Reaching Beyond the Standard Model with the LHC

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Outline:

- **Many signatures that need to be searched for.**
- **Case study: how to find a t'.**

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- **Probing the unknown ...**

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

CDF and D0 do many things right. CMS and ATLAS should definitely follow those. There are also many things that need to be improved.

The theorist's wish:

Given a new theoretical model, CMS and ATLAS will be able to search for its signatures within weeks rather than years.

The theorist can easily implement the model in MadGraph or CalcHEP/CompHEP, which may be linked to Pythia.

MadGraph can be run within the CMS software framework! The CMS experimentalists should be able to handle efficiently new model files.

Search for:

- resonances in all 2-body final states.
- resonances in final states with three or more objects.
- resonances $+$ X.
- pairs of resonances.
- various cascade decays with $\not{E}_T$.
- ...

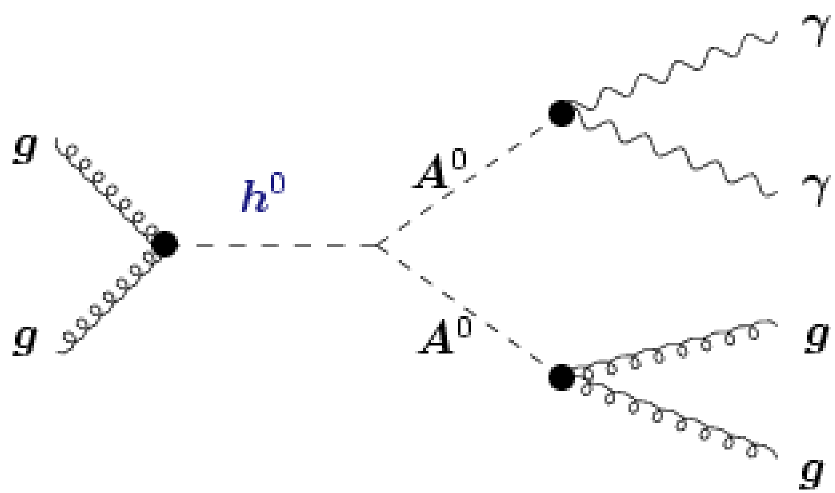
Search for resonances

Try all combinations of two objects: jj, $\mu\mu$, ee, $\gamma\gamma$, $t\bar{t}$, tb, $\tau\mu$, ...

Don't make simplifying assumptions such as lepton universality or gauge coupling unification ...

Example of $j\gamma$ resonance:

$h \to A^0 A^0 \to (\gamma\gamma)(jj)$ **may be the most interesting decay, with the diphoton and dijet peaks having same mass.** *(Chang, Fox, Weiner, hep-ph/0608310, ...)*



For a light A^0, this may appear in the detector as

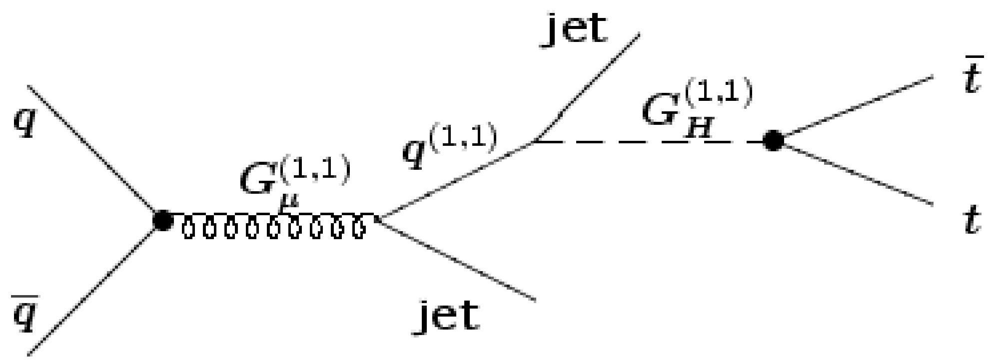
$h \to A^0 A^0 \to (\gamma\gamma)j$ **or** $h \to A^0 A^0 \to$ "γ" j. *(Dobrescu, Landsberg, Matchev, hep-ph/0005308)*

Search for resonances + X

E.g., 2 universal extra dimensions:

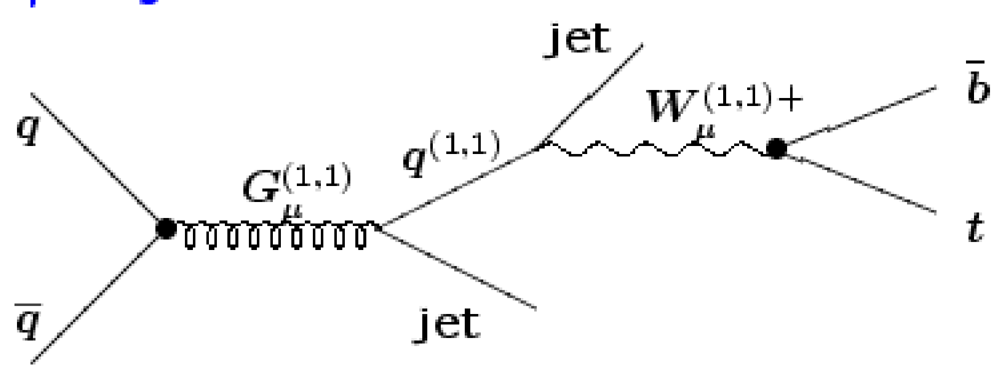
s-channel production of a KK gluon followed by a cascade decay

$\rightarrow$ $t\bar{t}$ resonance + 2 jets



(Burdman, Dobrescu, Ponton, hep-ph/0601186)

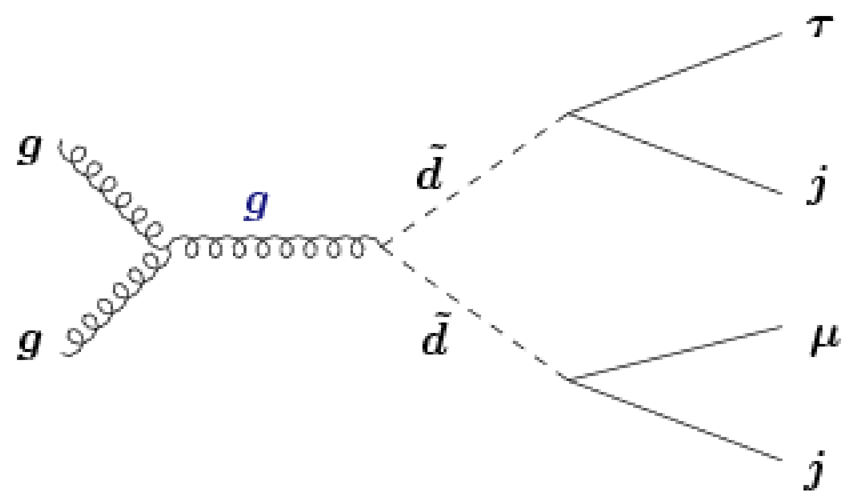
$\rightarrow$ $t\bar{b}$ resonance + 2 jets



Look for pairs of resonances

E.g., leptoquarks coupling to the 2nd and 3rd generations

— *these may explain why the D_s meson decays to $\tau\nu$ and $\mu\nu$ at a rate 3σ higher than the SM prediction.* Dobrescu, Kronfeld, 0803.0512



Note: D0 and CDF search for $(\mu j)(\mu j)$ and $(\tau j)(\tau j)$ but not for the $(\mu j)(\tau j)$, which could be the most important channel.

Is the top the last quark?

All Standard Model fermions are chiral: their masses are not gauge invariant, and arise from the coupling to the Higgs doublet.

Vectorlike (*i.e.* non-chiral) fermions may also exist. Their masses are allowed by the $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry, $\Rightarrow$ may naturally be heavier than the t quark.

A vectorlike quark χ which transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the top quark:

$$\mathcal{L} = -\left(\overline{u}_L^3 \ , \ \overline{\chi}_L\right) \begin{pmatrix} \lambda_t v_H & 0 \\ M_0 & M_\chi \end{pmatrix} \begin{pmatrix} u_R^3 \\ \chi_R \end{pmatrix}$$

$v_H \simeq 174$ GeV is the Higgs vacuum expectation value

λ_t is the top Yukawa coupling

M_0 and M_χ are mass parameters

Transform the gauge eigenstates u^3 and χ to the physical states t (discovered at the Tevatron) and t' (remains to be discovered):

$$\begin{pmatrix} t_L \\ t'_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} u^3_L \\ \chi_L \end{pmatrix}$$

The three initial parameters λ_t, M_0, M_χ are replaced by physical parameters: m_t (measured!), $m_{t'}$ and θ_L.

Interactions of left-handed quarks with W and Z:

$$t_L - \bar{b}_L - W^+_\mu \quad : \quad i\frac{g}{\sqrt{2}}\cos\theta_L\,\gamma_\mu \quad \Rightarrow \quad \sin\theta_L < 0.67 \;\; \text{(from single top production)}$$

$$t'_L - \bar{b}_L - W^+_\mu \quad : \quad i\frac{g}{\sqrt{2}}\sin\theta_L\,\gamma_\mu$$

$$t_L - \bar{t}_L - Z_\mu \quad : \quad i\frac{g}{\cos\theta_W}\left(\frac{1}{2}\cos^2\theta_L - \frac{2}{3}\sin^2\theta_W\right)\gamma_\mu$$

$$t_L - \bar{t'}_L - Z_\mu \quad : \quad i\frac{g}{\cos\theta_W}\frac{1}{2}\sin\theta_L\cos\theta_L\,\gamma_\mu$$

$$t'_L - \bar{t'}_L - Z_\mu \quad : \quad i\frac{g}{\cos\theta_W}\left(\frac{1}{2}\sin^2\theta_L - \frac{2}{3}\sin^2\theta_W\right)\gamma_\mu$$

Decay widths of t':

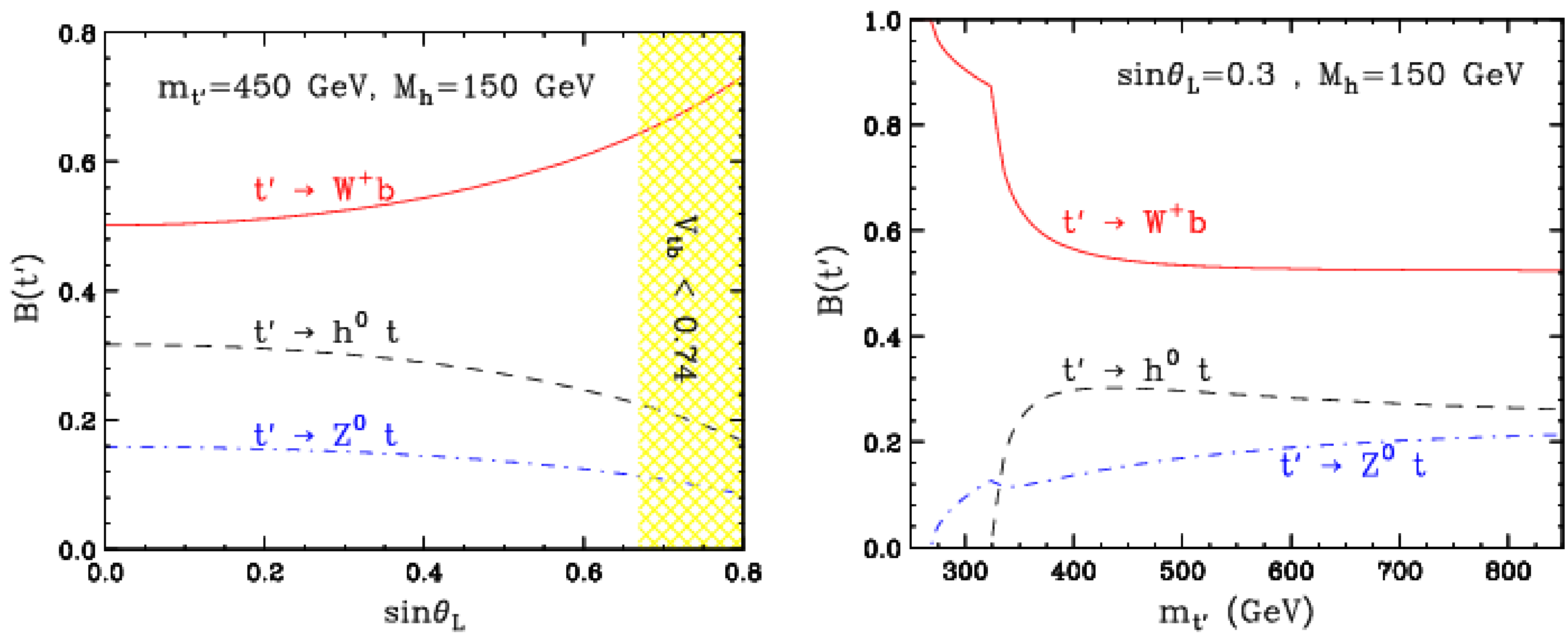
$$\Gamma(t' \to W^+ b) = \frac{\sin^2\theta_L\, m_{t'}^3}{32\pi v_H^2}\left(1-\frac{M_W^2}{m_{t'}^2}\right)^2\left(1+\frac{2M_W^2}{m_{t'}^2}\right)$$

$$\Gamma(t' \to Z t) = \frac{\cos^2\theta_L\,\sin^2\theta_L\, m_{t'}^3}{64\pi v_H^2}\left[1+O\left(\frac{M_Z^4}{m_{t'}^4}\right)\right]$$

If $m_{t'} > M_h + m_t$:

$$\Gamma(t'\to h t) = \frac{c_L^2 s_L^2 m_{t'}^3}{64\pi v_H^2}\left[\left(1+\frac{m_t^2-M_h^2}{m_{t'}^2}\right)\left(1+\frac{m_t^2}{m_{t'}^2}\right)+\frac{4m_t^2}{m_{t'}^2}\right]\left[\left(1-\frac{m_t^2+M_h^2}{m_{t'}^2}\right)^2-4\frac{m_t^2 M_h^2}{m_{t'}^4}\right]^{1/2}$$

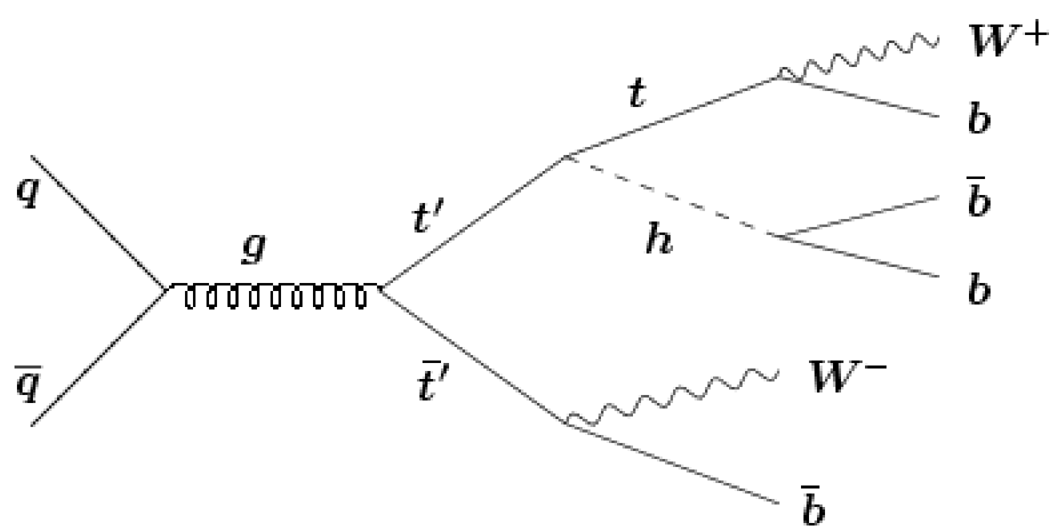
Branching fractions of t':



QCD production of $t'\bar{t}'$ pairs, followed by t' decays, leads to various final states:

- $(W^+b)(W^-\bar{b})$ usual "t' search"
- $(Zt)(W^-\bar{b})$ or $(Z\bar{t})(W^+b)$
- $(ht)(W^-\bar{b})$ or $(h\bar{t})(W^+b)$, with $h \to b\bar{b}$ or $h \to W^+W^-$
- ...

Example:

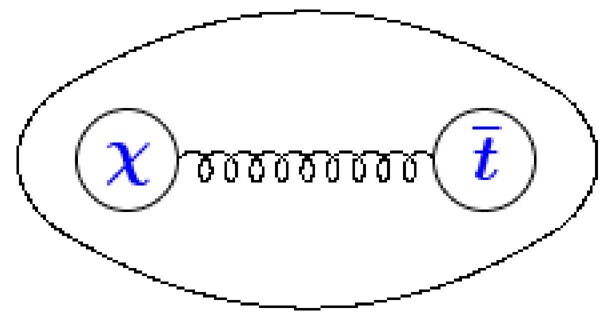


The Higgs boson could be discovered in the W^+W^-+4b sample...

Various theories that include vectorlike quarks also include a heavy spin-1 color-octet particle ("gluon-prime" or "coloron")

Example:

In the Top-quark seesaw model, the Higgs boson is a $\bar{t}\chi$ bound state, with binding due to a heavy color-octet gauge boson. *(B. Dobrescu, C. Hill: hep-ph/9712319)*



Other models: QCD and top in extra dimensions, UED, warped ED, ...

Let us consider a simple extension of the SM that includes a G'_μ boson and a χ quark.

$SU(3)_1 \times SU(3)_2 \to SU(3)_c$ spontaneously broken by the **VEV** of a scalar transforming as $(3, \bar{3})$

SM quarks transform as 3 of $SU(3)_1$

Vectorlike quark transforms as 3 of $SU(3)_2$

G^a_μ - massless gluon of **QCD**, with $g_s = \frac{h_1 h_2}{\sqrt{h_1^2+h_2^2}}$ where $h_{1,2}$ are the $SU(3)_{1,2}$ gauge couplings.

G'^a_μ - massive gluon ("coloron") with couplings: $g_s \frac{h_1}{h_2} G'^a_\mu \, \bar{q}\gamma^\mu T^a q$

$$g_s G'^a_\mu \, \bar{t} \left[\left(\frac{h_1}{h_2} \cos^2\theta_L - \frac{h_2}{h_1} \sin^2\theta_L \right) P_L + \left(\frac{h_1}{h_2} \cos^2\theta_R - \frac{h_2}{h_1} \sin^2\theta_R \right) P_R \right] \gamma^\mu T^a \, t$$

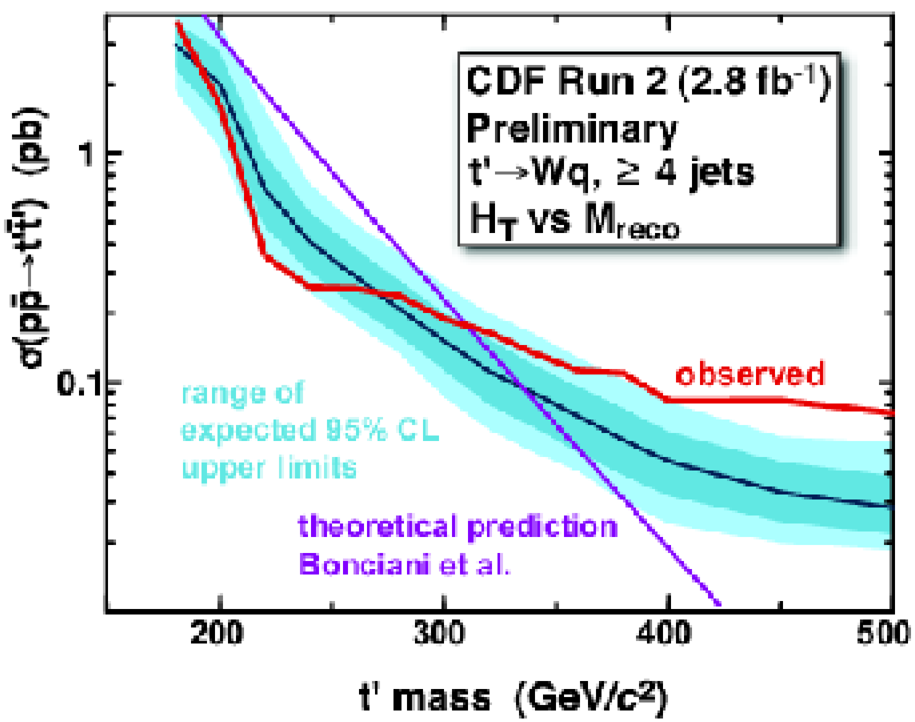
$$g_s G'^a_\mu \, \bar{t}' \left[\left(\frac{h_1}{h_2} \sin^2\theta_L - \frac{h_2}{h_1} \cos^2\theta_L \right) P_L + \left(\frac{h_1}{h_2} \sin^2\theta_R - \frac{h_2}{h_1} \cos^2\theta_R \right) P_R \right] \gamma^\mu T^a \, t'$$

$$g_s \left(\frac{h_1}{h_2} + \frac{h_2}{h_1} \right) G'^a_\mu \, \bar{t} \left[\sin\theta_L \cos\theta_L P_L + \sin\theta_R \cos\theta_R P_R \right] \gamma^\mu T^a \, t'$$

$$\text{RH mixing}: \ \sin\theta_R = \left[1 + \left(\frac{m_t}{m'_t \, \tan\theta_L} \right)^2 \right]^{-1/2} \quad : \quad \text{chirality projectors}: P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$$

CDF search for $t' \to W^+ b$:

www-cdf.fnal.gov/physics/new/top/2008/tprop/Tprime2.8/public.html



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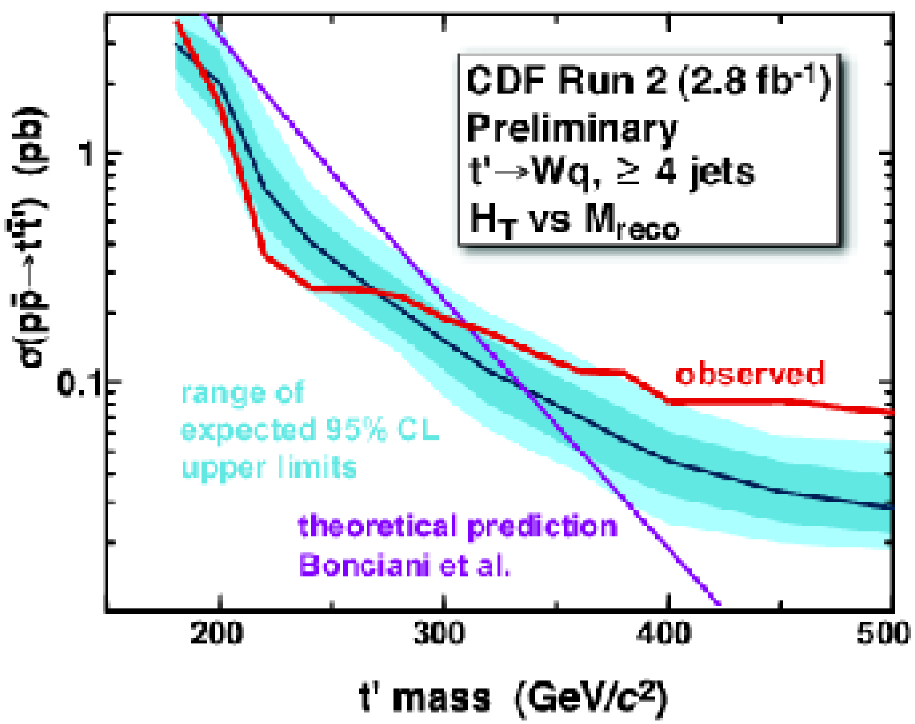
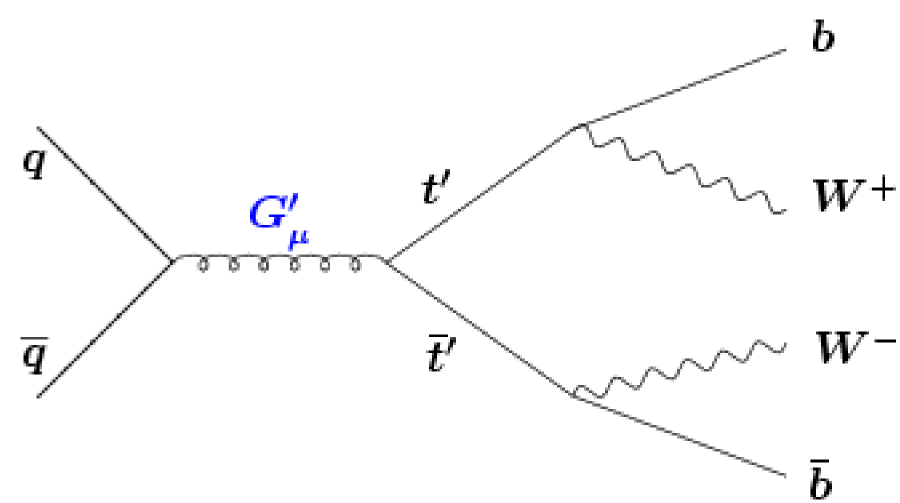


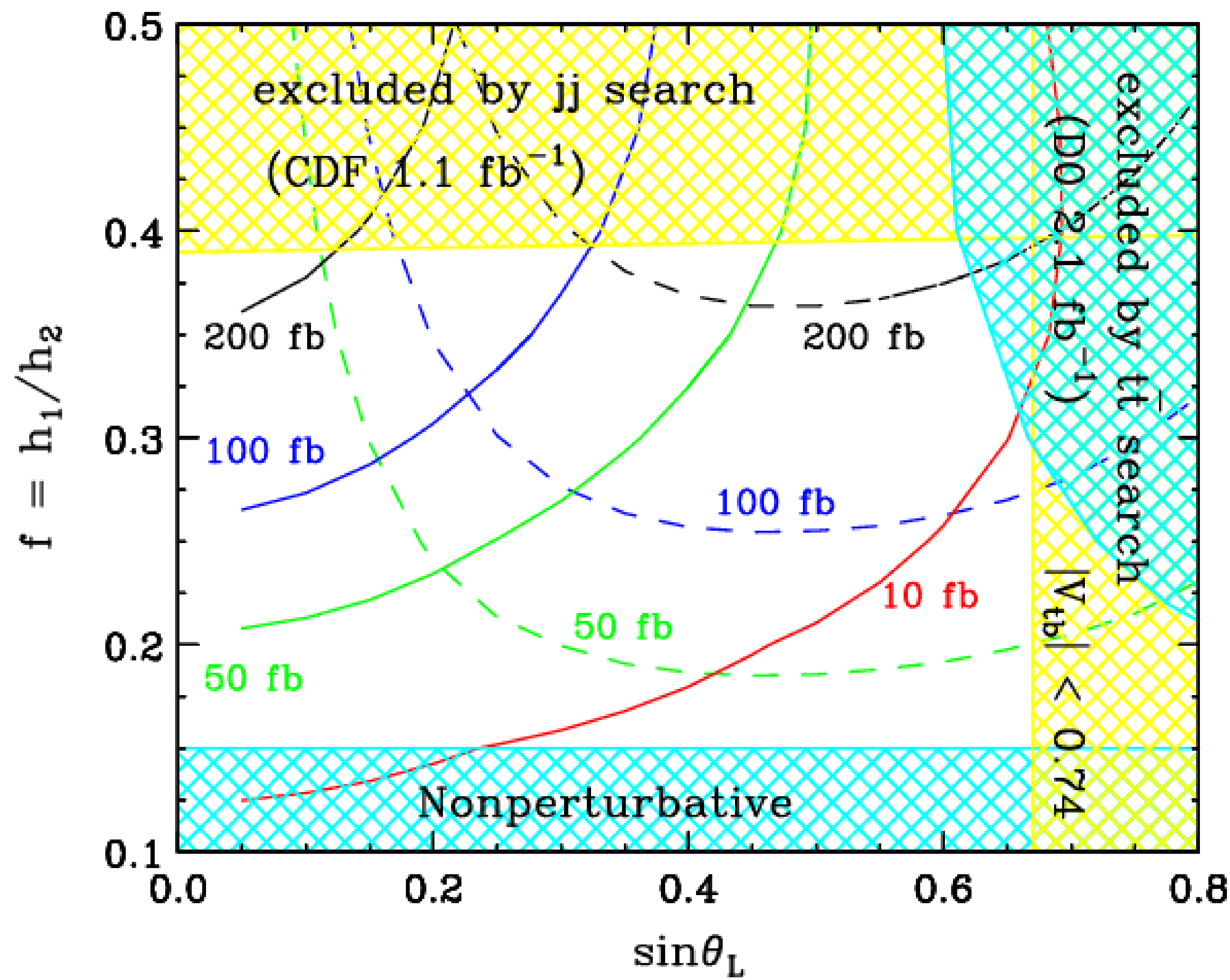
Our interpretation: G'_μ resonance

B. Dobrescu, K. Kong, R Mahbubani: hep-ph/0901.????



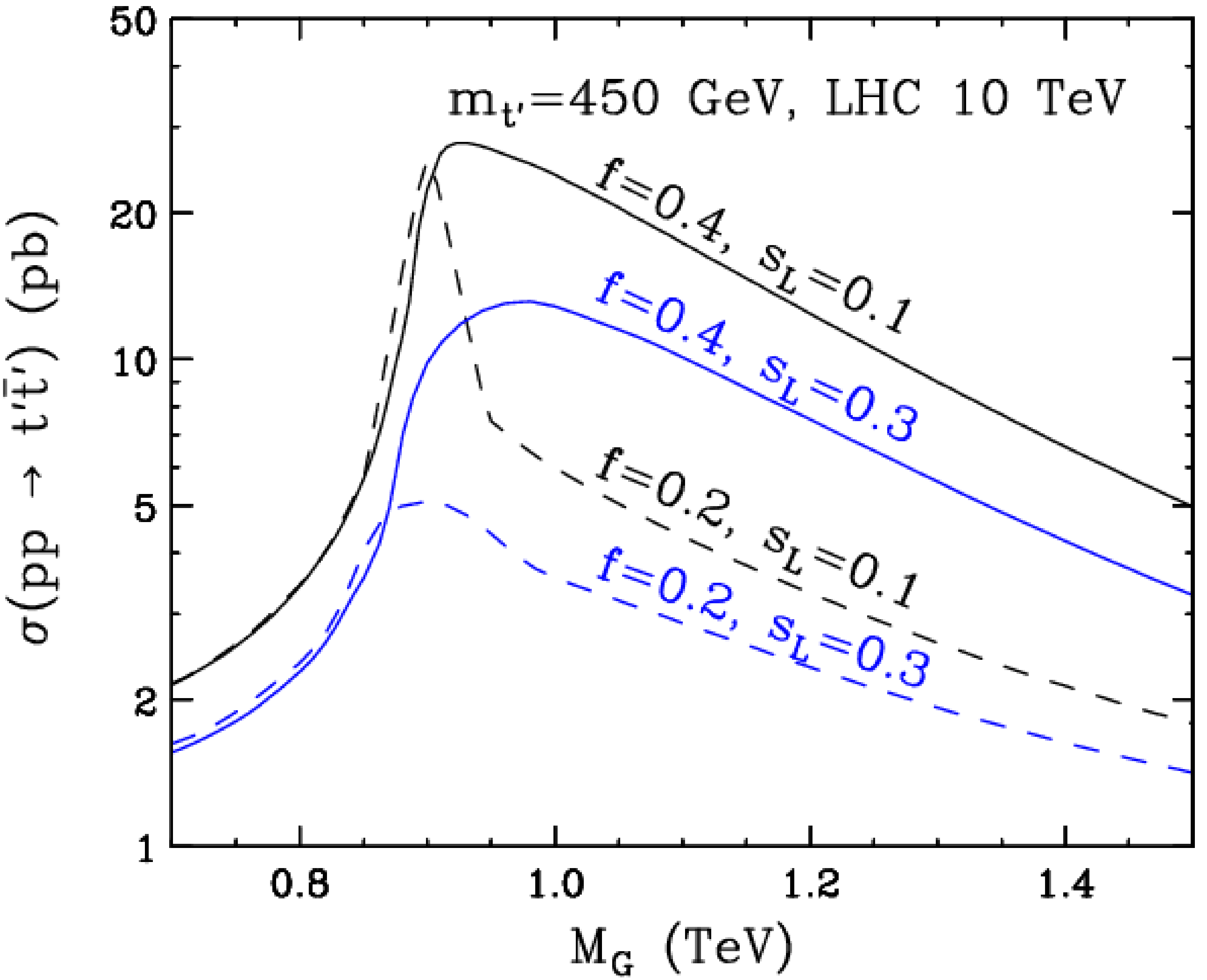
G' also induces resonances in the $t'\bar{t}$, $t\bar{t}$, and dijet invariant masses.

Production cross sections at the Tevatron for $t'\bar{t}'$ (solid lines) and $t\bar{t}' + t'\bar{t}$ (dashed lines):



At the LHC:

G' **may also enhance substantially the** $t'\bar{t}'$ **production.**



Things CMS can do:

1. See if there is an excess in $t'\bar{t}' \to (Wb)(Wb)$.

2. Check if there is a mass peak in $t'\bar{t}'$.

3. Look for the $t'\bar{t}$ signal. Event selection is similar as for $t'\bar{t}'$, but the background is somewhat different.

4. Search aggressively for $t\bar{t}$ and dijet resonances, including wide ones.

5. ...

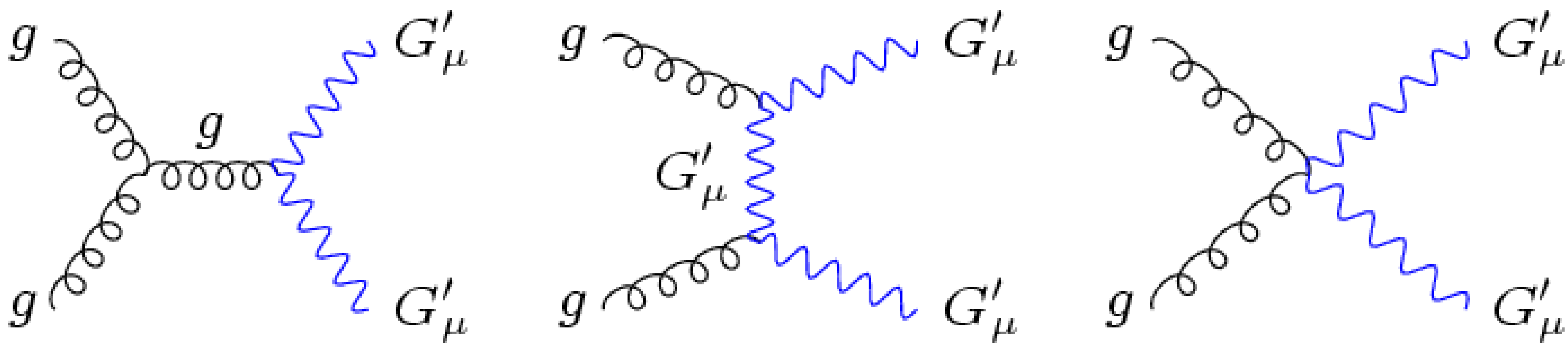
Model "independent" search for Gluon-prime

work with KC Kong and Rakhi Mahbubani hep-ph/0709.2378

G'_μ couplings to quarks are model dependent: if they are small enough, the mass limits from dijet resonance searches are evaded.

G'_μ couplings to gluons are fixed by gauge invariance. G'_μ couples only in pairs to the gluon.

Pair production of heavy gluons from gluon-gluon initial state:



A pair of gluon-primes decays to 2 pairs of dijets (or $jjb\bar{b}$, $b\bar{b}b\bar{b}$).

Dominant background: QCD 4-jet production.
We simulated the background at tree level using MadGraph (checked with NJETS), taking the b-tagging efficiency to be 50%.

Production and decay of gluon-primes (G'_μ) at the LHC:

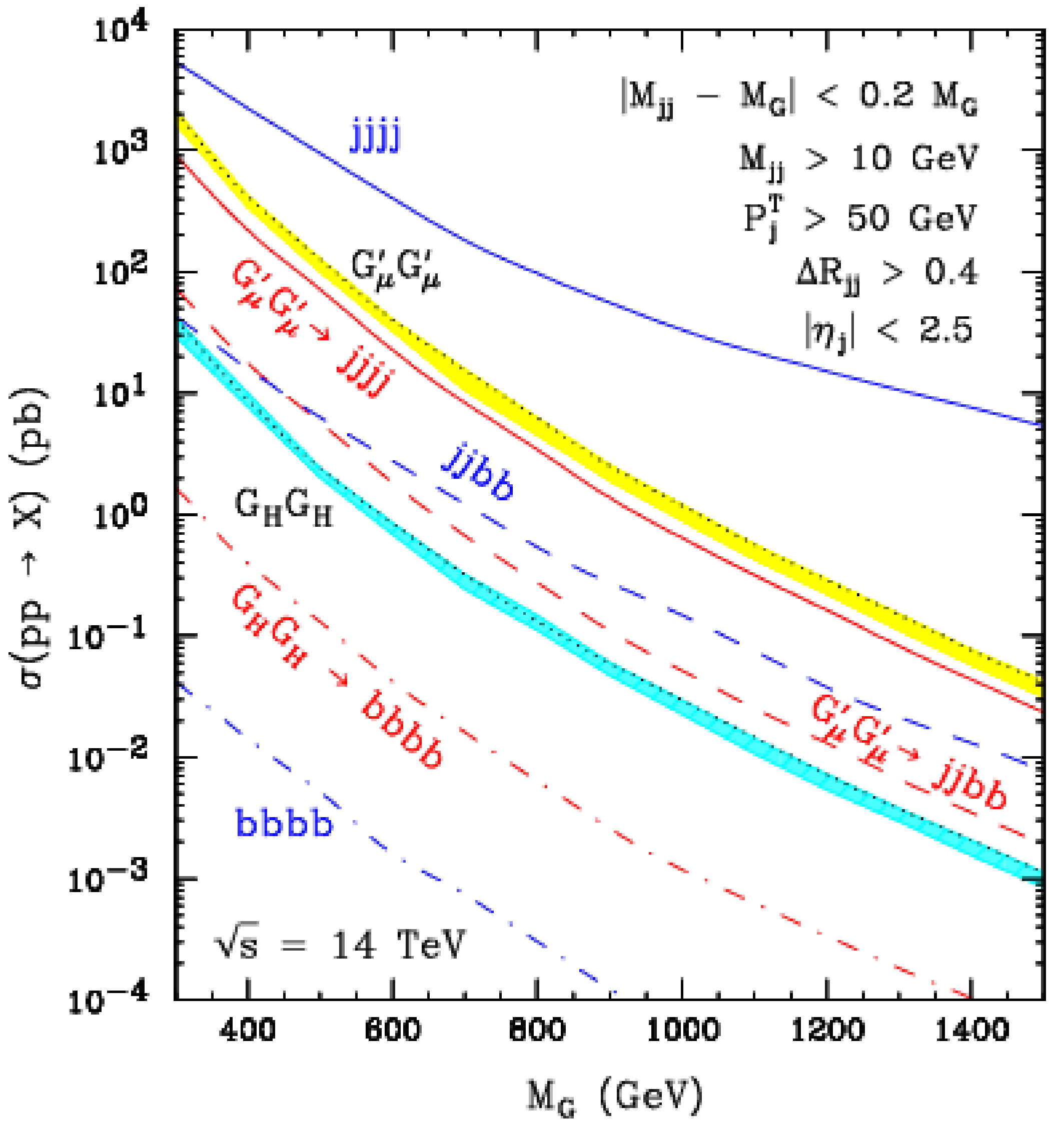
The jets reconstruct (in pairs) resonances of equal mass.

Cutting around the resulting peak decreases the background dramatically.

A spin-0 color octet (G_H) has similar properties, except it decays into the heaviest quarks.

Signal: $p\bar{p} \to G_H G_H \to (b\bar{b})(b\bar{b})$

We estimate that the **LHC.** mass reach for a G'_μ is $M_G \lesssim 1$ TeV with 1 fb^{-1}



Conclusions

The LHC will explore the TeV scale (= "terra incognita").

Many possibilities for what you could discover:

- Vectorlike fermions
- New gauge bosons (Z', W', G', ...)
- extended Higgs sectors
- UED, little Higgs, susy, warped ED, ...

This talk – Signals motivated by simple extensions of the SM:

- $h \to A^0 A^0 \to (\gamma\gamma)(jj)$ or $(\gamma\gamma)j$ or "γ" j
- $t\bar{t}$ or $t\bar{b}$ resonance $+ jj$ from 2UED
- leptoquark pair $\to (\mu j)(\tau j)$
- $G' \to t'\bar{t} \to (Wb)(Wb)$
- $G' \to t'\bar{t}' \to (Zt)(Wb)$ or $(ht)(Wb)$
- $G'G' \to (jj)(jj)$ or $(bb)(jj)$