Heavy color-octet bosons and multi-(b)-jet signals at the Tevatron

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Outline:

- **Color-octet scalars**
- **CDF MSSM Higgs search**
- **Gluon-prime**
- **Vectorlike quarks**

Discovering particles one 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, ...*

In this talk:

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

predicted in theoriess with 2 universal extra dimensions, technicolor, ...

- **Color-octet spin-1 particles:** G'_μ **"gluon-prime" (topgluon, coloron, Kaluza-Klein gluon, techni-**ρ**, ...)**

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,...*

Scalar octet

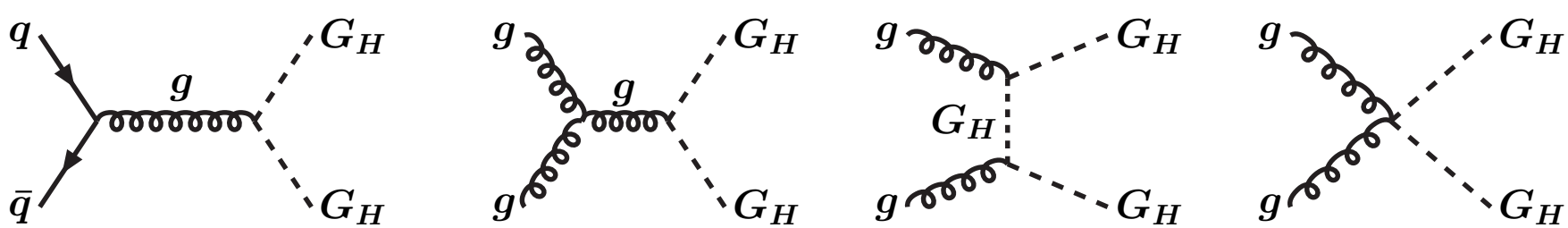
G_H: spin 0, transforms as (8,1,0) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

$SU(2)_W$ 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.



Decays of the scalar octet

Only renormalizable interaction that 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:

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

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:

$$\frac{C_b}{M_\psi} H G_H^a (\overline{Q}_L^3 T^a b_R) + \frac{C_c}{M_{\psi'}} H G_H^a (\overline{Q}_L^2 T^a c_R) + \ldots$$

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

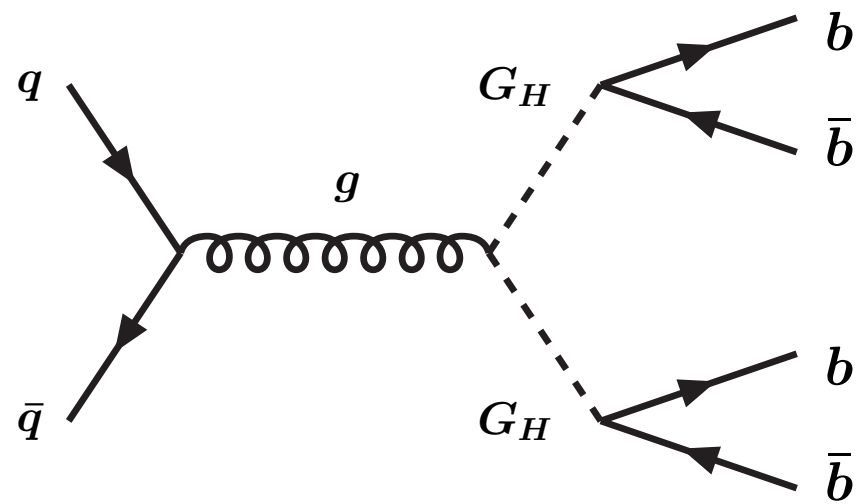
C_b, C_c are complex parameters; M_ψ, $M_{\psi'}$ are masses of some heavy particles.

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

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

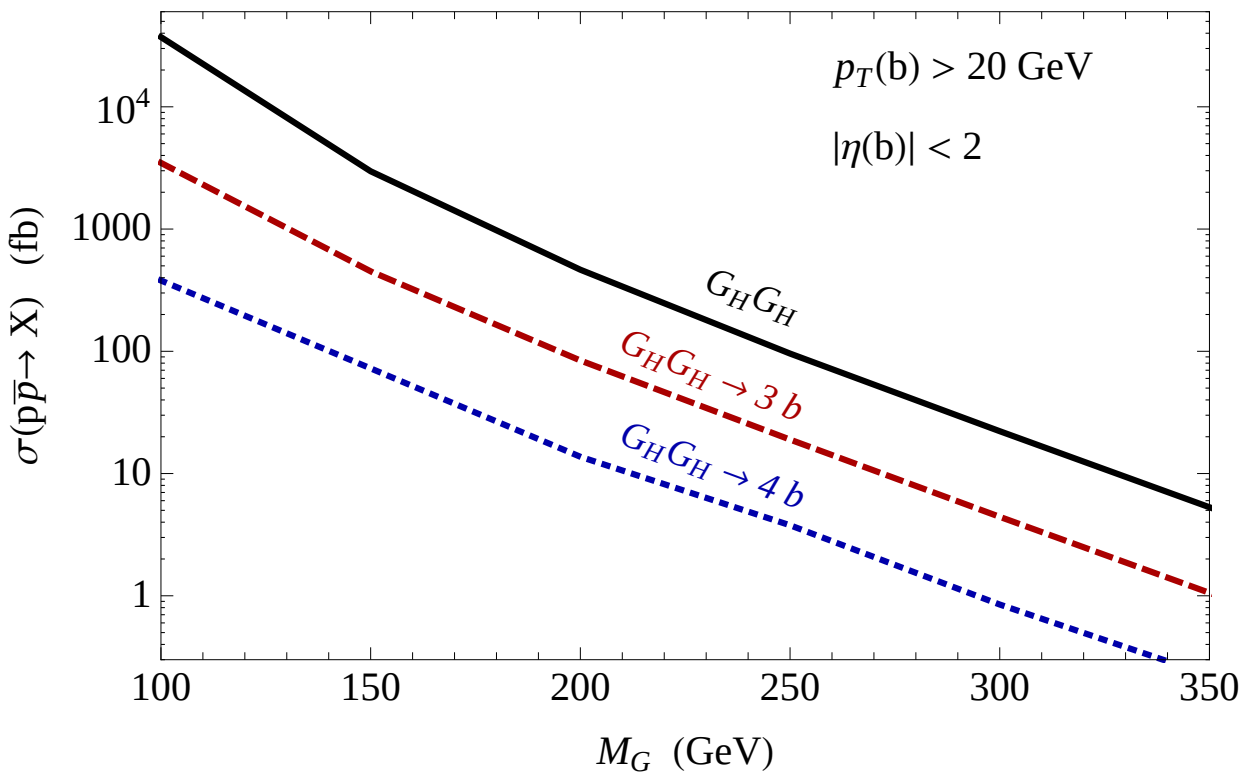
$$\Gamma\left(G_H \to b\bar{b}\right) \simeq \frac{|C_b|^2}{24\,\pi}\frac{v^2}{(M_\psi)^2}M_{G_H} \simeq 10^{-3}M_{G_H}\left(\frac{1\ \text{TeV}}{M_\psi/|C_b|}\right)^2$$

Signal: a pair of narrow $b\bar{b}$ (or $c\bar{c}$) resonances of same mass M_{G_H}



Partonic cross section: $\sigma(q\bar{q} \to G_H G_H) = \frac{2\,\pi\,\alpha_s^2}{9\,\hat{s}} \left(1 - 4\frac{M_{G_H}^2}{\hat{s}}\right)^{3/2}$

Cross section for $p\bar{p} \to G_H G_H$ at the Tevatron :



MadGraph/MadEvent: generate parton level events

Pythia: showering, hadronization

PGS: detector simulation.

Assume: $\mathcal{B}(G_H \to b\bar{b}) = 100\%$

Dominant background: QCD 4-jet production.

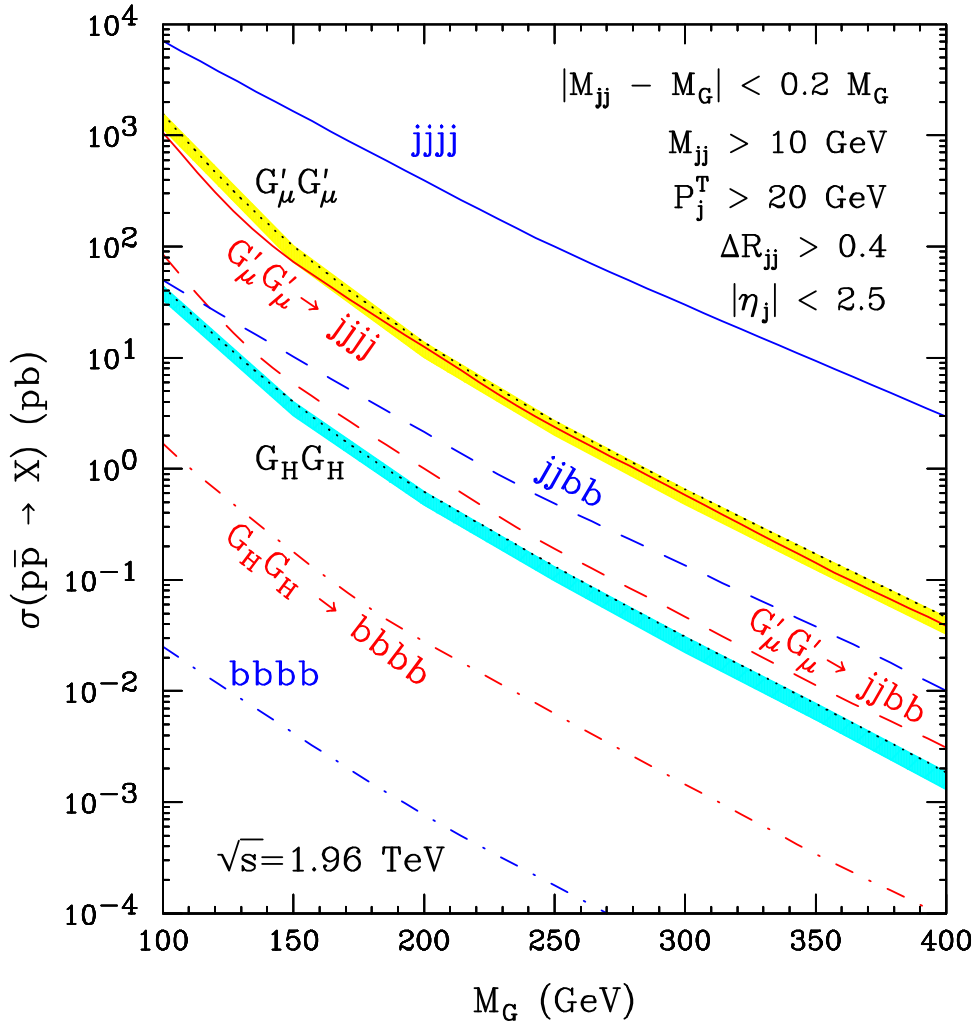
Background simulated at tree level using MadGraph/MadEvent (checked with NJETS), assuming a b-tagging efficiency of 50%.

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

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

Cutting around the resulting peak decreases the background dramatically.

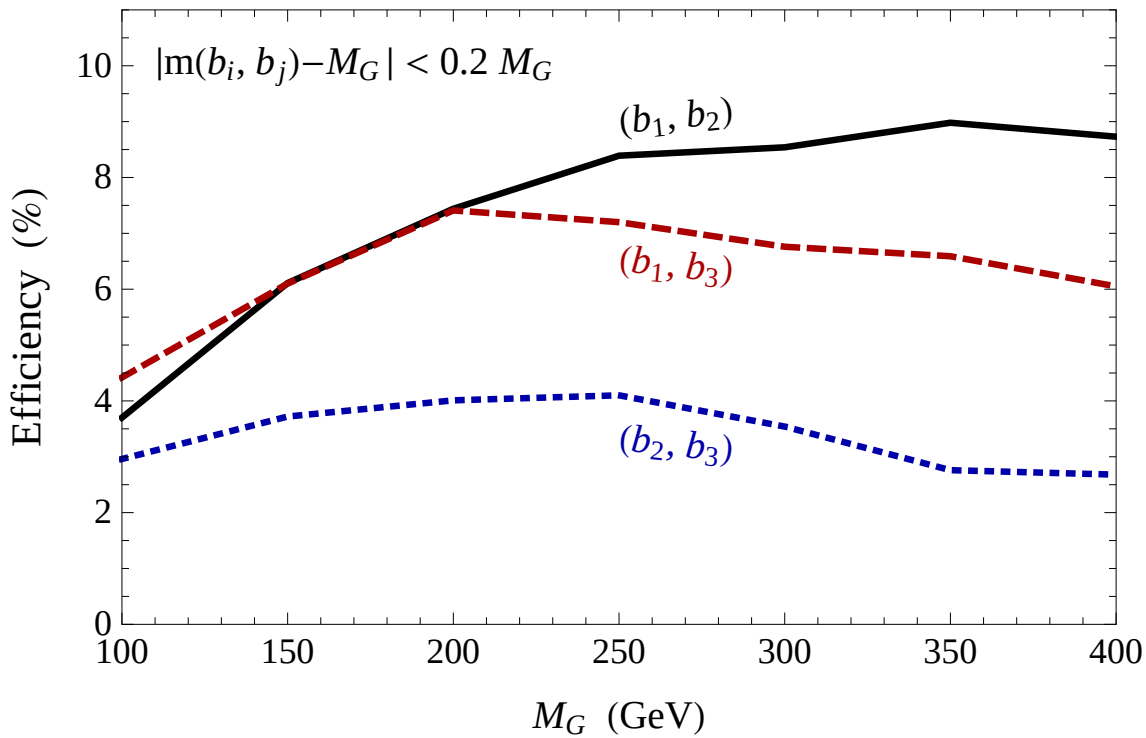
We estimate that the Tevatron mass reach in the $4b$ channel is $M_{G_H} \lesssim$ 300 GeV with 2×10 fb^{-1} for $\mathcal{B}(G_H \to b\bar{b}) = 100\%$.



Properties of the $3b$ signal

Two of the three b jets form a narrow resonance of mass $\sim M_{G_H}$.

Efficiency of basic and invariant mass cuts:

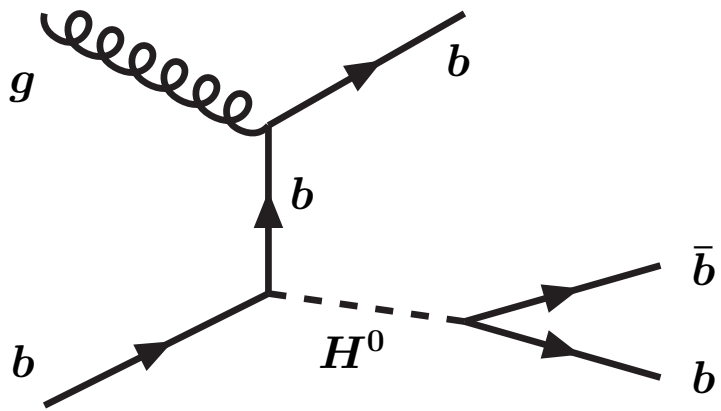


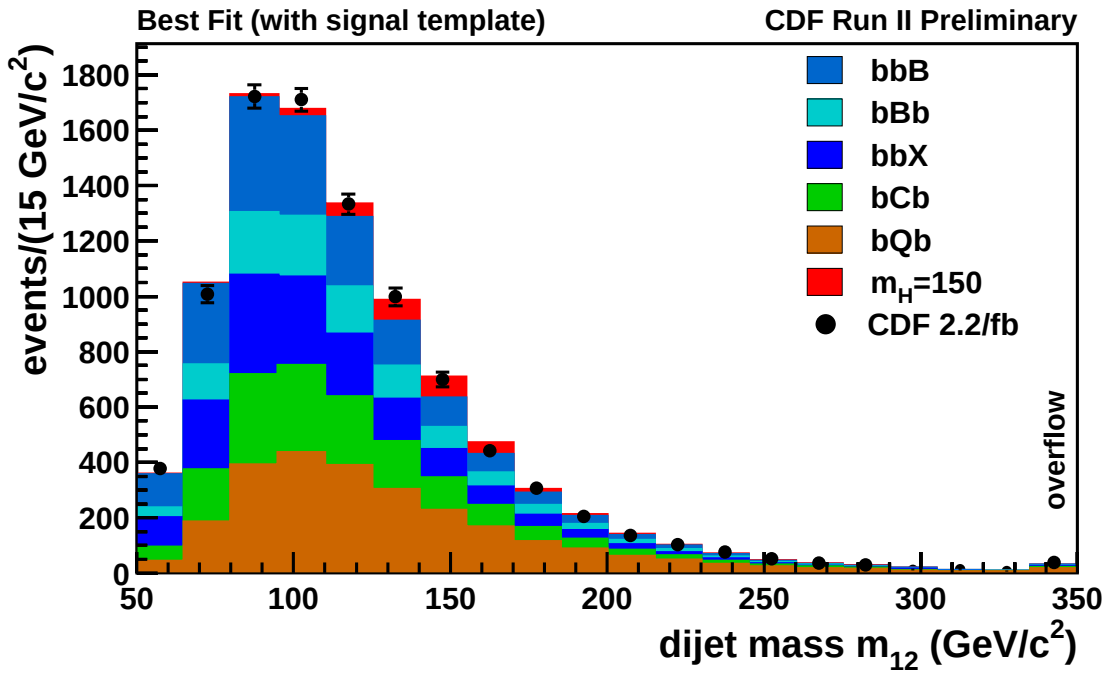
Efficiencies for (b_1, b_2) and (b_1, b_3) events are comparable

$\Rightarrow$ can use both m_{12} and m_{13} as discriminants between the octet signal and the QCD background.

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

www-cdf.fnal.gov/physics/new/hdg//Results_files/results/3b_susyhiggs_jun10





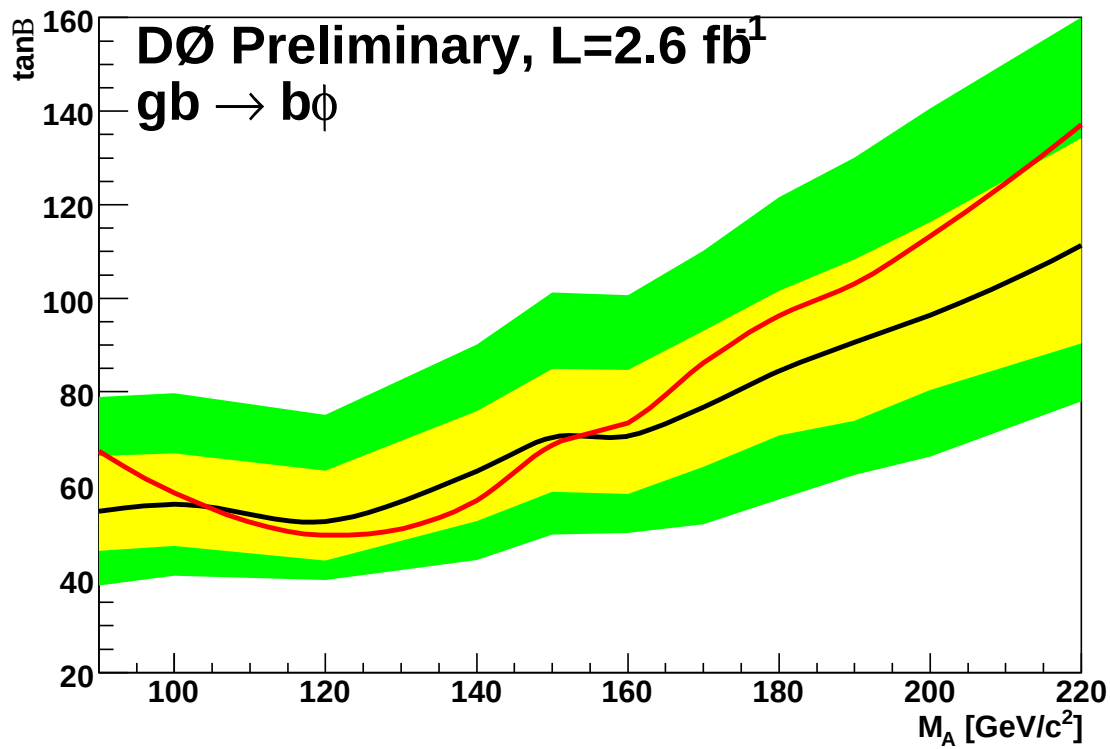
Excess of events with $m_{12} \approx 125 - 155$ GeV (consistent with $M_H \approx 150$ GeV).

The probablity for this excess to be due to a fluctuation of the SM background is 0.9%, and increases to 5.7% when the whole range of invariant masses is taken into account.

D0 search in the $3b$ channel with 2.6 fb^{-1} is optimized for the MSSM Higgs bosons through the use of a likelihood discriminant

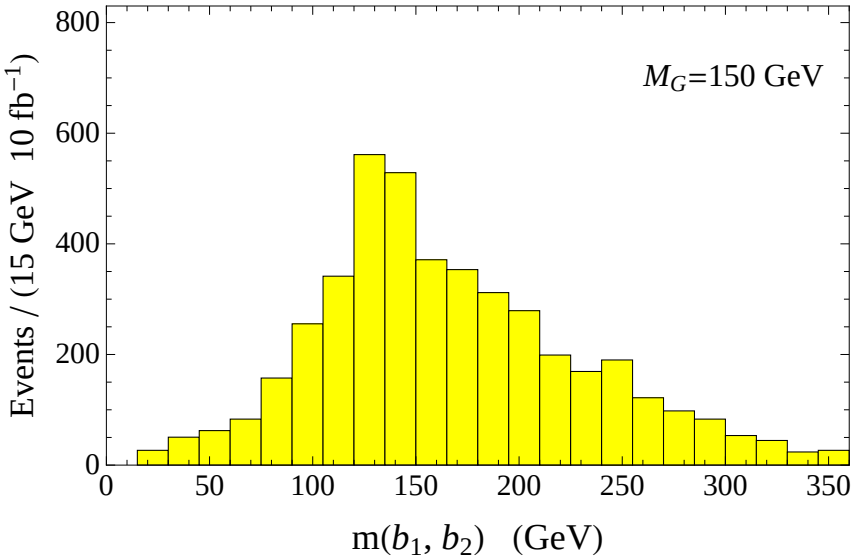
$\Rightarrow$ may not apply to a $G_H G_H \rightarrow bbb(b)$ signal.

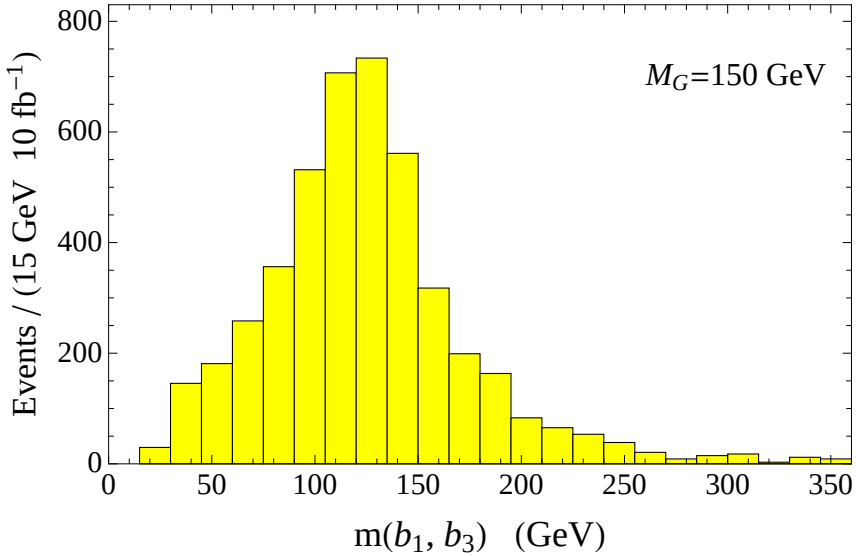
Impressive limit on $tan\beta$:



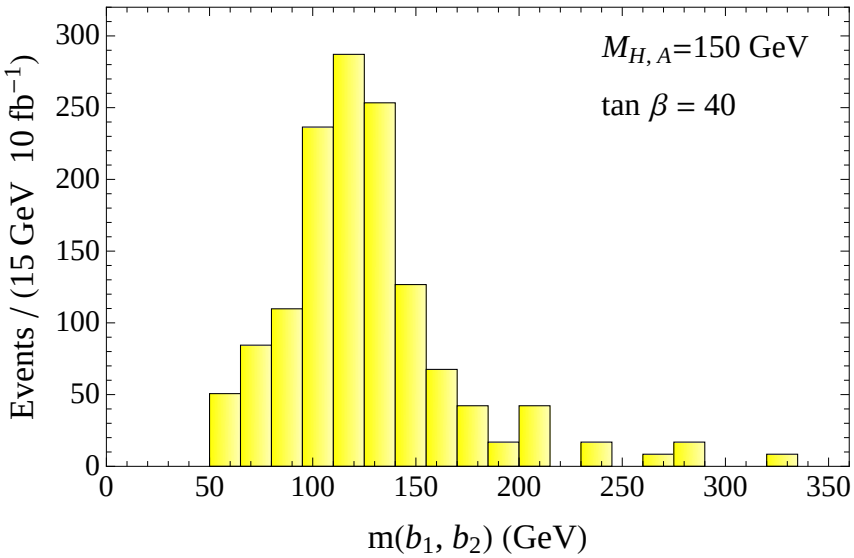
m_{12} versus m_{13} invariant mass distributions

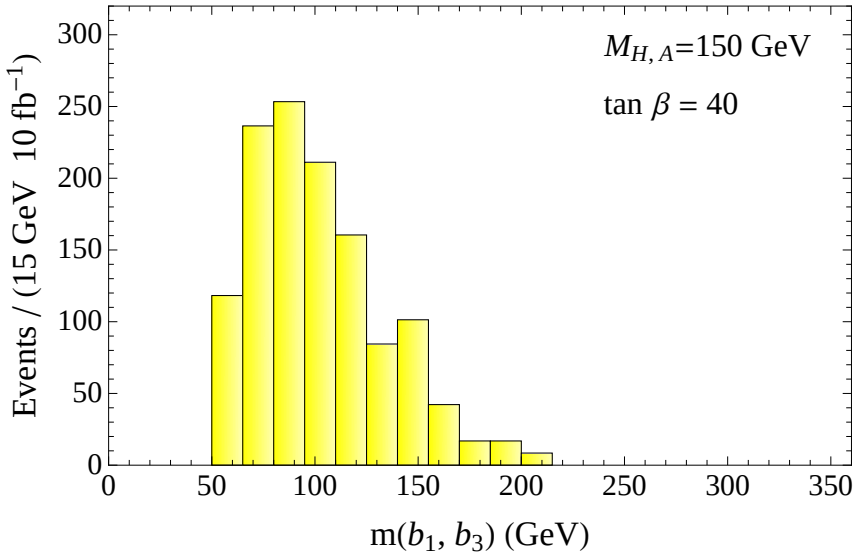
Scalar octet:





Supersymmetric Higgs boson:





"Gluon-prime": a heavy spin-1 color-octet particle

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

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

G^a_μ **- 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_μ **- massive "gluon-prime"**

("topgluon" or "coloron" depending on its couplings to t, b)

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

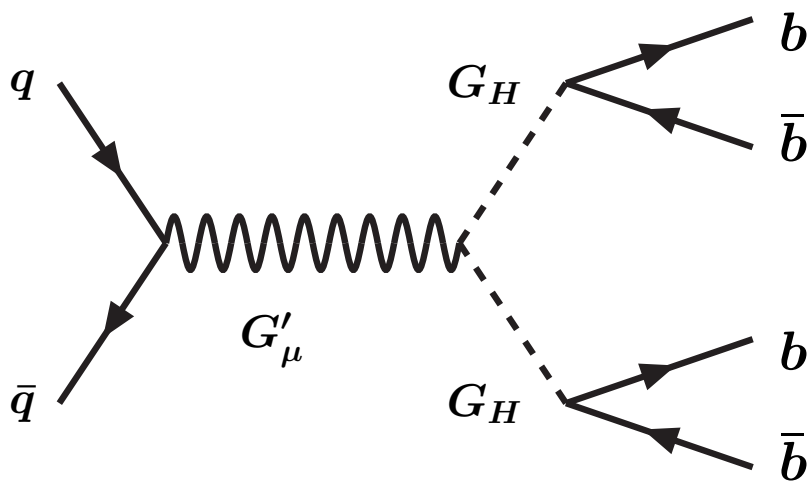
Scalar whose VEV breaks $SU(3)_1 \times SU(3)_2$:

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

G_I becomes the longitudinal G'_μ;

ϕ is a scalar singlet.

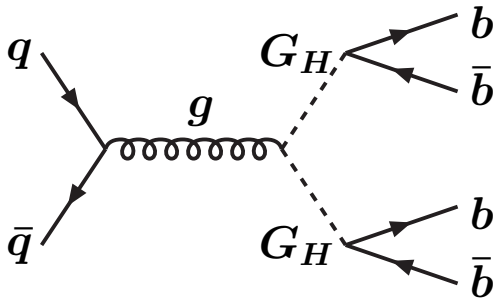
$$-\frac{h_1^2 - h_2^2}{2\sqrt{h_1^2 + h_2^2}}\, G'^{\,a}_\mu G_H^b\,(\partial_\mu G_H^c)\, f^{abc}$$

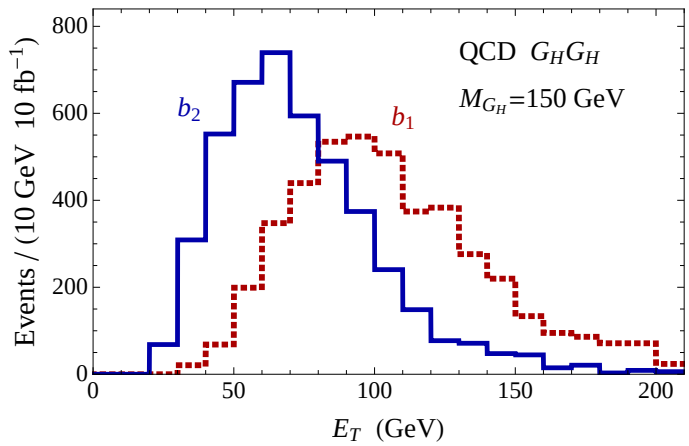


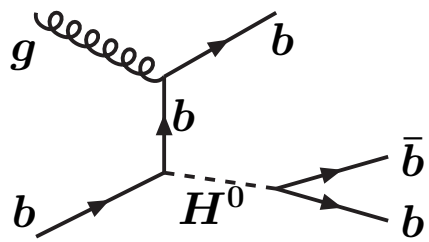
Similar process in technicolor: $q\bar{q} \to \rho_T \to \pi_8\pi_8$.

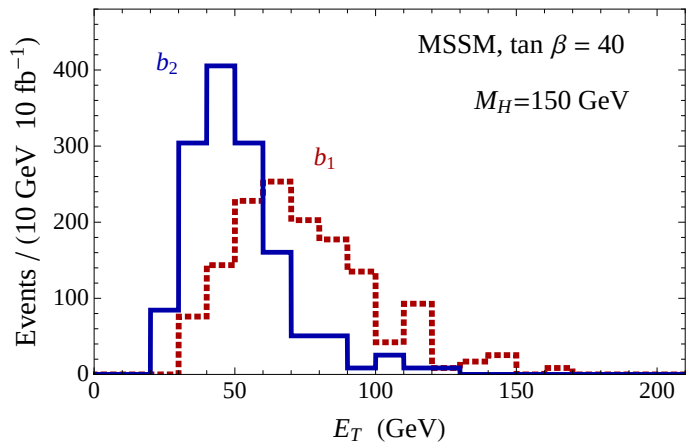
Use kinematic distributions to differentiate between models

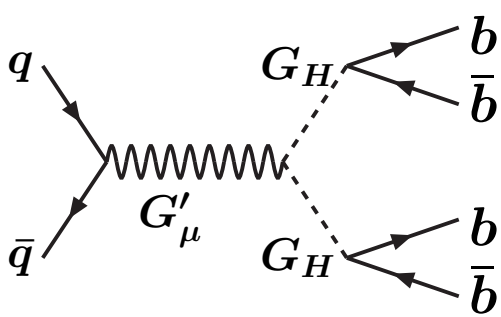
Transverse energy (E_T) distributions of the two leading b-jets:

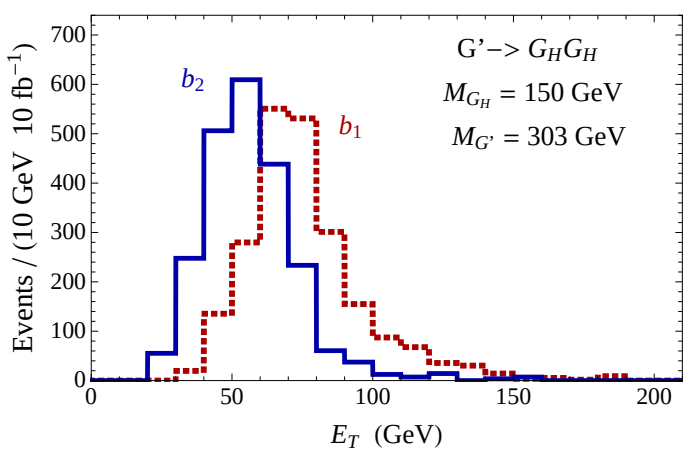












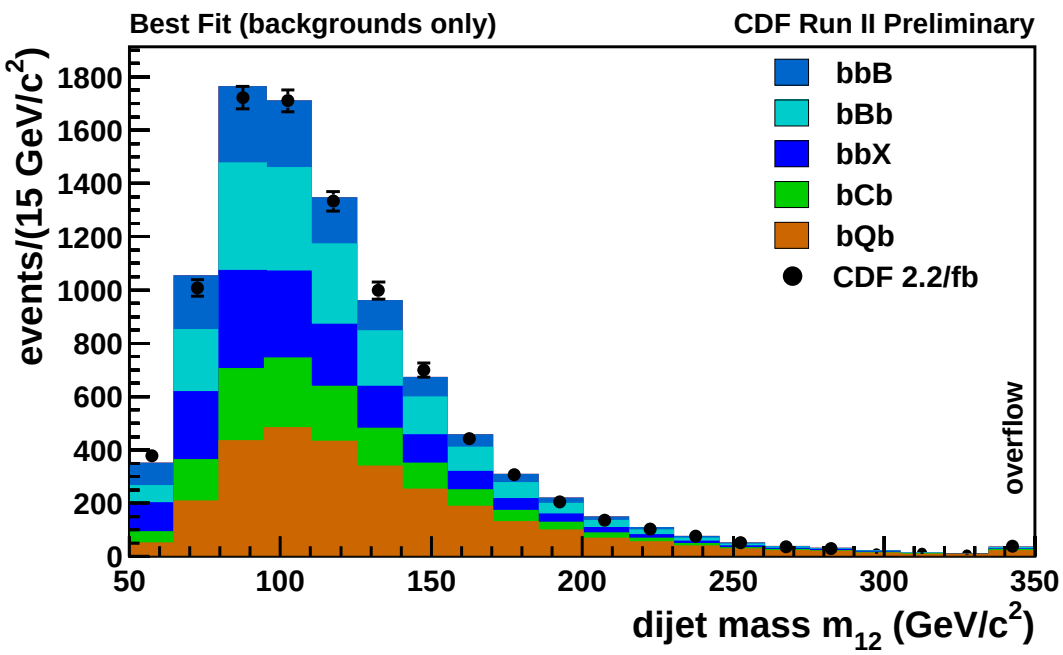
CDF search in the $3b$ final state

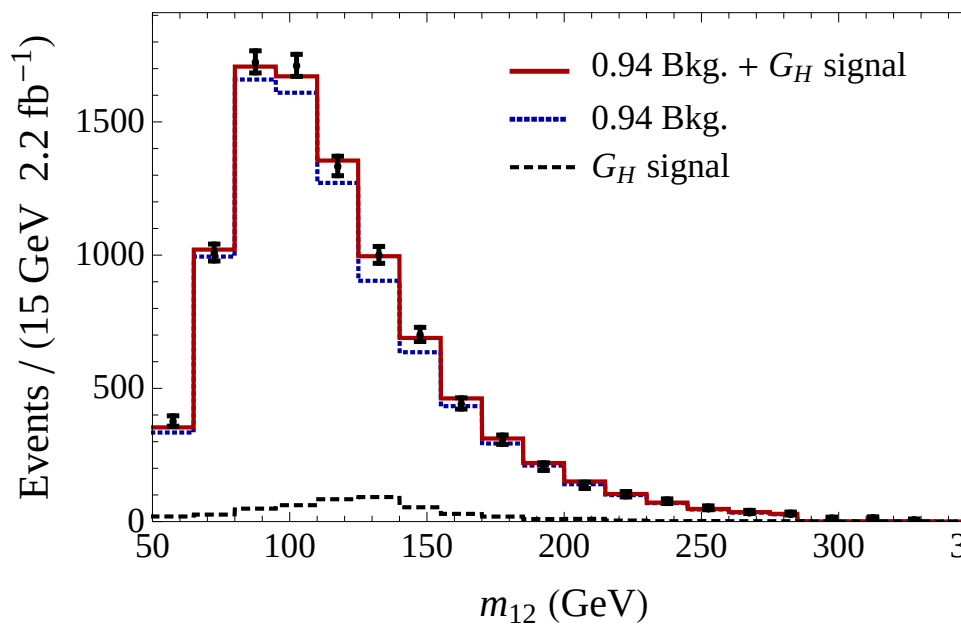
www-cdf.fnal.gov/physics/new/hdg//Results_files/results/3b_susyhiggs_jun10/more_plots.html

Invariant mass distribution of the leading two jets:

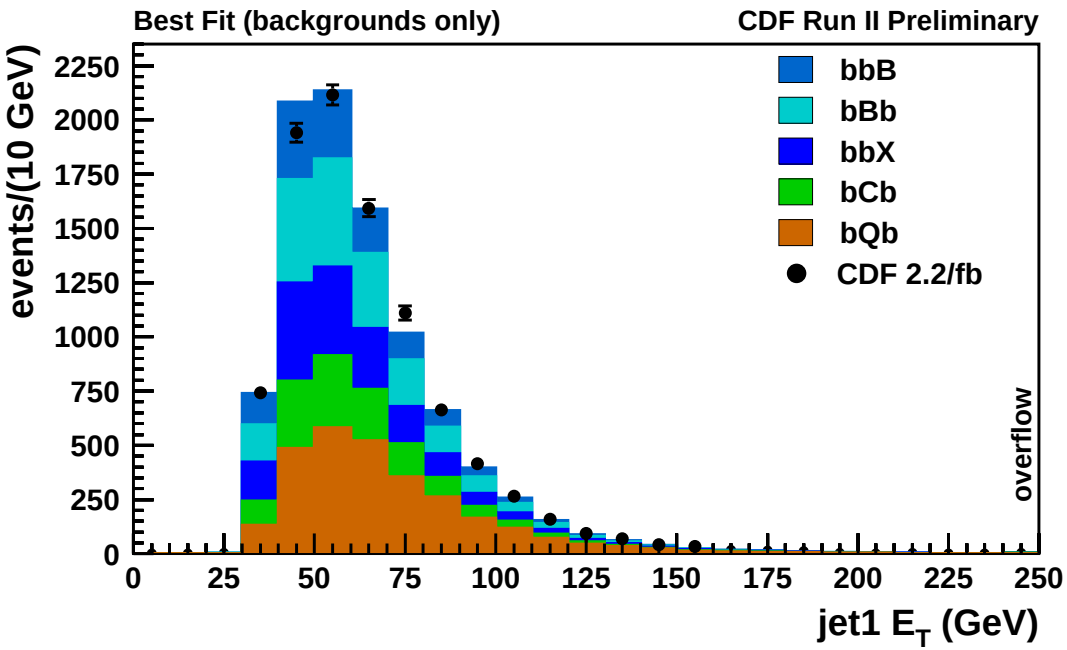
CDF data (and background) compared to $G'_\mu \to G_H G_H$ model

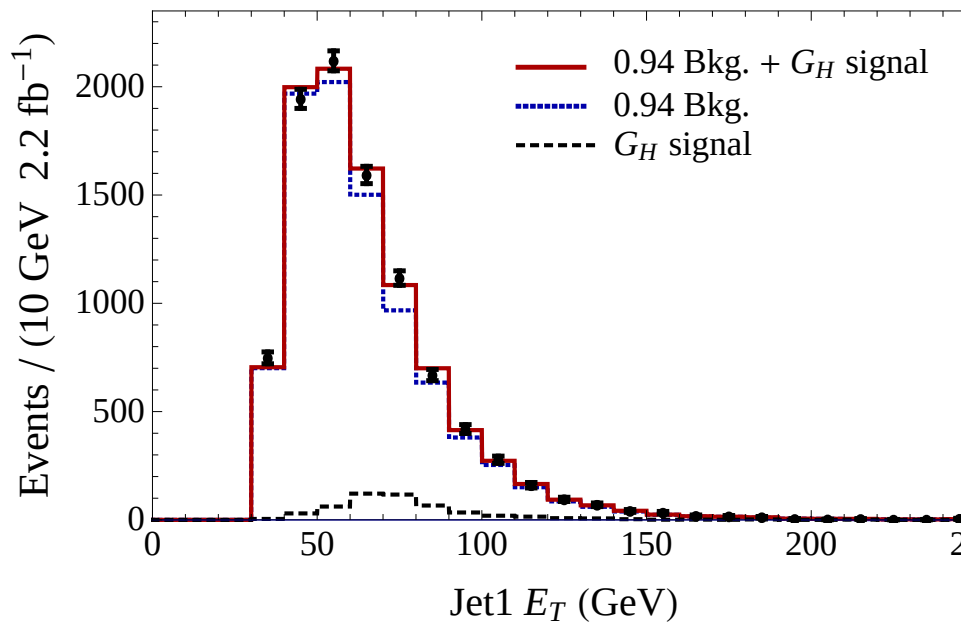
($M_{G'} = 303$ GeV, $\sigma \times \mathcal{B} = 1.8$ pb):

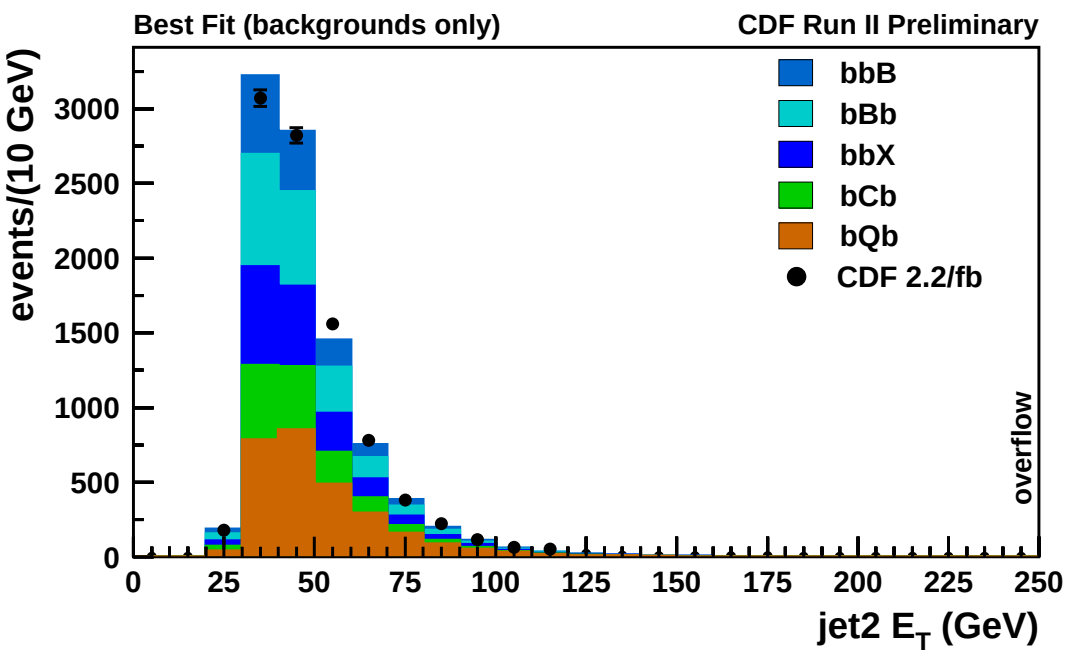


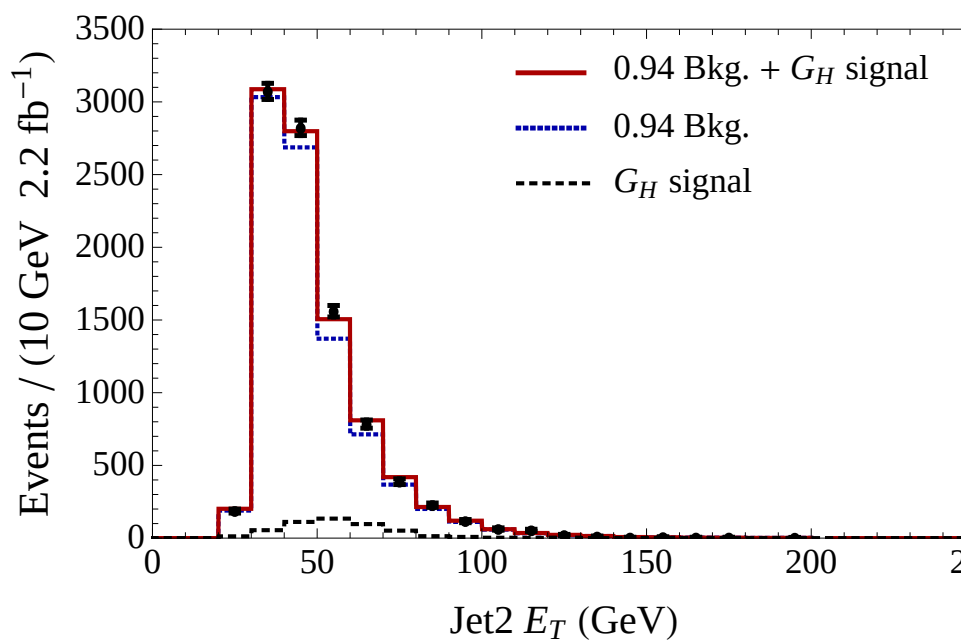


CDF $3b$ data and background compared to $G'_\mu \to G_H G_H$ model ($M_{G'} = 303$ GeV, $\sigma \times \mathcal{B} = 1.8$ pb):

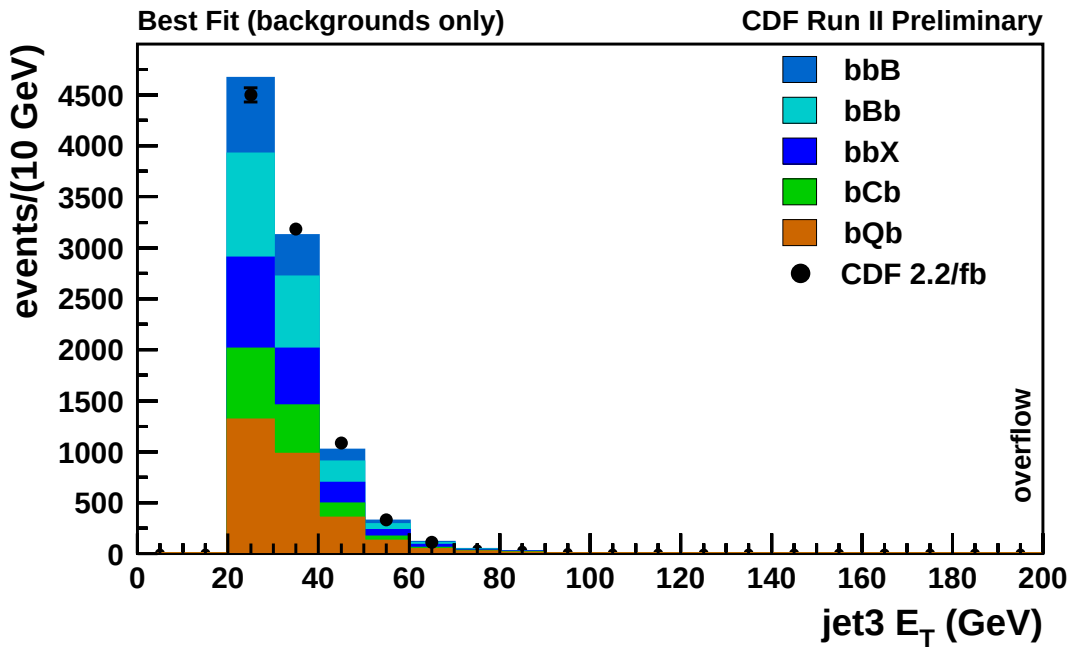


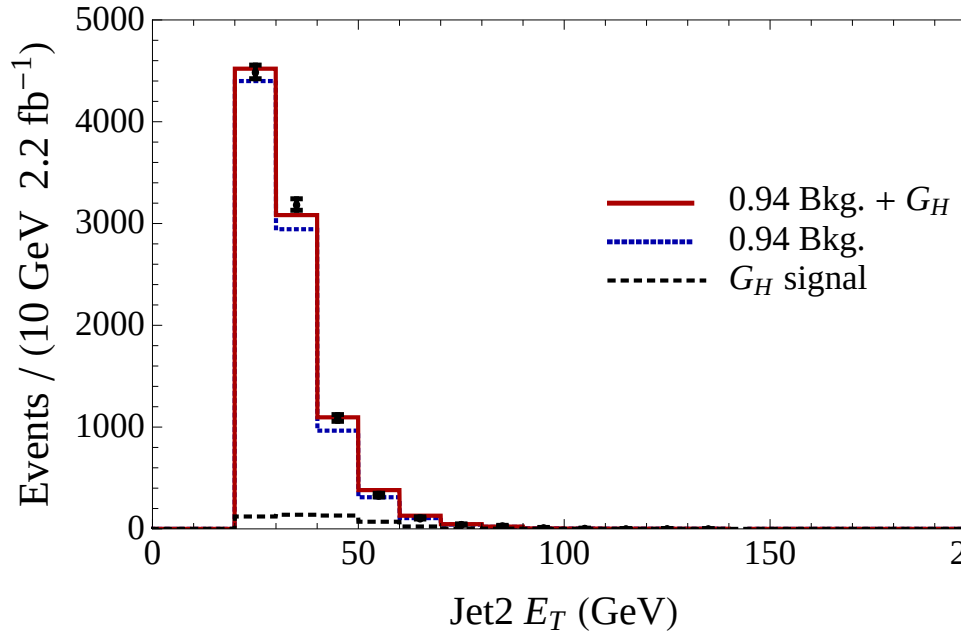


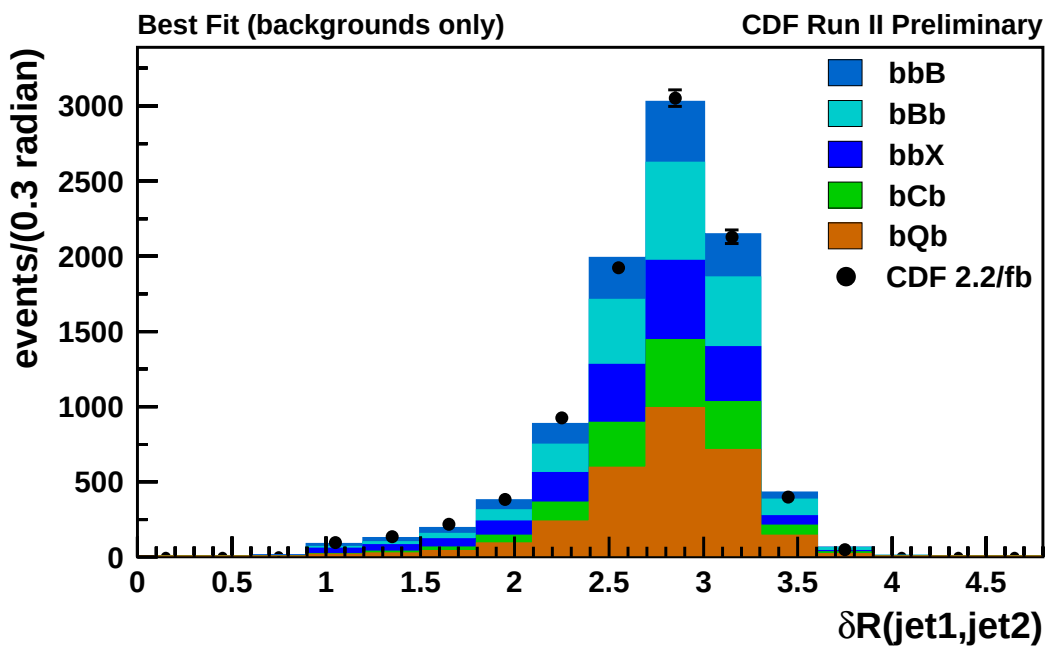


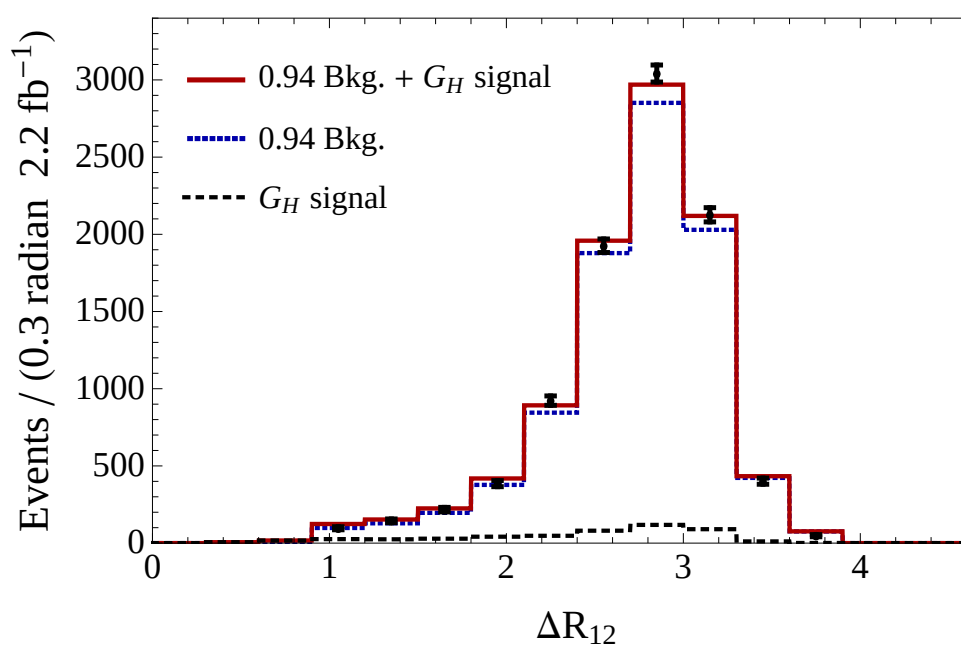


More CDF $3b$ data compared to $G'_\mu \to G_H G_H$ model ($M_{G'} = 303$ GeV, $\sigma \times \mathcal{B} = 1.8$ pb):



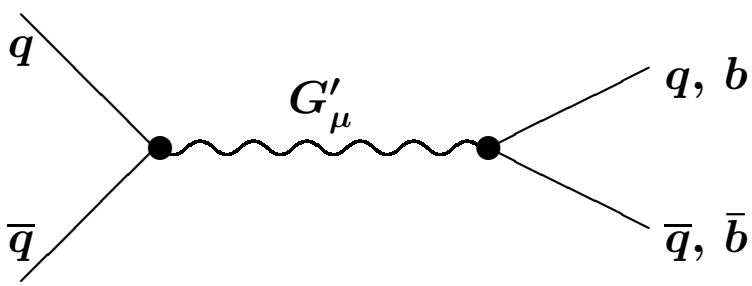


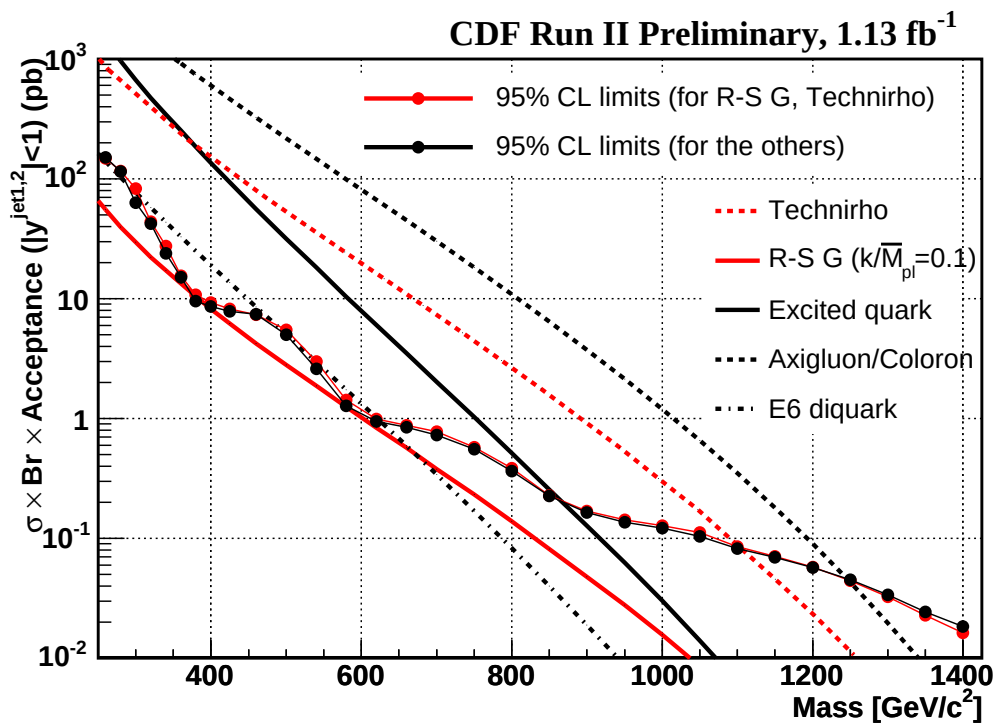




G'_μ production (in the narrow width approximation):

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





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 (?!)

Vectorlike quark

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

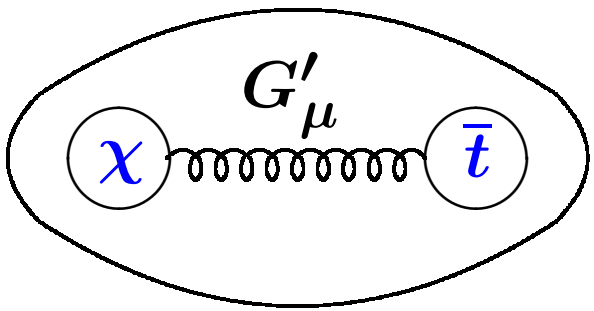
Vectorlike (*i.e.* non-chiral) fermions may also exist. Their masses are allowed by the $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry,

$\Rightarrow$ may naturally be heavier than the electroweak scale.

Various theories that include octet bosons also include vectorlike quarks.

Example:

In the Top-quark seesaw model, the Higgs boson is a $\bar{t}\chi$ bound state, with binding due to a G'_μ *(BD, C. Hill: hep-ph/9712319)*

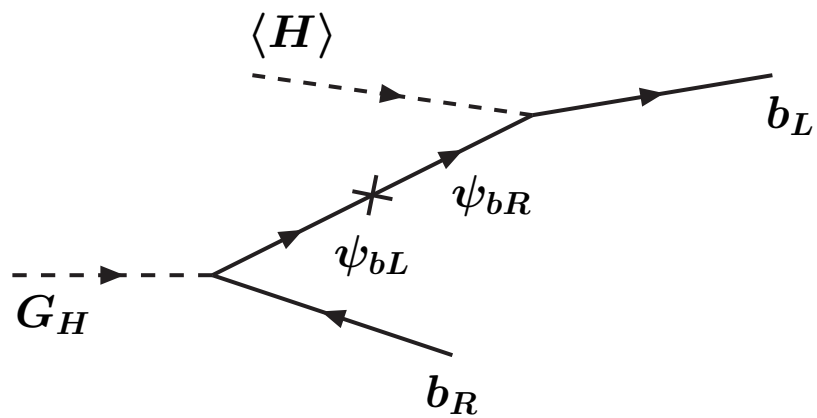


Short-distance origin for $G_H \to b\bar{b}$

A vectorlike quark, ψ_b, having the same gauge charges as b_R:

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

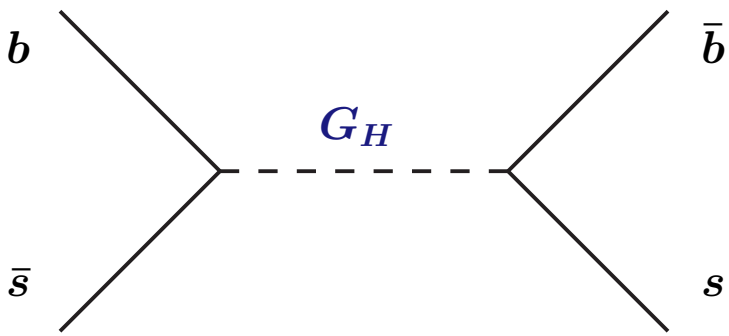
Effective coupling of a scalar octet to b quarks and Higgs VEV:

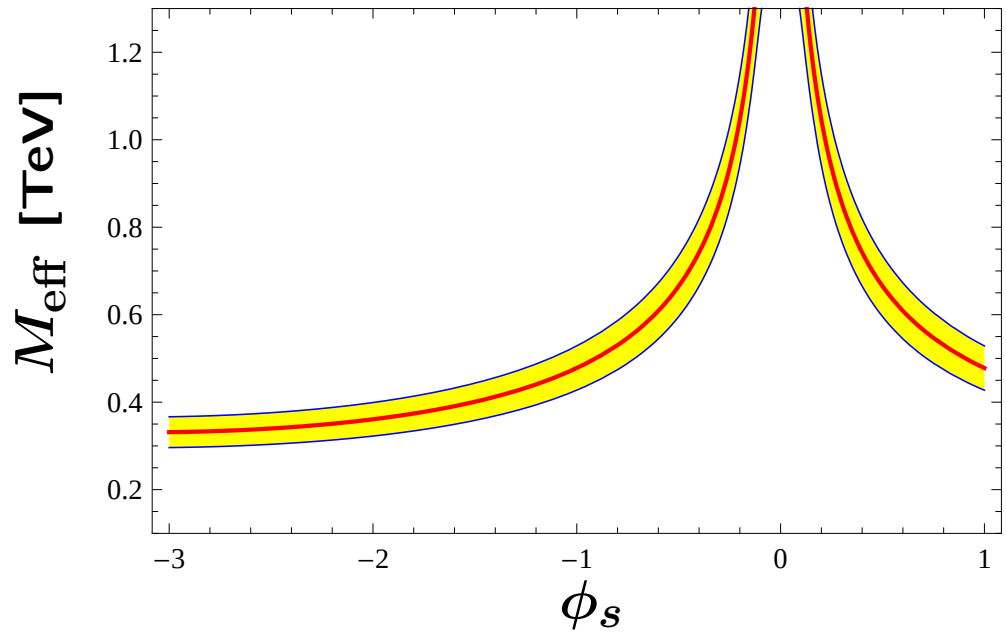


This generates the dimension-5 coupling of G_H to b quarks:

$$\frac{C_b}{M_\psi} H G^a_H (\overline{Q}^3_L T^a b_R) \quad with \quad C_b \approx \lambda_3\, \eta^*_3$$

CP violation in $B_s - \bar{B}_s$ mixing due to scalar exchange can explain the D0 dimuon anomaly *(Dobrescu, Fox, Martin, 1005.4238)*





In the mass eigenstate basis:

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

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

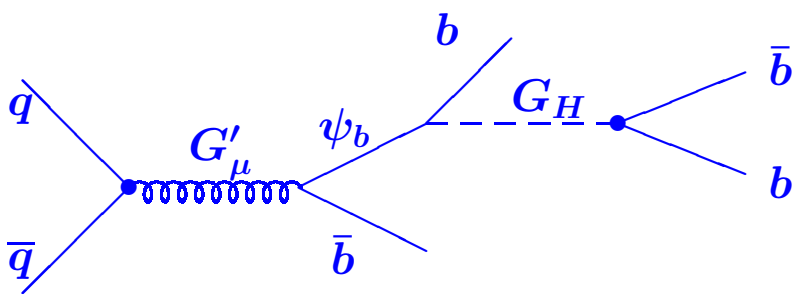
$$M_{12}^{\rm NP} = \frac{v^2}{48\, M_{G_H}^2} \frac{C_{32}^d\, C_{23}^{d*}}{M_\psi^2} \frac{M_{B_s}^3}{(m_b + m_s)^2} f_{B_s}^2 \left(B_5 - B_4\right),$$

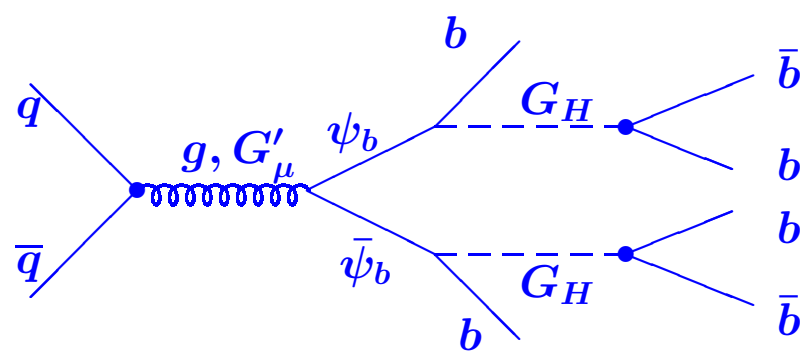
G_H exchange can explain the D0 anomalous dimuon charge asymmetry if the vectorlike quark mass is near the electroweak scale:

$$M_\psi \approx 350 \text{ GeV} \frac{\sqrt{|C^d_{32}\, C^{d*}_{23}|}}{10^{-2}} \left(\frac{150 \text{ GeV}}{M_G}\right) \frac{1}{\sqrt{-\cos\phi}}$$

where $\phi \equiv \arg(C^d_{32}\, C^{d*}_{23})$

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

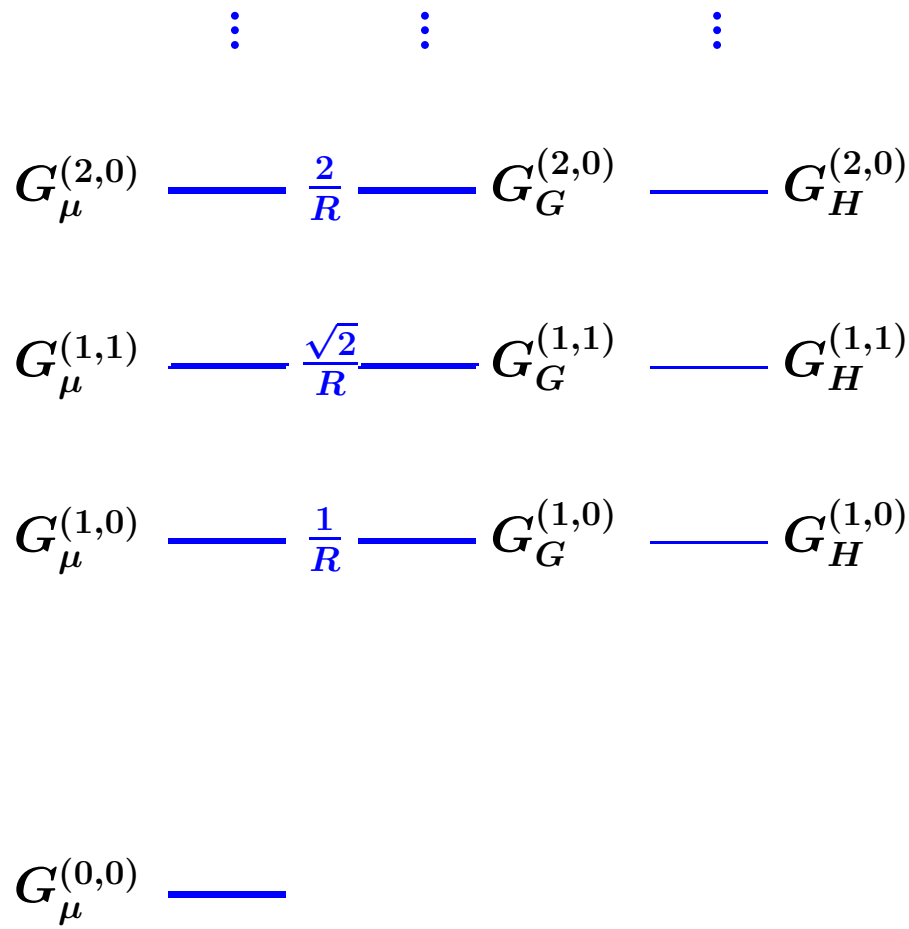




Gluon in two extra dimensions

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

$G_G^{(j,k)}(x^\nu)$ *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:

$$\vdots \qquad \vdots \qquad\qquad \vdots$$

$$(t_L^{(2,0)}, b_L^{(2,0)}) \;\text{———}\; \frac{2}{R} \;\text{———}\; (T_R^{(2,0)}, B_R^{(2,0)}) \qquad B_L^{(2,0)} \;\text{———}\; \frac{2}{R} \;\text{———}\; b_R^{(2,0)}$$

$$(t_L^{(1,1)}, b_L^{(1,1)}) \;\text{———}\; \frac{\sqrt{2}}{R} \;\text{———}\; (T_R^{(1,1)}, B_R^{(1,1)}) \qquad B_L^{(1,1)} \;\text{———}\; \frac{\sqrt{2}}{R} \;\text{———}\; b_R^{(1,1)}$$

$$(t_L^{(1,0)}, b_L^{(1,0)}) \;\text{———}\; \frac{1}{R} \;\text{———}\; (T_R^{(1,0)}, B_R^{(1,0)}) \qquad B_L^{(1,0)} \;\text{———}\; \frac{1}{R} \;\text{———}\; b_R^{(1,0)}$$

$$(t_L, b_L) \;\text{———}\qquad\qquad \text{———}\; b_R$$

Conclusions

There is a nontrivial agreement between the $3b$ distributions reported by CDF and those predicted by the $G'_\mu \to G_H G_H$ model.

This suggests that D0 and CDF should compare the $3b$ data for several kinematic distributions with the QCD background as well as with the $G'_\mu \to G_H G_H$ predictions.

More generally, D0 and CDF should search for pairs of $b\bar{b}$, $c\bar{c}$ or jj resonances, which combined also give an invariant mass peak ("nested resonances"), and other multi-jet topologies.

Heavier "copies" of the new colored particles are common in various theories (bound states, Kaluza-Klein modes, ...).

$\Rightarrow$ Both the LHC and the Tevatron experiments could soon get spectacular results!