Beyond the Standard Model: Theoretical status

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Outline:

- **Reasons to expect new phenomena**
- **Hypothetical particles** *(G', W', new scalars, vector-like quarks)*
- **Outlook**

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Particle Physics has established that all known natural phenomena can be described (in principle) by a local quantum field theory which is invariant under:

- **3+1 dimensional Lorentz transformations and translations**
- $SU(3)_C \times \underbrace{SU(2)_W \times U(1)_Y}$ **gauge transformations**

  broken by the VEV of the Higgs doublet ($H \supset W_L^{\pm}, Z_L, h^0$)

$\Longrightarrow$ *all elementary fields have certain spin, color, and electroweak charges.*

SM

Spin-1 fields:

$$\begin{cases} G^\mu & (8,1, \ \ 0) \\ W^\mu & (1,3, \ \ 0) \\ B^\mu & (1,1, \ \ 0) \end{cases}$$

Spin-0 field: $H \ (1,2, \ +1/2)$

Spin-1/2 fields:

$$3 \times \begin{cases} q_L & (3,2, \ \ +1/6) \\ u_R & (3,1, \ \ +2/3) \\ d_R & (3,1, \ \ -1/3) \\ l_L & (1,2, \ \ -1/2) \\ e_R & (1,1, \ \ -1) \end{cases}$$

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SM

Spin-2 field: graviton with $M_{\rm Planck}$-suppressed interactions

(effective theory breaks down near 10^{16} TeV)

ν masses require:

$\frac{c}{M} H H l_L l_L$ interactions, suppressed by $M/c \approx 10^{14}$ GeV

or

additional spin-1/2 fields: $3 \times \nu_R(1, 1, 0)$ which together with the SM ν_L acquire Dirac masses.

SM

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SMνg

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Dark matter requires particle(s) beyond the SM$\nu\mathcal{G}$

DM particle can be a fermion (Majorana or Dirac) or a boson (spin 0 or 1).

DM particle may be part of a large hidden sector *(talk by R. Foot)*

There can be several particles contributing to the DM density *(talks by K. Dienes and B. Thomas)*

WIMP miracle: relic density $\propto m^2/g^4$ is correct for

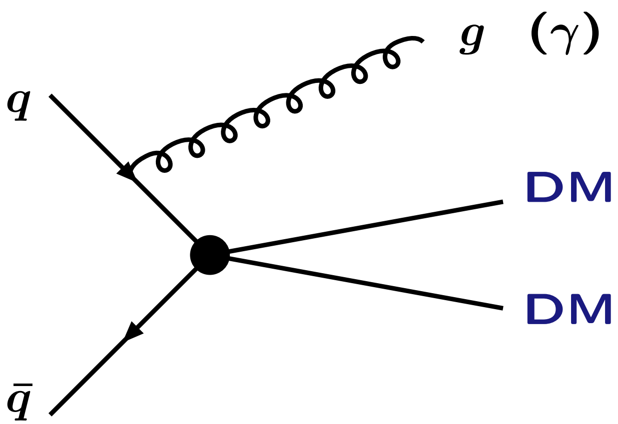
$$m = 0.1 - 1 \text{ TeV and } g = O(1).$$

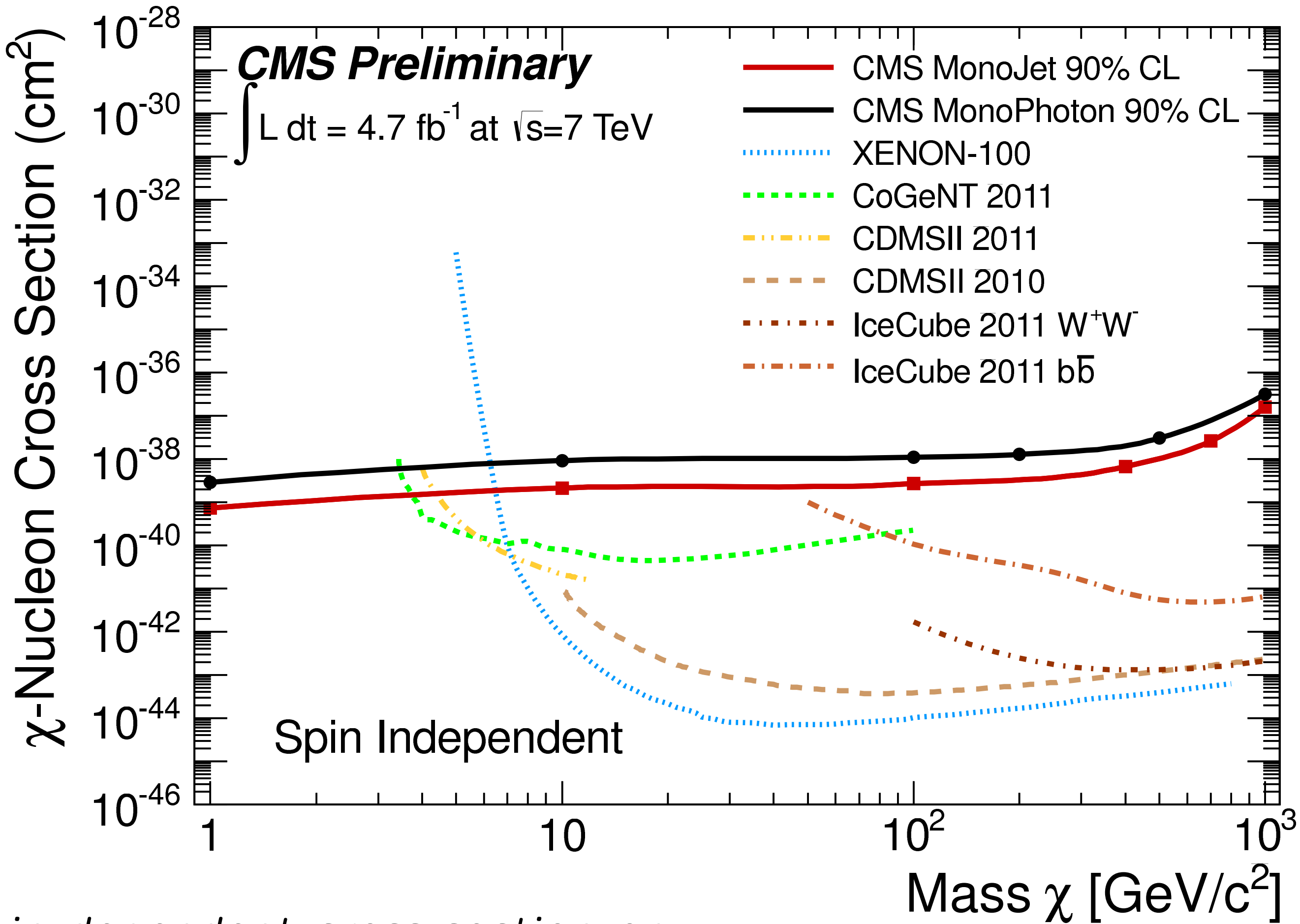
$\Rightarrow$ this suggests that DM may be produced at the LHC

(complementary to searches based on direct detection or indirect detection)

If DM has contact interactions with quarks:

(Bai, Fox, Harnik, 1005.3797; Fox et al, 1109.4398)





Competitive with limits on spin-dependent cross section on nuclei up to higher DM masses.

Also limits set by ATLAS *(talk by D. Salek)* **and CDF.**

Various other DM searches at the LHC: *e.g.,* $t'\bar{t}' \to t\bar{t} + \not{E}_T$ *(talk by W. Reece, CMS)*

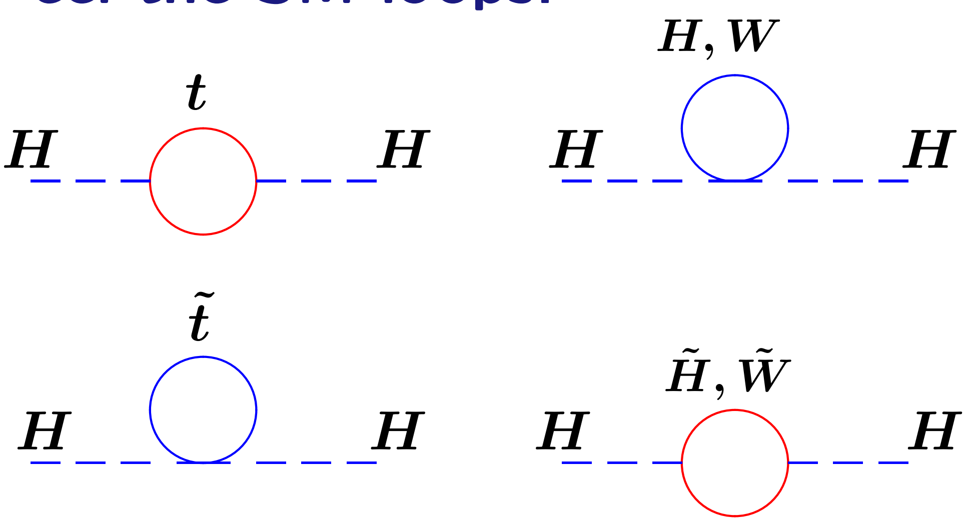
Hierarchy problem

Quantum fluctuations tend to increase the vacuum expectation value of the Higgs doublet.

Stability of the electroweak scale requires a modification of SM at scales not far above ~ 1 TeV, or fine-tuning.

Solution #1: Supersymmetry

No quadratic divergences because loops with superpartners cancel the SM loops:



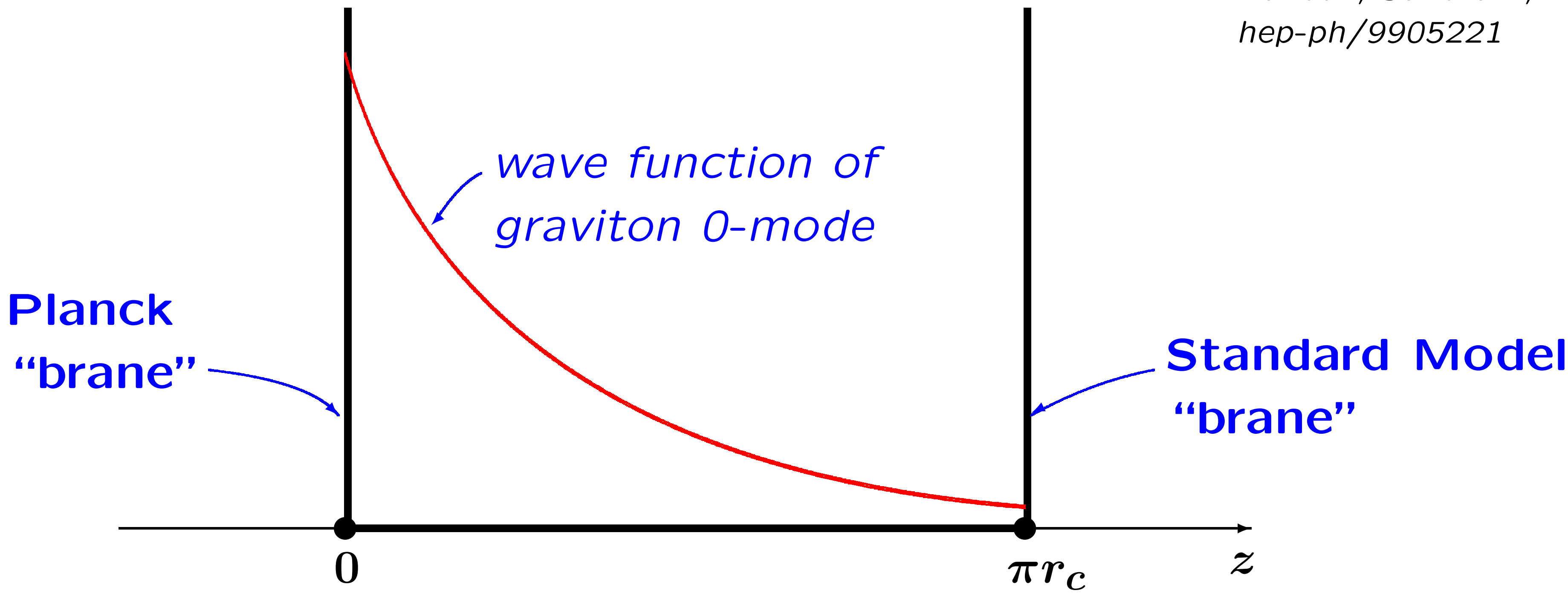
Additional structures required to explain why $\mu \sim \langle H \rangle$, and to break supersymmetry dynamically.

Prediction: $\tilde{H}^{\pm}$, $\tilde{H}^{0}$, $\tilde{t}_1$, $\tilde{t}_2$ have masses $\lesssim O(1)$ TeV.

(review talk by R. Sundrum)

Solution #2: A warped extra dimension

Randall, Sundrum, hep-ph/9905221



Interaction of the graviton 0-mode (the massless 4D spin-2 field) with SM particles is suppressed by its exponentially small wave function at the SM brane $\longrightarrow \langle H \rangle \ll M_{\rm Planck}$. *(talk by A. Soni)*

Prediction: **graviton KK modes $\Rightarrow$ s-channel spin-2 resonances.**

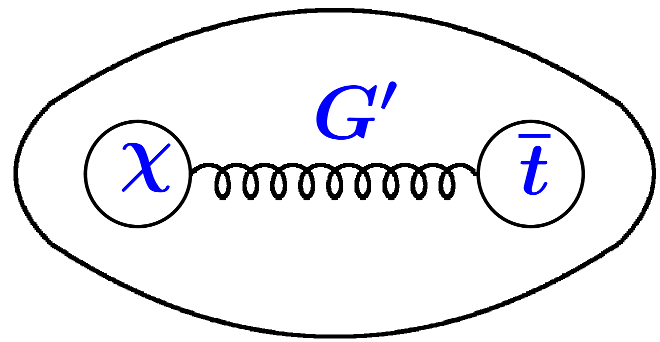
New limits from $\ell^+\ell^-$, $\gamma\gamma$ resonance searches at CMS & ATLAS

(talks by C. Wulz, X. Anduaga, ...)

Solution #3: Composite Higgs models

Higgs boson may be a bound state of top quark with a new (vector-like) quark χ: "Top seesaw model" *(Chivukula et al, hep-ph/9809470,...)*

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



Scale of Higgs compositeness $\gtrsim \mathbf{5}$ TeV.

Solution #4: Higgs doublet as a (composite) pseudo Nambu-Goldstone boson

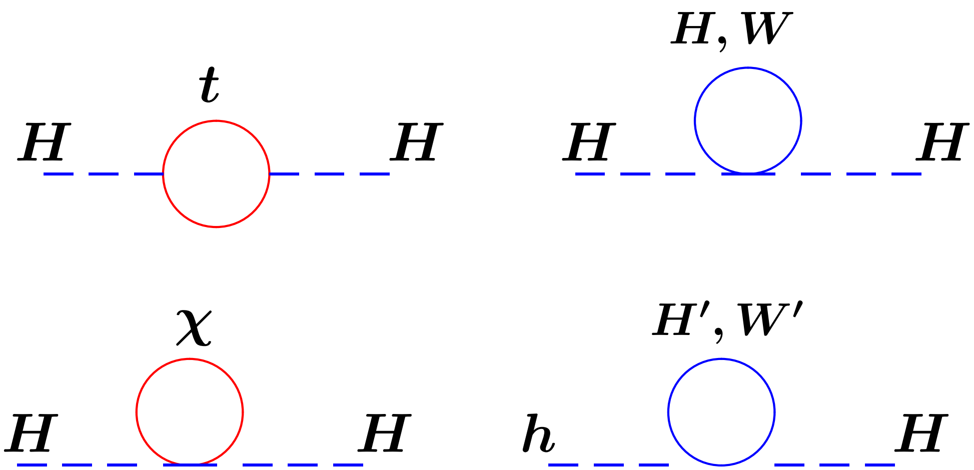
(Georgi, Kaplan, 1984, ... ; Agashe, Contino, Pomarol, hep-ph/0412089, ...)

(talk by M. Redi)

(Partial) Solution #5: "Little Higgs"

1-loop quadratic divergences cancelled by same-spin partners

(Arkani-Hamed et al, hep-ph/020602, ...)



Effective theory valid up to scales of order ~ 5 TeV, where some unspecified new dynamics takes over.

(Partial) Solution #6: "Twin Higgs"

(Chacko, Goh, Harnik, hep-ph/0506256)

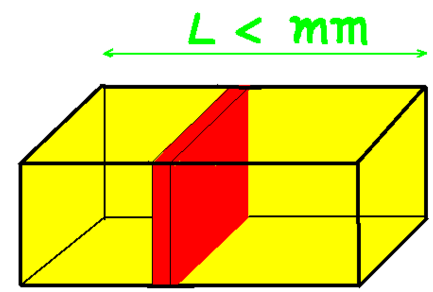
1-loop quadratic divergences are cancelled if a parity interchanges each SM particle with a particle transforming under a twin group.

Unlike other known solutions, where $\tilde{t}$ squarks or a χ quark or KK gravitons are at the TeV scale, Twin Higgs does not include colored or strongly coupled new particles.

(Potential) solution #7: Large extra dimensions (ADD)

Graviton only in flat extra dimensions

We may live on a wall in extra dimensions



Newton's law in extra dimensions: $F_N = \dfrac{m_1 m_2}{(M_s r)^{2+n}}$

New limits from monojet, mono-γ searches at CMS and ATLAS *(talks by ....)*, and from searches for new macroscopic forces.

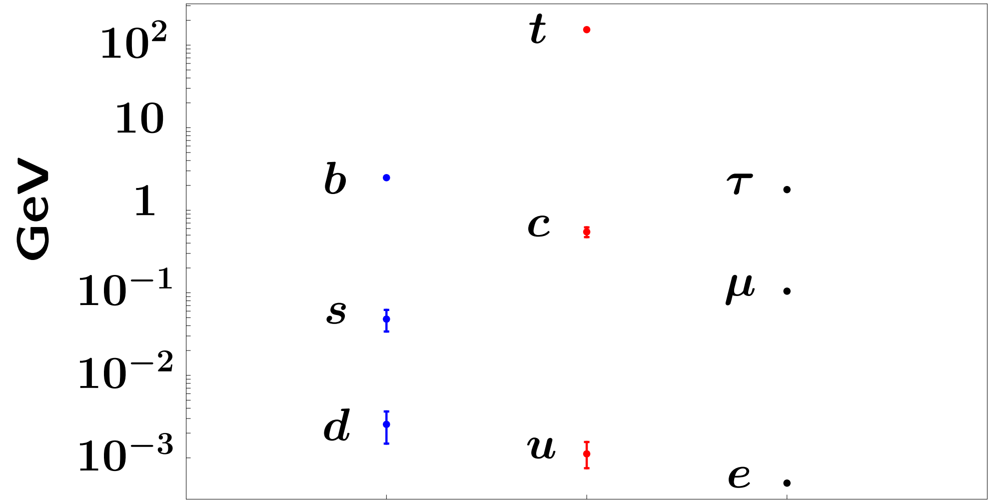
(Potential) Solution #8: approximate scale invariance

(C. Hill, hep-th/0510177, ...)

Solution #9: ???

Hierarchy argument for new phenomena: **naturalness requires new physics at the TeV scale, but there are many possibilities.**

Quark and lepton masses:
(at 1 TeV)



Any explanation for the hierarchy of Higgs Yukawa couplings (proportional to fermion masses) requires physics beyond the SM:

- **discrete symmetries** $\to$ $(\langle\phi\rangle/M)^n$ **suppressions**
- **loop suppressions**
- **grand unification**
- **wave function overlaps in extra dimensions**
- **...**

Scale of fermion-mass generation may be large: need to study rare K, D, B *decays, LFV processes, ...*

Other theoretical reasons to expect phenomena beyond the SM$\nu\mathcal{G}$:

strong CP problem, baryogenesis, inflation, successes of GUTs, why 3 generations, ...

The hierarchy problem, the pattern of quark and lepton masses, and other theoretical arguments suggest the existence of structures beyond the SM, but leave room for many manifestations.

Furthermore, there might be novel phenomena that are not related to these.

Let's not search only under the lamppost ...

What kind of new particles may exist?

Discovering particles one at a time

It may very well be that our first glimpse of physics beyond the SM will be due to the production of only one new particle.

New spin-1 particles – results presented at ICHEP2012:

- $q\bar{q} \to Z' \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, t\bar{t}, jj, b\bar{b}$ *(CMS, ATLAS, D0, CDF)*
- $u\bar{d} \to W' \to e\nu, \mu\nu, t\bar{b}, WZ, jj$ *(ATLAS, CMS)*
- $q\bar{q} \to G'_\mu \to jj$ *(CMS, ATLAS)*
- $gg \to G'_\mu G'_\mu \to (jj)(jj)$ *(CMS)*
- $qg \to Xt \to (tj)j$ *(ATLAS)*
- **leptoquarks:** $ep \to LQ \to ej$ *(H1, ZEUS)*
- ...

"Gluon-prime" (or "coloron"): *a heavy spin-1 color-octet particle*

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

E.g., SM quarks transform as 3 of $SU(3)_1$

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 $SU(3)_{1,2}$ gauge couplings.

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

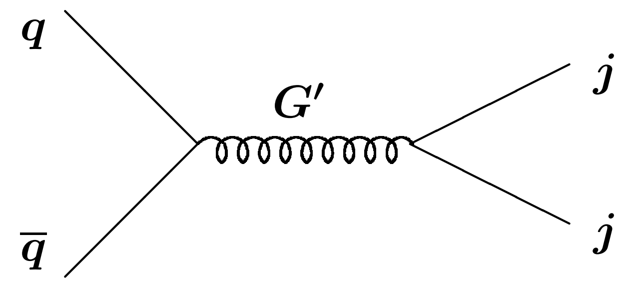
Particular types of colorons: axigluon (opposite sign couplings to q_L, q_R)
topgluon (larger coupling to 3rd generation)

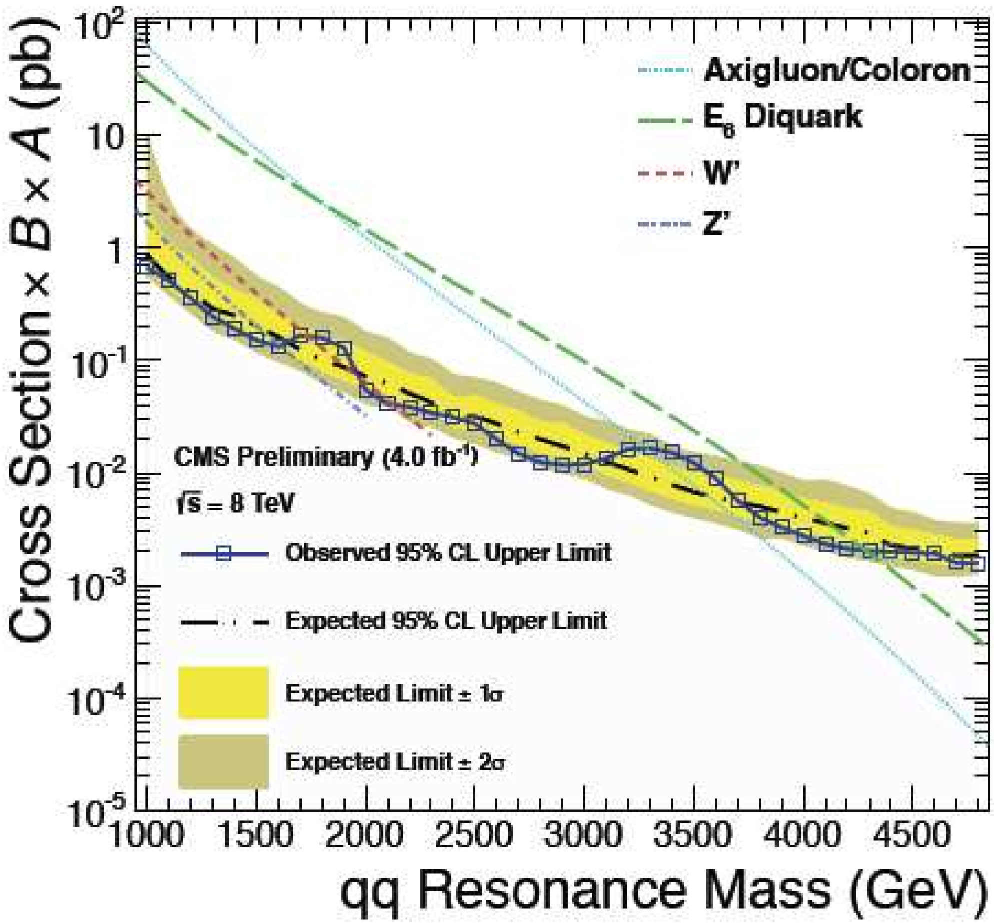
Other models with G'_μ: QCD in extra dimensions, UED, ...

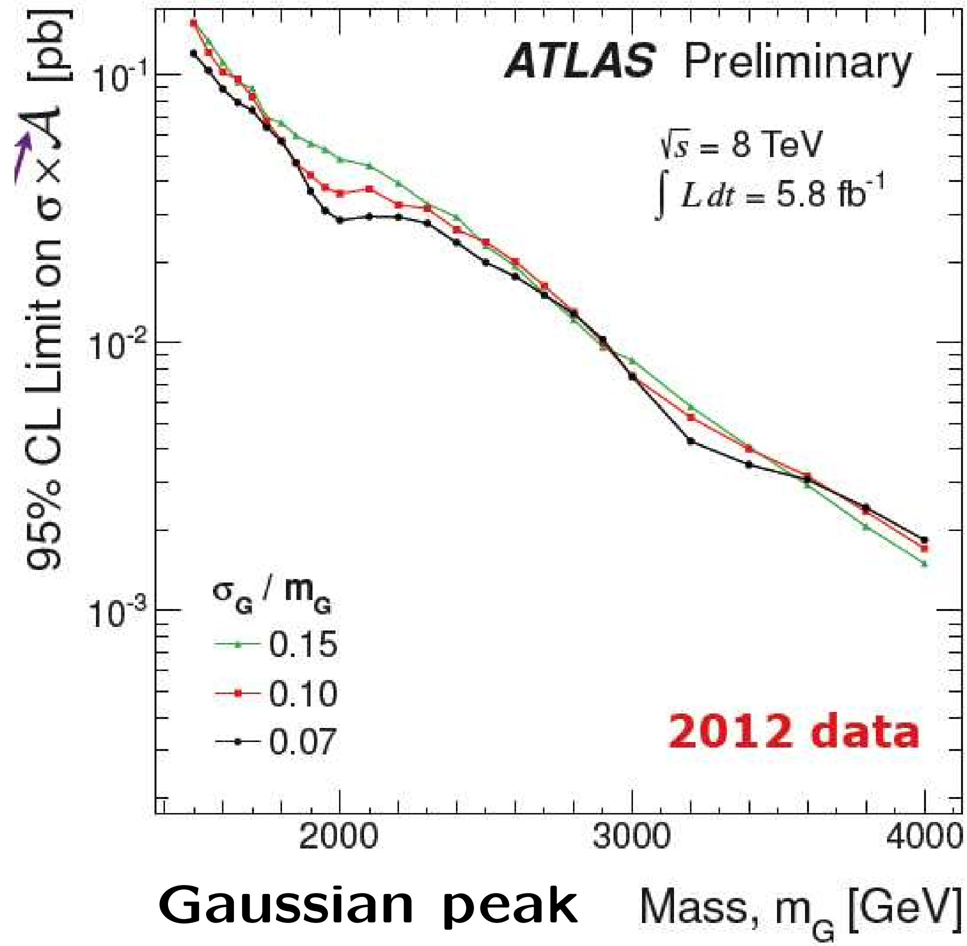
Dijet resonance

Very important signature:

Any new particle produced in the s channel at hadron colliders can decay into a pair of jets!

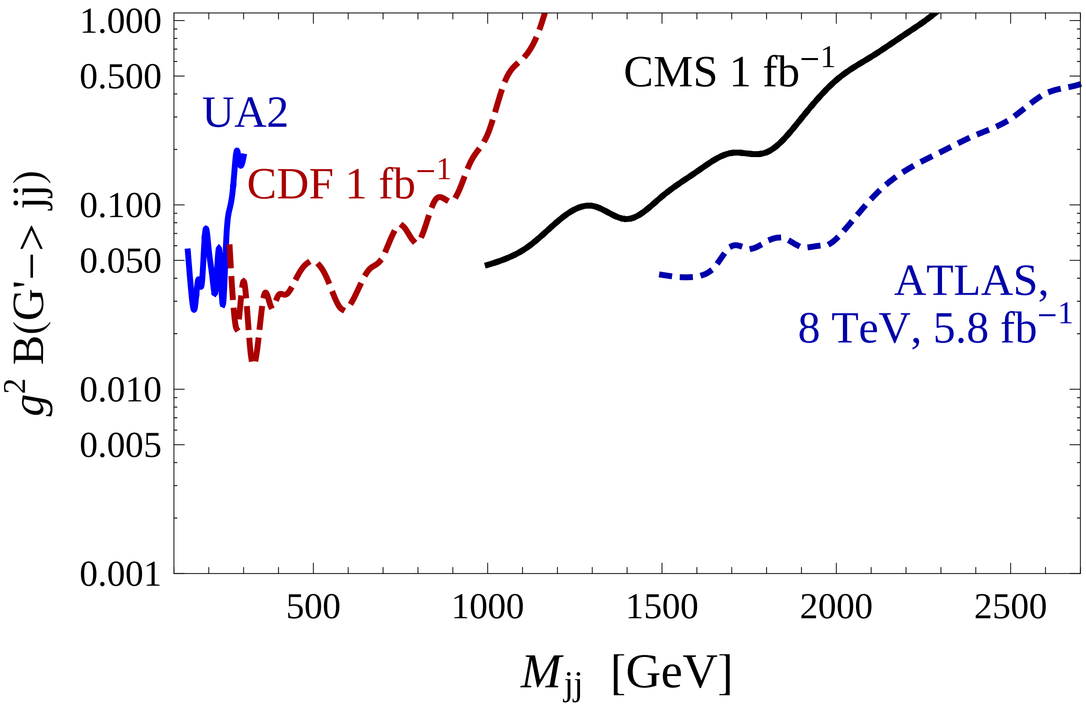






Gaussian peak

ATLAS & CMS jj resonance searches start typically at $M_{jj} \gtrsim 1$ TeV.
For $M_{jj} < 200$ GeV, limits only from UA2 & UA1.



Plot by Felix Yu

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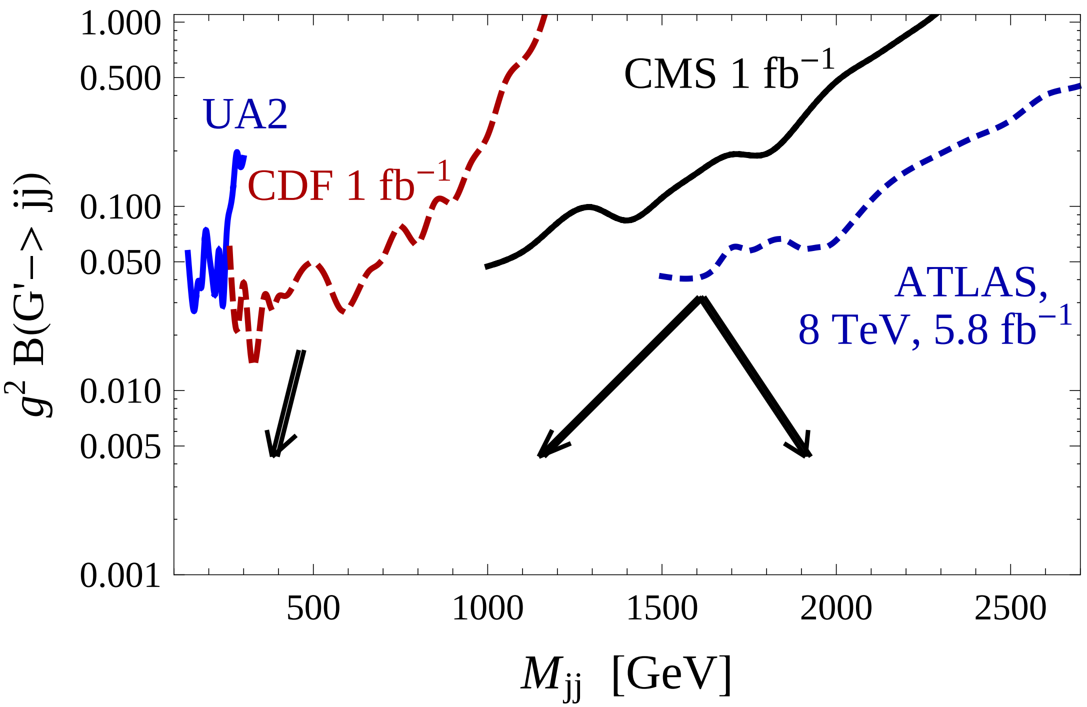

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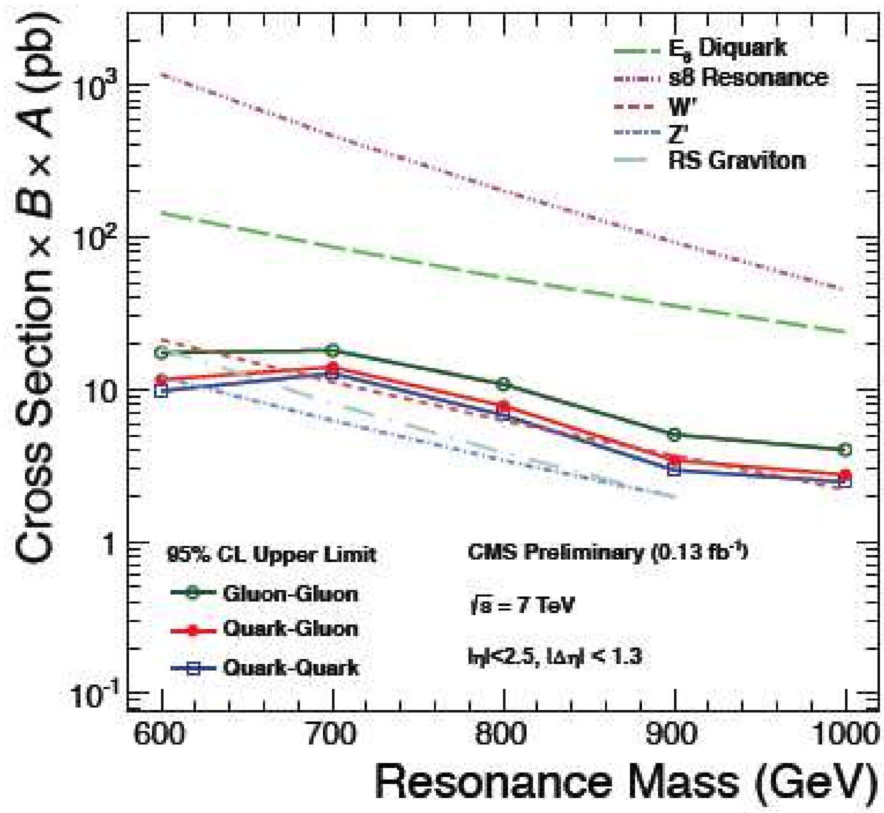
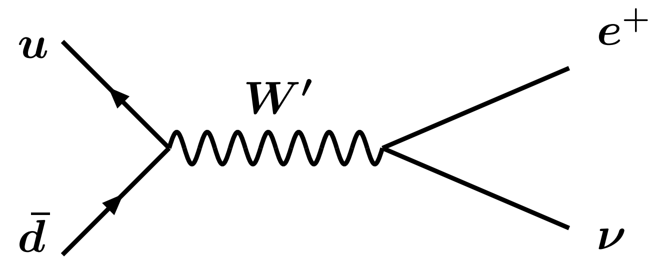


CMS low jet-trigger thresholds for low $m_{jj} < 1$ TeV *(new for ICHEP)*.

$W' \to e + \not{E}_T$ resonance

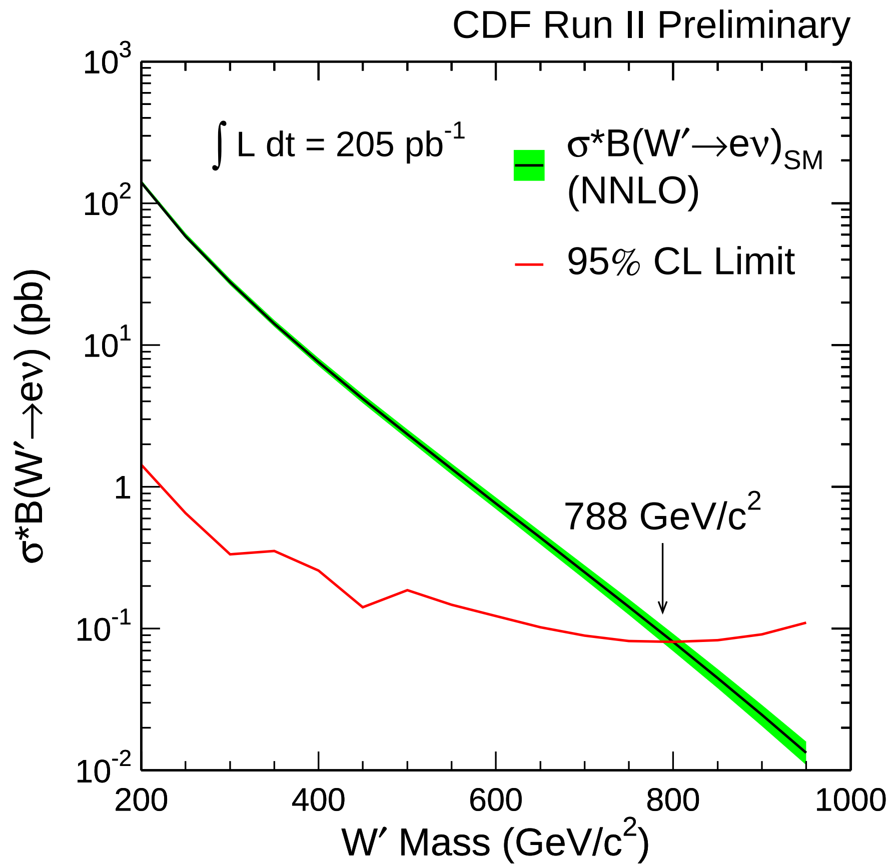


ATLAS & CMS searches start at $M_{W'} \geq 500$ GeV.

105 GeV $\leq M_{W'} \leq 200$ GeV: limits only from UA1 & UA2

$\sigma \propto g^2_{W'} B(W' \to e\nu)$

$\Rightarrow$ $g_{W'} \approx 0.1 g_{\mathrm{SM}}$ **is viable for any** $M_{W'} < 500$ **GeV.**



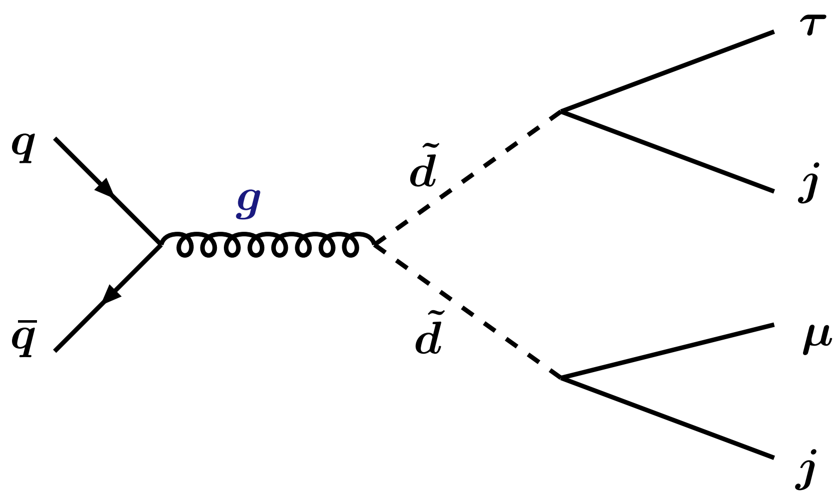
Particles of masses near the electroweak scale should be searched for in more detail.

One new particle at a time: spin-0

More results presented at ICHEP2012:

- **leptoquarks:** $ep \to LQ \to ej$ *(HERA, ZEUS)*
- **LQ LQ** $\to (\ell j)(\ell j), (\ell j)(\nu j), (\tau b)(\tau b)$, **...** *(CMS, ATLAS, D0, CDF)*
- **color-octet:** $gg \to G_H G_H \to 4j$ *(CMS, ATLAS)*
- **color-octet:** $gg \to S_8 \to gg$ *(ATLAS)*
- **gauge singlet:** $gg \to A^0 \to \mu^+\mu^-$ *(ATLAS,CMS)*
- **doubly-charged scalar:** $q\bar{q} \to \phi^{++} \to \ell^+\ell^+$ *(ATLAS,CMS)*
- ...

Leptoquarks coupling to the 2nd and 3rd generations



CDF, D0, ATLAS, CMS have searched for $(\mu j)(\mu j)$ and $(\tau b)(\tau b)$ but not for $(\mu j)(\tau j)$.

$(\mu j)(\mu j)$ is likely to have a smaller rate due to small $B(\tilde{d} \to \mu c)$.

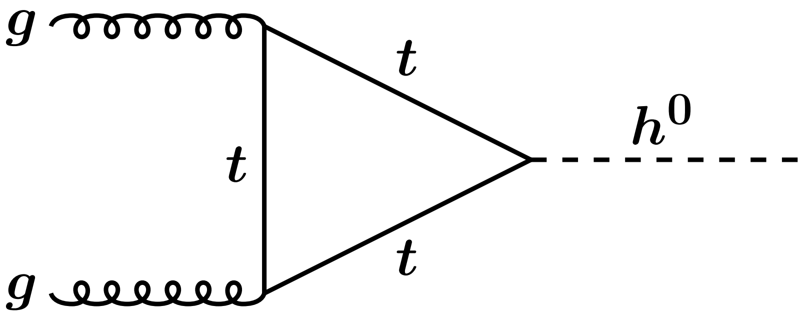
$(\tau j)(\tau j)$ has large backgrounds

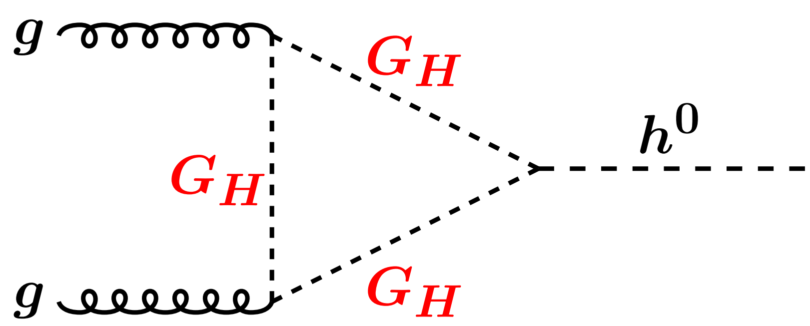
$(\mu j)(\tau j)$ is a useful leptoquark search.

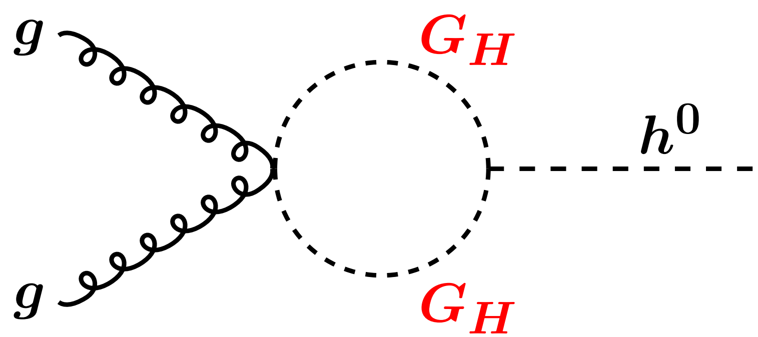
Strong limits from $\mu\mathcal{N} \to e\mathcal{N}$ transition on leptoquarks which couple to both eq and μq.

Higgs boson – a tool sensitive to new scalars

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







$\kappa\, G_H^a G_H^a H^\dagger H$ **portal**

The cross section for gluon fusion is reduced (increased) for $\kappa < 0$ ($\kappa > 0$).

$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \approx \left| 1 + 3\kappa \frac{v^2}{8M_{G_H}^2} \right|^2$$

(1112.2208, 1112.1964, 1205.4244)

Scalar octet

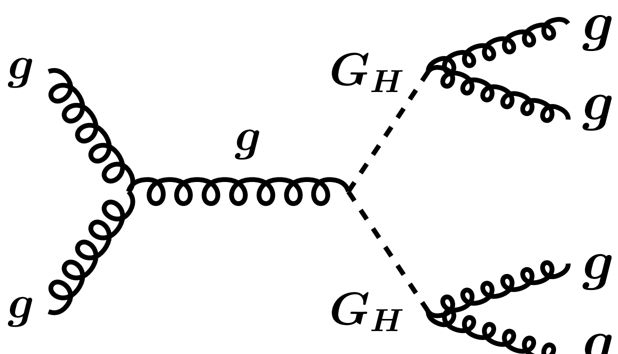
G_H: spin 0, transforms as (8,1,0) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

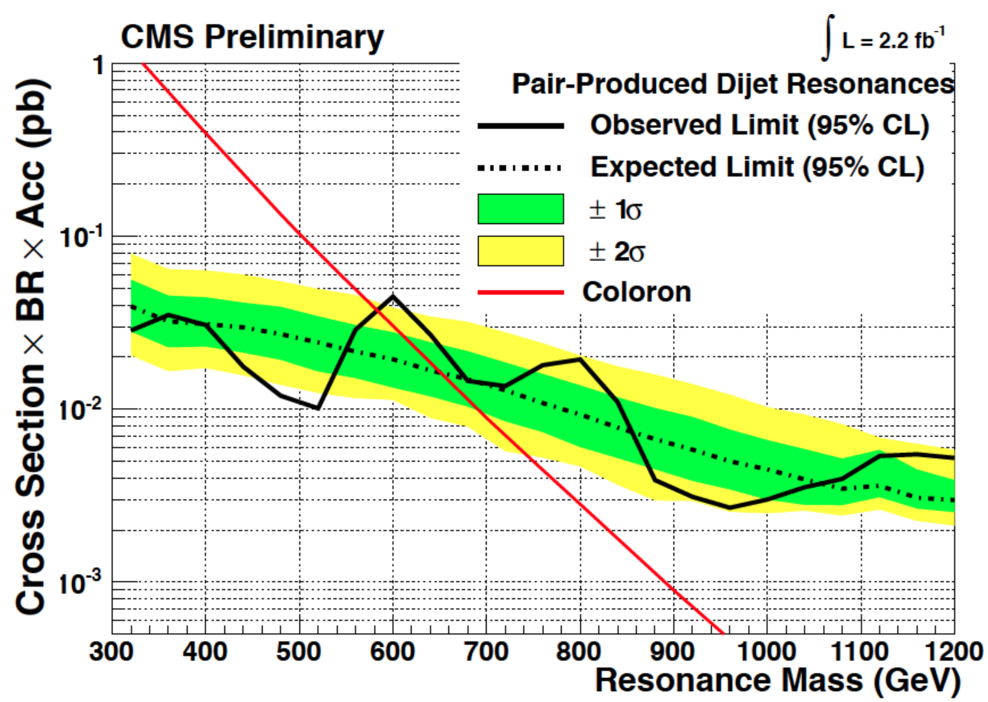
$SU(2)_W$ forbids renormalizable couplings of G_H to SM quarks.

Renormalizable couplings of G_H to gluons are fixed by $SU(3)_c$ gauge invariance: $\Rightarrow$ production of G_H occurs in pairs.

$G_H \to gg$ decay occurs at one loop.

Signal: a pair of narrow gg resonances of same mass





Also: coloron pair production $\to 8j$

(talk by C. Kao)

(talk by A. Hinzmann)

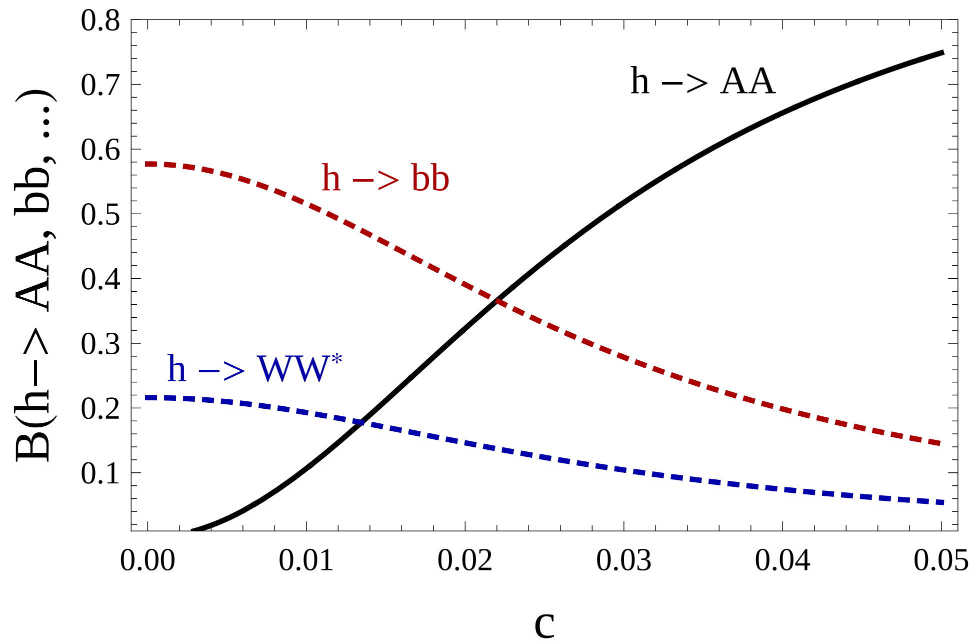
Nonstandard Higgs decays

Standard model + a gauge-singlet complex scalar 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

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

For $2M_A \ll M_h = 125$ GeV:



It is essential to measure the

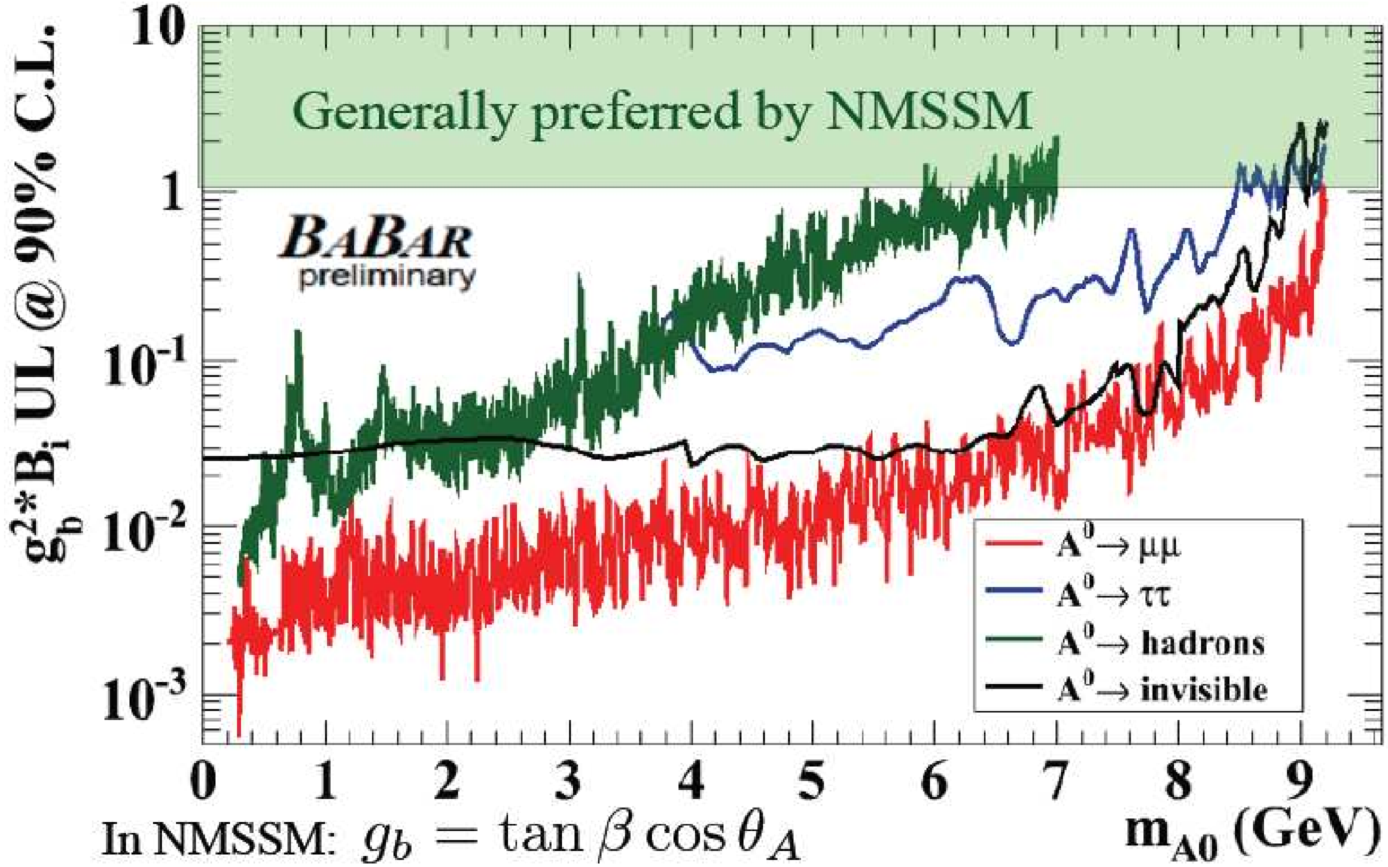
hWW *and* $hb\bar{b}$ *couplings.*

Very light new bosons

A^0 – a spin-0 particle.

Searches for $\Upsilon \to \gamma A^0$ decays at Belle & BaBar:

(talks by D. Kim and Y. Kolomensky)



Vectorlike quarks

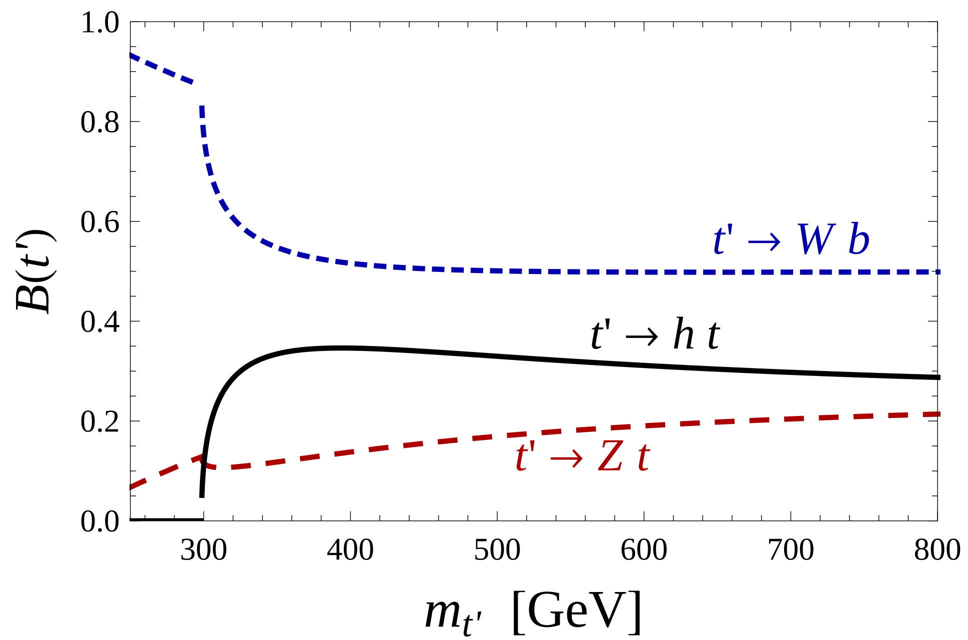
All Standard Model fermions are chiral: their masses are not gauge invariant, and arise from the Higgs coupling.

Vectorlike (*i.e.* non-chiral) fermions – *a new form of matter.*
Masses allowed by $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry,
$\Rightarrow$ naturally heavier than the t quark.

A vectorlike quark 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.

Branching fractions of t':

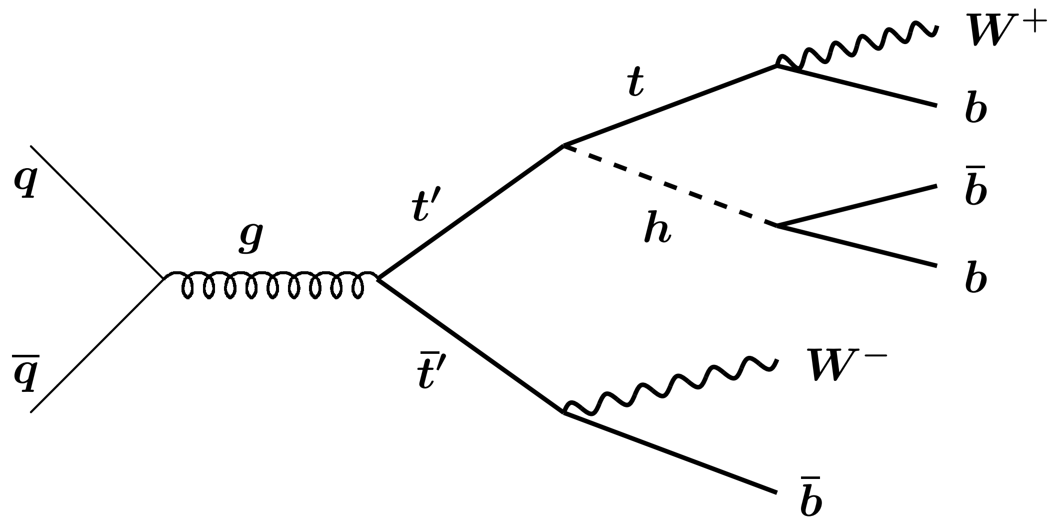
($M_h = 125$ GeV, $\sin\theta_L = 0.1$)



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:



Higgs boson could show up in the $W^+W^- + 4b$ final state!

SM$\nu\mathcal{G}$ + DM describes well a large array of data.

Same is true for any model with a decoupling limit

(*i.e.*, effects of new particles are suppressed by $1/M_{\rm new}$ or $g_{\rm new} \ll 1$), including larger gauge symmetries, vectorlike quarks, or new scalars.

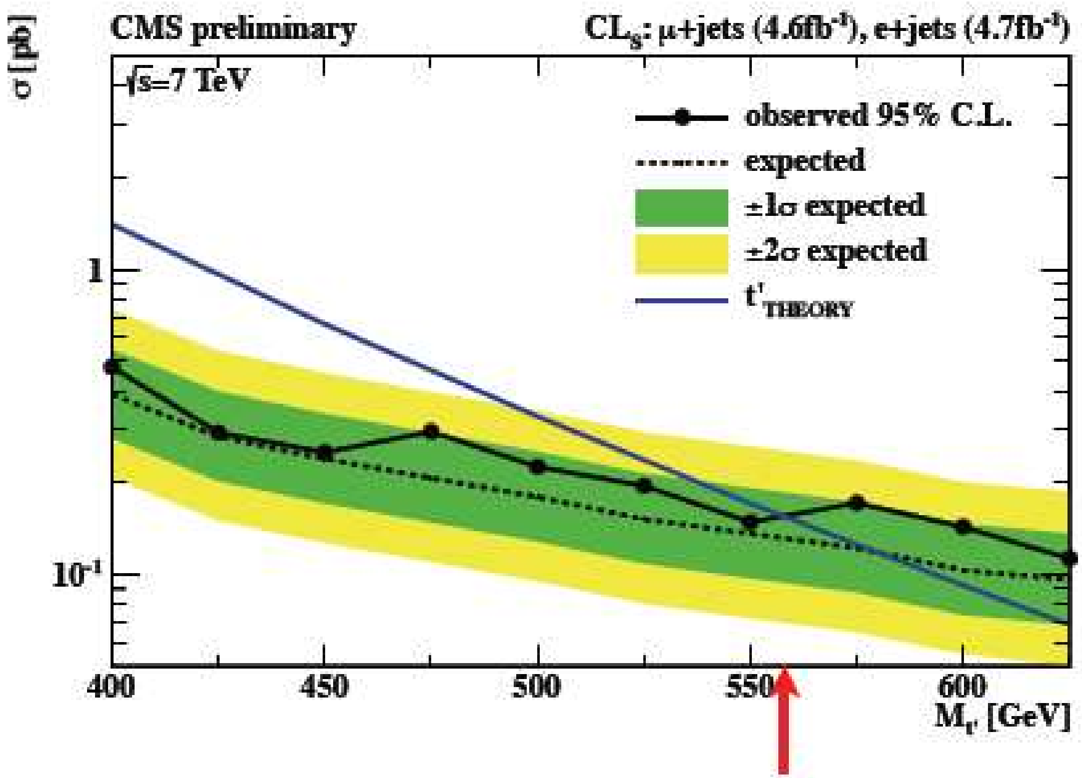
Models without a decoupling limit are likely to be ruled out:

- Higgsless models
- SM + 4th generation

Fermion coupling to Higgs is proportional to mass: perturbative limit $m_f \lesssim 600$ GeV

(talk by G. Hou)

Talk by S. Khalil:



Observed limit: $m_{t'} > 560$ GeV/c^2 @ 95% CL

One new particle at a time: spin-1/2

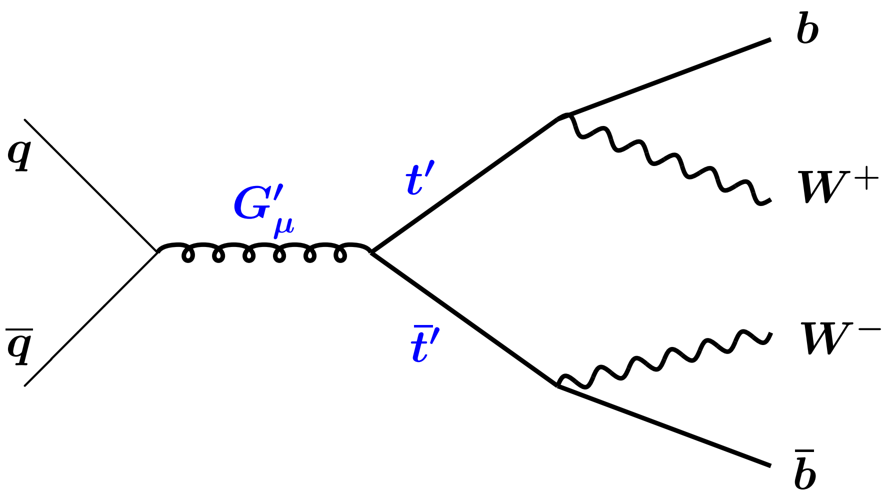
More results presented at ICHEP2012:

- $gg \to t'\bar{t}' \to (Wb)(W\bar{b}), (Zt)(Z\bar{t})$ *(ATLAS, CMS)*
- $gg \to b'\bar{b}' \to (Wt)(W\bar{t}), (Zb)(Z\bar{b})$ *(ATLAS, CMS)*
- $u\bar{d} \to t'\bar{b}' \to (Wb)(W\bar{t})$ *(CMS)*

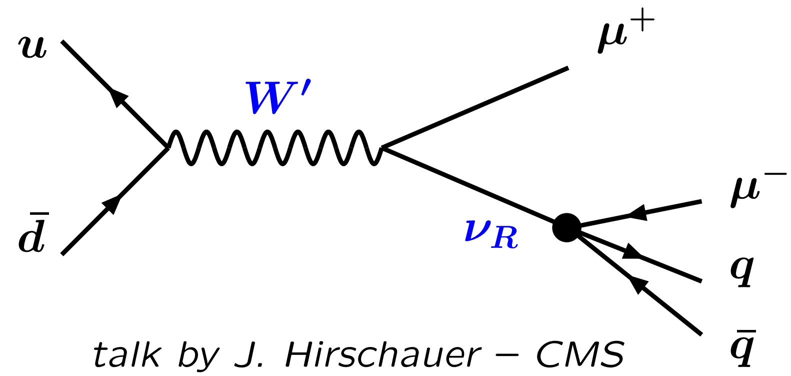
- $u\bar{d} \to t'\bar{b} \to (Wb)\bar{b}$ *(CMS)*
- $u\bar{d} \to \bar{b}'t \to (Wt)\bar{t}$ *(CMS)*
- $qq \to Qq \to (Wj)j, (Zj)j$ *(ATLAS)*
- $qg \to Q \to jj, j\gamma$ *(ATLAS, CMS)*
- $gg \to QQ \to (Wj)(Wj)$ *(ATLAS)*
- ...

Discover two (or more) new particles at the same time

Resonant $t'\bar{t}'$ production:



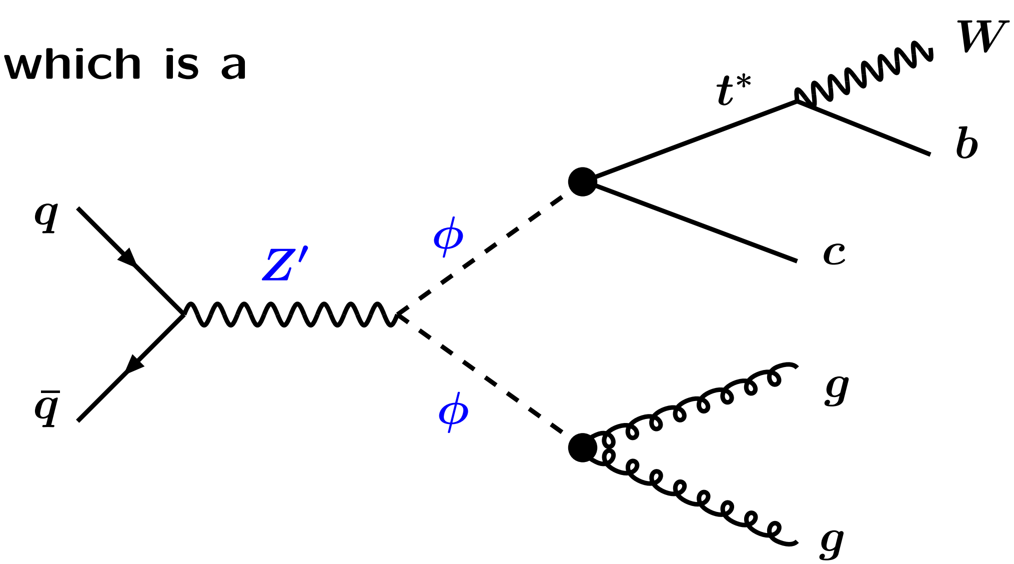
W' decay to a heavy RH neutrino:



Resonant pair production of a scalar which is a singlet under $SU(3) \times SU(2) \times U(1)$:

jj resonance $+W+$ softer jets (bc)

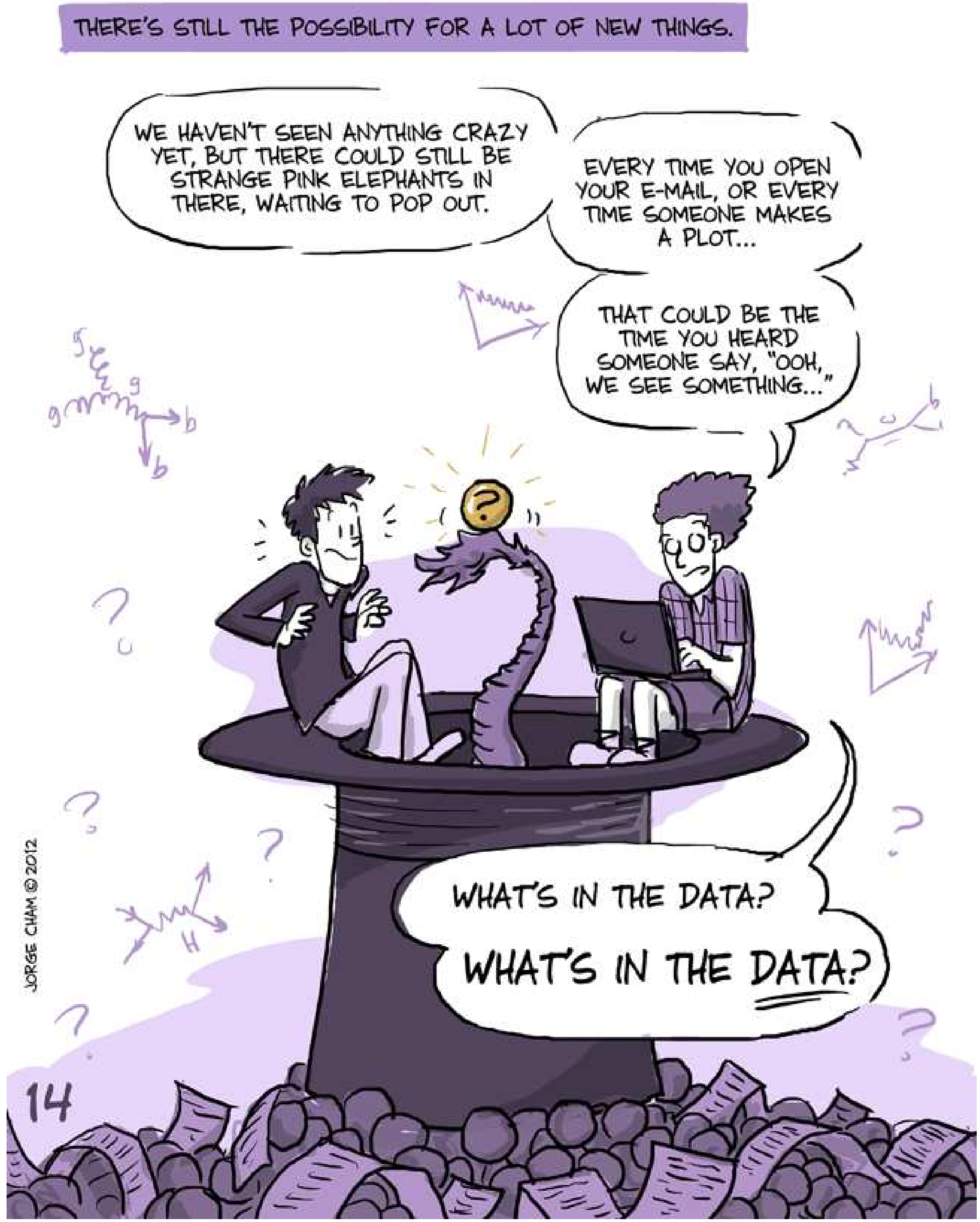
and also a $W + 4j$ resonance.



Many other final states arising from SM + 2 new particles.

Various unsolved puzzles:

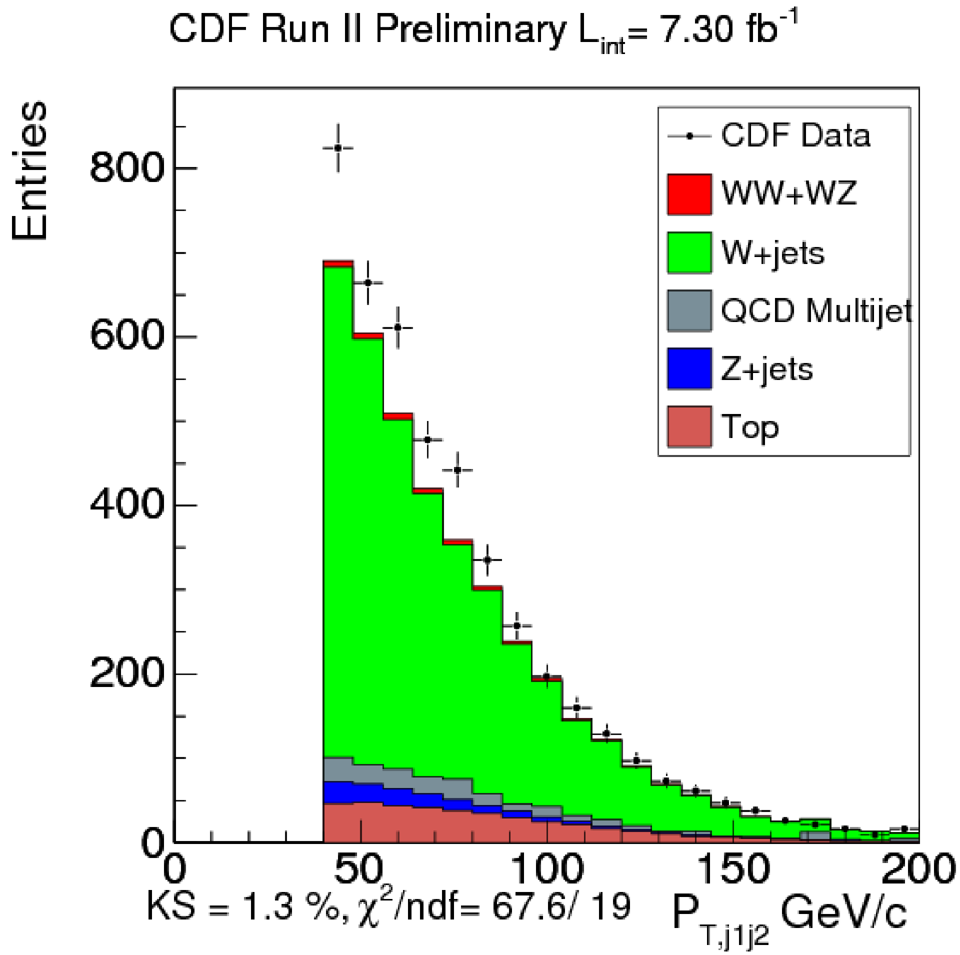
- $jj + W$ excess – CDF
- $A_{\rm FB}^{t\bar{t}}$ – D0 & CDF
- $\mu^\pm\mu^\pm$ asymmetry – D0
- Cosmic γ line @ 130 GeV
  talk by J. Wacker
- Muon $g-2$
- MiniBoone low energy data
- $B \to D^{(*)}\tau\nu$ – BaBar
- CPV in D decays – LHCb
- $(bb)b$ final state – CDF & D0
- ...

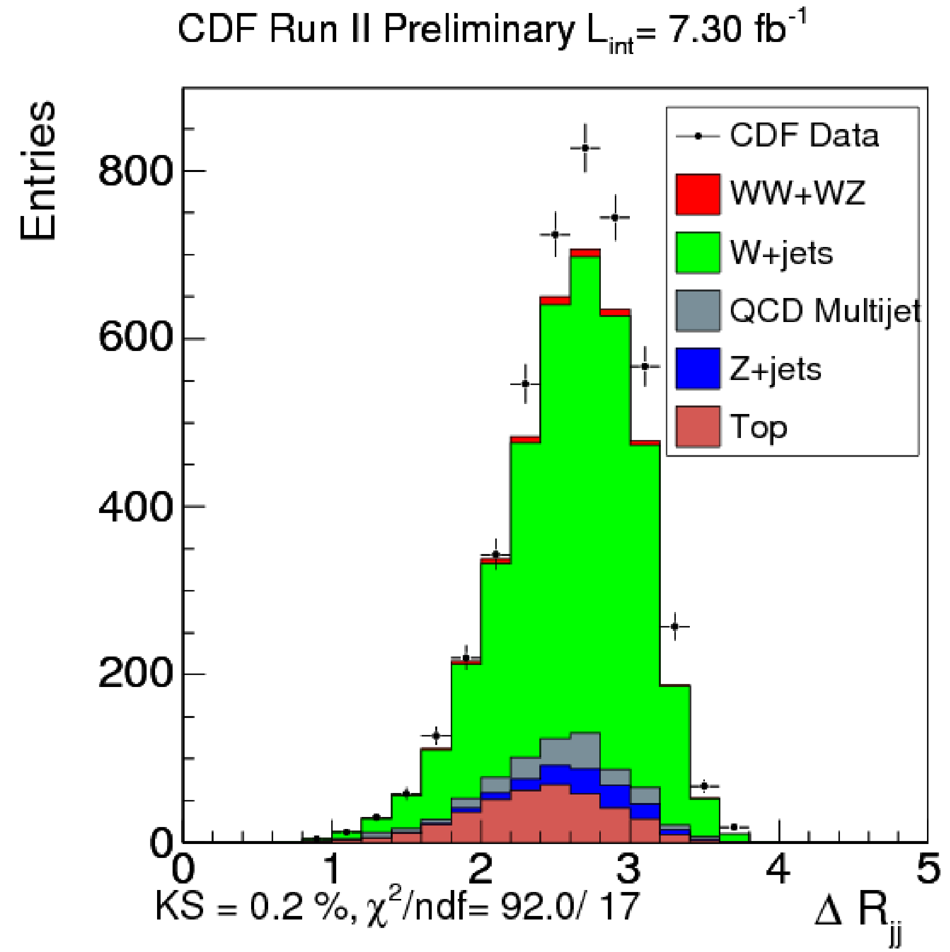


phdcomics.com/higgs

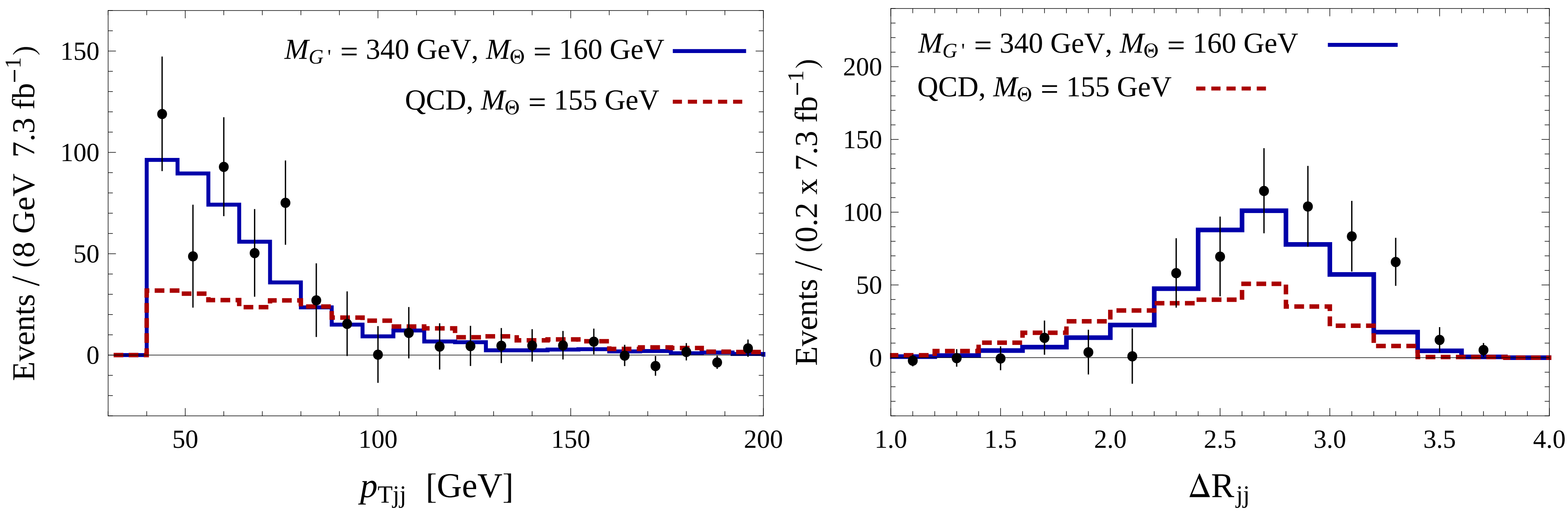
Large deviations from SM in various kinematic variables measured by CDF in the Wjj final state

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





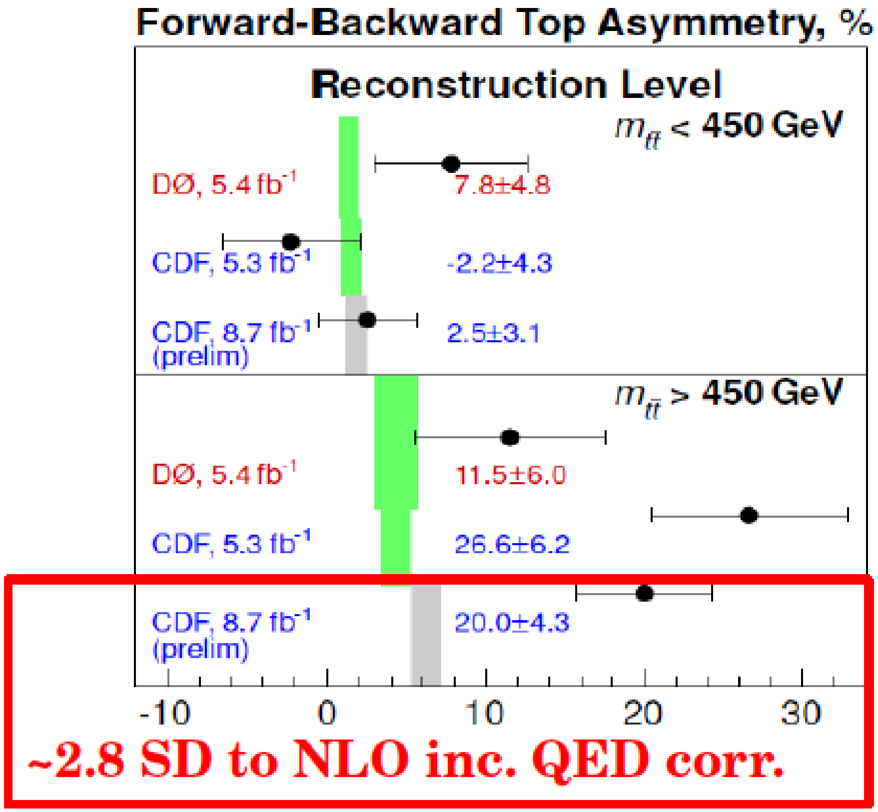
CDF Wjj – Background-subtracted data (SM = 0):



Blue lines: $G' \to \Theta\Theta \to (Wbb)(jj)$ *1104.2893*

If the deviations from the SM are due to some background mis-modelling, it is a remarkable coincidence that simple new physics models fit well the kinematic distributions in the Wjj *final state.*

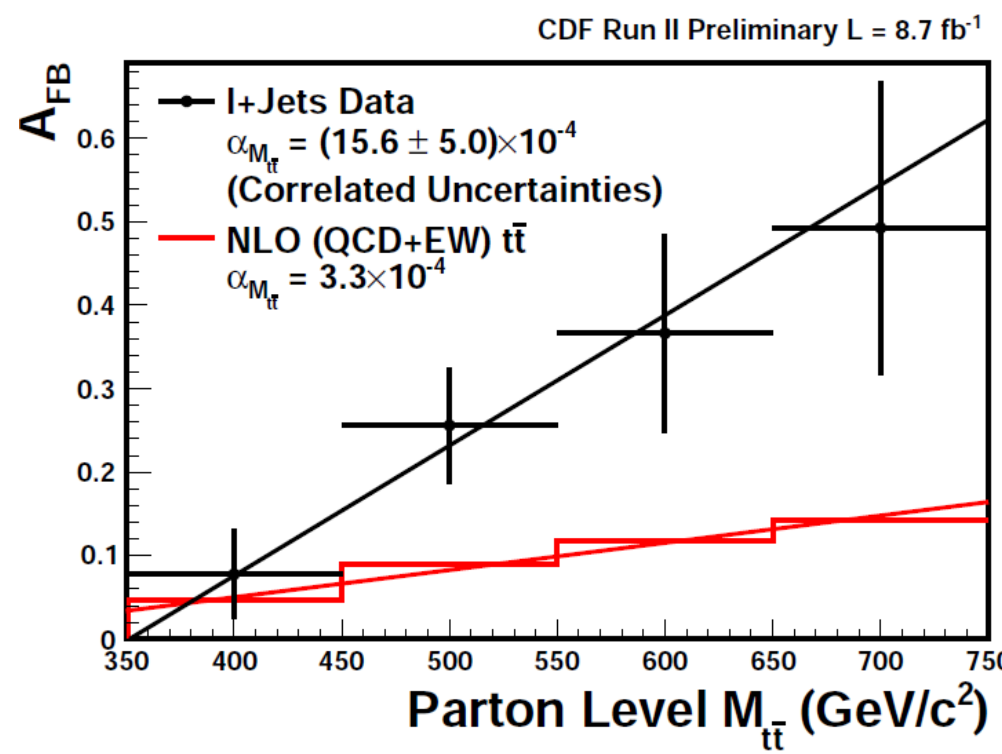
It is imperative to sort out the origin of these large deviations.



New D0 lepton-based $A_{FB}^{t\bar{t}}$ measurement:

2.2σ away from the SM

talk by A. Grohsjean (see also 1207.0364)



Monte Carlo mis-modelling

or physics beyond SM:

flavor gauge bosons *(talk by K. Babu)*,

axigluons, ... ?

talk by C. Hays

Synergy between physics probed at colliders and in searches for rare decays or DM

Neutrino masses require the coupling of ν's to the Higgs doublet.

The origin of quark and lepton masses (arising from physics at a high scale, between v_H and the GUT scale) is likely to induce various flavor-changing processes involving mesons, muons, ...

Dark matter particle is likely to have a mass of the order of the electroweak scale (WIMP miracle).

Whether new very light particles exist is probably determined by the symmetries of the underlying theory at a very high scale.

Conclusions

Many possible new particles:

- **New gauge bosons (Z', W', G', γ', ...)**
- **Vectorlike fermions, Majorana fermions, ...**
- **Various scalar particles, extended Higgs sectors, ...**
- **...**

Discovering such particles at colliders, or observing their effects in rare processes at low-energies, would point to new symmetries or deeper organizing principles.

More exotic phenomena (strongly coupled sectors, deviations from field theory, etc.) could be uncovered. We need a ‘wide-net’ approach, using diverse experiments and many searches.