Multi-leptons in non-supersymmetric theories

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How many is many?

- Prehistoric mathematics:

Our prehistoric ancestors would have had a general sensibility about amounts, and would have instinctively known the difference between, say, one and two antelopes. But the intellectual leap from the concrete idea of two things to the invention of a symbol or word for the abstract idea of "two" took many ages to come about.

Even today, there are isolated hunter-gatherer tribes in Amazonia which only have words for "one", "two" and "many", and others which only have words for numbers up to five. In the absence of settled agriculture and trade, there is little need for a formal system of numbers.

- In this talk, “3” is many.
- Consider three or more leptons.
- 2 leptons are also interesting. SSDL.

Sources

- Particles with non-standard charges
- Multi-gauge bosons (multi-tops)
- Cascade decays
- Mixed cases

I. Particles with Non-standard Charges

- Double charged heavy fermions

$$u\bar{d} \to L^{++}\,\ell^- \to W^+\,\ell^+\,\ell^-$$

1201.3764 Biondini, Panella, Pancheri, Srivastava, Fano

$$\bar{u}d \to L^{--}\,\ell^+ \to W^-\,\ell^-\,\ell^+$$

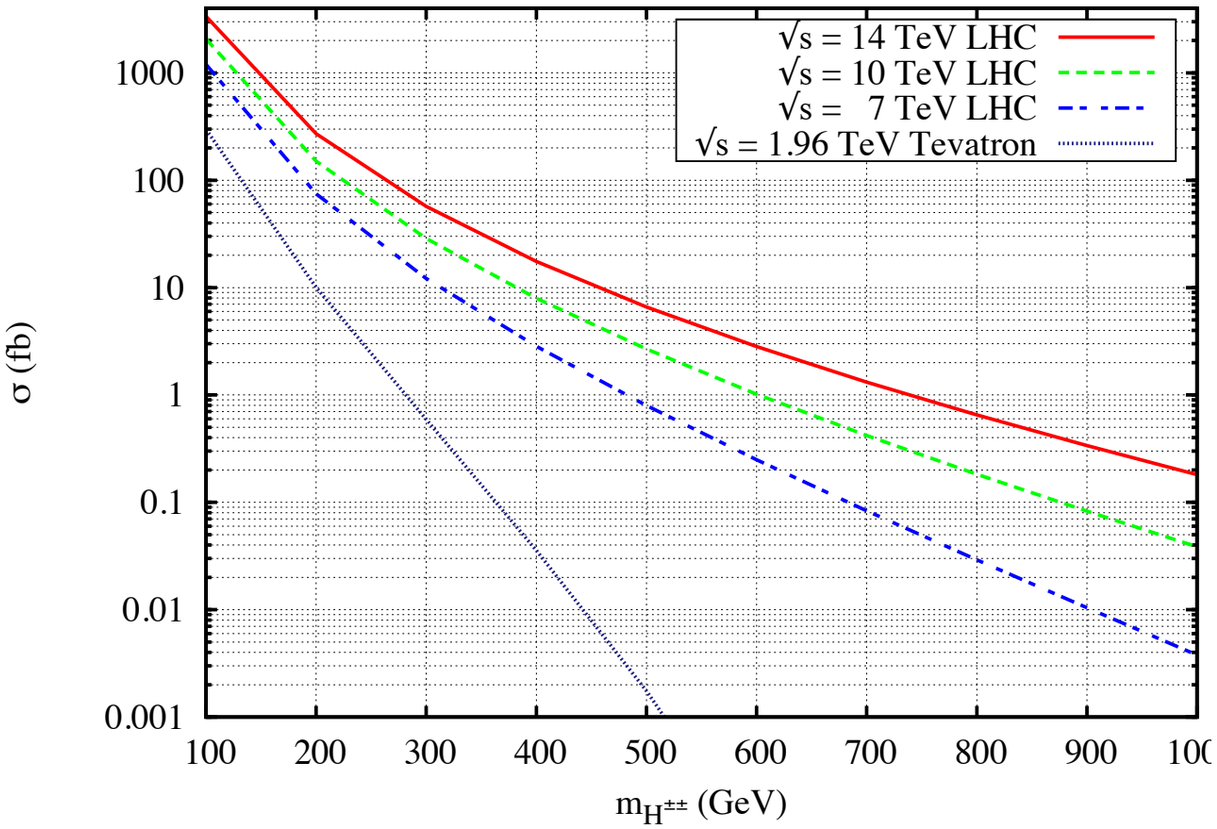
- Doubly charged Higgs boson

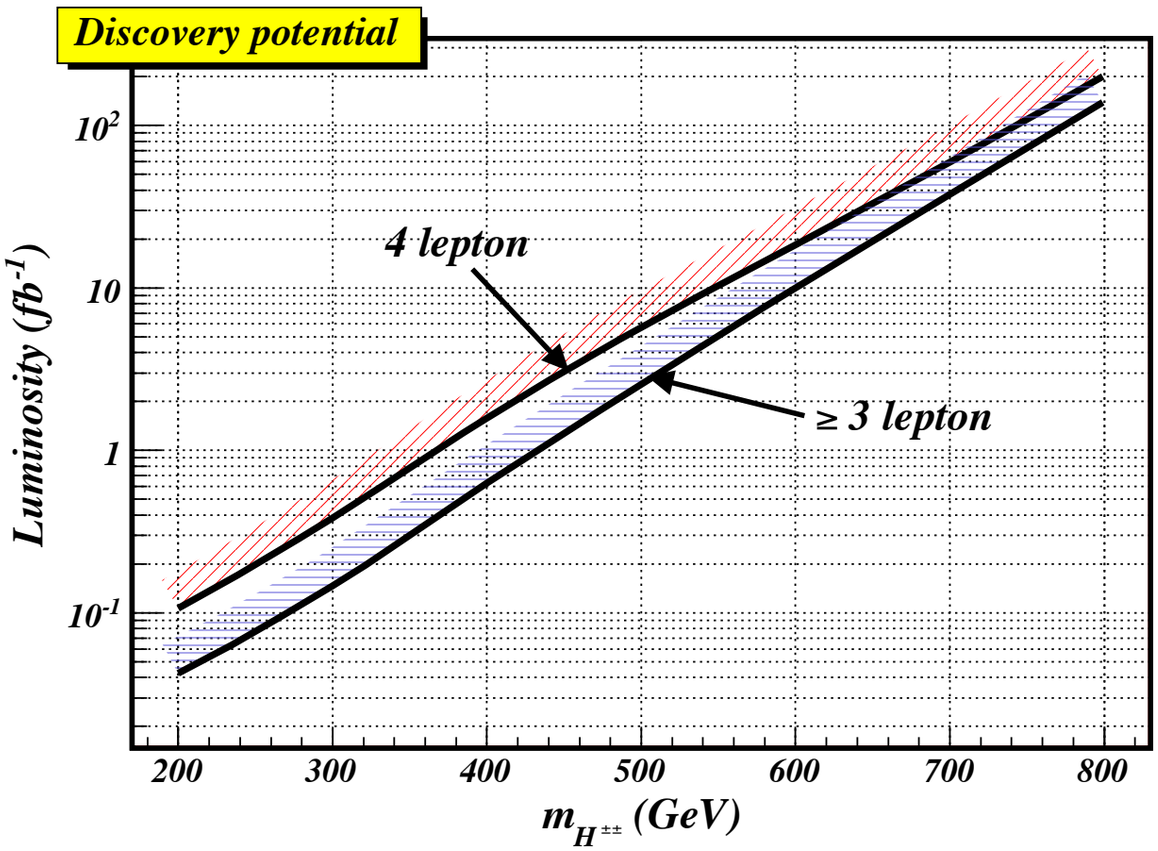
$$q\bar{q} \to \gamma^*, Z^* \to H^{++}H^{--} \qquad H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-$$

$$pp \to H^{\pm\pm}H^{\mp}$$

1009.2780 Akeroyd, Chiang, Gaur

Doubly Charged Higgs Boson





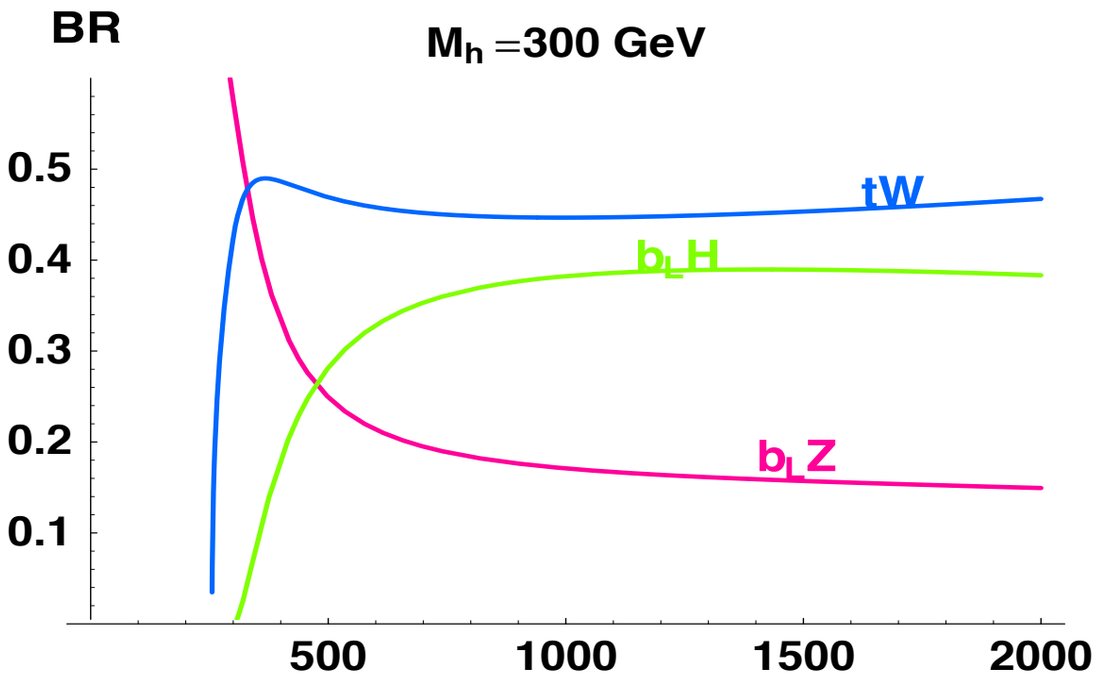
1009.2780 Akeroyd, Chiang, Gaur

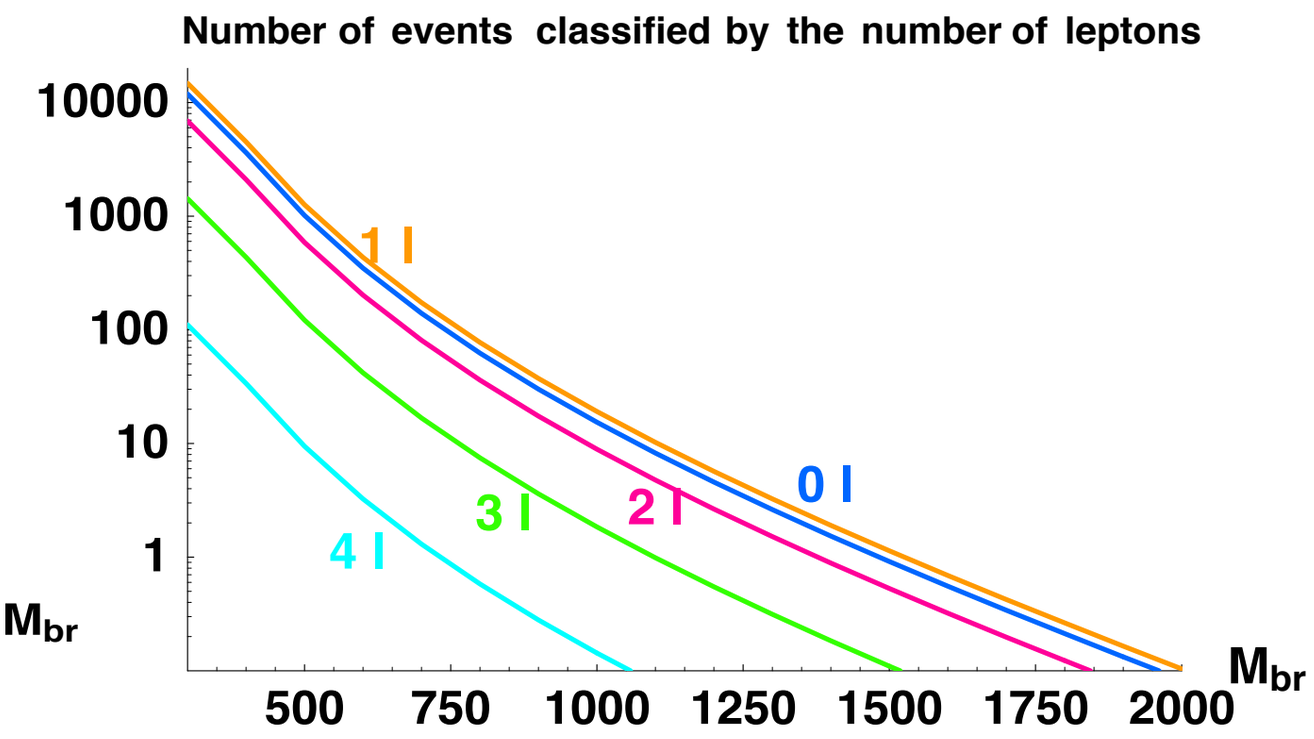
II. Multi-gauge bosons

- See talks by Lian-Tao and Matt for multi-top signals.
- Multi-Lepton Signals of the Higgs Boson

1112.2298, Contreras-Campana, Craig, Gray, Kilic, Park, Somalwar, Thomas

- KK quarks carrying electric charge 5/3





- Tprime

0701158, Dennis, Unel, Servant, Tseng

MH=125 GeV and Tprime

- MH125 GeV, SM4 is excluded at 99.6% C.L.
- MH > 123 GeV, exclusion limit is > 95% C.L.

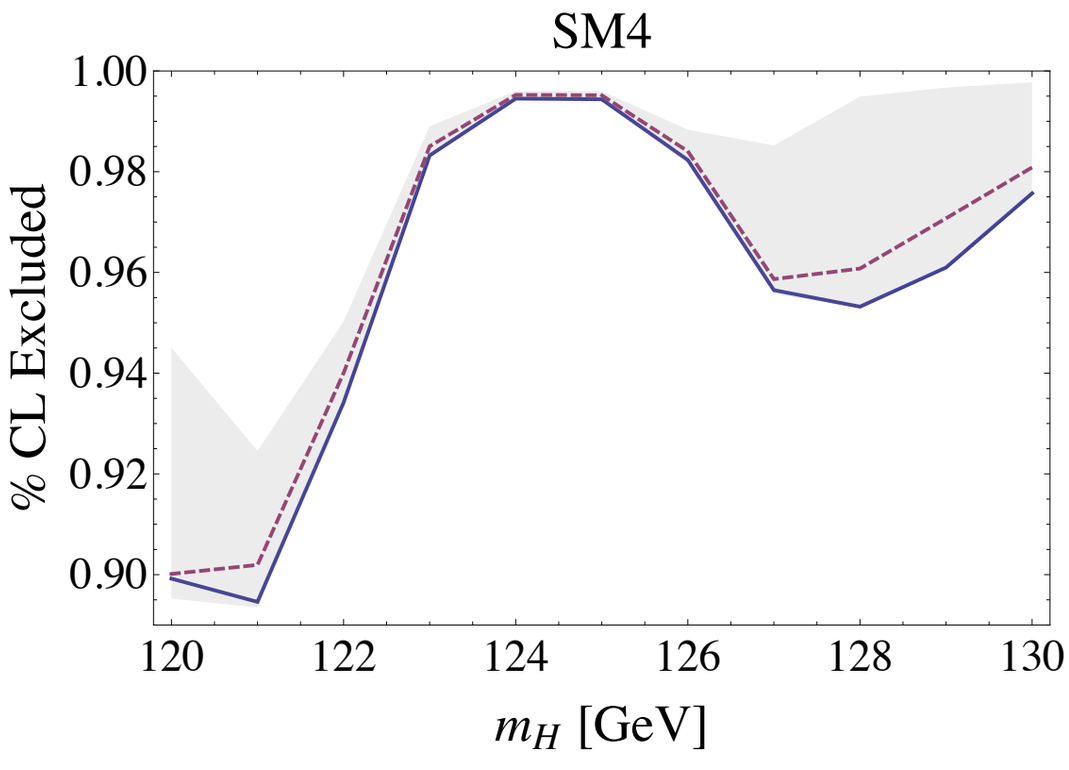
$$\text{Spectrum A}: \quad m_{t'} = 500\text{GeV}, \quad m_{b'} = 450\text{GeV}$$
$$m_{l'} = 450\text{GeV}, \quad m_{\nu'} = 375\text{GeV}$$

$$\text{Spectrum B}: \quad m_{t'} = 650\text{GeV}, \quad m_{b'} = 600\text{GeV}$$
$$m_{l'} = 600\text{GeV}, \quad m_{\nu'} = 600\text{GeV}$$

$$100 \geq m_{t'}/\text{GeV} \leq 650, \quad m_{b'} = m_{t'} + \{-50, 0, 50\} \ \text{GeV}$$

$$50 \geq m_{\nu'}/\text{GeV} \leq 600, \quad m_{l'} = m_{\nu'} + \{50, 75, 100\} \ \text{GeV}$$

1204.1975, Kuflik, Nir, Volansky



Multi-bosons in Tprime + Gprime model

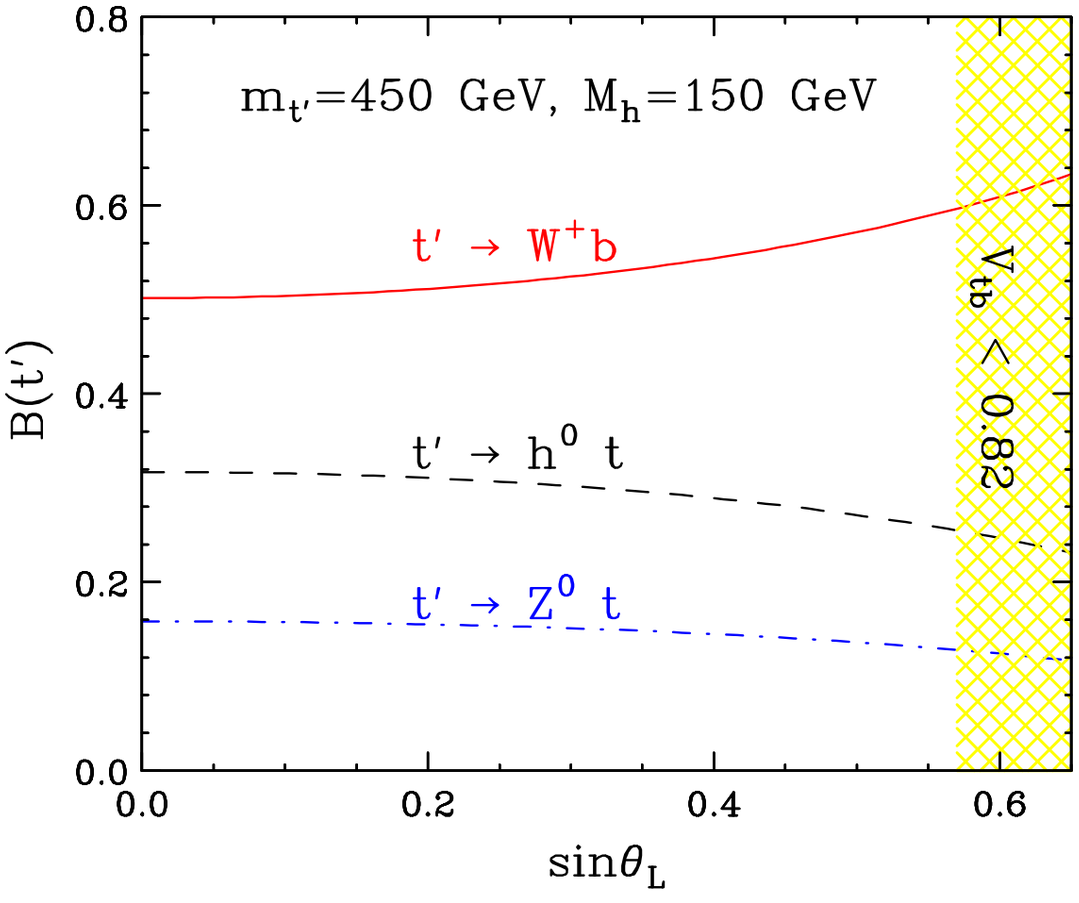
- A vectorlike quark: (3, 1, 2/3) under SM group

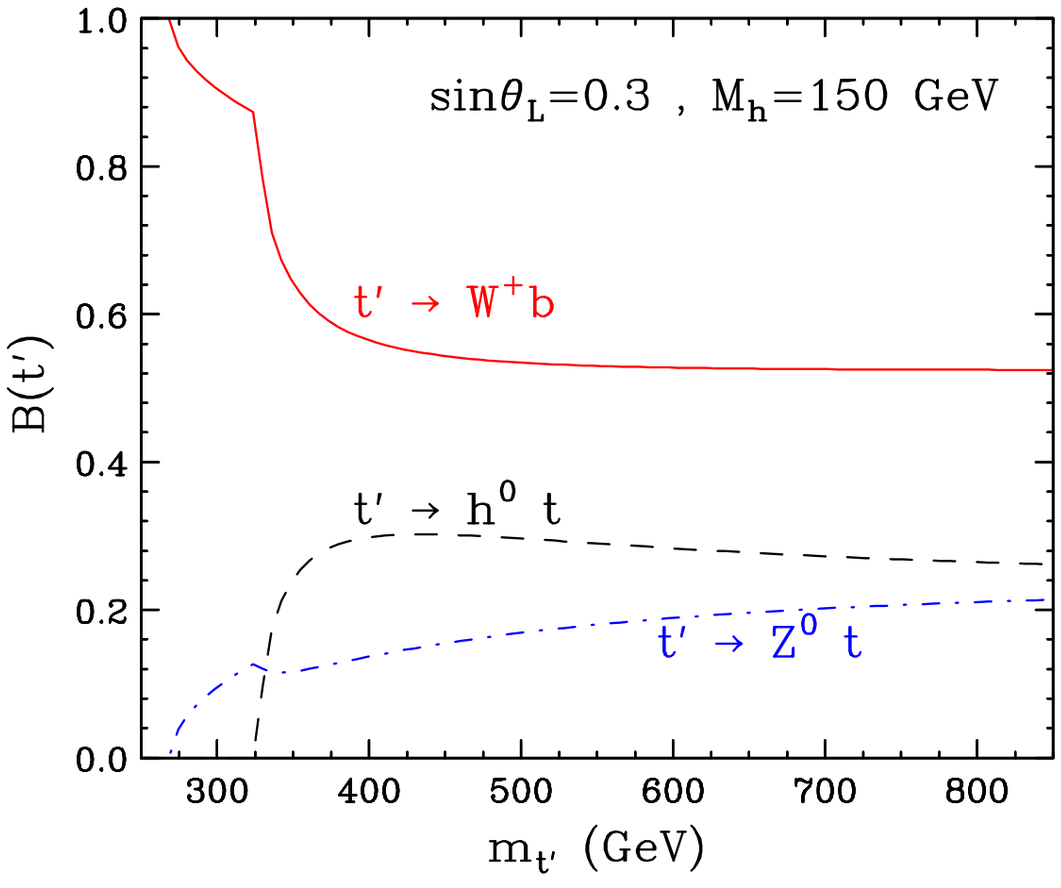
$$\mathcal{L} = -\left(\overline{u}_L^3\ ,\ \overline{\chi}_L\right)\begin{pmatrix} \lambda_t\left(v_H + h^0/\sqrt{2}\right) & 0 \\ M_0 & M_\chi \end{pmatrix}\begin{pmatrix} u_R^3 \\ \chi_R \end{pmatrix} + \text{H.c.}$$

$$\begin{pmatrix} t_{L,R} \\ t'_{L,R} \end{pmatrix} = \begin{pmatrix} c_{L,R} & -s_{L,R} \\ s_{L,R} & c_{L,R} \end{pmatrix}\begin{pmatrix} u_{L,R}^3 \\ \chi_{L,R} \end{pmatrix}$$

- Two mixing angles are related for a given Tprime mass

Tprime decays





In the limit of $m_{t'} \gg m_t + M_h$

$$B(t' \to W^+ b) = \frac{1}{1 + c_L^2} \geq 50\% \ ,$$

$$B(t' \to Z^0 t) = B(t' \to h^0 t) = \frac{c_L^2}{2\,(1 + c_L^2)} \leq 25\% \ .$$

0902.0792, Dobrescu, Kong, Mahbubani

See Lian-Tao's talk

- Extending gauge symmetry

$$SU(3)_1 \times SU(3)_2 \longrightarrow SU(3)_c$$

$$\begin{pmatrix} G_\mu^1 \\ G_\mu^2 \end{pmatrix} = \frac{1}{\sqrt{h_1^2 + h_2^2}} \begin{pmatrix} h_2 & -h_1 \\ h_1 & h_2 \end{pmatrix} \begin{pmatrix} G_\mu \\ G'_\mu \end{pmatrix}$$

	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_Y$
SM quarks: $q_L^i,\ u_R^i,\ d_R^i$	3	1	2, 1, 1	$+1/6,\ +2/3,\ -1/3$
vectorlike quark: $\chi_L,\ \chi_R$	1	3	1	$+2/3$
scalar with VEV: Σ	3	$\overline{3}$	1	0

0902.0792, Dobrescu, Kong, Mahbubani

- Interactions with EW bosons and Tprime

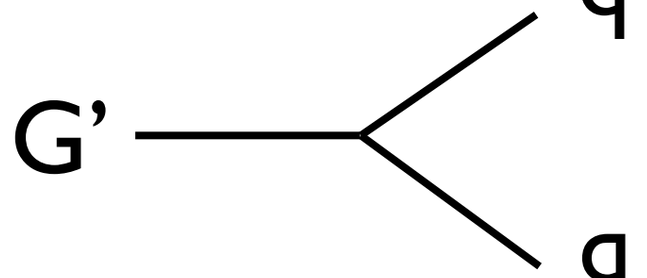
$$\frac{-1}{v_H\sqrt{2}}h^0\left(c_L^2 m_t\ \bar{t}_L t_R + s_L^2 m_{t'}\ \overline{t'}_L t'_R + c_L s_L m_{t'}\ \bar{t}_L t'_R + c_L s_L m_t\ \overline{t'}_L t_R\right) + \text{H.c.}$$

$$\frac{g}{\cos\theta_W} Z_\mu \left[\left(\frac{c_L^2}{2} - \frac{2}{3}\sin^2\theta_W\right)\bar{t}_L\gamma_\mu t_L + \left(\frac{s_L^2}{2} - \frac{2}{3}\sin^2\theta_W\right)\overline{t'}_L\gamma_\mu t'_L \right.$$
$$\left. + \frac{s_L c_L}{2}\left(\overline{t'}_L\gamma_\mu t_L + \text{H.c.}\right)\right] \quad .$$

$$\frac{g}{\sqrt{2}}\, W_\mu^+\ \bar{b}_L\gamma_\mu\left(c_L t_L + s_L t'_L\right) + \text{H.c.}$$

- Interaction b/w quarks and Gprime

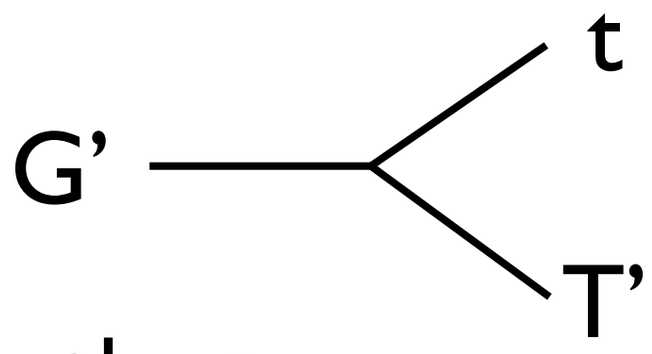
$$g_s r\ G'^a_\mu\ \bar{q}\gamma^\mu T^a q$$



- Interaction b/w Tprime and Gprime

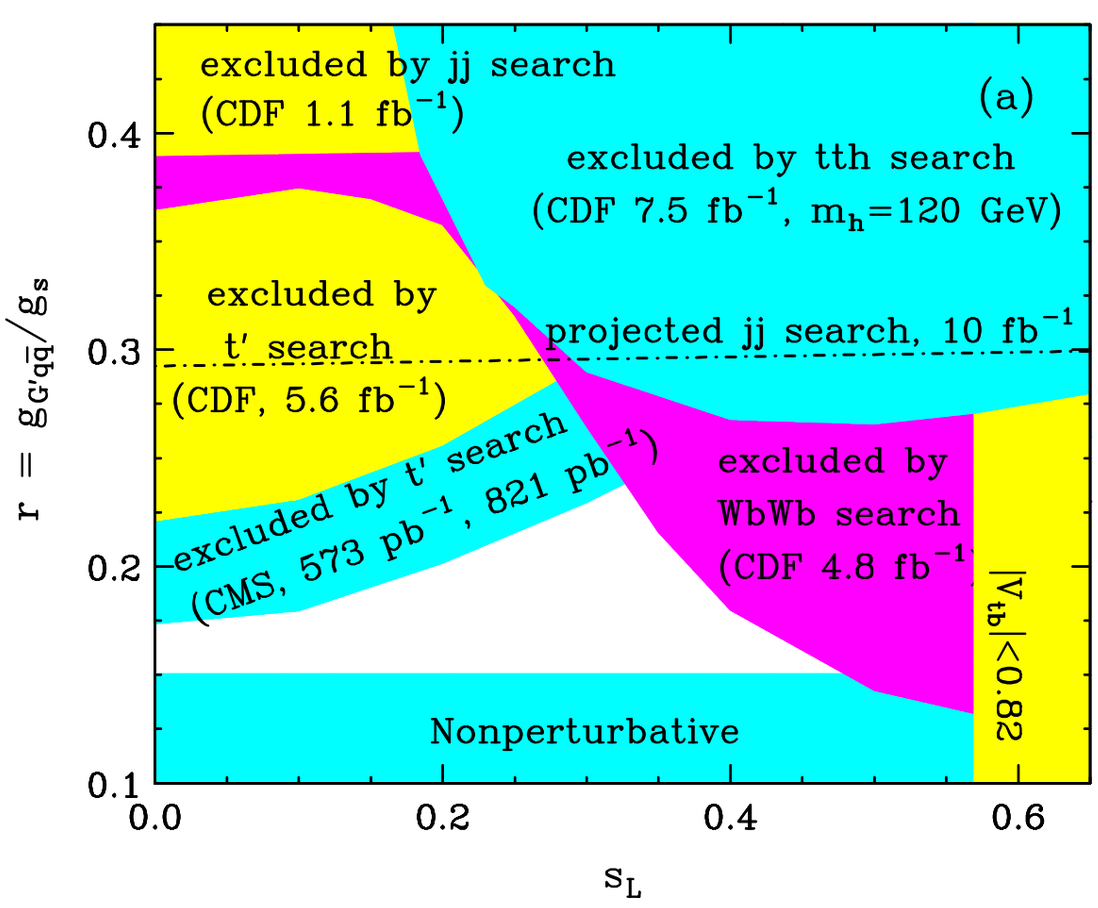
$$g_s G'^a_\mu\left[\bar{t}\gamma^\mu\left(g_L P_L + g_R P_R\right)T^a t + \overline{t'}\gamma^\mu\left(g''_L P_L + g''_R P_R\right)T^a t'\right]$$

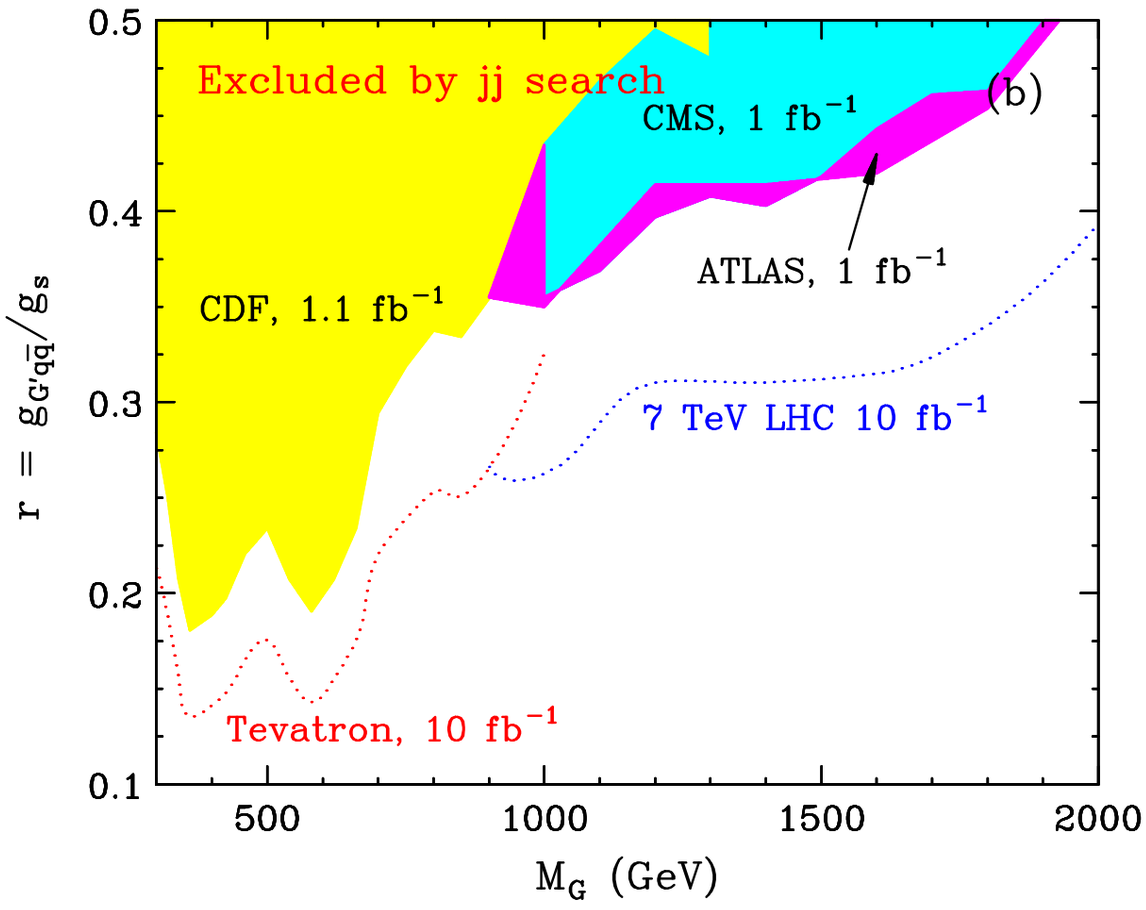
$$g_s G'^a_\mu\ \bar{t}\gamma^\mu\left(g'_L P_L + g'_R P_R\right)T^a t'$$



- 4 parameters: mTprime, mGprime, sL, r

Constraints



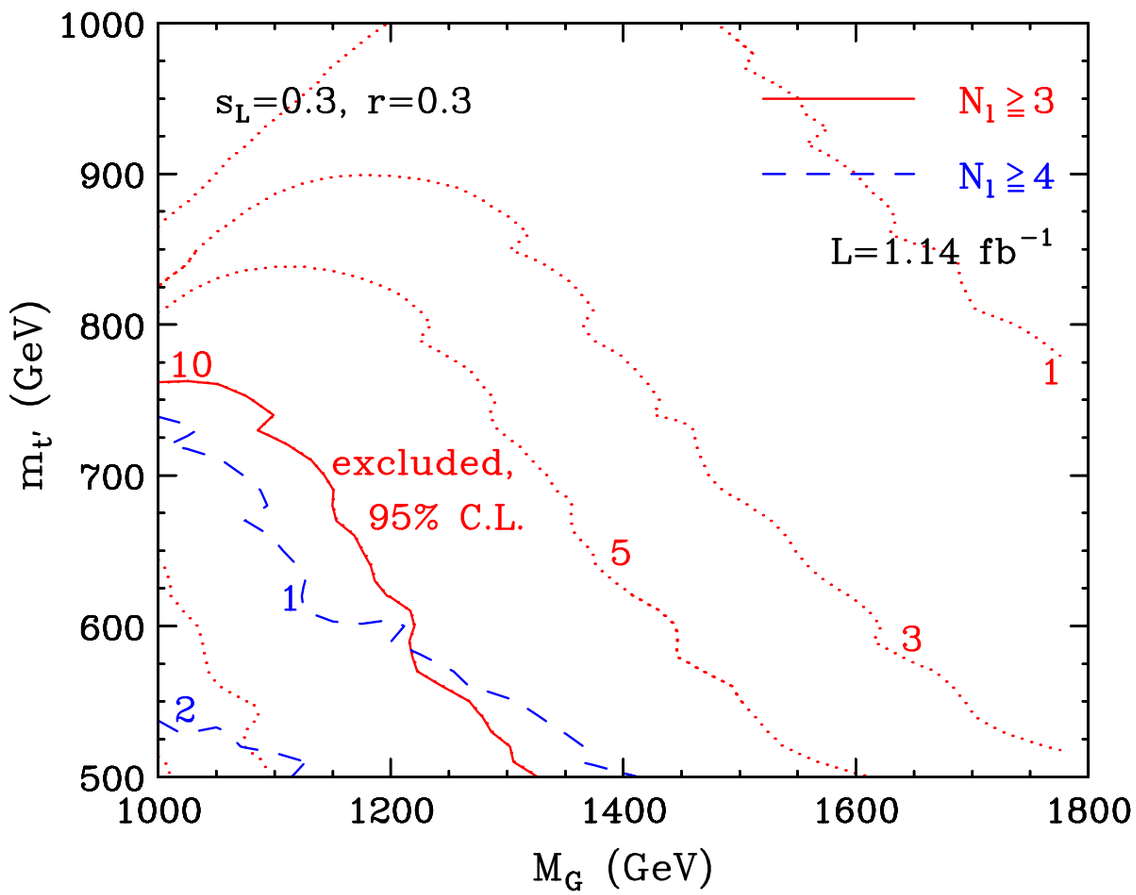


- Tprime = 450 GeV
- Gprime = 1 TeV

1112.3041, Kong, McCaskey, Wilson

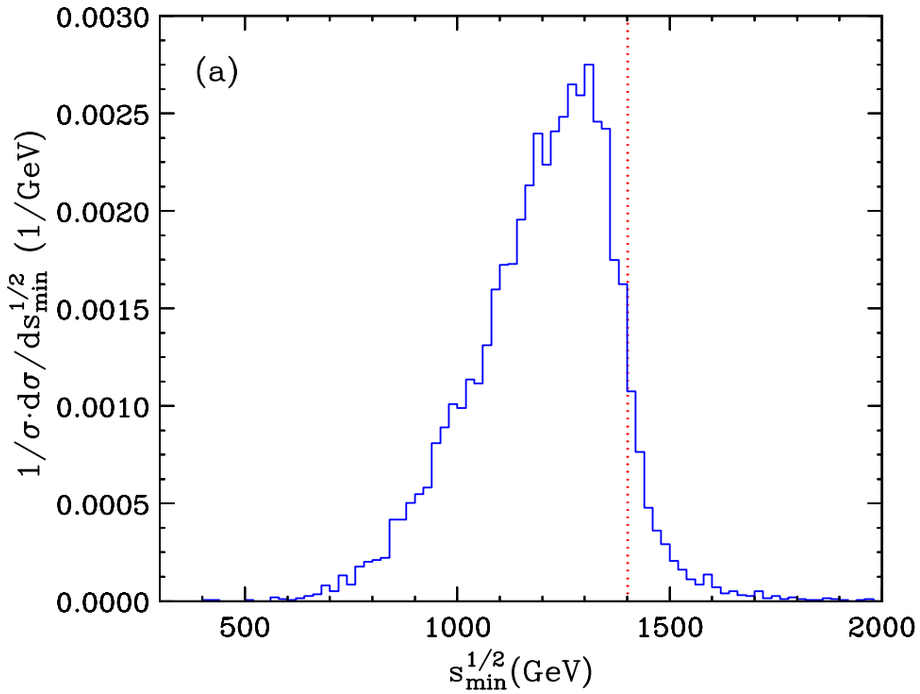
N_ℓ	$t\bar{t}' + t'\bar{t}$	$t'\bar{t}'$
0	$0.57\ b_{Zt} + 0.61\ b_{Wb}$	$(0.72\ b_{Zt} + 0.78\ b_{Wb})^2$
1	$0.32\ b_{Zt} + 0.34\ b_{Wb}$	$2 \times (0.21\ b_{Zt} + 0.22\ b_{Wb})$ $\times(0.73\ b_{Zt} + 0.78\ b_{Wb})$
2	$0.086\ b_{Zt} + 0.048\ b_{Wb}$	$(0.21\ b_{Zt} + 0.22\ b_{Wb})^2$ $+ 2 \times (0.052\ b_{Zt})$ $\times(0.73\ b_{Zt} + 0.78\ b_{Wb}\ )$
3	$0.023\ b_{Zt}$	$2 \times (0.0147\ b_{Zt})$ $\times(0.73\ b_{Zt} + 0.78\ b_{Wb})$ $+2 \times (0.052\ b_{Zt})$ $\times(0.21\ b_{Zt} + 0.22\ b_{Wb})$
4	$0.0032\ b_{Zt}$	$2 \times (0.015\ b_{Zt})$ $\times(0.21\ b_{Zt} + 0.22\ b_{Wb})$ $+(0.052\ b_{Zt})^2$
5	0	$2 \times (0.052\ b_{Zt})$ $\times(0.015\ b_{Zt})$
6	0	$(0.015\ b_{Zt})^2$

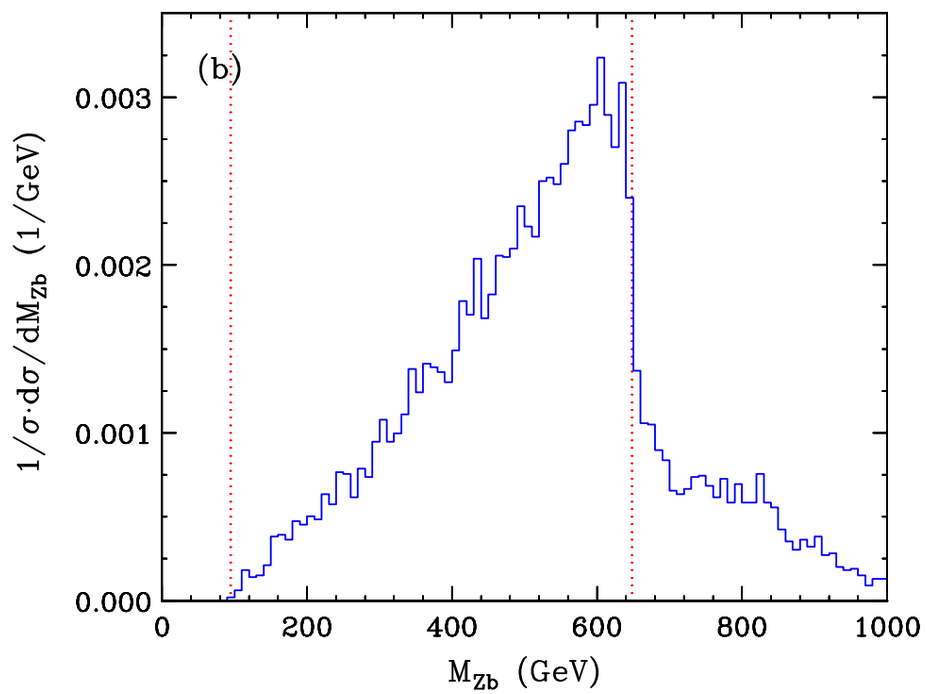
$$
\begin{aligned}
b_{Zt} &= Br(t' \to Zt)\,, \\
b_{Wb} &= Br(t' \to W^+ b)\,, \\
b_{Z,2l} &= BR(Z \to \ell^+\ell^-) = 0.067\,, \\
b_{W,1l} &= BR(W^+ \to \ell^+\nu_\ell) = 0.22\,.
\end{aligned}
$$

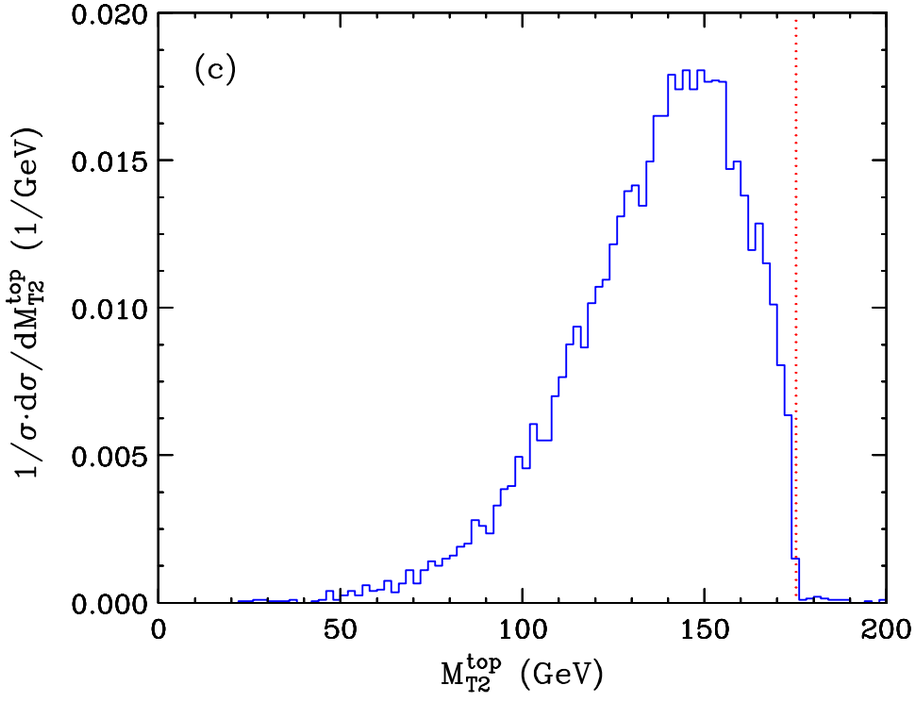


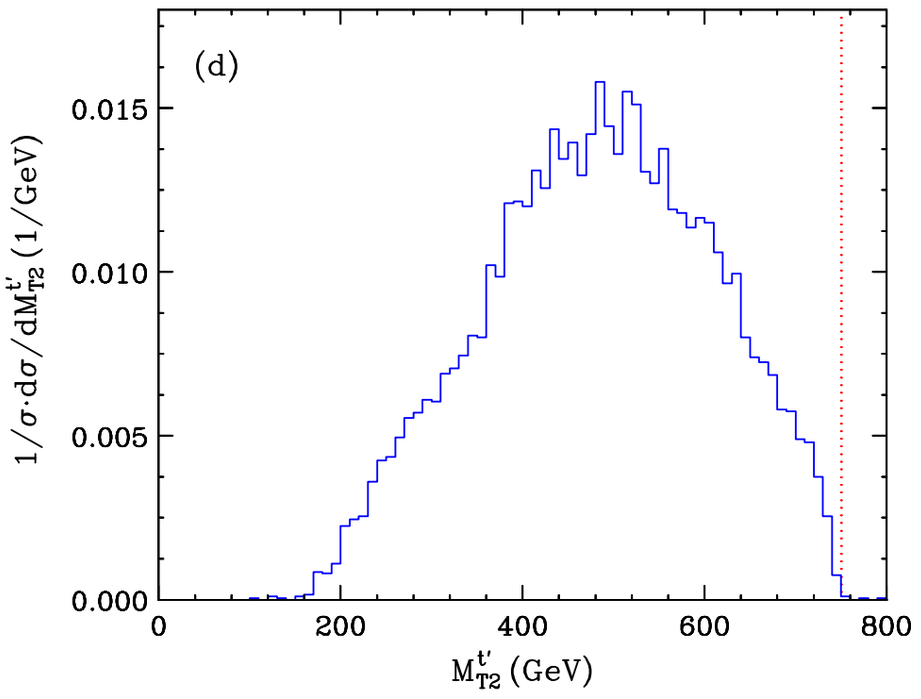
- CMS, L=1.14 /fb, 7 TeV

1112.3041, Kong, McCaskey, Wilson









$$pp \to G' \to t\bar{t}' + t'\bar{t} \to t\bar{t}Z \to W^+W^-Zb\bar{b} \to b\,\bar{b}\,\ell^+\,\ell^-\,\ell'^+\,\nu_{\ell'}\,\ell''^-\,\bar{\nu}_{\ell''}$$

1112.3041, Kong, McCaskey, Wilson

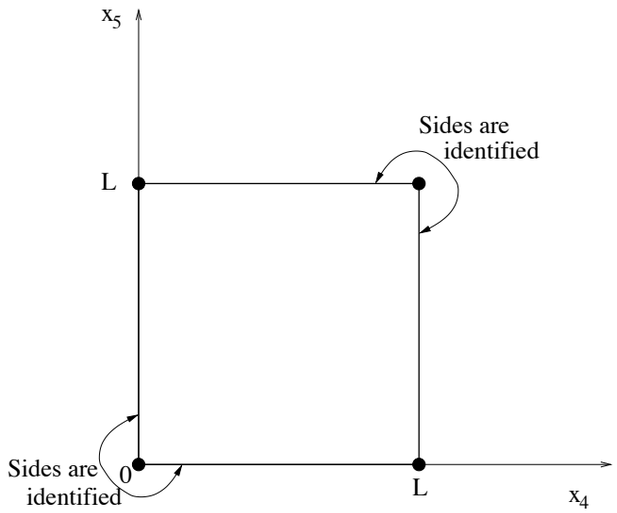
III. Cascade decays

- SUSY: 4 leptons + Z ? 1008.2483, Konar, Matchev, Park, Sarangi
  - gluino to bino + 2 jets (3 body)
  - bino to right handed slepton + lepton
  - right handed slepton to left handed slepton + 2 leptons
  - left handed slepton to wino + 1 lepton
  - wino to higgsino + Z (or Higgs)

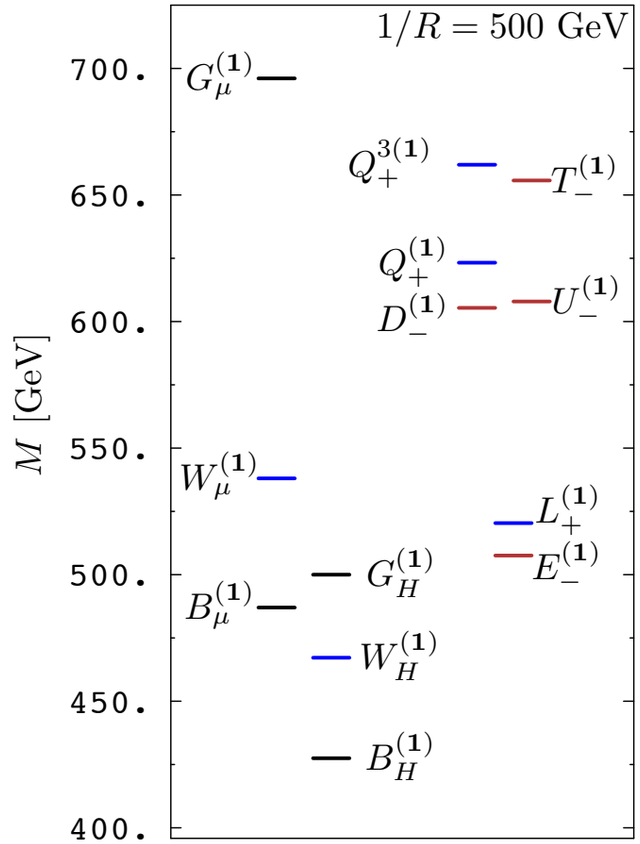
III. Cascade decays

- UED: 4 leptons + Z ? 1008.2483, Konar, Matchev, Park, Sarangi
  - KK G to KK A + 2 jets (3 body)
  - KK A to right handed KK L + lepton
  - right handed KK L to left handed KK L + 2 leptons
  - left handed KK L to KK W + 1 lepton
  - KK W to KK H + Z (or Higgs)

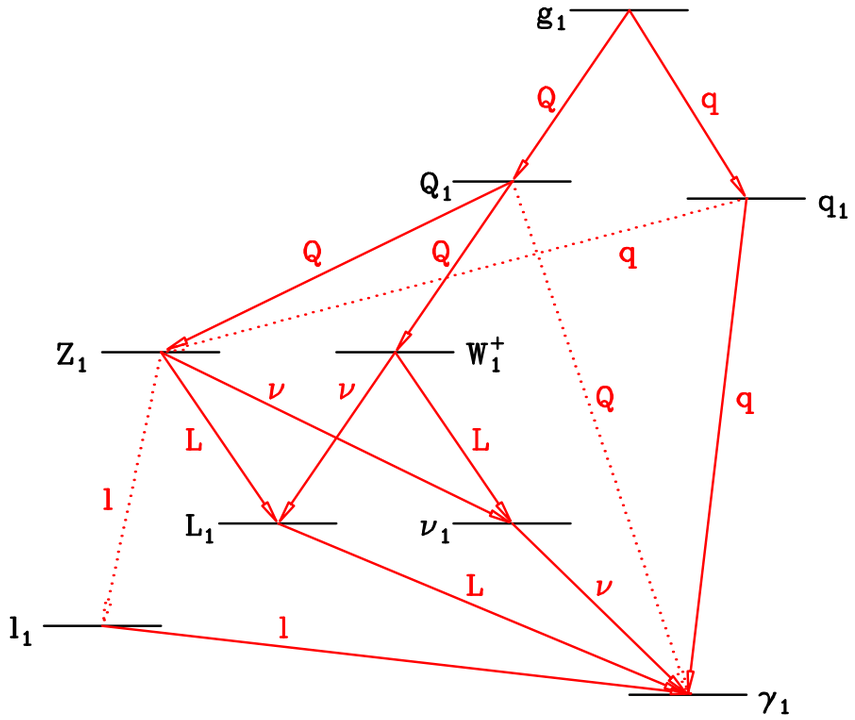
Leptons from cascade decays: Two Universal Extra Dimensions



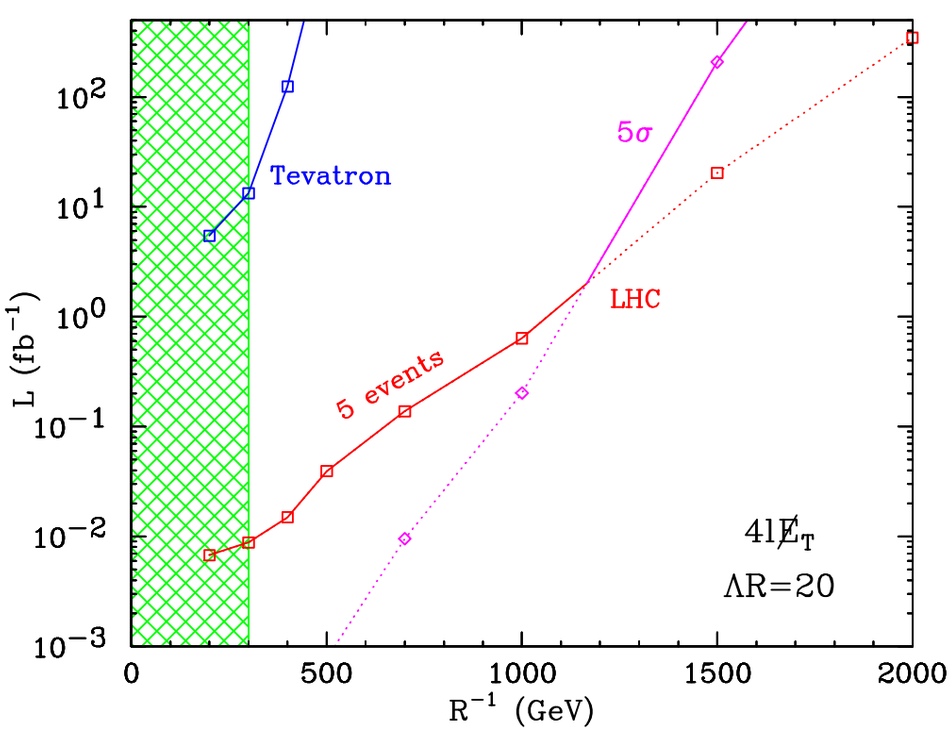
boson	MR	fermion	MR
$G_\mu^{(1)}$	1.392	$Q_+^{(1)3}$	$1.265 + \frac{1}{2}(m_t R)^2$
$W_\mu^{(1)}$	$1.063 + \frac{1}{2}(M_W R)^2$	$T_-^{(1)}$	$1.252 + \frac{1}{2}(m_t R)^2$
$G_H^{(1)}$	1.0	$Q_+^{(1)}$	1.247
$B_\mu^{(1)}$	0.974	$U_-^{(1)}$	1.216
$W_H^{(1)}$	$0.921 + \frac{1}{2}(m_W R)^2$	$D_-^{(1)}$	1.211
$B_H^{(1)}$	0.855	$L_+^{(1)}$	1.041
		$E_-^{(1)}$	1.015



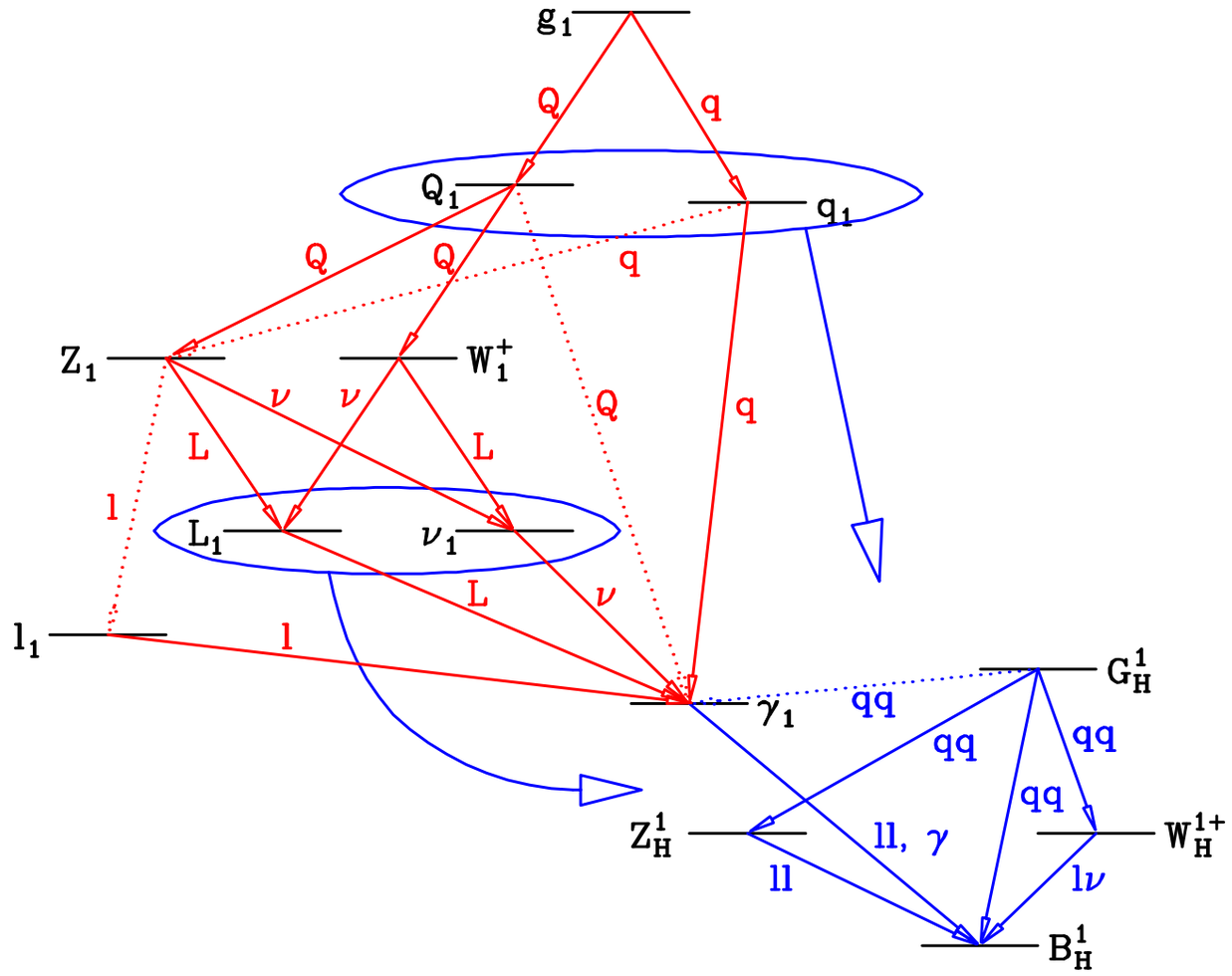
0703231, Dobrescu, Kong, Mahbubani



0205314, Cheng, Matchev, Schmaltz



- 4 leptons with large branching fractions

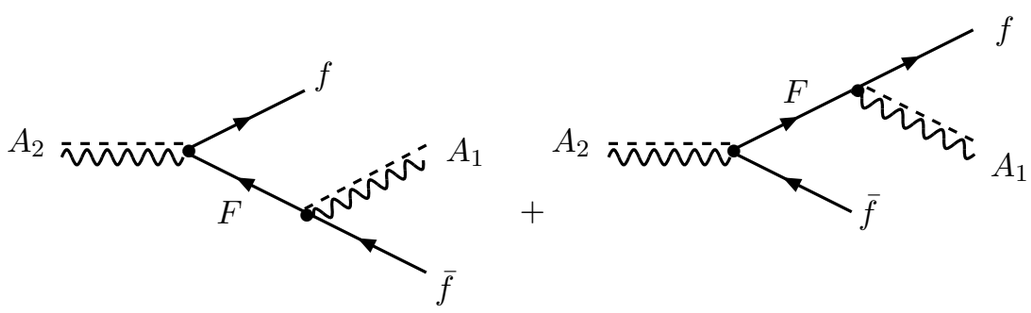


- Extra “spinless” states: GH, ZH, WH, BH
- KK photon is NOT DM and decays to spinless photon via 1-loop or 3 body decay

0703231, Dobrescu, Kong, Mahbubani

Decay of KK photon

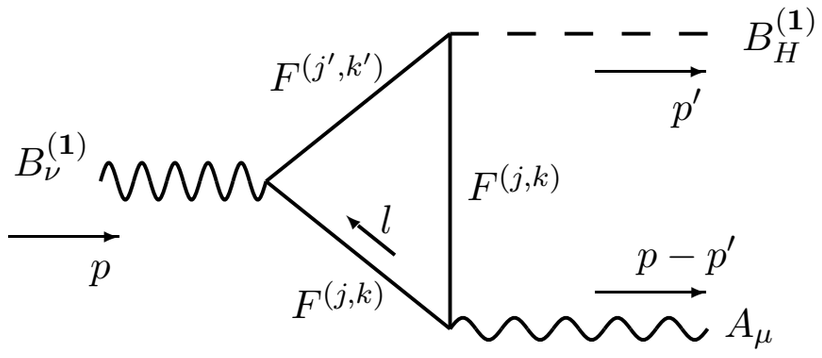
- 3 body decay



$$\mathrm{Br}\left(B_\mu^{(1)} \to B_H^{(1)}\gamma\right) \equiv b_{B\gamma} \approx 34.0\%$$

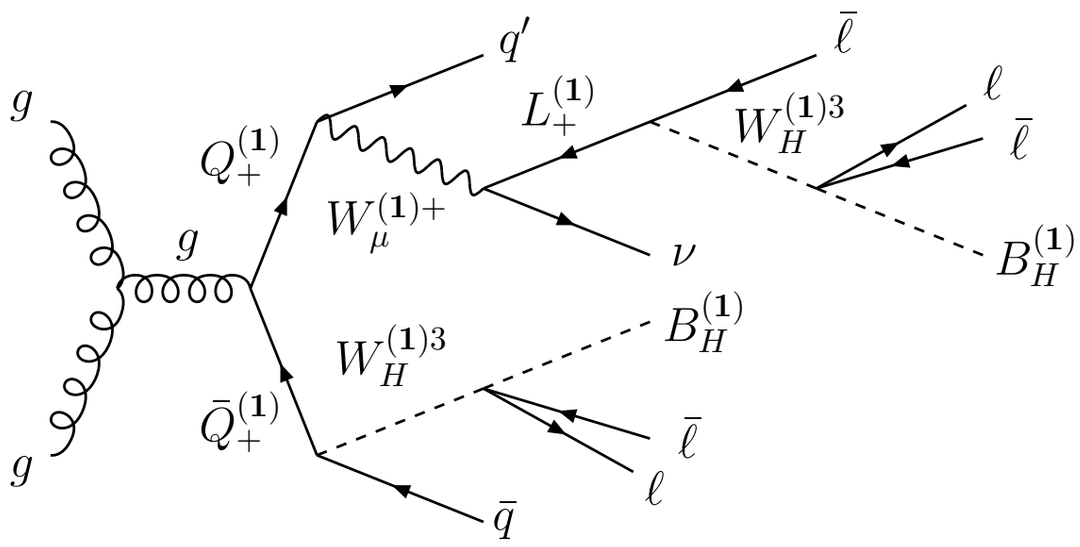
$$\mathrm{Br}\left(B_\mu^{(1)} \to B_H^{(1)}e^+e^-\right) \equiv b_{Be} \approx 21.3\%$$

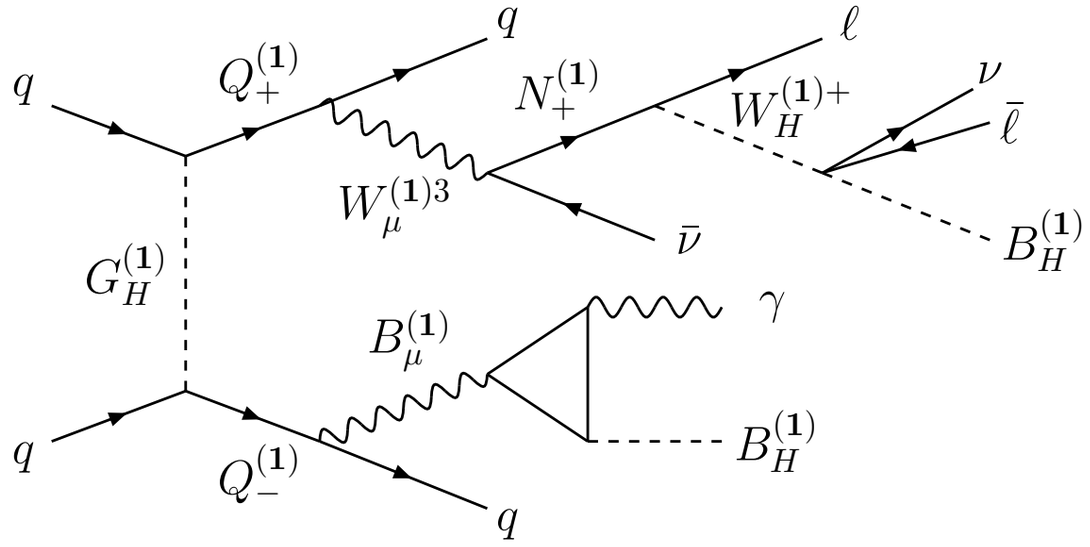
- 1-loop 2-body decay

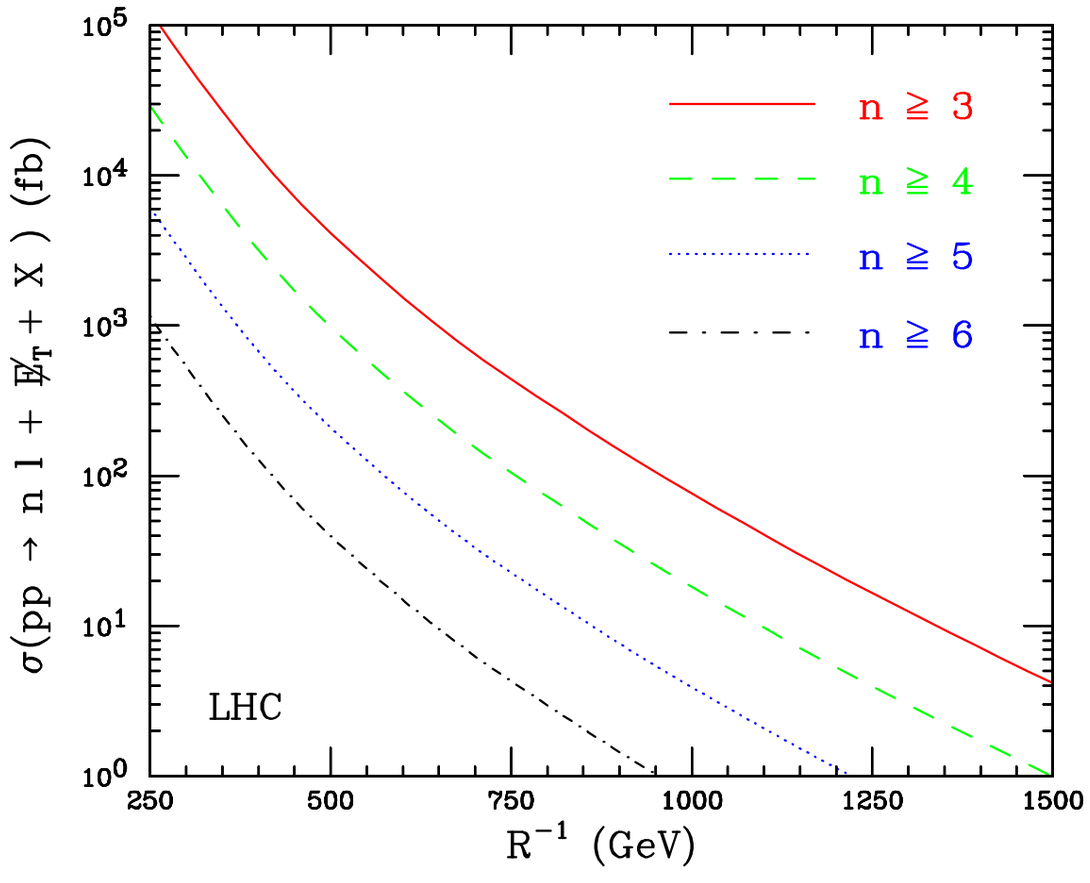


$$-\frac{R}{4}\left(\mathcal{C}_B\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}B^{(1)}_{\alpha\beta}B^{(1)}_H + \mathcal{C}_G\epsilon^{\mu\nu\alpha\beta}G_{\mu\nu}B^{(1)}_{\alpha\beta}G^{(1)}_H\right)$$

0703231, Dobrescu, Kong, Mahbubani







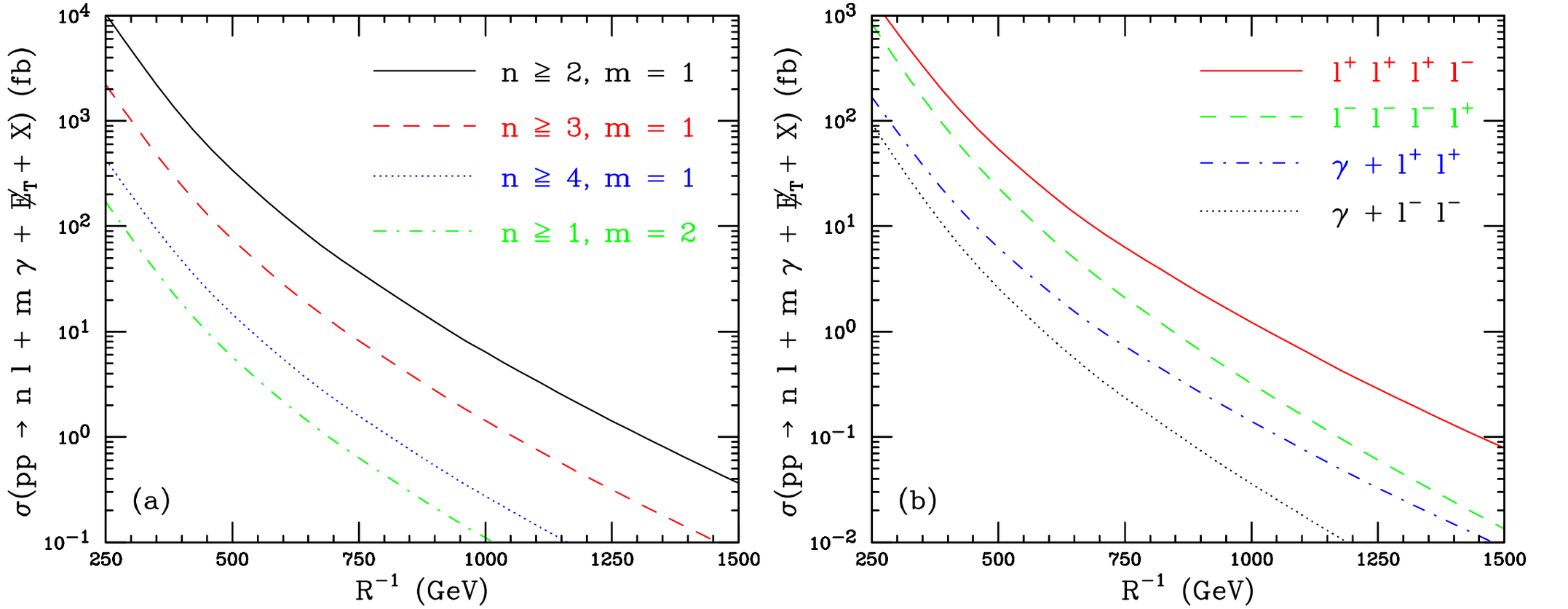
$$\sigma(pp \to n\ell + m\gamma + \not{E}_T\ , n \geq n_{min}) = \sum_{i=1}^{11}\sum_{j\geq i}^{11} \sigma(pp \to A_i^{(1)} A_j^{(1)}) B_{ij}$$

$$B_{ij} = \sum_{\substack{a,b=0 \\ a+b\geq n_{min}}}^{4} \sum_{\substack{a',b'=0 \\ a'+b'=m}}^{1} \mathrm{Br}(i,a,a')\mathrm{Br}(j,b,b')$$

$$0 \leq n + 2m \leq 8$$

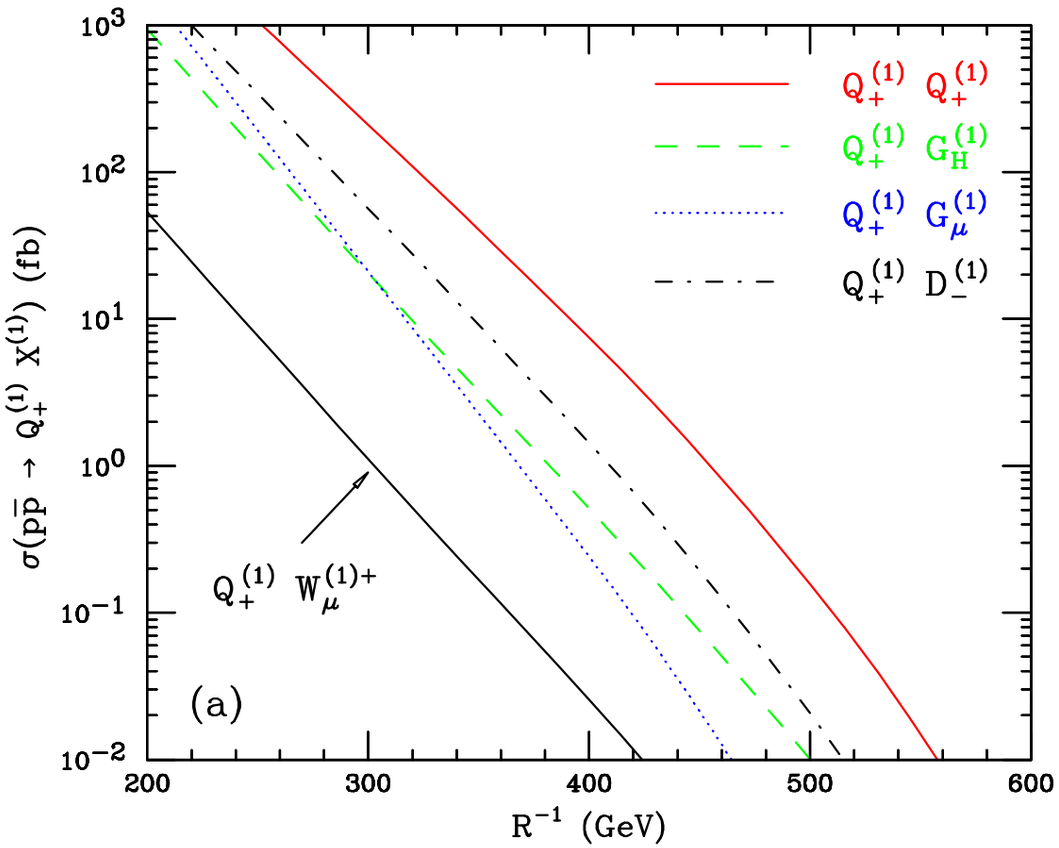
- The number of multi-lepton events at 14 TeV LHC
- No acceptance cuts

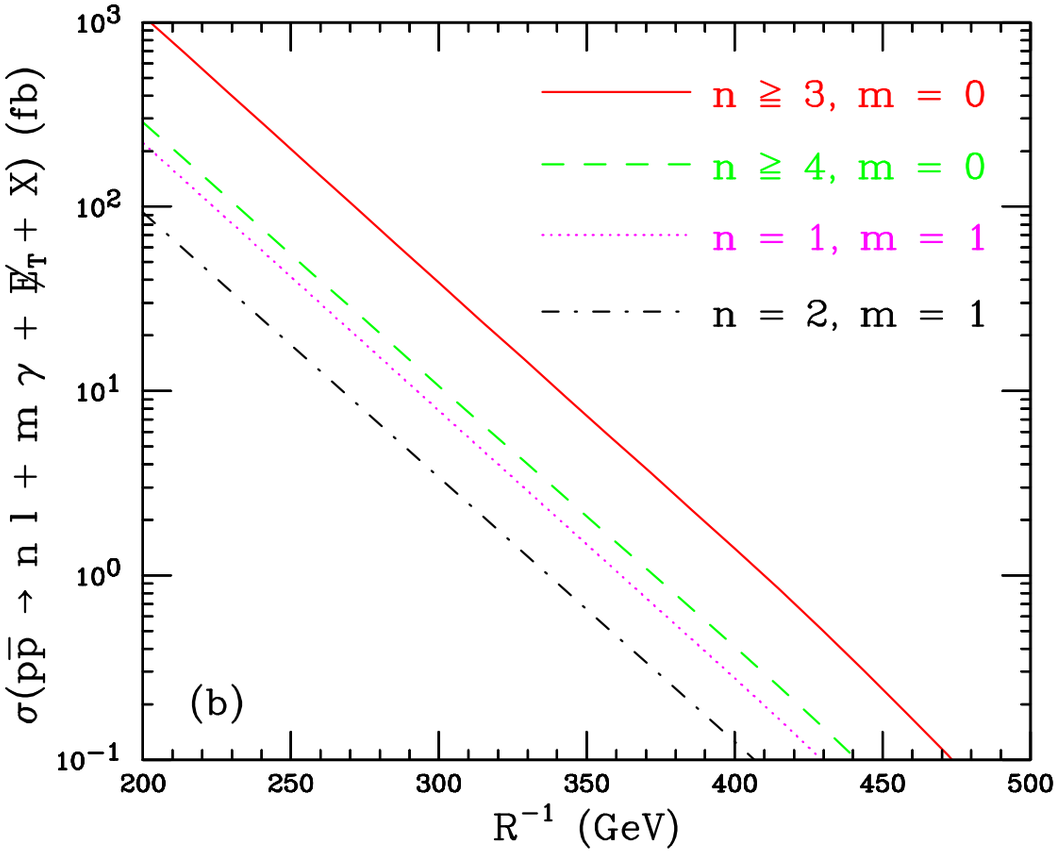
0703231, Dobrescu, Kong, Mahbubani



- The number of lepton + photon events (14 TeV)
- Roughly 1 photon ~ 2 leptons

Tevatron


$Q_+^{(1)}$ $Q_+^{(1)}$
$Q_+^{(1)}$ $G_H^{(1)}$
$Q_+^{(1)}$ $G_\mu^{(1)}$
$Q_+^{(1)}$ $D_-^{(1)}$
$Q_+^{(1)}$ $W_\mu^{(1)+}$
(a)
$\sigma(p\bar{p} \to Q_+^{(1)} X^{(1)})$ (fb)
R^{-1} (GeV)


n ≧ 3, m = 0
n ≧ 4, m = 0
n = 1, m = 1
n = 2, m = 1
(b)
$\sigma(p\bar{p} \to n\ l + m\ \gamma + \not{E}_T + X)$ (fb)
R^{-1} (GeV)

Summary

- Multi-Lepton signals are interesting
- Good background suppression
- There are many non-SYSY models
- (Relatively) small branching fractions
- (potential) combinatorial issues