The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

**2400-17**

**Workshop on Strongly Coupled Physics Beyond the Standard Model**

***25 - 27 January 2012***

# Massive color-octet bosons

Bogdan Dobrescu
*Fermilab*

# Heavy color-octet bosons

**Bogdan Dobrescu** (*Fermilab*)

*Work with:*

**Yang Bai (SLAC) - 1012.5814**

**Gordan Krnjaic (Johns Hopkins Univ.) - 1104.2699**

**Graham Kribs (Oregon) and Adam Martin (Fermilab) - 1112.2208**

*Outline:*

- **Color-octet scalars**
- **A gluon-prime model**
- **Signatures of scalar octets at the Tevatron and LHC**

*Talk at Workshop on strongly coupled physics, ICTP, Trieste - January 25, 2012*

# Discovering particles one (or two) at a time

**It may very well be that our first glimpse of new physics will be due to the production of only one or two new particles.**

*Examples:* $Z'$, $W'$, *leptoquarks, ...*

**Particles related to this talk:**

• **Color-octet spin-0 particles: "scalar octet"**

*predicted in theories with 2 extra dimensions, technicolor,* $\mathcal{N} = 2$ *susy,...*

• **Color-octet spin-1 particles:** $G'_\mu$ **"gluon-prime" (topgluon, coloron, Kaluza-Klein gluon, techni-**$\rho$**, ...)**

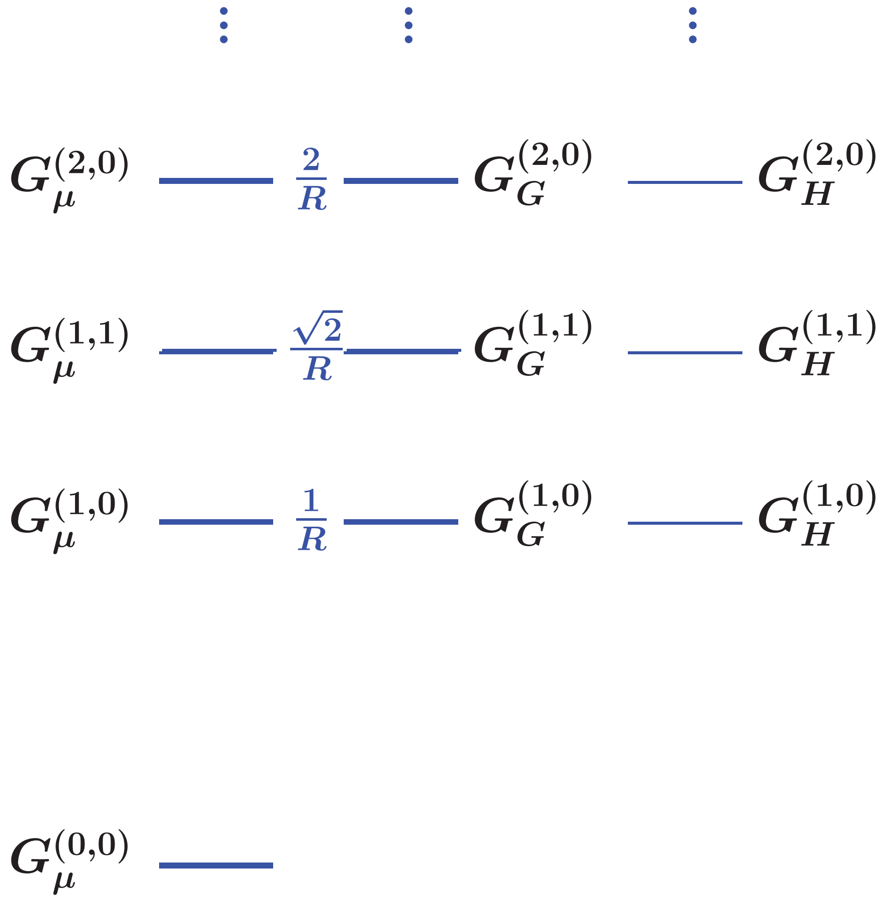
*predicted in topcolor, extra dimensions, technicolor,...*

• **Vectorlike quarks (spin-1/2, color triplets; same electroweak charges for LH and RH components)**

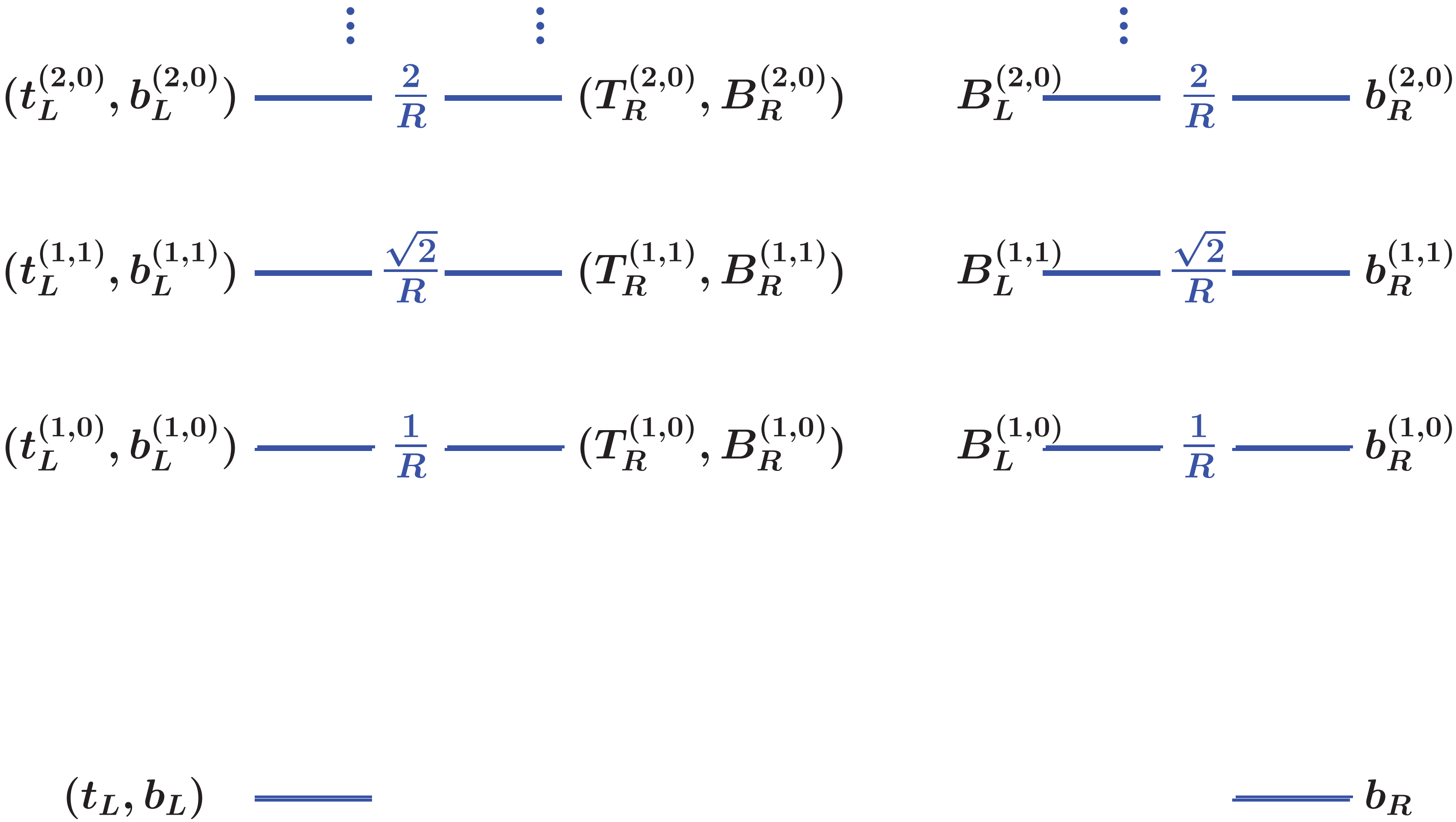
*predicted in top-quark seesaw, little-Higgs,* $E_6$ *GUT, extra dimensions,...*

# Gluon in two flat extra dimensions

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



# Kaluza-Klein spectrum of quarks in 2 flat extra dimensions:



# Scalar octet

$G_H$ (also known as $\Theta$): spin 0,

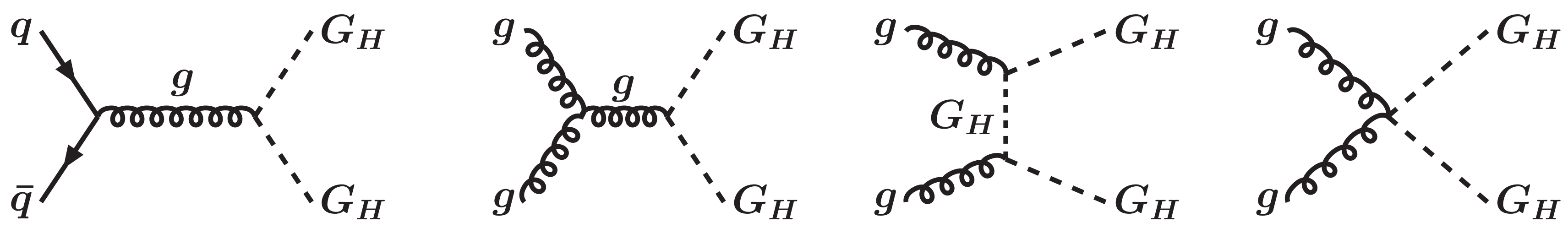
transforms as (8,1,0) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

$SU(2)_W$ forbids renormalizable couplings of $G_H$ to SM quarks.

Renormalizable couplings of $G_H$ to gluons are fixed by $SU(3)_c$ gauge invariance:

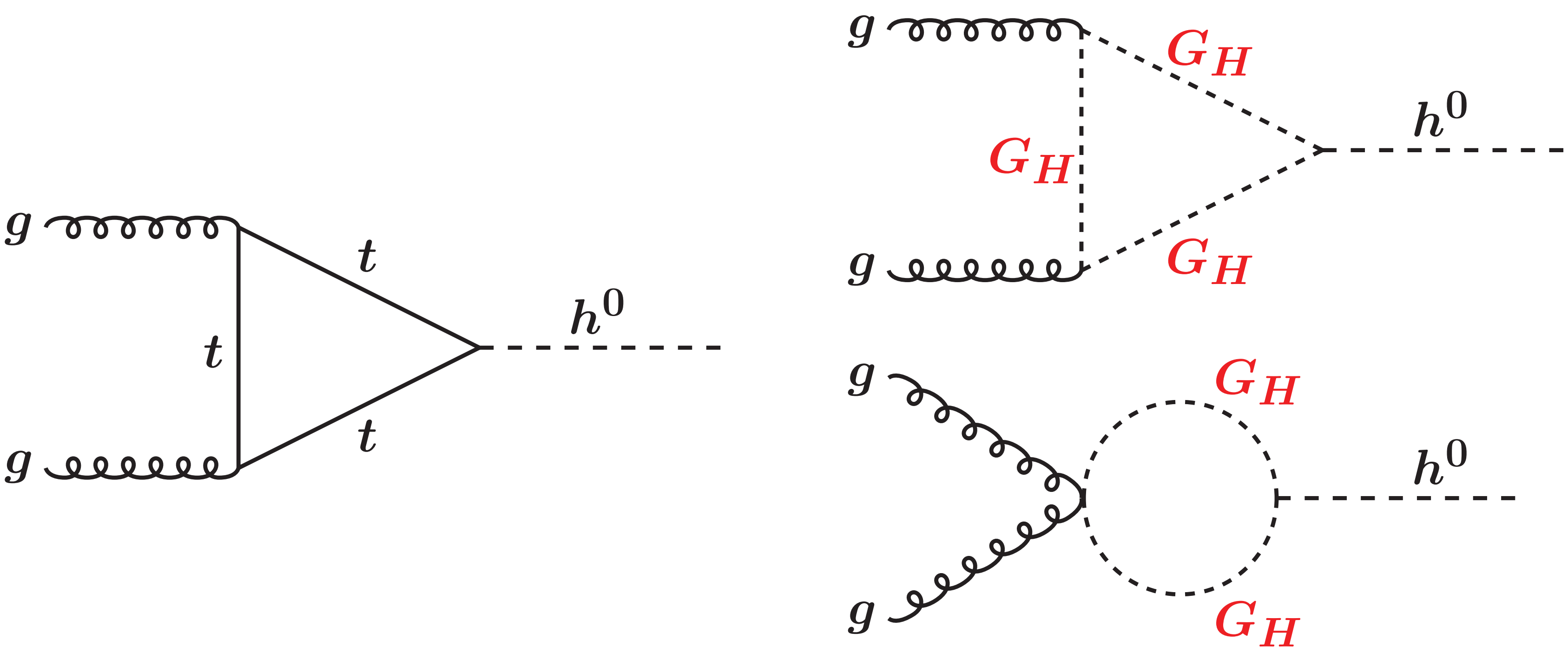
$$\frac{g_s^2}{2} f^{abc} f^{ade} G^b_\mu G^{\mu\, d} G^c_H G^e_H + g_s f^{abc} G^a_\mu G^b_H \partial^\mu G^c_H$$

$\Rightarrow$ production of $G_H$ at hadron colliders occurs in pairs.



# Changing the Higgs production

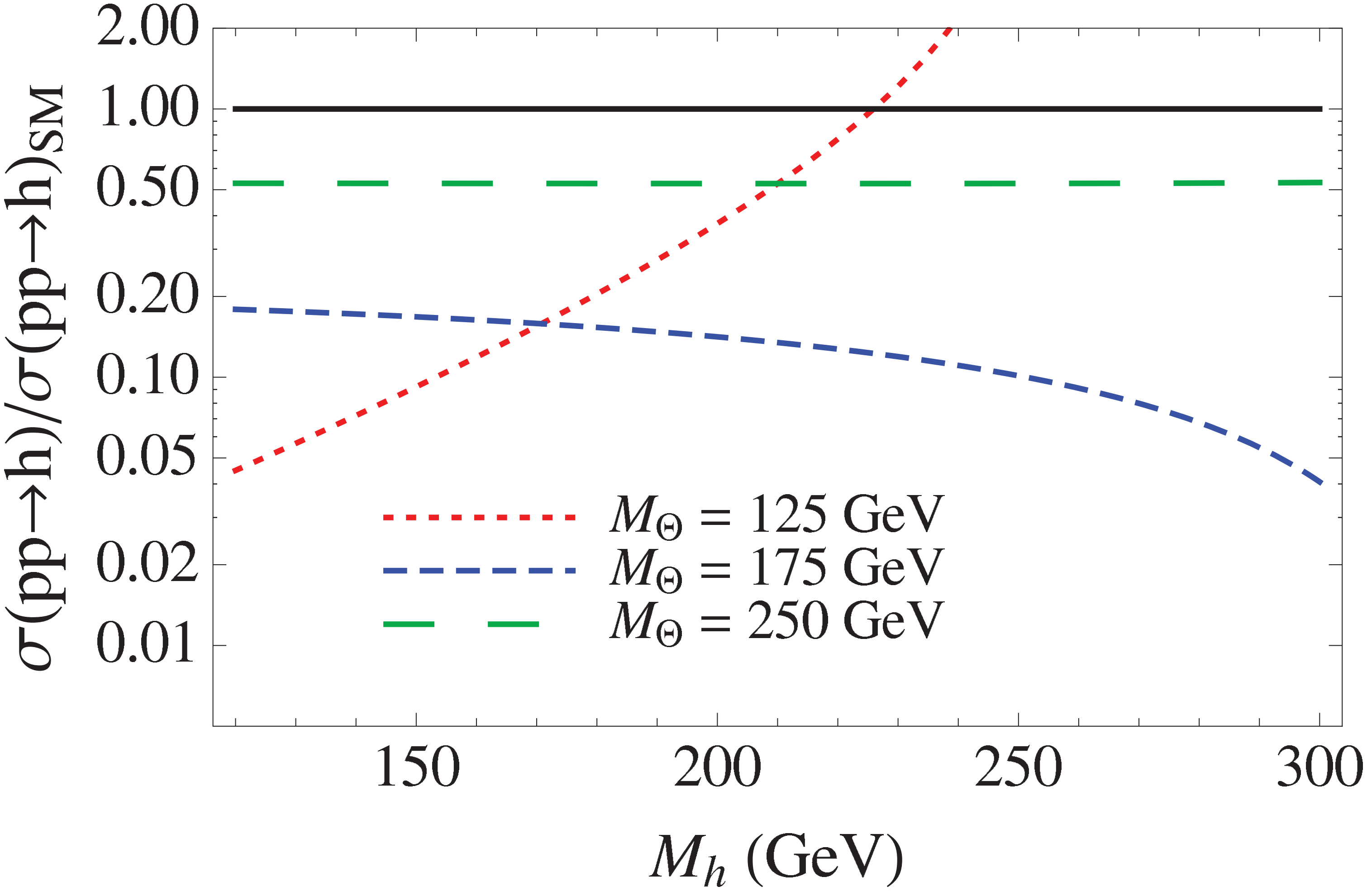
Standard-Model gluon fusion $\pm$ non-standard production




$\mathcal{L} = -\frac{1}{2}\kappa\, G_H^a G_H^a H^\dagger H$

Cross section for gluon fusion is reduced (increased) for $\kappa < 0$ ($\kappa > 0$). Effect may be large for $M_{G_H}$ near the electroweak scale.

**Higgs production for $\kappa = -0.75$:**




*work with Graham Kribs and Adam Martin: 1112.2208*

# Decays of the scalar octet

Only one renormalizable interaction violates invariance under the $G_H \to -G_H$ transformation: $\mu\, d_{abc}\, G_H^a G_H^b G_H^c$

This allows the $G_H \to gg$ decay at one loop:


$$\Gamma(G_H \to jj) = \frac{15\, \alpha_s^2\, \mu^2}{128\, \pi^3\, M_{G_H}} \left( \frac{\pi^2}{9} - 1 \right)^2$$

*work with Yang Bai: 1012.5814*

Tiny width $\Rightarrow$ decays induced by nonrenormalizable couplings of $G_H$ to quarks may have large branching fractions.

Dimension-5 operators coupling $G_H$ and SM quarks:

$$\frac{C_b}{M_\psi} H G_H^a (\overline{Q}_L^3 T^a b_R) + \frac{C_c}{M_{\psi'}} \tilde{H} G_H^a (\overline{Q}_L^3 T^a c_R) + \ldots$$

$Q_L^3 \equiv (t_L, b_L)$; $i, j = 1, 2, 3$ label the generations;

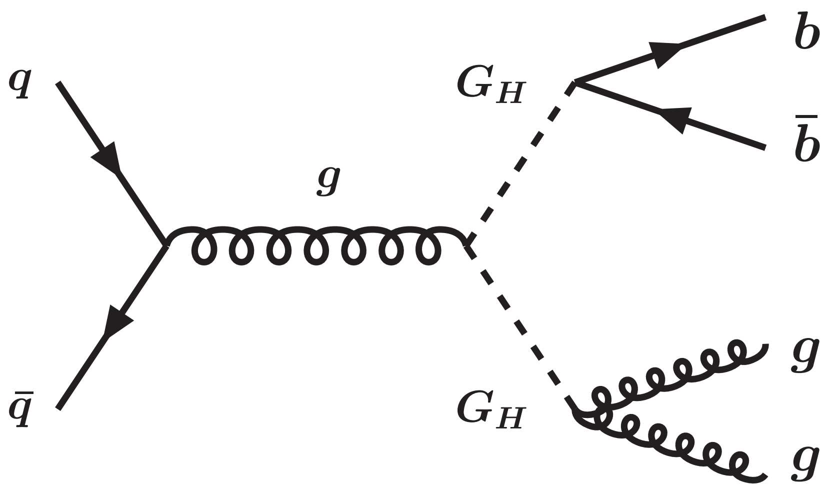
$C_b, C_c$ are complex parameters; $M_\psi$, $M_{\psi'}$ are masses of some heavy particles.

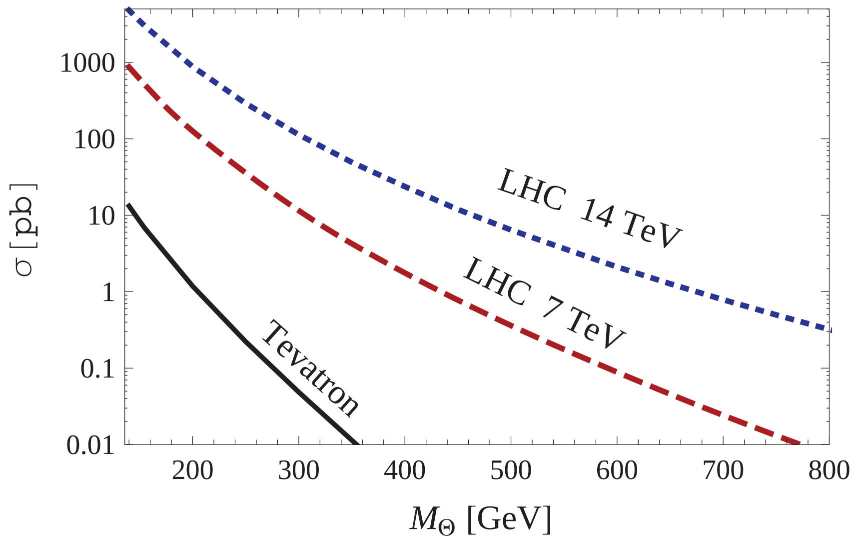
Operators involve the Higgs doublet: coefficients are typically proportional to the quark mass

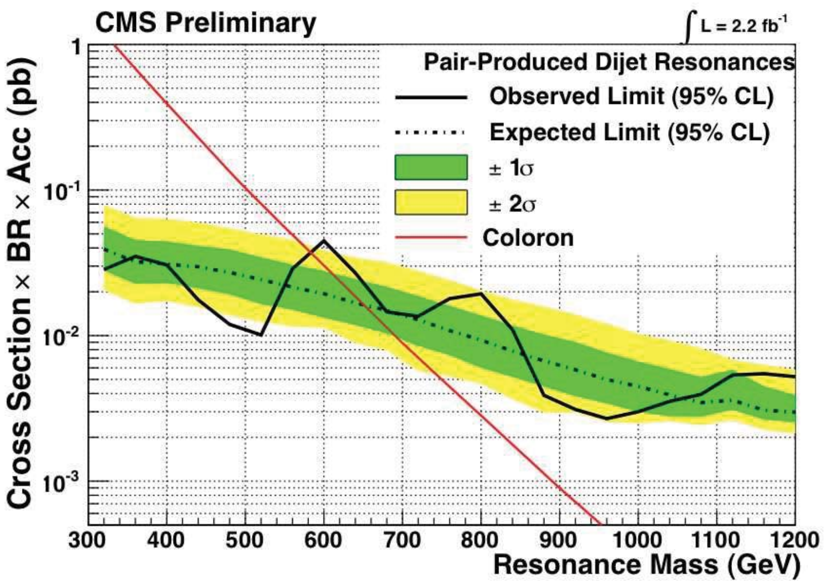
$\Rightarrow$ dominant decay modes for $M_{G_H} < 350$ GeV are $G_H \to b\bar{b}, t\bar{c}$:

$$\Gamma\left(G_H \to b\bar{b}\right) \simeq \frac{|C_b|^2}{24\,\pi} \frac{v^2}{(M_\psi)^2} M_{G_H} \simeq 10^{-3} |C_b|^2 M_{G_H} \left(\frac{1 \text{ TeV}}{M_\psi}\right)^2$$

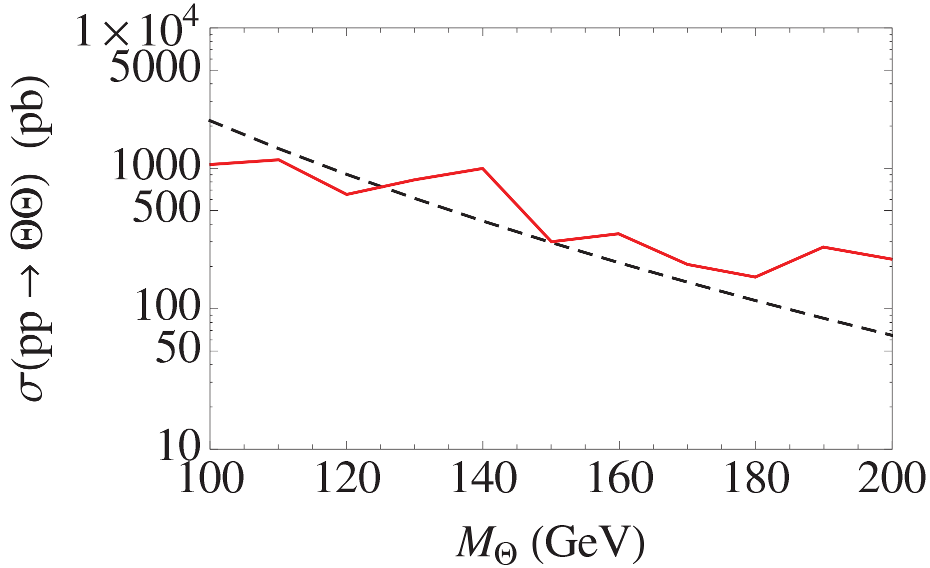
# Signal: a pair of narrow $gg$ or $b\bar{b}$ or $t\bar{c}$ resonances of same mass






CMS search for $(jj)(jj)$ (2.2 fb$^{-1}$)




ATLAS search for $(jj)(jj)$ (2010 data)

# “Gluon-prime”: a heavy spin-1 color-octet particle

Gauge extension of QCD (“Topcolor”, C. Hill 1991):

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

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

$G'^a_\mu$ - massive “gluon-prime”

*(“topgluon” or “coloron” depending on its couplings to $t$, $b$)*

Assume all SM quarks transform under $SU(3)_1$:

Interactions: $g_s r\, G'^a_\mu\, \bar{q}\gamma^\mu T^a q$ where $r = h_1/h_2$.

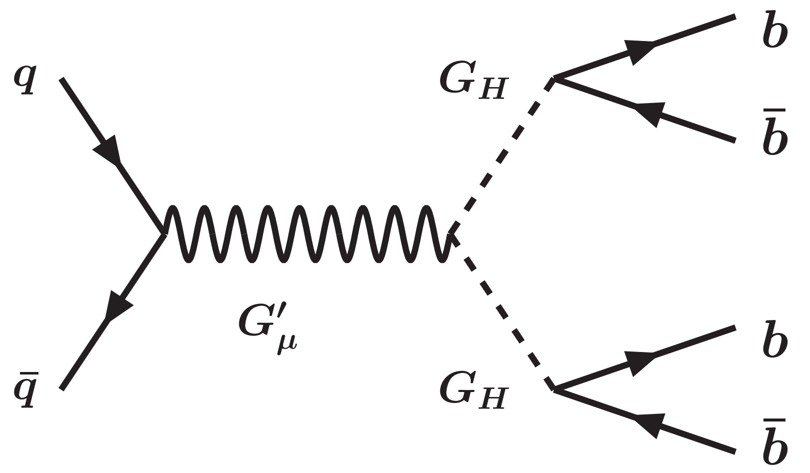
Scalar whose VEV breaks $SU(3)_1 \times SU(3)_2$:

$$\Sigma = \frac{1}{\sqrt{6}}(f + \phi)\,\mathbb{I}_3 + (G_H^a + i\,G_I^a)T^a$$

$G_I$ becomes the longitudinal $G'_\mu$; $\phi$ is a scalar singlet.

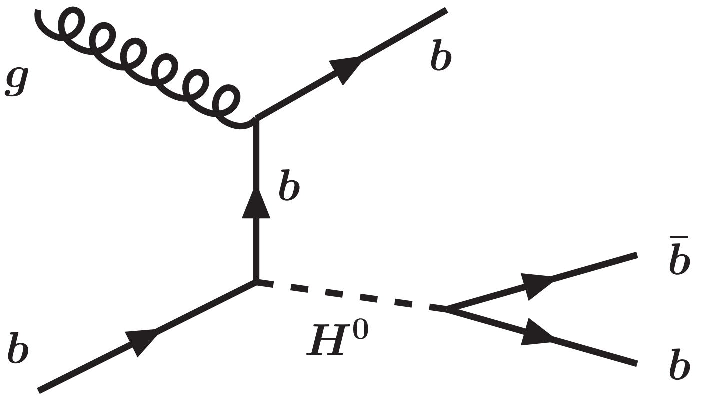
$$-\frac{h_1^2 - h_2^2}{2\sqrt{h_1^2 + h_2^2}}\, G'^{\,a}_{\mu} G^b_H \,(\partial_\mu G^c_H)\, f^{abc}$$

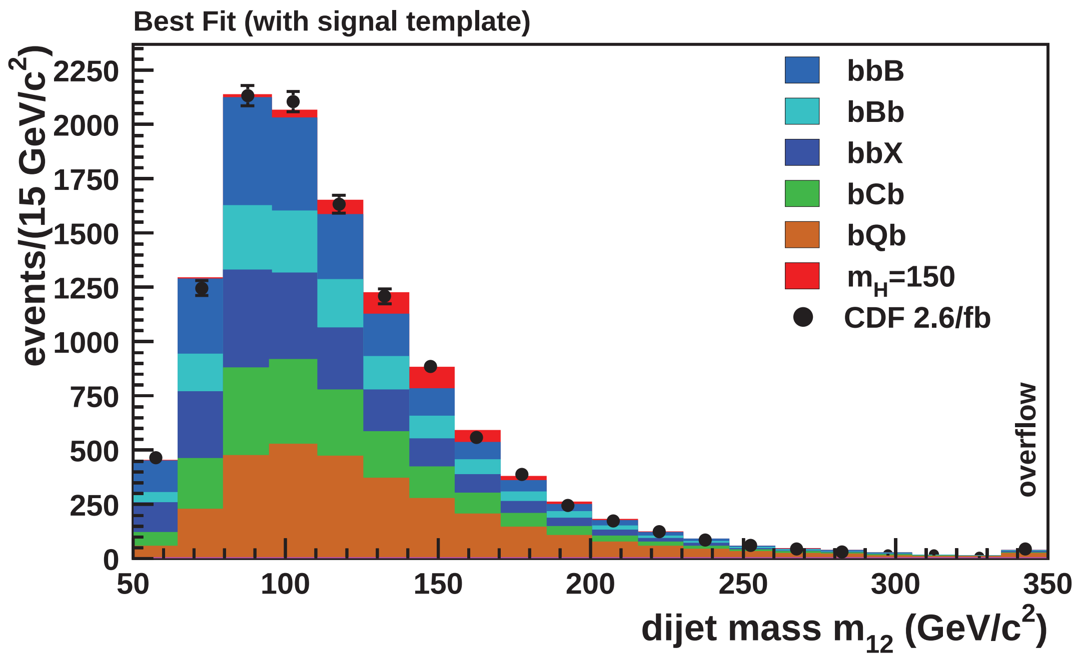
(*work with Yang Bai – 1012.5814*)



## CDF search for $3b$ signal predicted in the MSSM at large $\tan\beta$:

1106.4782




**Excess of events with $m_{12} \approx 130 - 160$ GeV (consistent with $M_H \approx 150$ GeV).**

*The probablity for this excess to be due to a fluctuation of the SM background is 0.23%, and increases to 2.5% when the whole range of invariant masses is taken into account.*

D0 search in the $3b$ channel with 5.2 fb$^{-1}$ is optimized for the MSSM Higgs bosons through the use of a likelihood discriminant $\Rightarrow$ may not apply to a $G_H G_H \rightarrow bbb(b)$ signal.

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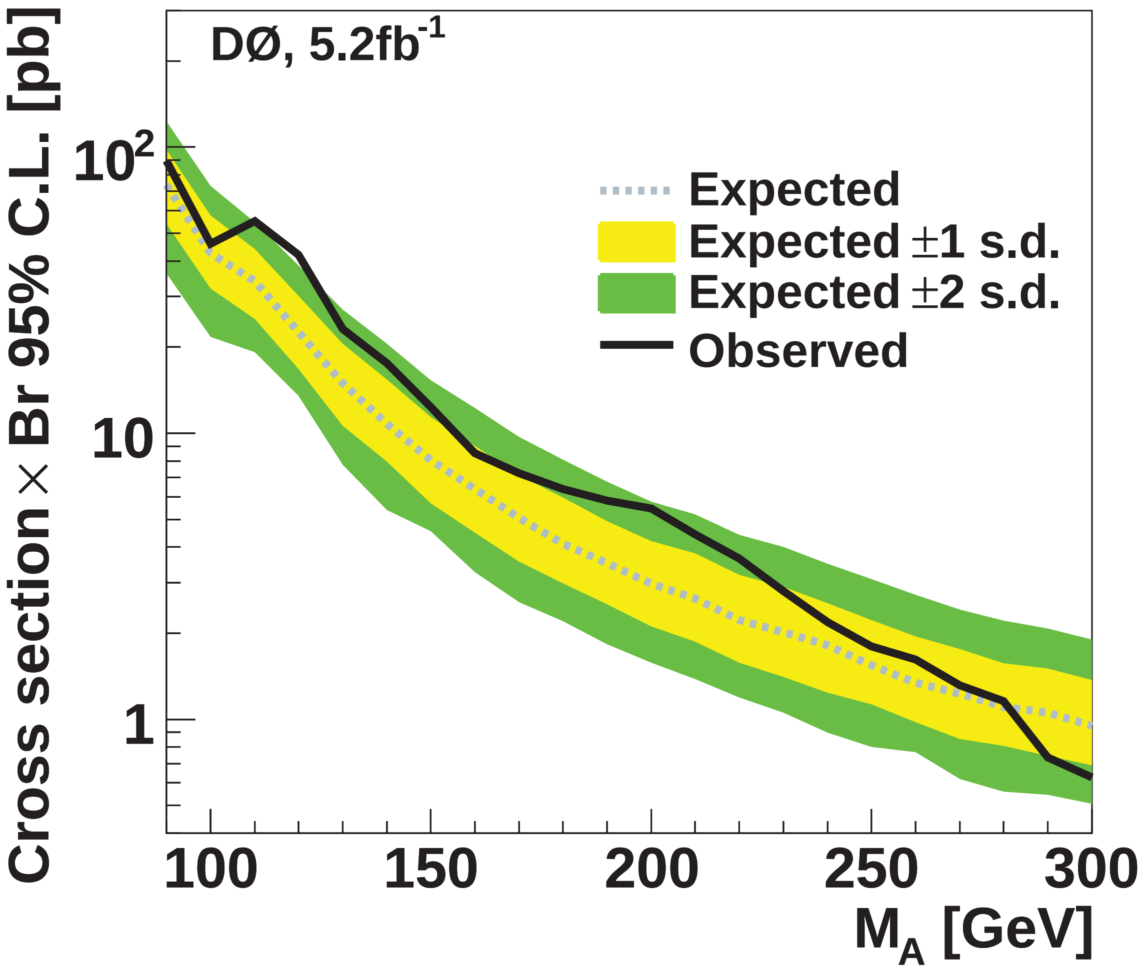
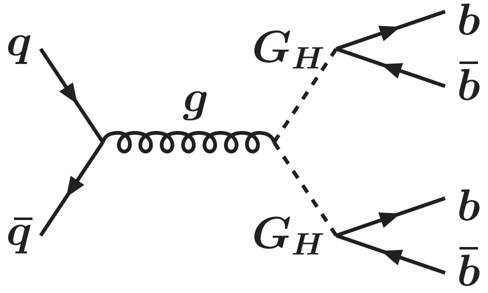
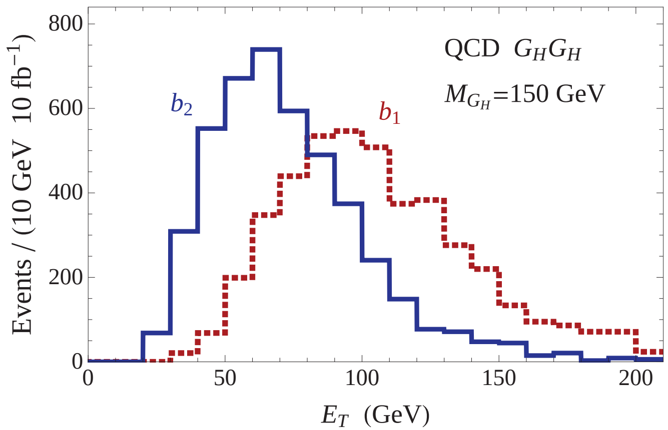
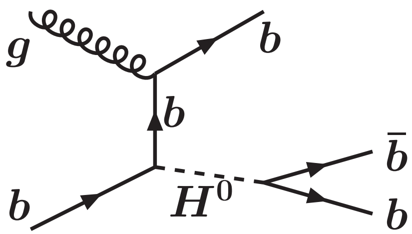


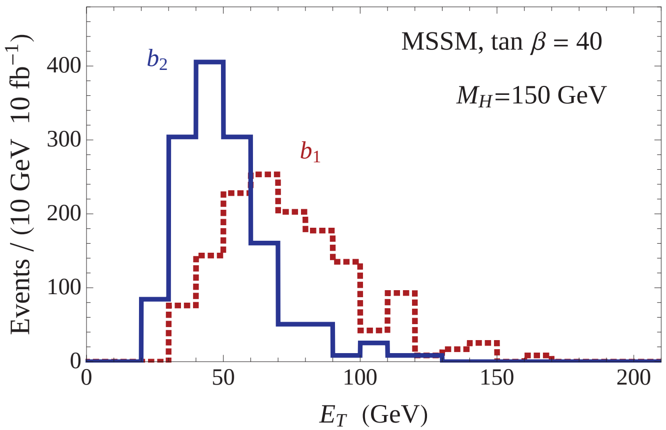
*Use kinematic distributions to differentiate between models*

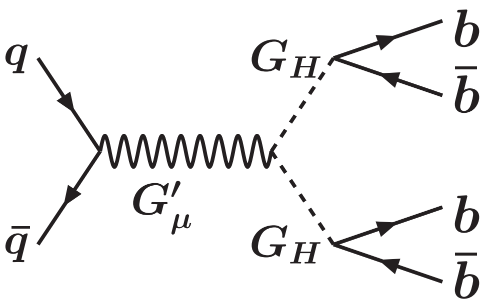
## Transverse energy ($E_T$) distributions of the two leading $b$-jets:

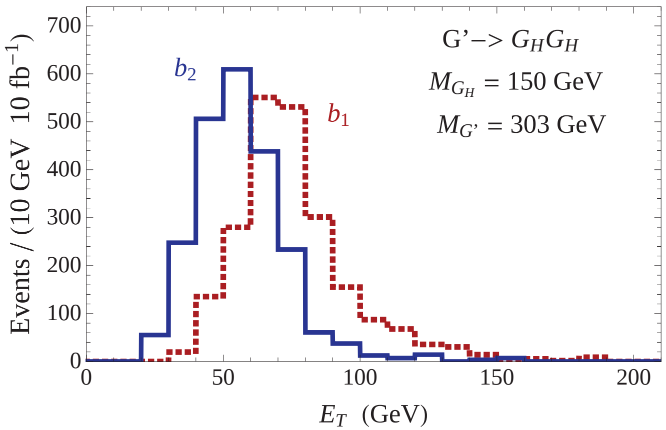


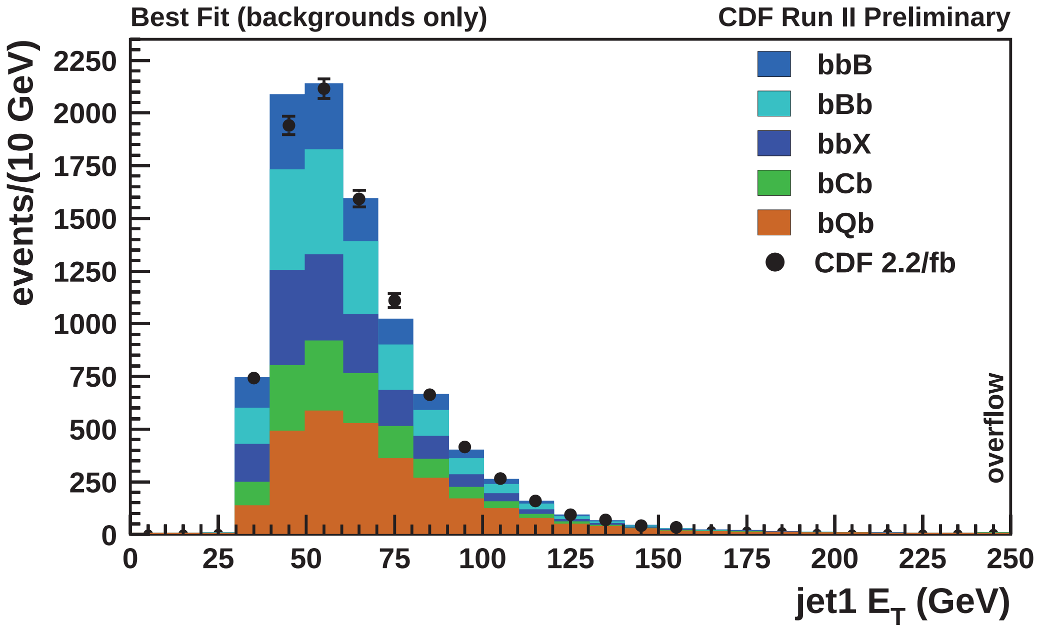



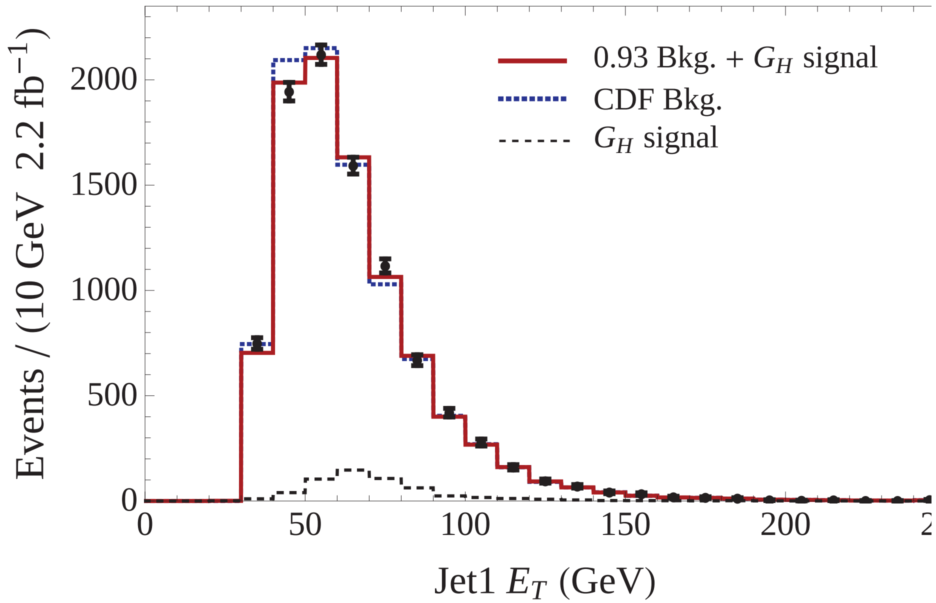



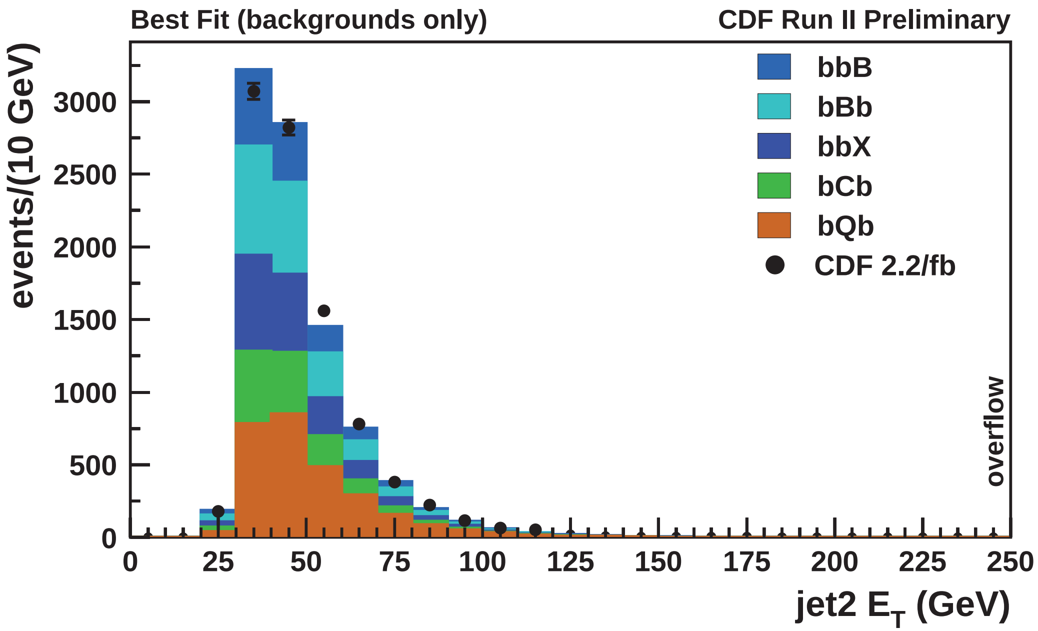



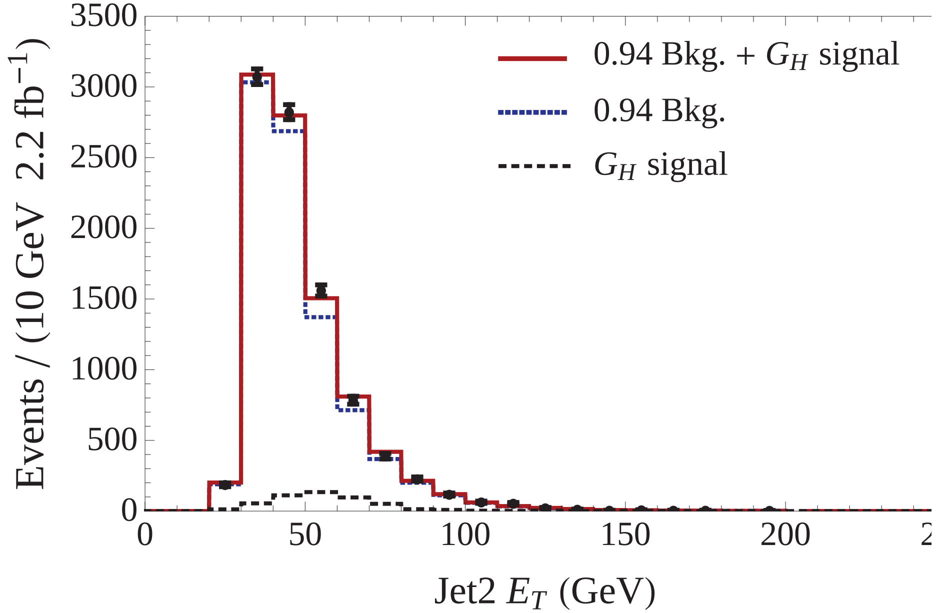



# CDF $3b$ data and background compared to $G'_\mu \to G_H G_H$ model ($M_{G'} = 303$ GeV, $\sigma\times\mathcal{B} = 1.8$ pb):



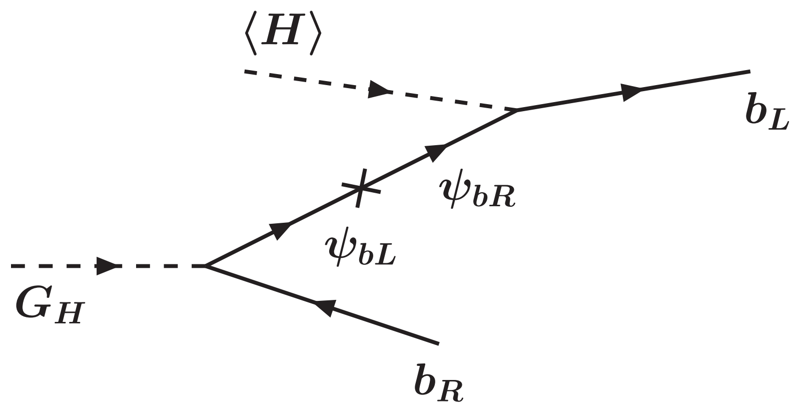



# Short-distance origin for $G_H \to b\bar{b}$

A vectorlike quark, $\psi_b$, having the same gauge charges as $b_R$:

$$M_\psi \overline{\psi}_{bL}\psi_{bR} + \lambda_3 H \overline{Q}^3_L \psi_{bR} + \eta_3 G^a_H \overline{\psi}_{bL} T^a b^3_R$$

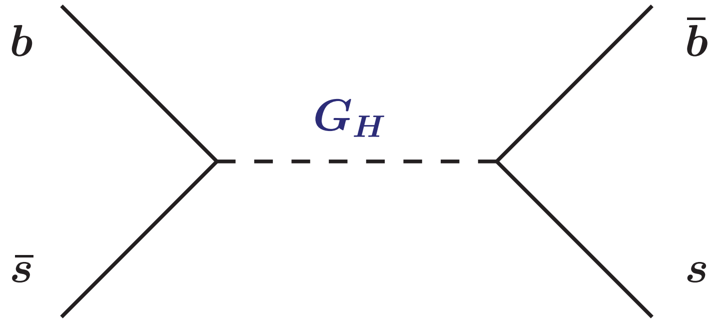
Effective coupling of a scalar octet to $b$ quarks and Higgs VEV:




This generates the dimension-5 coupling of $G_H$ to $b$ quarks:

$$\frac{C_b}{M_\psi} H G^a_H (\overline{Q}^3_L T^a b_R) \quad with \quad C_b \approx \lambda_3\, \eta_3^*$$

## $B_s - \bar{B}_s$ mixing due to scalar octet exchange




**In the mass eigenstate basis:**

$$\frac{C_{23} v}{M_\psi} G_H^a (\overline{s}_L T^a b_R) + \frac{C_{32} v}{M_\psi} G_H^a (\overline{b}_L T^a s_R)$$

**Contribution to the dispersive part of the $B_s - \overline{B}_s$ mixing:**

$$M_{12}^{\rm NP} = \frac{v^2}{48\, M_{G_H}^2} \frac{C_{32}^d\, C_{23}^{d*}}{M_\psi^2} \frac{M_{B_s}^3}{(m_b + m_s)^2}\, f_{B_s}^2\, (B_5 - B_4)\,,$$

The $m_t^2/m_c^2$ enhancement is so large that even for $M_{G_H} < m_t + m_b$ the 3-body decay through an off-shell top quark, $G_H \to W^+ b\,\bar{c}$, needs to be taken into account:

$$\Gamma(G_H \to W^+ b\bar{c}) = \frac{\alpha\, |\eta_3 \mu_3|^2\, m_t^4}{64\pi^2 \sin^2\theta_W\, m_\psi^4} \mathcal{F}(M_G)$$

The function $\mathcal{F}$ is given by integrating the matrix element over phase space:

$$\mathcal{F}(M_G) = \int_0^{E_0} d\overline{E}_{\bar{b}} \int_{E_0 - \overline{E}_{\bar{b}}}^{E_b^{\max}} dE_b \frac{E_b + (E_0 - \overline{E}_{\bar{b}}) \left[\frac{2M_G}{M_W^2}(E_0 - E_b) - 1\right]}{(M_G^2 - 2M_G \overline{E}_{\bar{b}} - m_t^2)^2 + m_t^2 \Gamma_t^2}$$

$E_0$ is the maximum energy of the $\bar{b}$ or $b$ jet,

$$E_0 = \frac{M_G^2 - M_W^2}{2M_G}$$

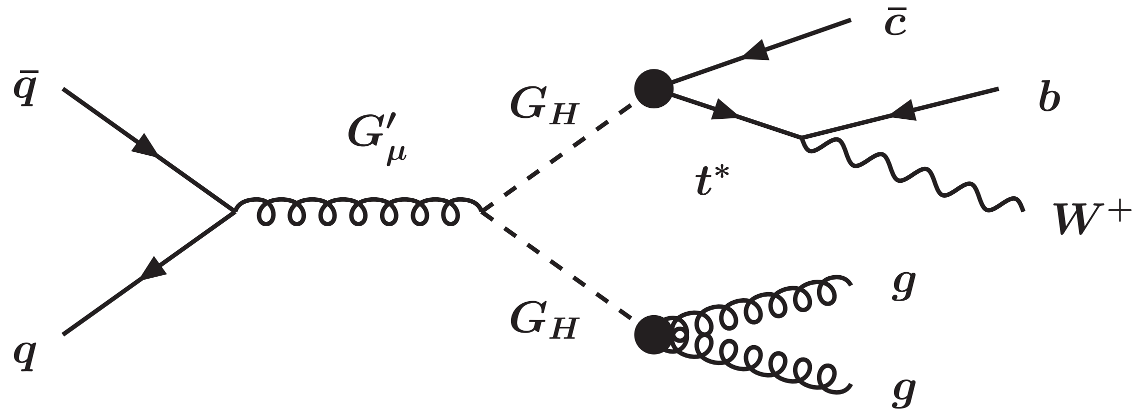
and $E_b^{\max}$ is the maximum $b$ energy for a fixed $\bar{b}$ energy $\overline{E}_{\bar{b}}$,

$$E_b^{\max} = \frac{E_0 - \overline{E}_{\bar{b}}}{1 - 2\overline{E}_{\bar{b}}/M_G}$$

$$\Gamma(\Theta^+ \to W^+ b\bar{c}) \simeq 3 \times 10^{-6}\,\mathrm{GeV}\,\frac{|\eta_3\mu_3|^2}{m_\psi^2}\frac{\mathcal{F}(M_G)}{\mathcal{F}(150\ \mathrm{GeV})}\left(\frac{1\,\mathrm{TeV}}{m_\psi}\right)^2$$

$\mathcal{F}(M_G)/\mathcal{F}(150\ \mathrm{GeV}) = 1.51$ **for** $M_\Theta = 155$ **GeV**

**It is remarkable that the 3-body decay through a virtual top quark has a width close to that for the 2-body decay into $c\bar{c}$.**

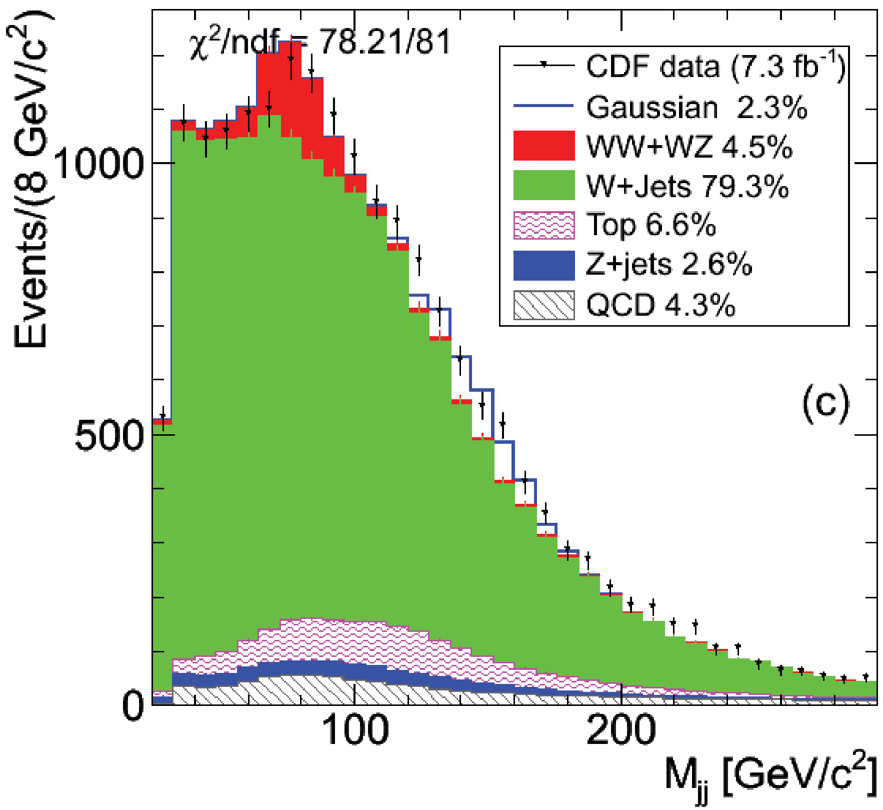


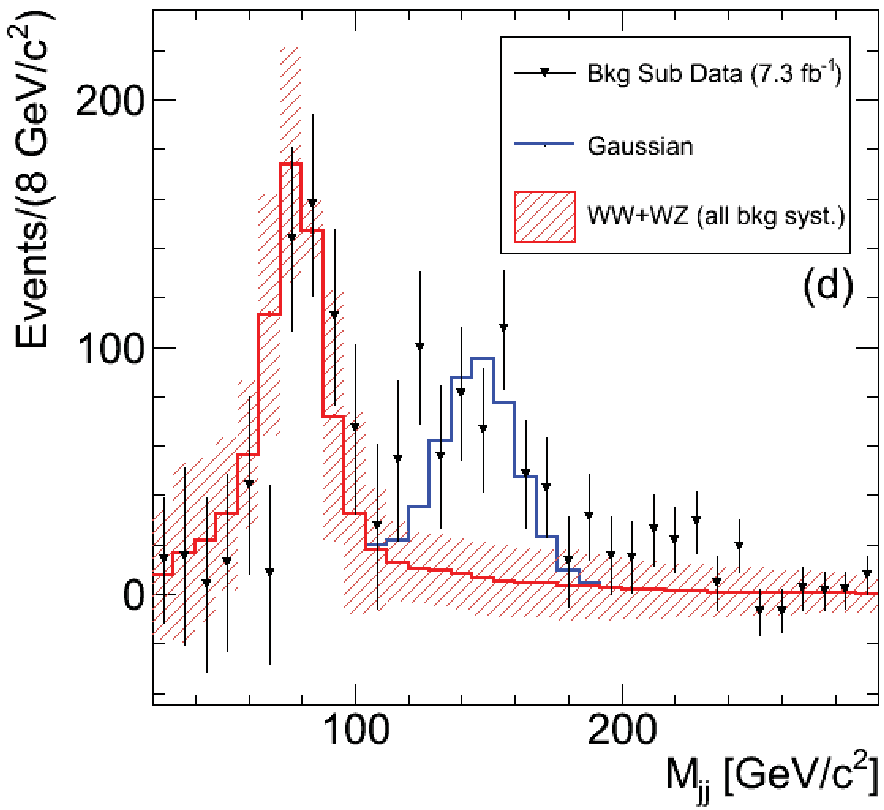

The $b$ and $c$ jets are rather soft. When they fall below the $E_T$ cut, the signal is a $(jj)$ resonance + $W$.

CDF $Wjj$ final state

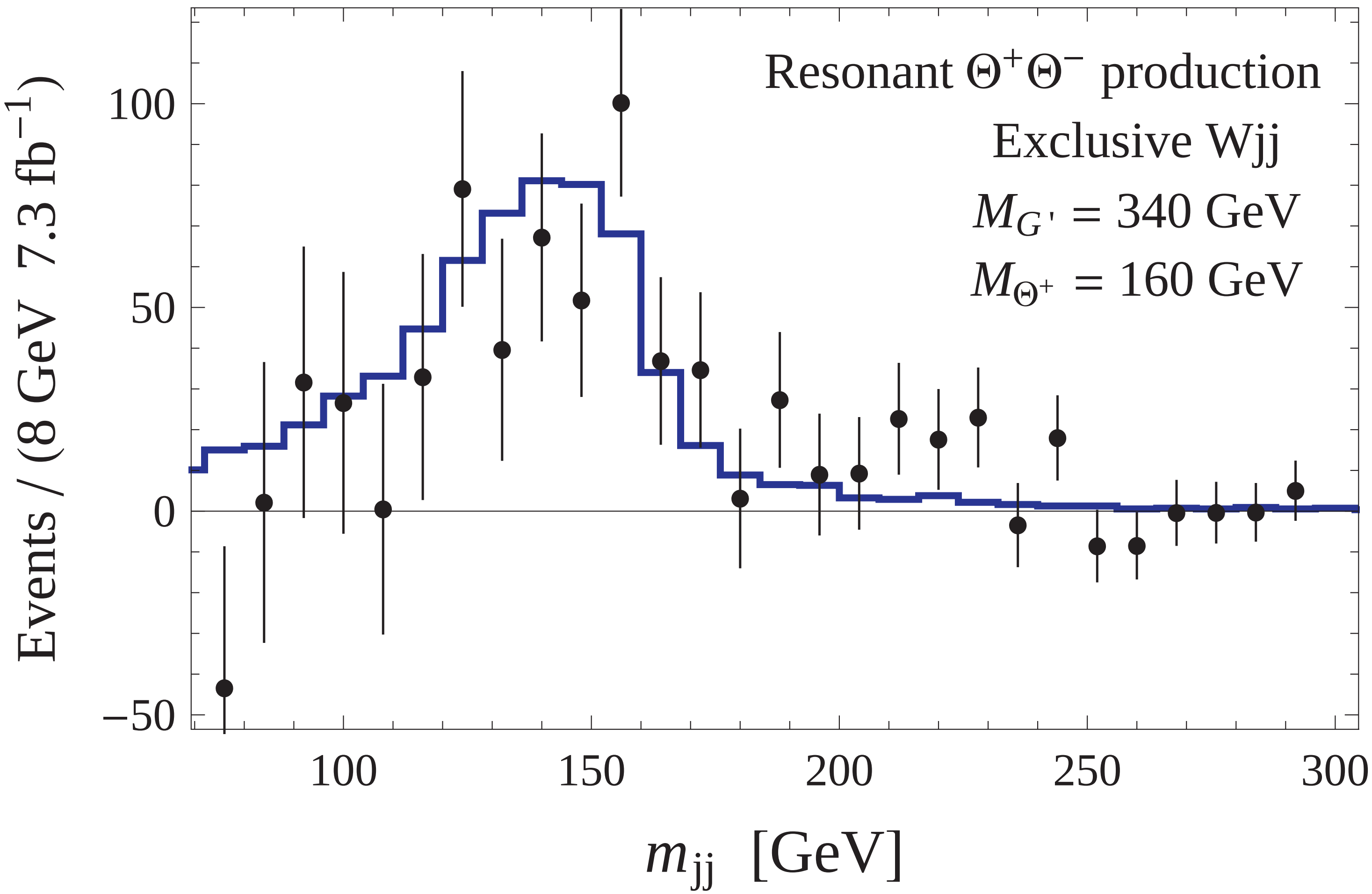
bump in $M_{jj}$ distribution at 147 GeV – 4.1$\sigma$ excess

http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html



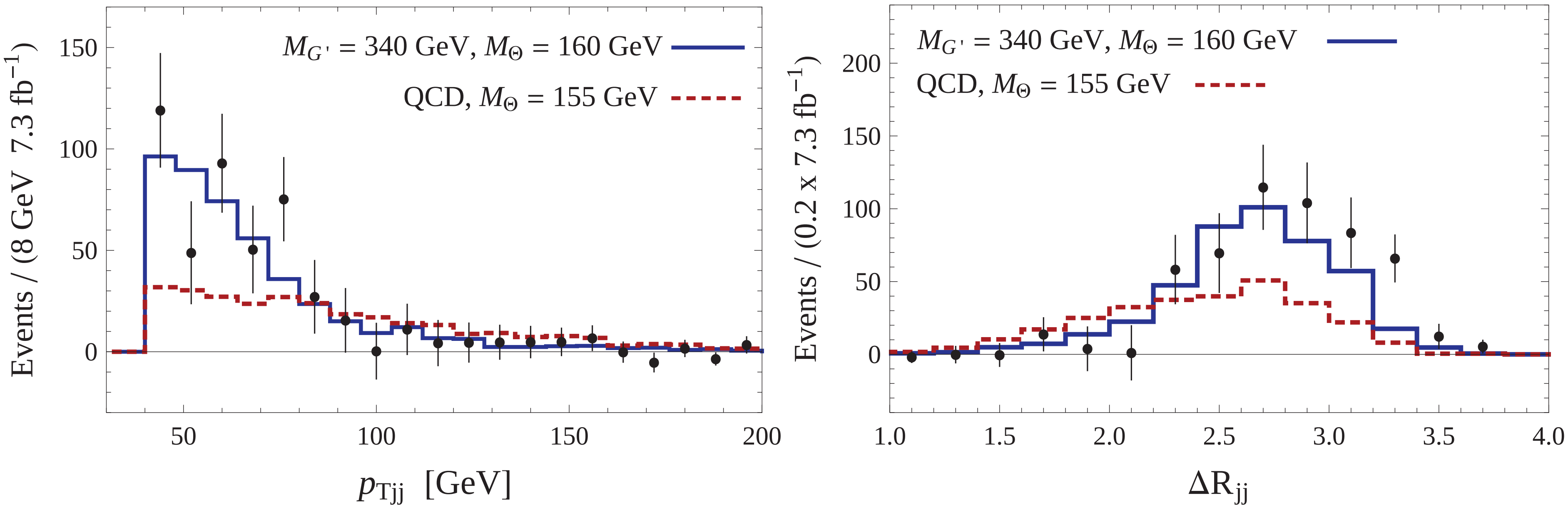



**Invariant mass distribution for the two leading jets**
**($M_{G_H} = 160$ GeV, $B(G_H \to W^+ b\bar{c}) = 20\%$):**



## Large deviations from SM in various kinematic variables measured by CDF in the $Wjj$ final state

**(http://www-cdf.fnal.gov/physics/ewk/2011/wjj/kinematics.html)**




*Blue lines:* $G' \to G_H G_H \to (Wbb)(jj)$

*(work with Gordan Krnjaic 1104.2893)*

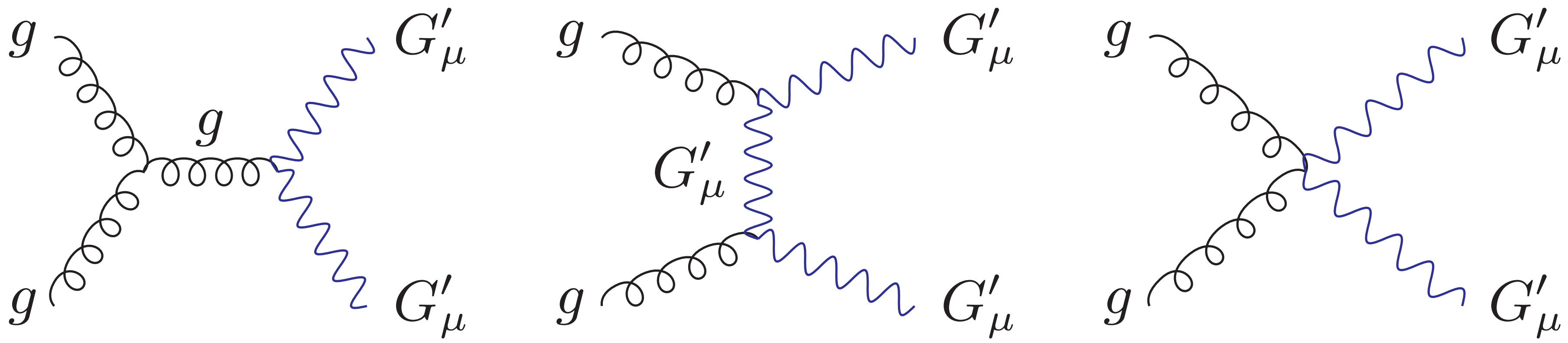
# Model "independent" search for Gluon-prime

*with KC Kong, Rakhi Mahbubani hep-ph/0709.2378*

**$G'_\mu$ couplings to quarks are model dependent: if they are small enough, the mass limits from dijet resonance searches are evaded.**

**$G'_\mu$ couplings to gluons are fixed by gauge invariance. $G'_\mu$ 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 $jjb\bar{b}$, $b\bar{b}b\bar{b}$).

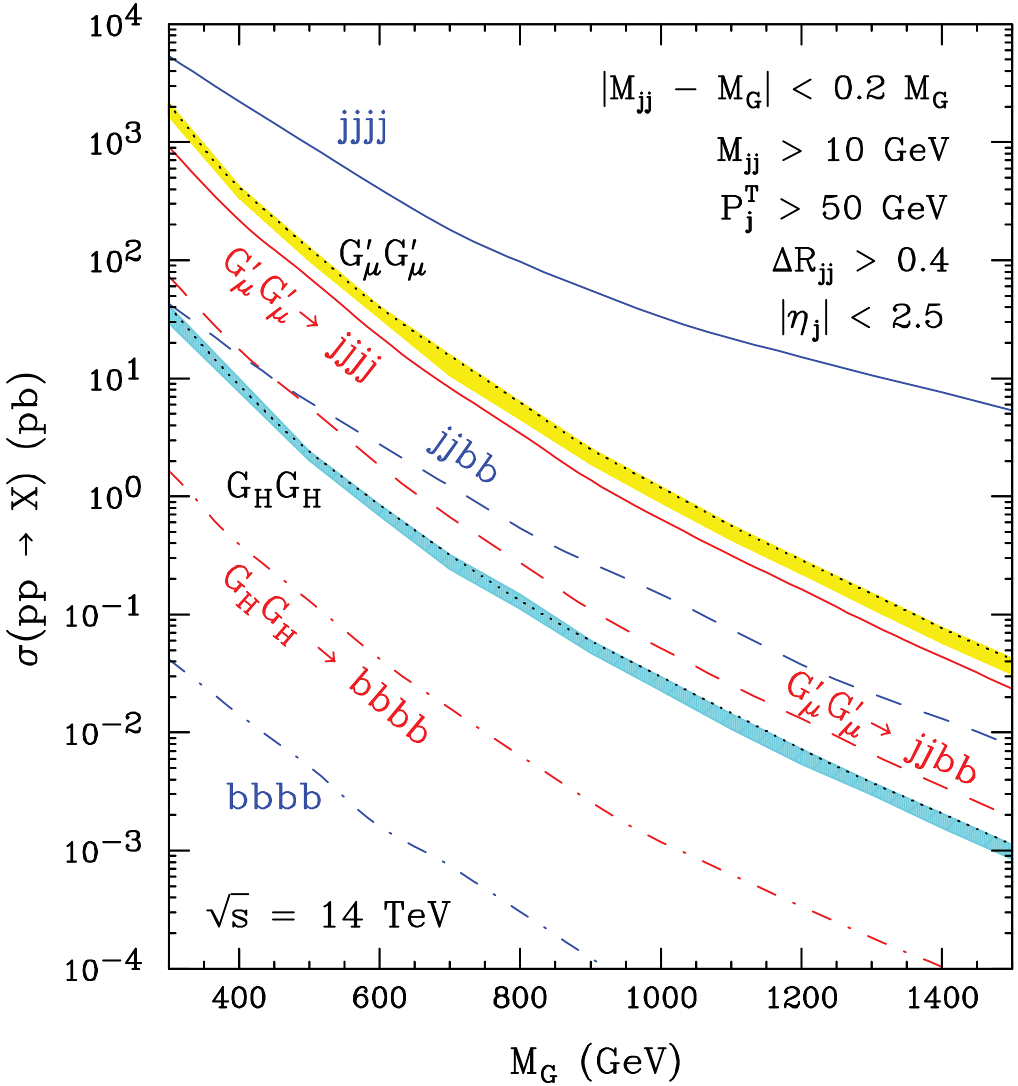
Dominant background: QCD 4-jet production.
We simulated the background at tree level using MadGraph (checked with NJETS), taking the b-tagging efficiency to be 50%.

Production of gluon-primes ($G'_\mu$) at the LHC:

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

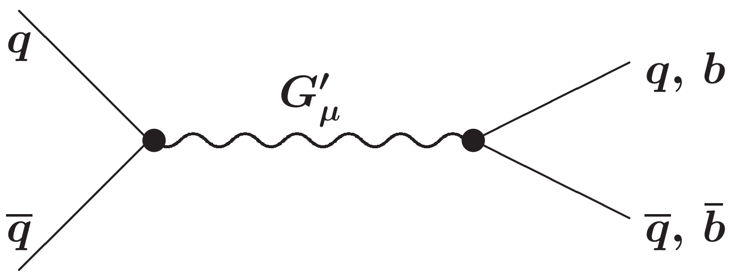
Cutting around the resulting peak decreases the background dramatically.

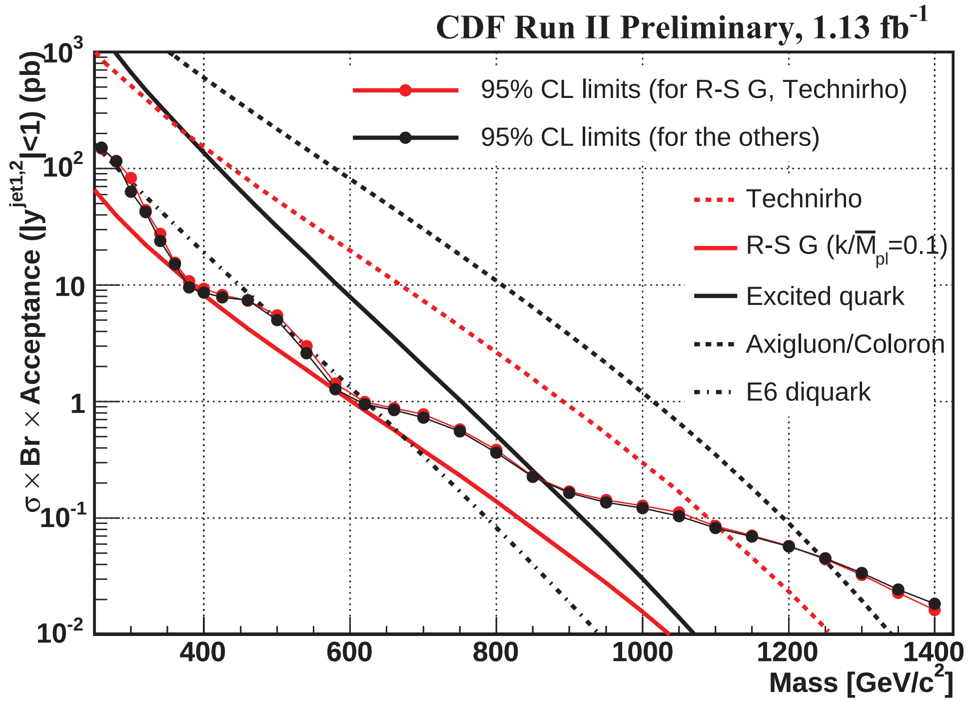
We estimate that the LHC. mass reach for a $G'_\mu$ is $M_G \lesssim$ 1 TeV with 1 fb$^{-1}$



## $G'_\mu$ production (in the narrow width approximation):

$$\sigma\left(p\bar{p} \to G'_\mu X\right) \approx \frac{16\pi^2 \alpha_s r^2}{9s} \sum_q \int_{M^2/s}^{1} \frac{dx}{x} \left[ q(x)\, q\left(\frac{M^2}{xs}\right) + \bar{q}(x)\, \bar{q}\left(\frac{M^2}{xs}\right) \right]$$



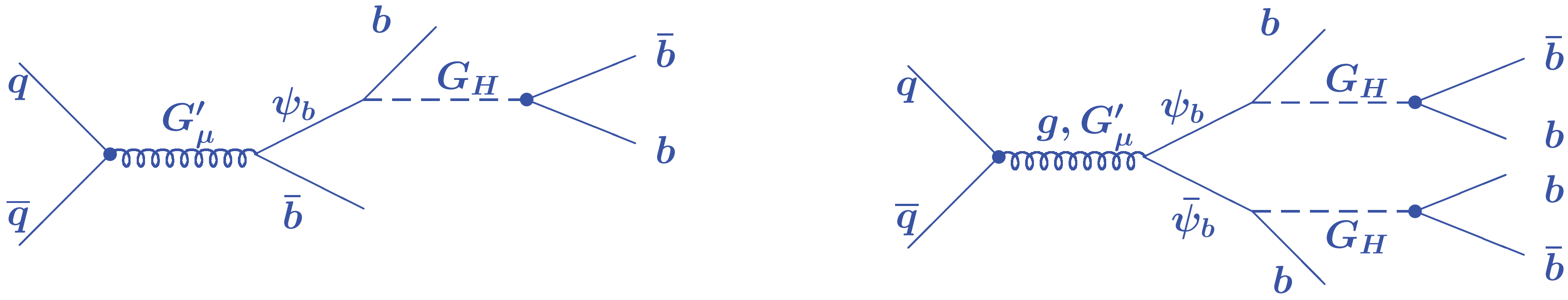

**Limit on dijet resonance of**

**$\sim$300 GeV:** $r^2 \mathcal{B}(G'_\mu \to jj) < 0.04$

*No search for $b\bar{b}$ resonance in Run II (?!)*

If the vectorlike quark mass is near the electroweak scale:

$\Rightarrow$ Additional interesting multi-$b$ signals:




similar topology for $(t\bar{t})jj$ final state *(Burdman, Dobrescu, Ponton, hep-ph/0601186)*

# Conclusions

Scalar octets are simple (hypothetical) particles which lead to various signals at the Tevatron and the LHC.

These may change the Higgs production at the LHC.

Pair production of scalar octets, with one of them decaying to $jj$ and the other to $Wbc$ may explain the CDF dijet excess.

Another deviation from the SM reported by CDF is an excess (also around 150 GeV) in the $bb$ invariant mass distribution, in the 3$b$ final state. This can be due to $G_H G_H \rightarrow (b\bar{b})(b\bar{b})$.

D0, CDF, CMS, ATLAS should continue to search for pairs of $b\bar{b}$, $c\bar{c}$ or $jj$ resonances.