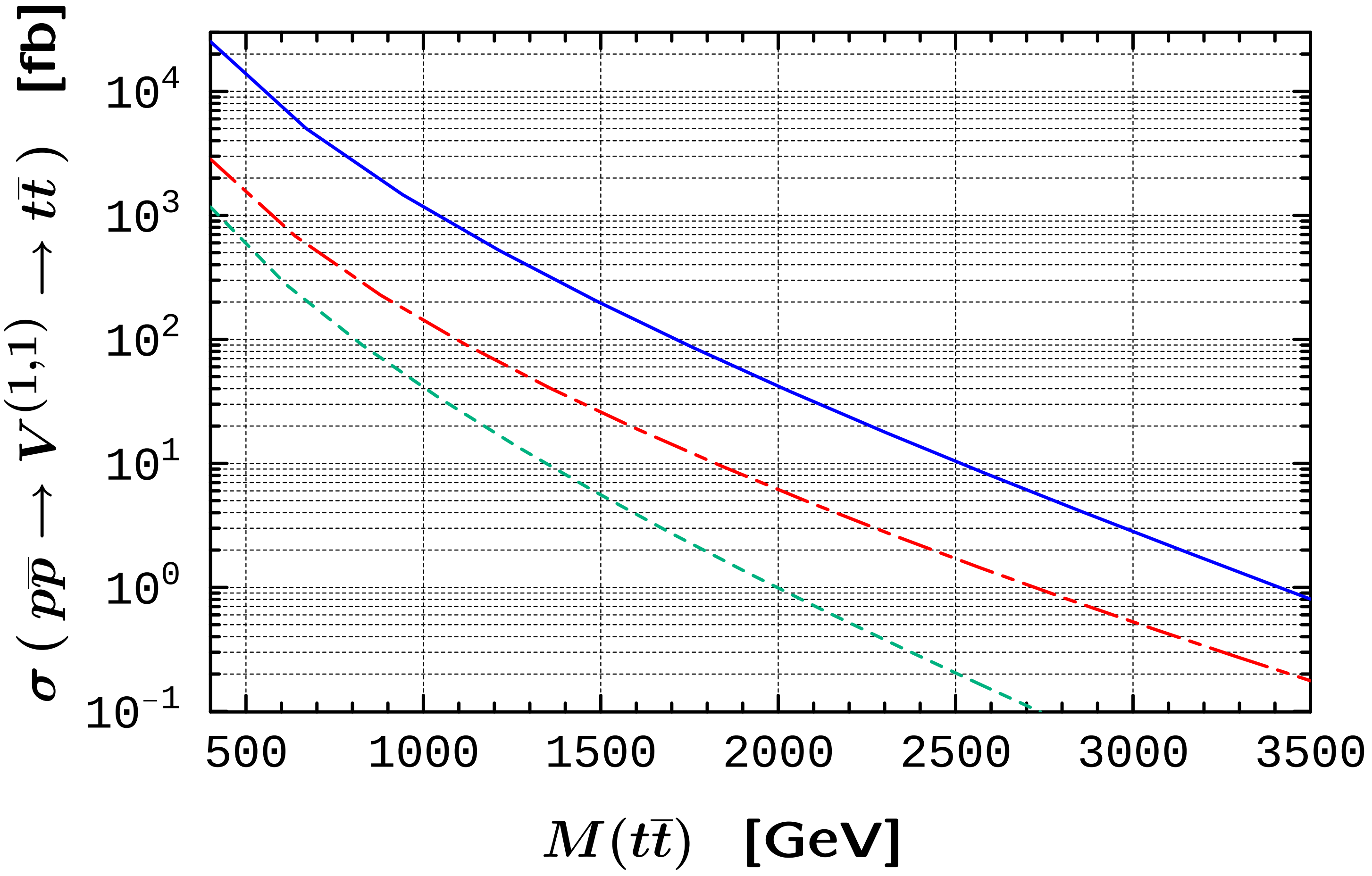


$\rightarrow$ $t\bar{t}$ resonance + 1 lepton ~ 70 GeV + 1 lepton ~ 20 GeV:



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

- $G_H^{(1,1)} + W_\mu^{(1,1)3}$ ——— $M_{t\bar{t}} \simeq 1.10\,\sqrt{2}/R$
- $W_H^{(1,1)3} + B_\mu^{(1,1)}$ – – – – $M_{t\bar{t}} \simeq 0.96\,\sqrt{2}/R$
- $B_H^{(1,1)}$ — — — $M_{t\bar{t}} \simeq 0.87\,\sqrt{2}/R$



Conclusions

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

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

Signals may include resonances (*e.g.*, $Z' \to \mu + \mu^-$), cascade decays (susy, UED, ...), or more complicated topologies.

6DSM predicts:
- $t\bar{t}$ and $t\bar{b}$ resonances
- many leptons + jets + missing E_T
- leptons + photons + jets + missing E_T
- other signatures of Kaluza-Klein particles