Energy Frontier

Bogdan Dobrescu

(*Fermilab, Theoretical Physics Department*)

Outline:

- *Electroweak symmetry breaking*
- *Dark matter at the LHC. Supersymmetry.*
- *Various signatures at the LHC and the Tevatron*
- *Deviations from the standard model*

December 9, 2011 - Fermilab – Physics Advisory Committee meeting

Electroweak symmetry breaking

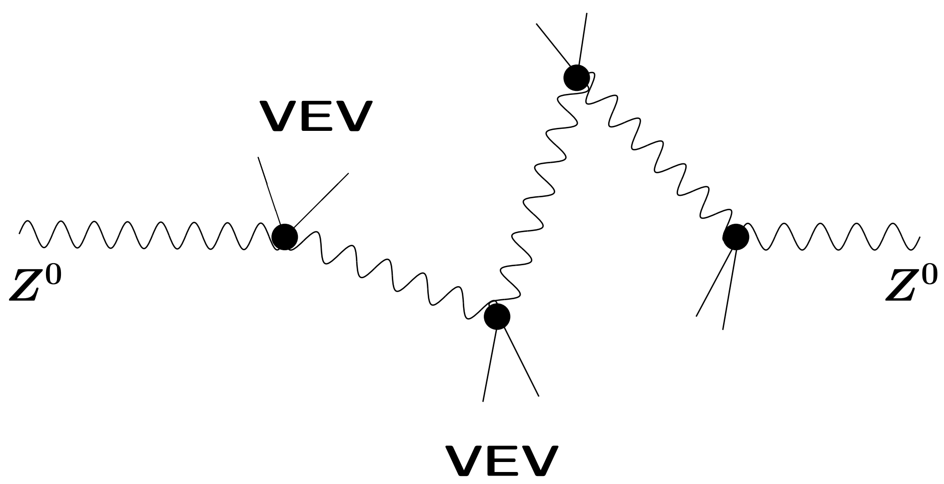
Lagrangian has an $SU(2)_W \times U(1)_Y$ gauge symmetry

Vacuum has only a $U(1)_{\text{em}}$ gauge symmetry.

$\Rightarrow$ **Electroweak symmetry is spontaneously broken**

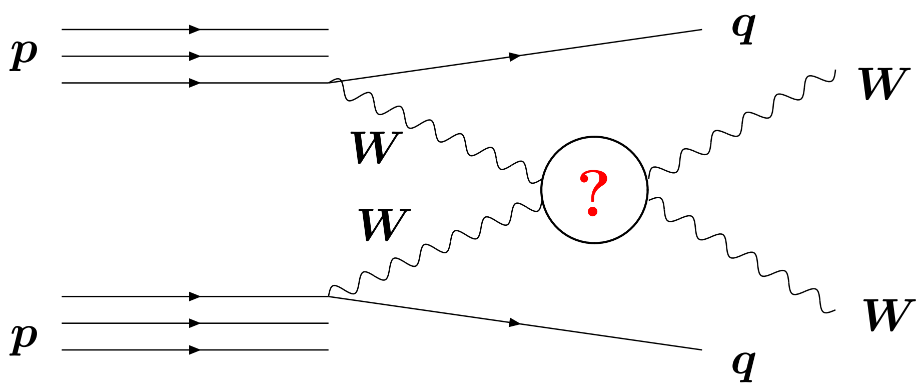
Some field 'condenses', has a Vacuum Expectation Value:

$v_H = (\sqrt{2}/g)M_W \approx 174$ **GeV (electroweak scale).**



Z^0 acquires a mass!

The LHC is not only a quark-quark or a gluon-gluon collider, but also a $\boldsymbol{WW}$ and a $\boldsymbol{WZ}$ collider!



Based on the properties of the particles known so far:

$$\text{cross section} \quad \sigma\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{(E_{\rm CM})^2}{256\pi\, v_H^4}$$

$\Rightarrow$ $W_L^+ W_L^-$ *scattering violates unitarity at high energies (i.e., computation gives nonsensical probabilities $> 100\%$)*

Thus, something new should show up at $E_{\rm CM} \lesssim 2$ TeV.

(Lee, Quigg, Thacker, 1977)

To restore unitarity at energy scales $\gtrsim 1$ TeV, there is need for:

⋆ **A new particle: Higgs boson**

OR

⋆ **New strong interactions** *(perturbative expansion breaks down; hard to compute ...)*

OR

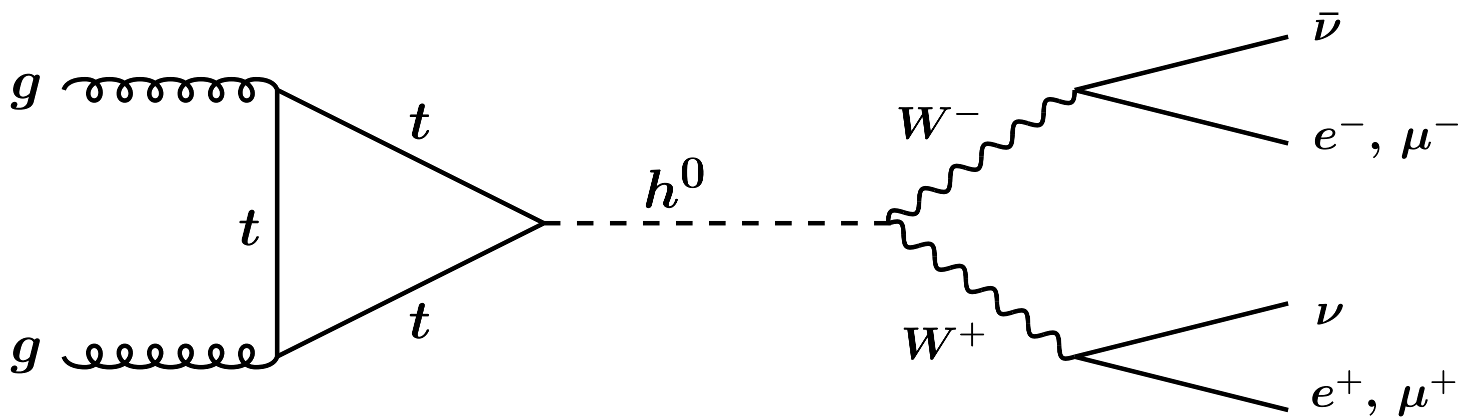
⋆ **Deviations from quantum field theory** *(???)*

The Higgs boson is a hypothetical particle of spin 0 which couples to WW and ZZ pairs:

$$g\, h^0 \left(M_W W^\mu W_\mu + \frac{M_Z}{2 \cos \theta_W} Z^\mu Z_\mu \right)$$

Whether a Higgs boson exists or not can be decided only by collider experiments.

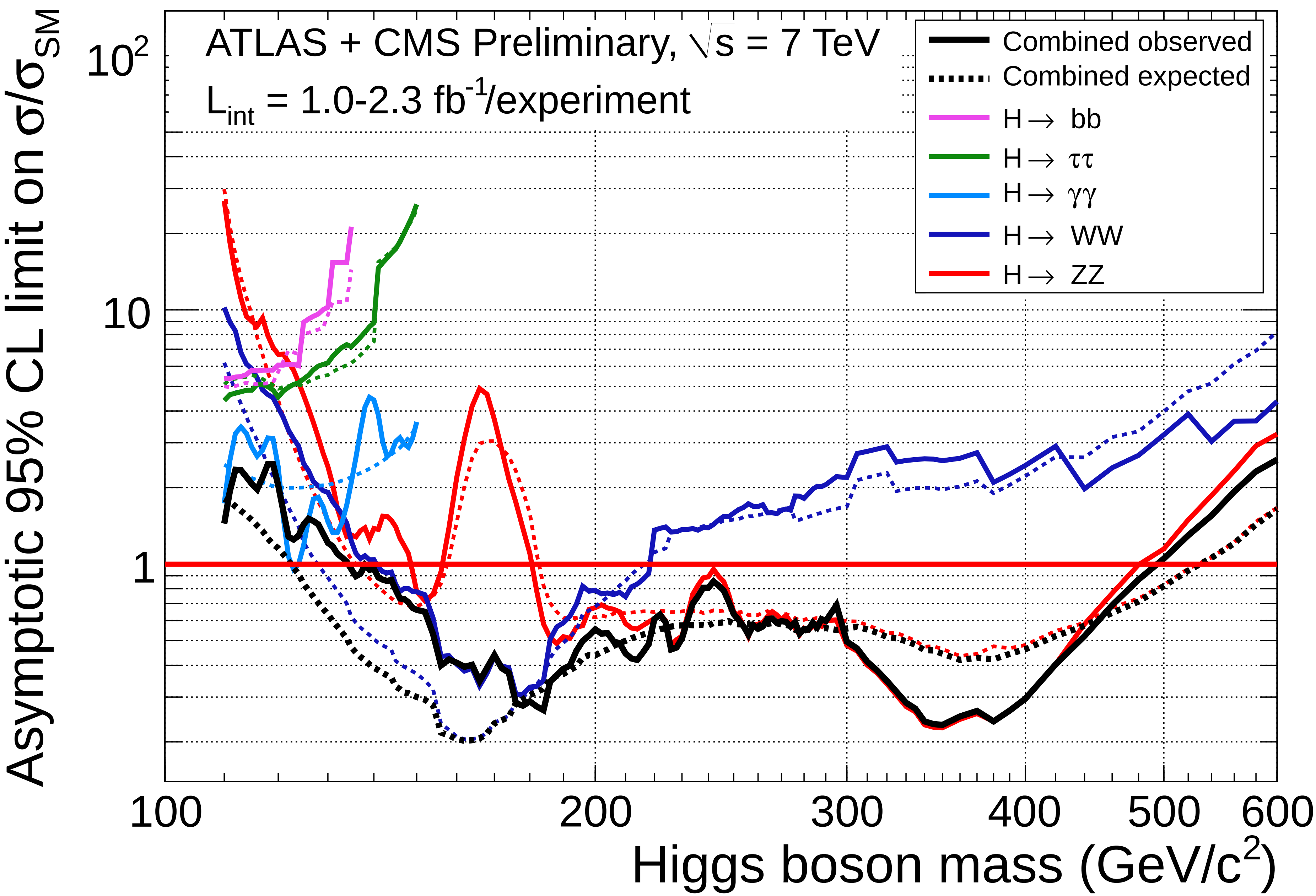
Large coupling of h^0 to the top quark implies that the Higgs boson may be produced in 'gluon fusion' at the LHC:



Also: $gg \to h^0 \to \gamma\gamma$ for $M_h \lesssim 140$ GeV

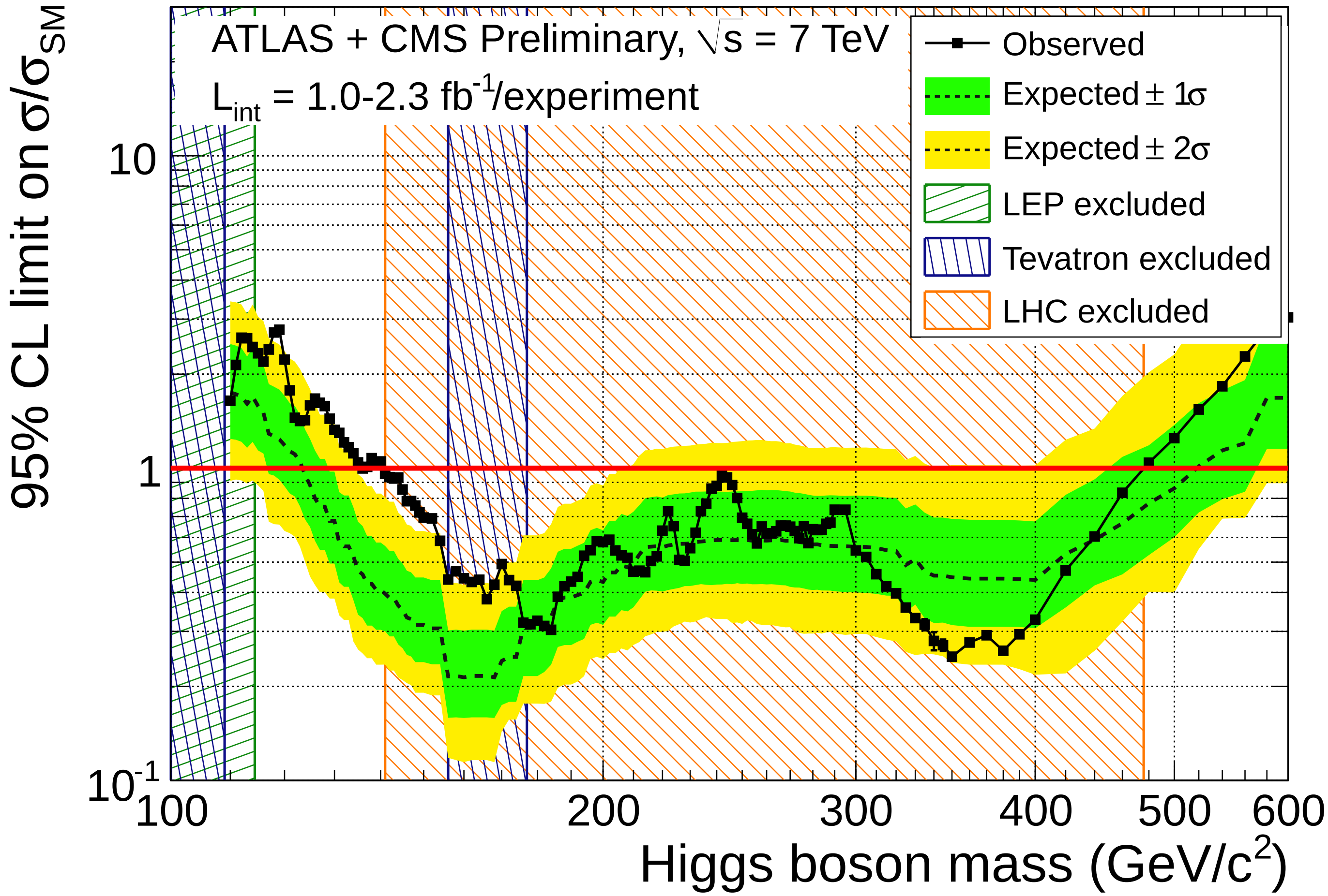
$gg \to h^0 \to ZZ \to 4\ell\,,\ \ell^+\ell^-\nu\nu\,, ...$

...



ATLAS + CMS Preliminary, √s = 7 TeV
L_int = 1.0-2.3 fb^-1/experiment
Combined observed
Combined expected
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
Asymptotic 95% CL limit on σ/σ_SM
Higgs boson mass (GeV/c^2)
10^2
10
1
100
200
300
400
500
600

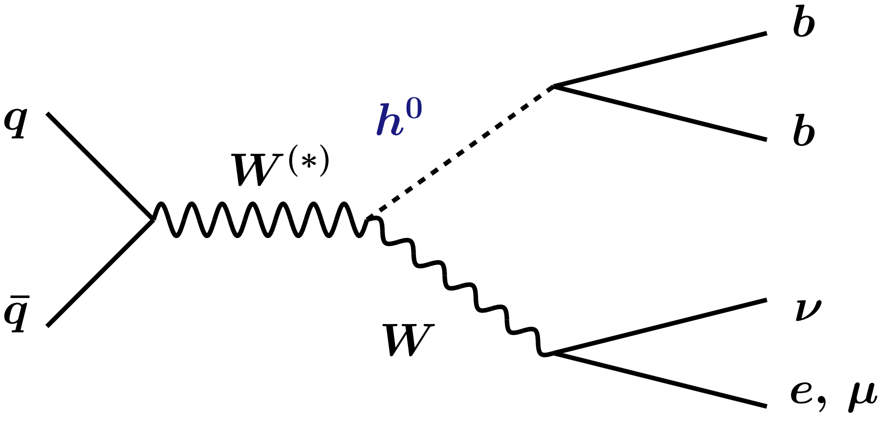
LHC searches for the Higgs boson:

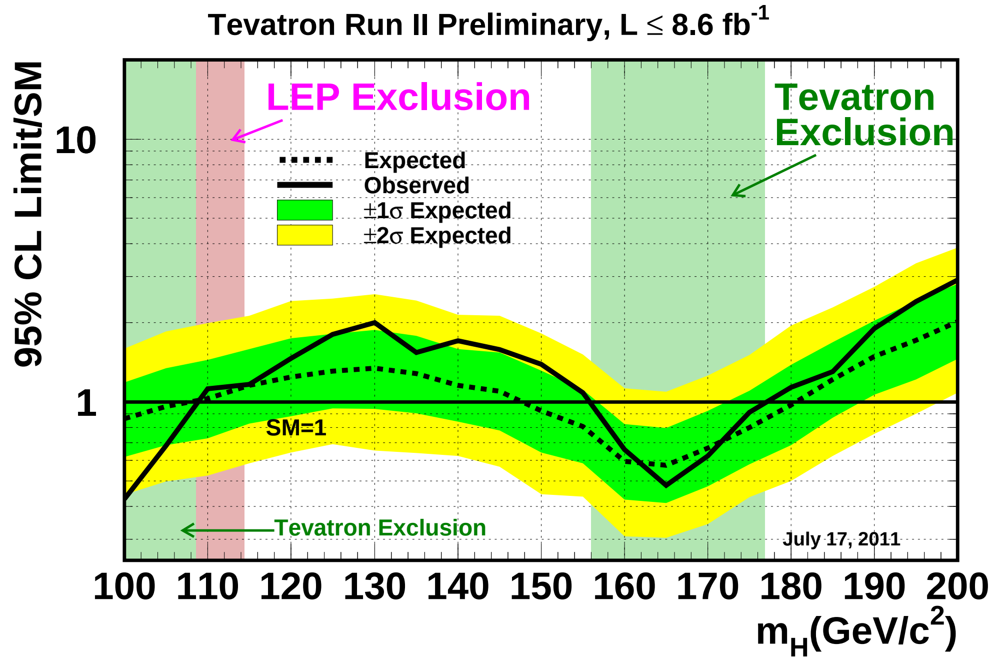


Only the 114 – 141 GeV and 480 - 700 GeV ranges are still available for the Higgs mass within the Standard Model.

High mass range requires new physics to enter the electroweak fits.

Tevatron: *better sensitivity than the LHC for* $M_h \lesssim 120$ *GeV due to associated production:*





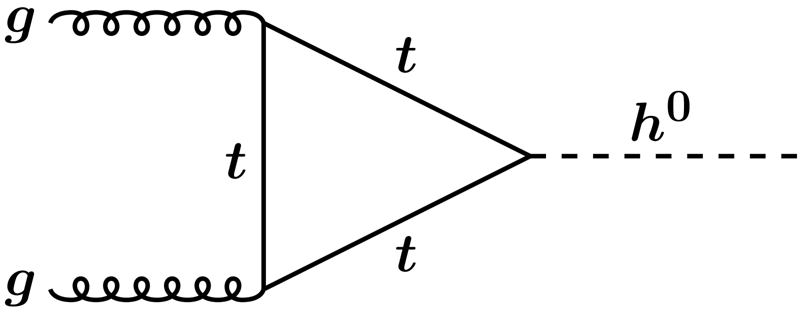
Test of the h^0WW *coupling*

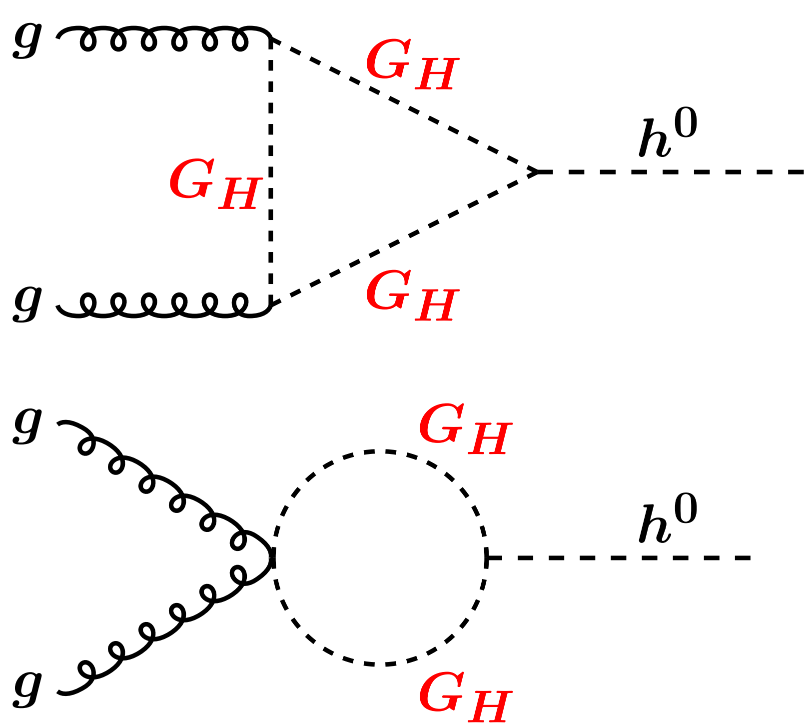
and of the $h^0b\bar{b}$ *coupling (responsible for* m_b*).*

Soon, ATLAS + CMS + D0 + CDF will either rule out the Standard Model or will find evidence for the Higgs boson.

Hidding the Higgs boson

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





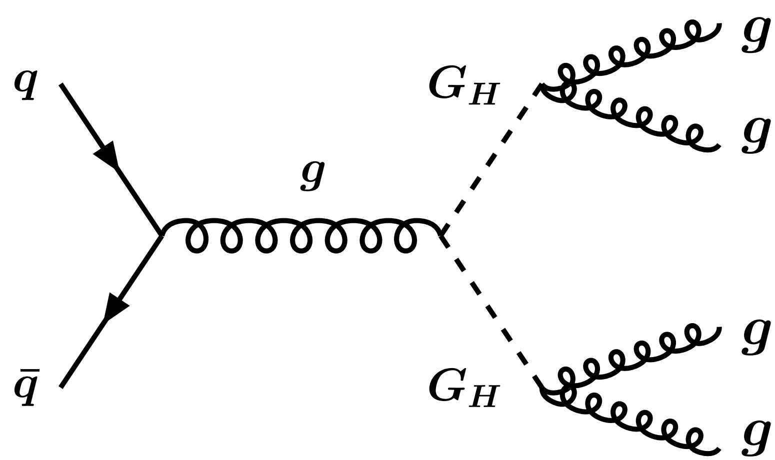
$\kappa\, G_H^a G_H^a H^\dagger H$

The cross section for gluon fusion is reduced for $\kappa < 0$.

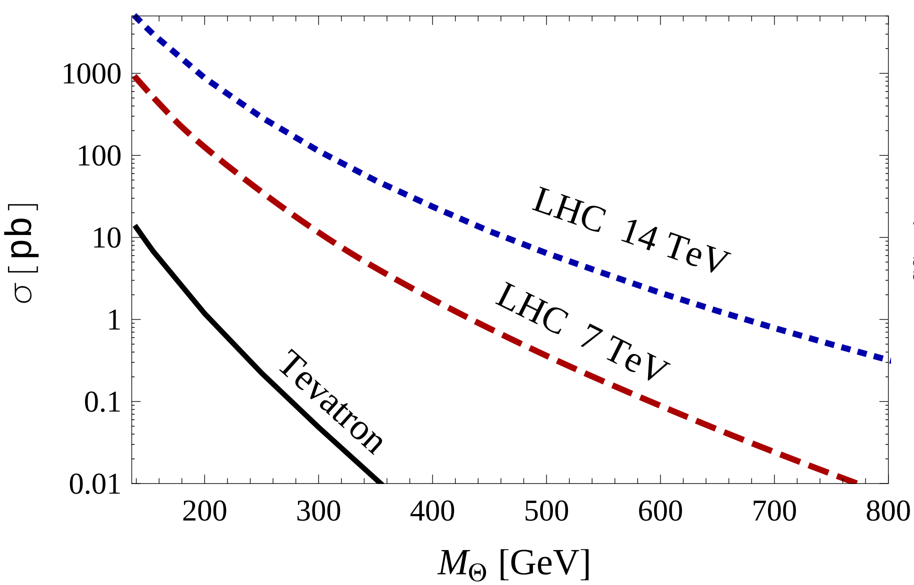
Effect is large for M_{G_H} near the electroweak scale.

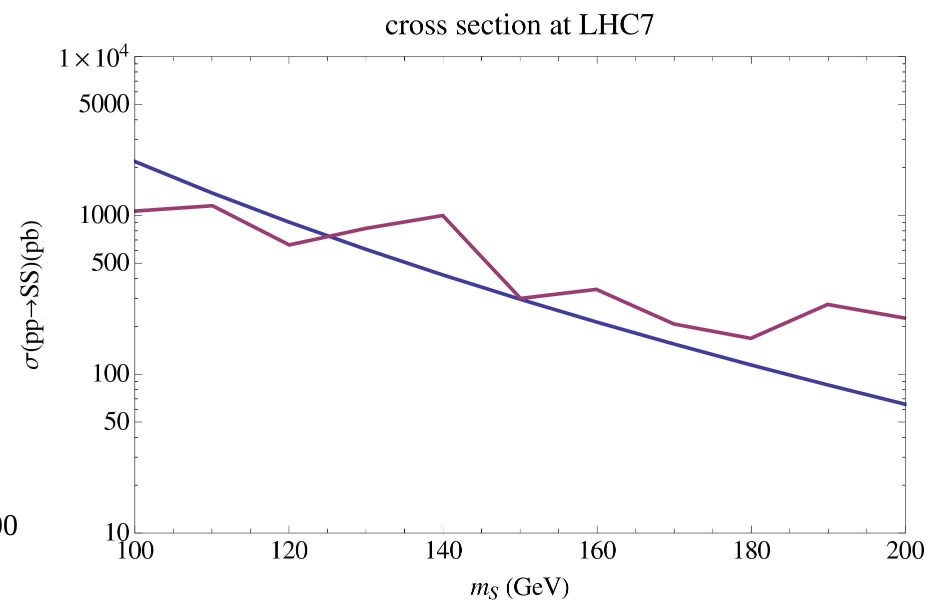
(work with G. Kribs and A. Martin)

Signal: a pair of narrow jj resonances of same mass *(0709.2378)*



CDF and D0 have not searched (yet?) for this important final state ...





plot by Adam Martin

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

Dark matter at the LHC

Standard model must be extended in order to include dark matter.

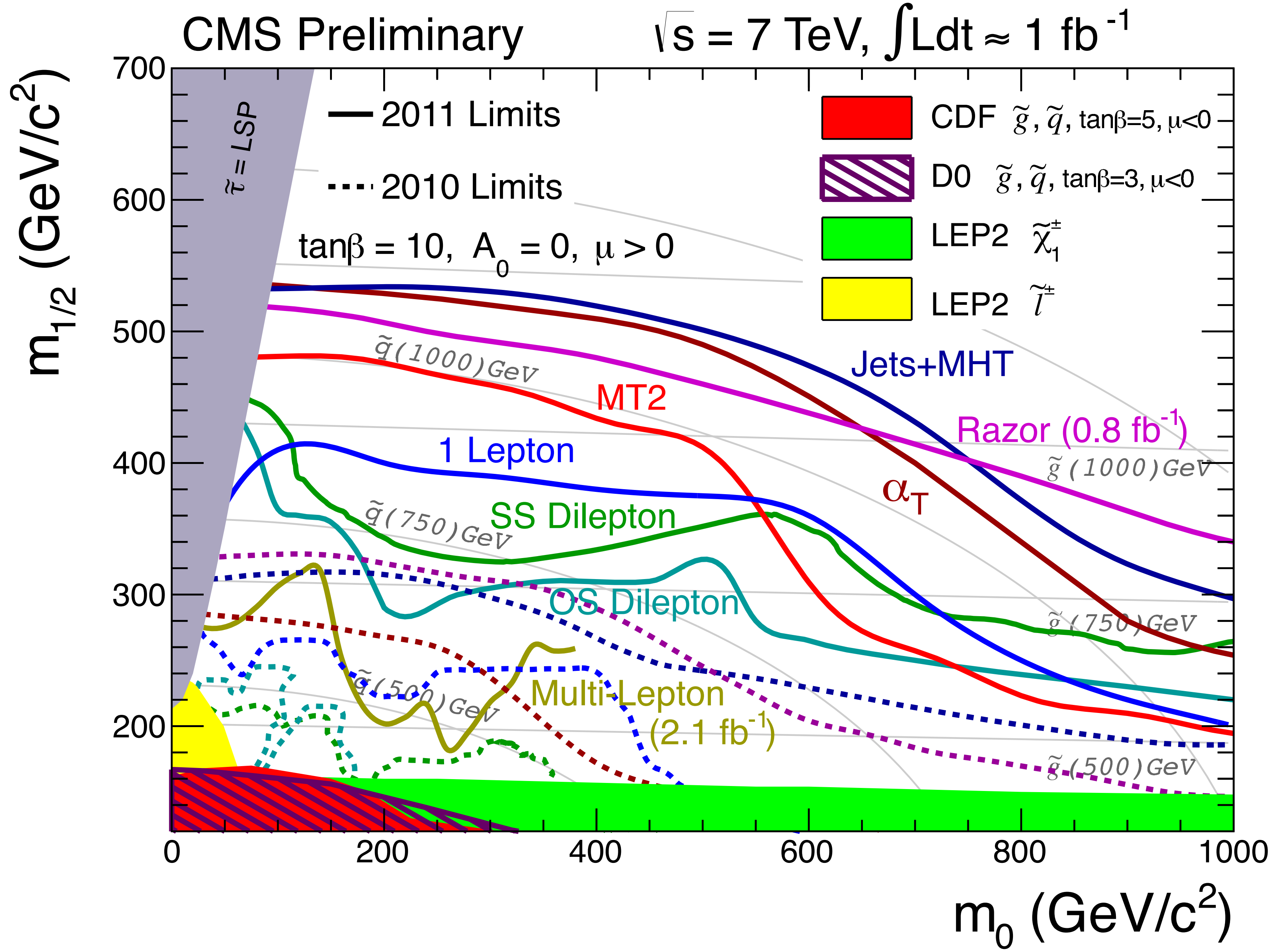
Stability of dark matter must be ensured by some symmetry.
Simplest possibility: a new discrete symmetry.

Examples:

- **Supersymmetry with R parity**
- **Universal extra dimensions (KK parity)**
- **Little Higgs models with T parity**

At the LHC (and the Tevatron): pair production of colored odd particles, followed by cascade decays through lighter odd particles, until a pair of dark matter candidates escapes the detector.

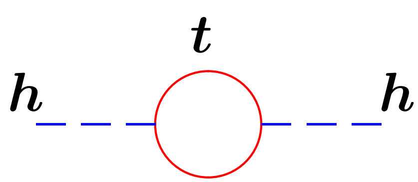
$\Rightarrow$ **Generic signal: missing E_T + jets + leptons**

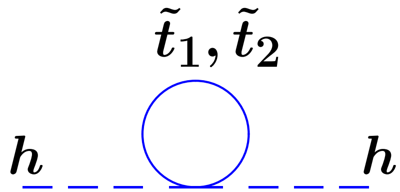

CMS Preliminary
$\sqrt{s}$ = 7 TeV, $\int$Ldt ≈ 1 fb^{-1}
2011 Limits
2010 Limits
tanβ = 10, A_0 = 0, μ > 0
$\tilde{\tau}$ = LSP
CDF $\tilde{g}, \tilde{q}$, tanβ=5, μ<0
D0 $\tilde{g}, \tilde{q}$, tanβ=3, μ<0
LEP2 $\tilde{\chi}_1^{\pm}$
LEP2 $\tilde{l}^{\pm}$
Jets+MHT
Razor (0.8 fb^{-1})
α_T
MT2
1 Lepton
SS Dilepton
OS Dilepton
Multi-Lepton
(2.1 fb^{-1})
$\tilde{q}$(1000)GeV
$\tilde{g}$(1000)GeV
$\tilde{q}$(750)GeV
$\tilde{g}$(750)GeV
$\tilde{q}$(500)GeV
$\tilde{g}$(500)GeV
$m_{1/2}$ (GeV/c^2)
m_0 (GeV/c^2)

Minimal Supersymmetric Standard Model

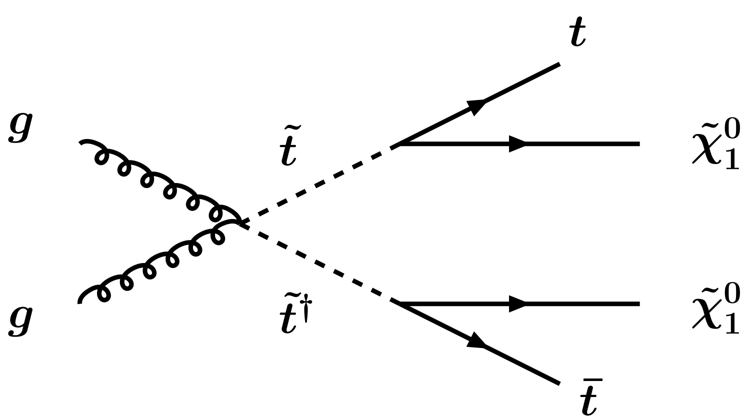
Many new particles (33), many new parameters (105)
$\rightarrow$ many interesting signatures.

Quadratic divergences in the Higgs self-energy due loops with SM particles are exactly cancelled by those due to loops with superpartners: requires mass of $\tilde{t}$ (and probably of $\tilde{g}$) to be near the electroweak scale.



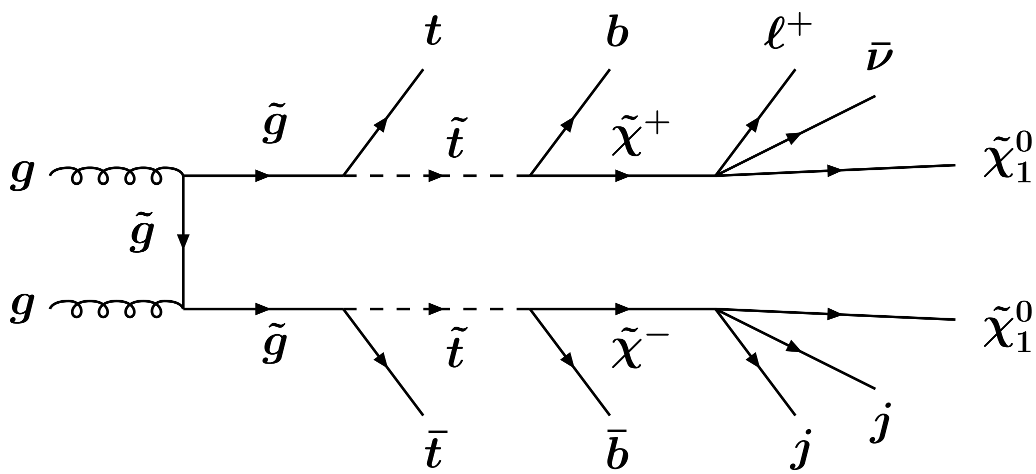


Convincing test of MSSM: $\tilde{t}\tilde{t}^{\dagger}$ production:

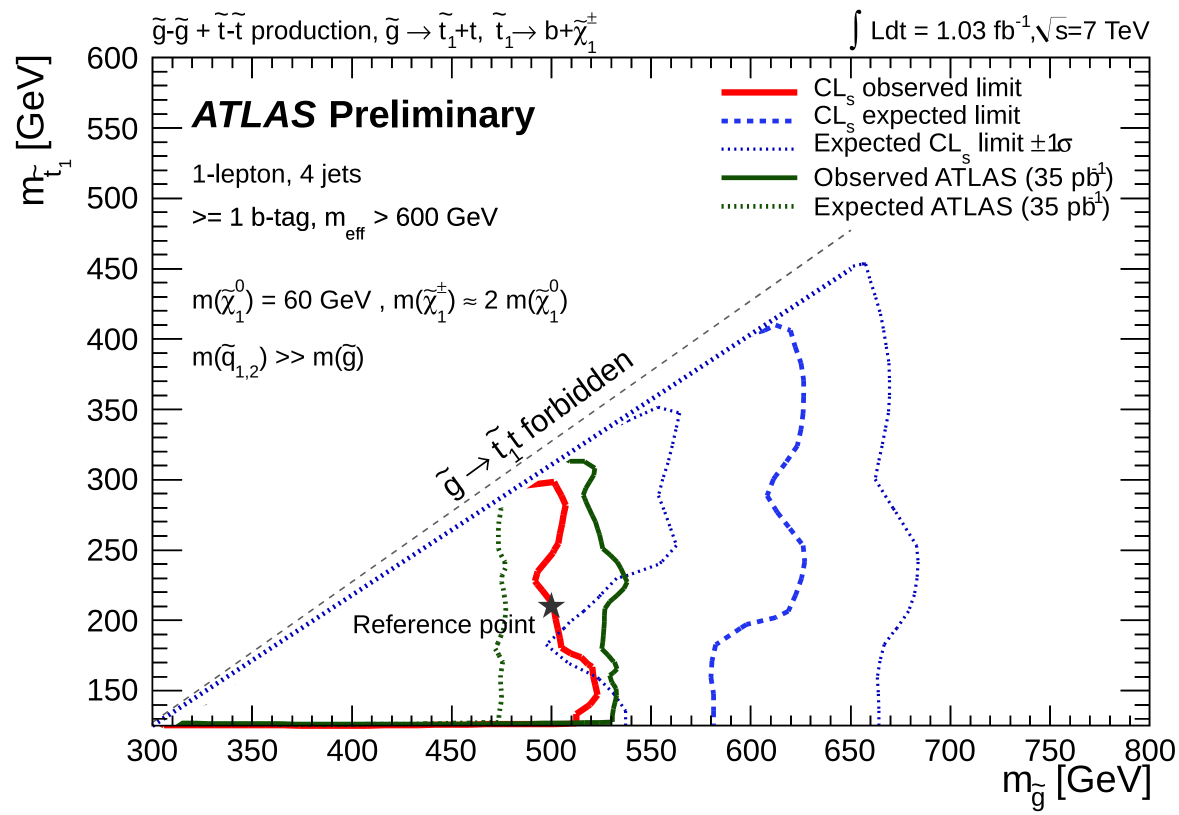


small rate,

large background.



- **Exactly one electron ($p_T > 25$ GeV) or muon ($p_T > 20$ GeV).**
- **≥ 4 jets with $p_T > 50$ GeV, with ≥ 1 of them b-tagged.**
- **missing $E_T > 80$ GeV.**

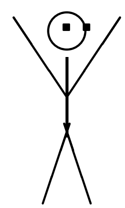


Energy

? **???????????????????????**

~ 2 TeV ?

Energy frontier – New Phenomena



Gauge and flavor sectors of the

Standard Model

~ 200 GeV

very weakly interacting particles??? (Intensity frontier)

- **Probing the unknown ...**

CMS and ATLAS are exploring physics at distances of $\sim \mathbf{10^{-19}}$*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".**

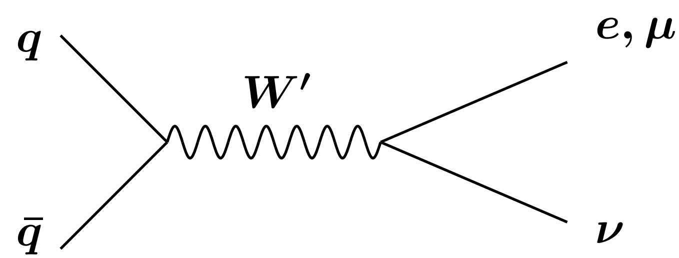
Search for two-body resonances

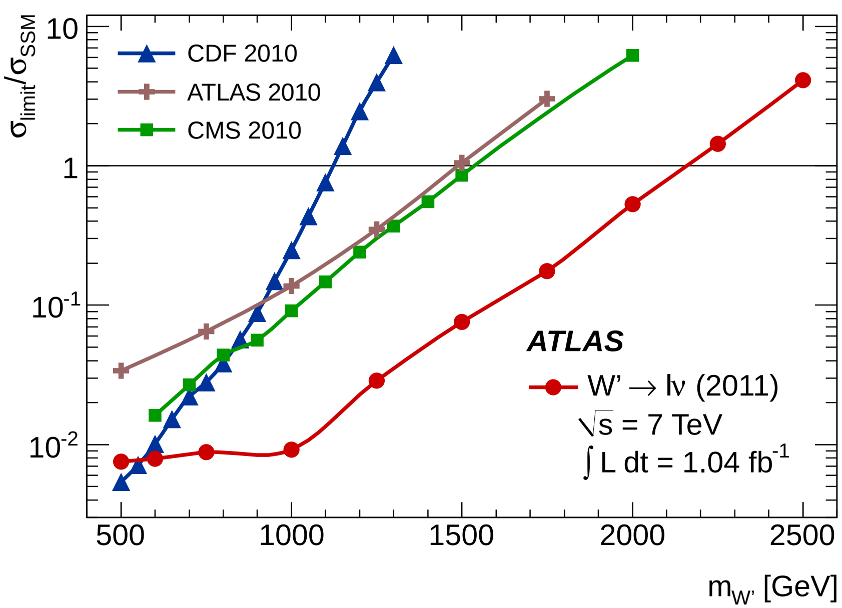
Try all combinations of two objects: jj, $\mu\mu$, ee, $\gamma\gamma$, $t\bar{t}$, tb, $\tau\mu$, ...

Avoid simplifying assumptions such as lepton universality or gauge coupling unification ...

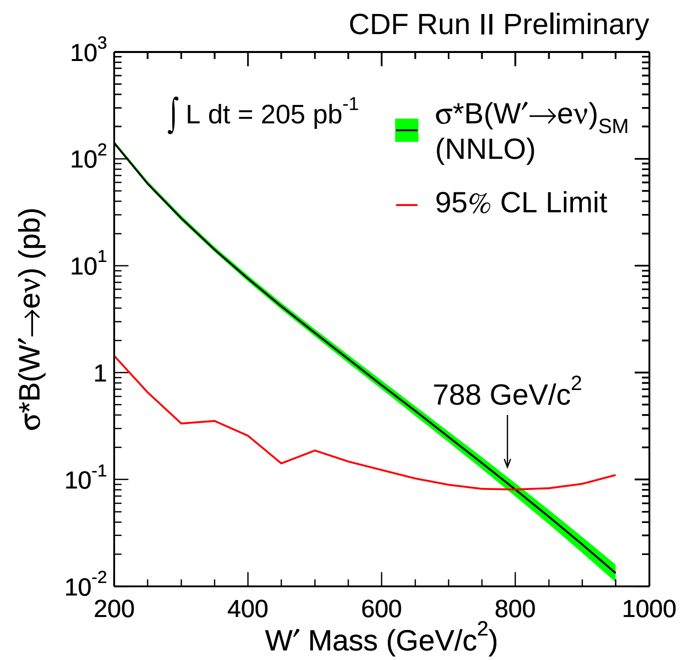
Example:

search for a W' boson





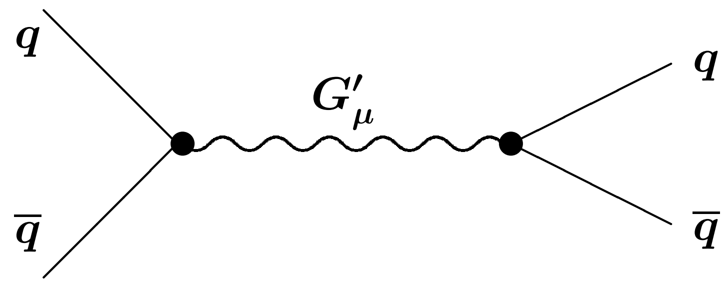
arXiv:1108.1316

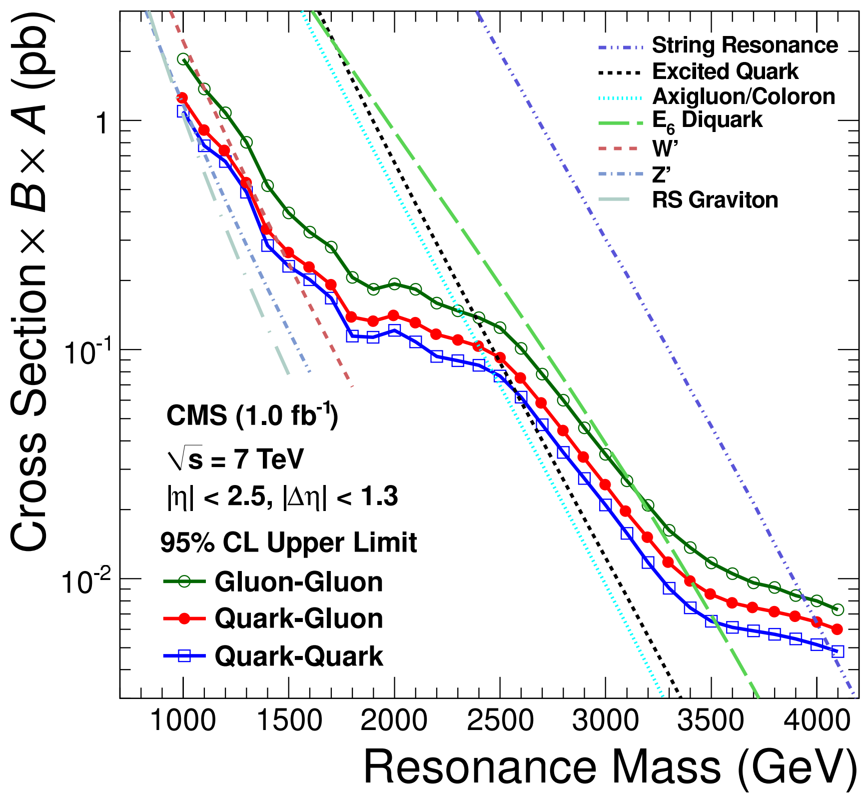


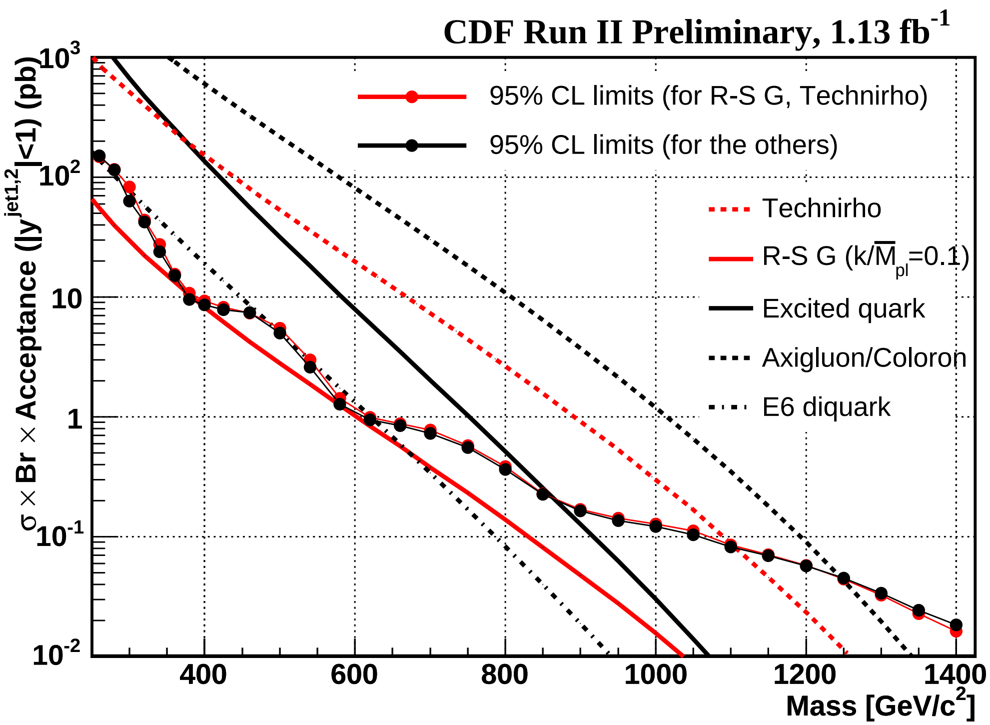
D0 & CDF should update searches with 10 fb^{-1} (~ 50 times more data for $M_{W'} < 500$ GeV)

$\rightarrow$ test of various models, e.g. $SU(2) \times SU(2)$.

Dijet resonance searches







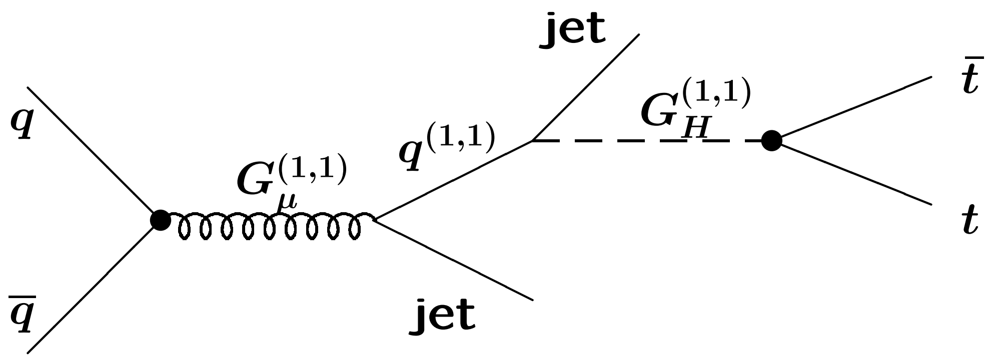
CDF (and D0) should update jj search with 10 fb^{-1} (~ 10 times more data), extend the search below $M_{jj} = 200$ GeV;

Search for resonances + X

E.g., 2 universal extra dimensions:

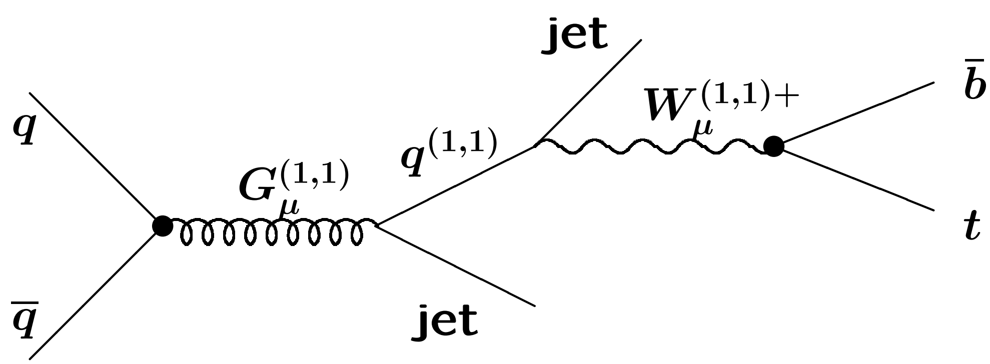
s-channel production of a KK gluon followed by a cascade decay

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



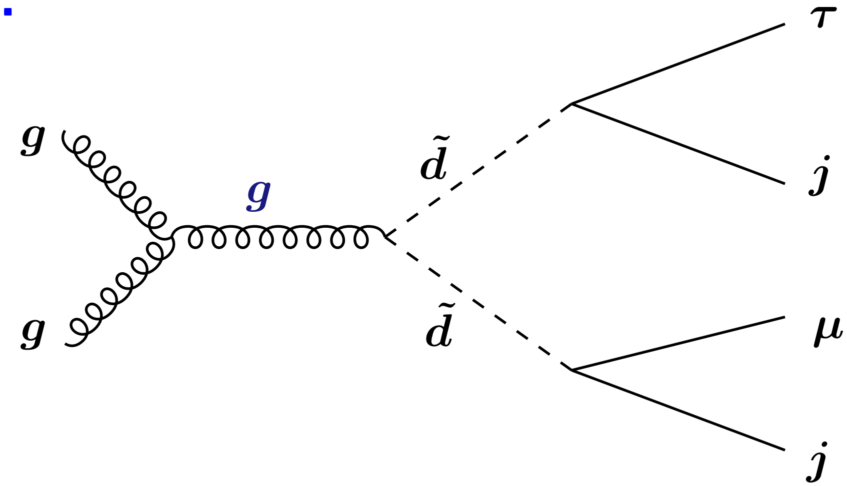
(hep-ph/0601186)

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

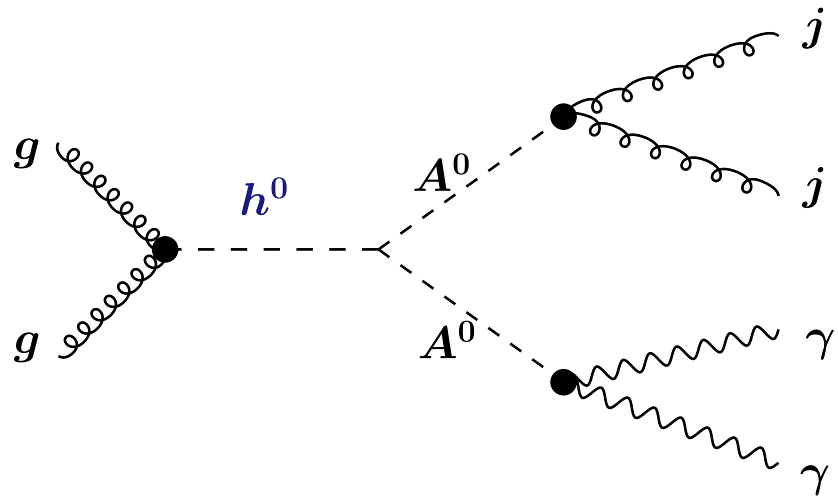


Search for pairs of resonances

E.g., leptoquarks:



E.g., nonstandard Higgs decays:

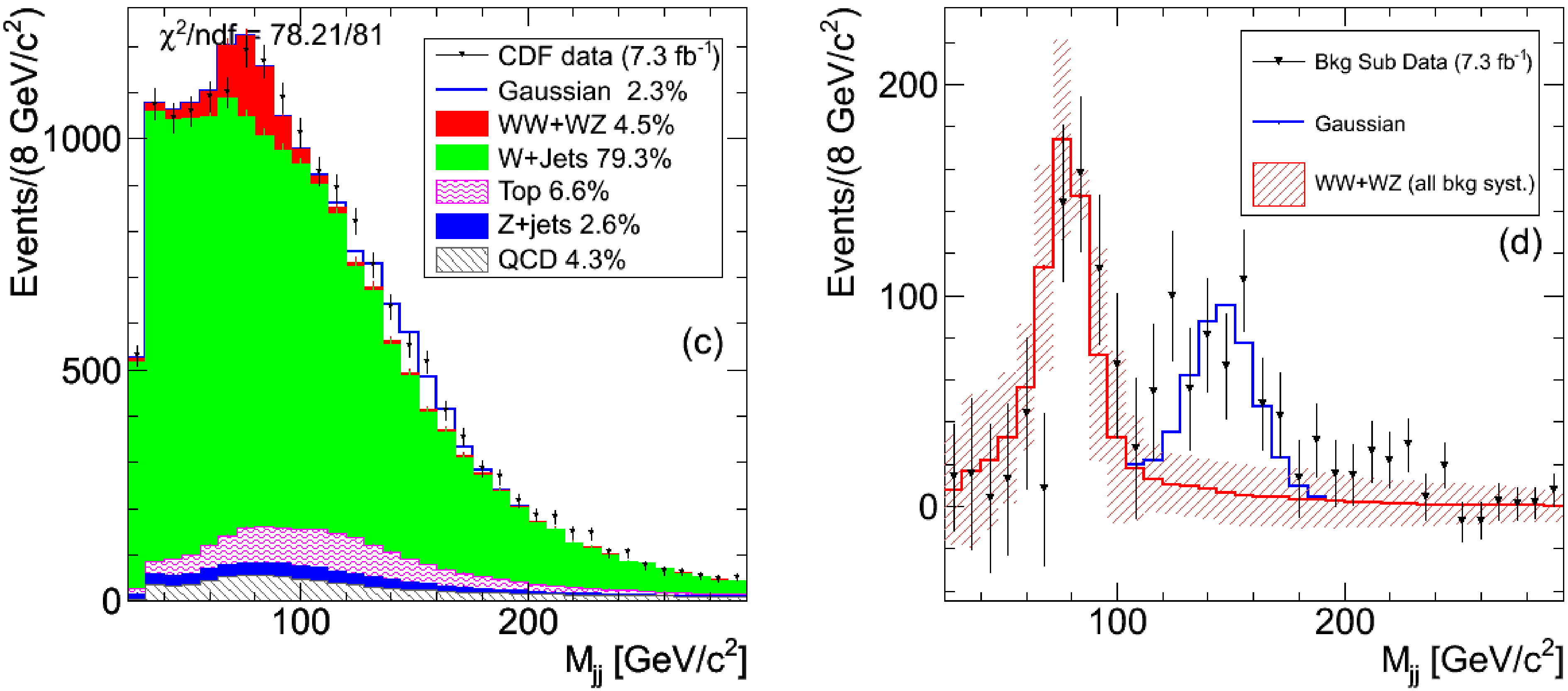


Wjj deviation from the SM at CDF

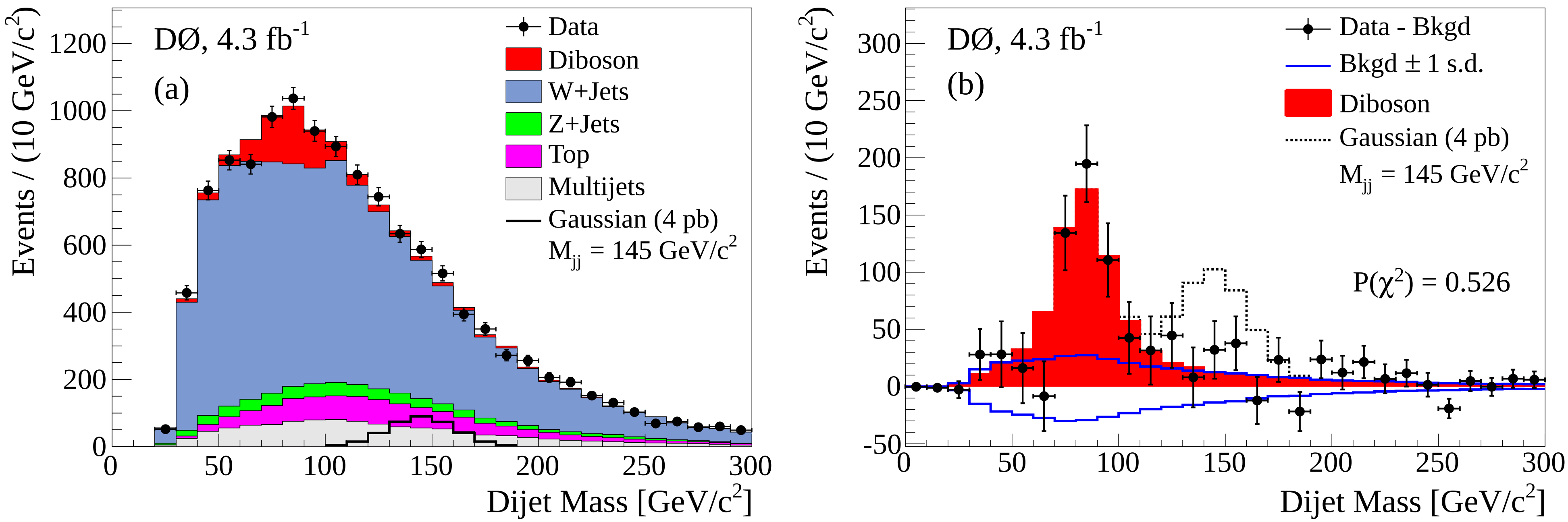
$W + jj$ final state studied by CDF:

unexpected peak in M_{jj} distribution at ~ 147 GeV (4.1σ excess)

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



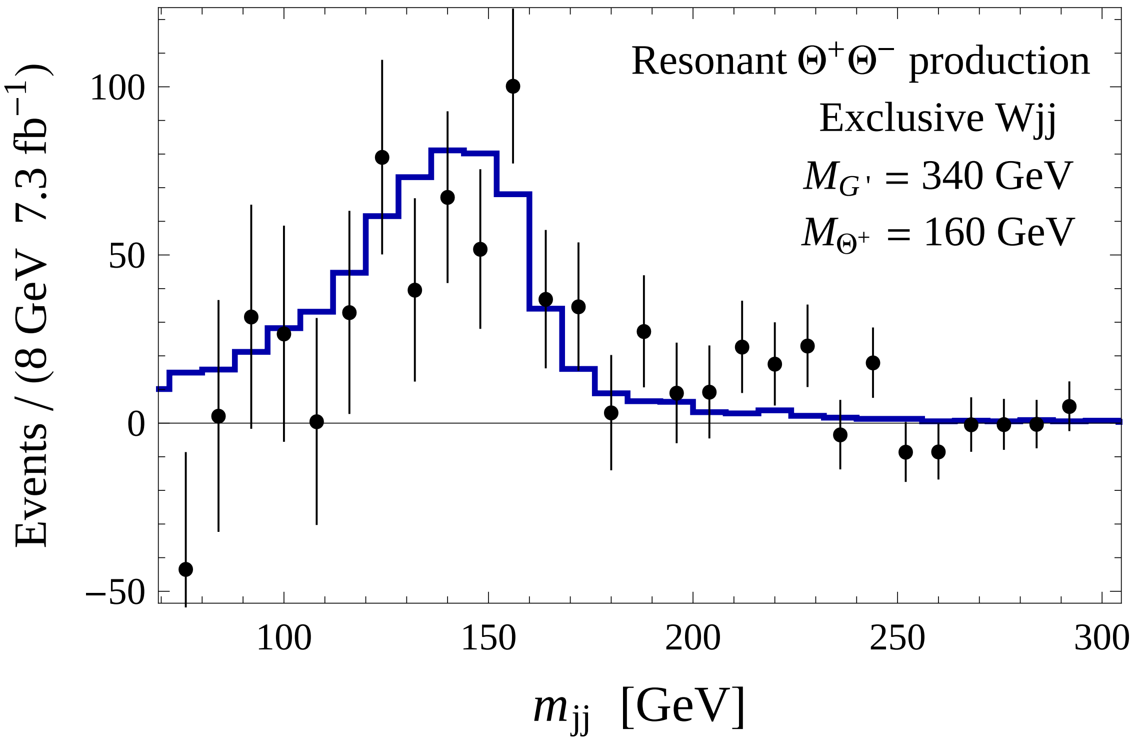
D0 Wjj measurement – 2.5σ tension with CDF result



- Same kinematic cuts as CDF
- Different treatment of systematics
- Inclusion of out-of-cone corrections (equivalent with lowering the p_T cut for jets in CDF, which reduces $S/\sqrt{B}$)
- More freedom in normalizations of the backgrounds?
  (*e.g.*, $W \to e\nu$ versus $W \to \mu\nu$)

Invariant mass distribution for the two leading jets from the CDF Wjj data, with all SM background subtracted:

Warning – plot made by theorists



far from a Gaussian; consistent with a real particle decaying to jj (QCD radiation distorts the shape).

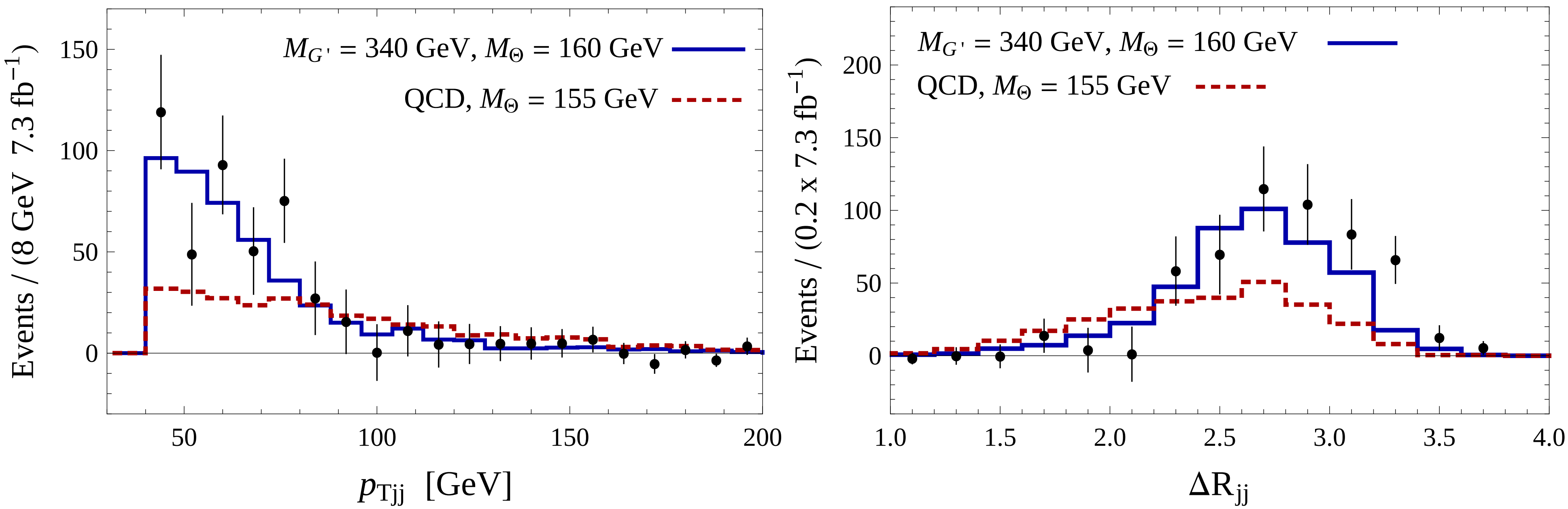
solid line: simulation (at LO) of a $G' \to \Theta\Theta \to (Wbb)(jj)$ signal
$M_\Theta = 160$ GeV, $B(G_H \to W^+ b\bar{b}) = 20\%$ (from 1104.2893)

CDF and D0 should compare data with particle signals (not with a Gaussian).

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

Warning – plots made by theorists:



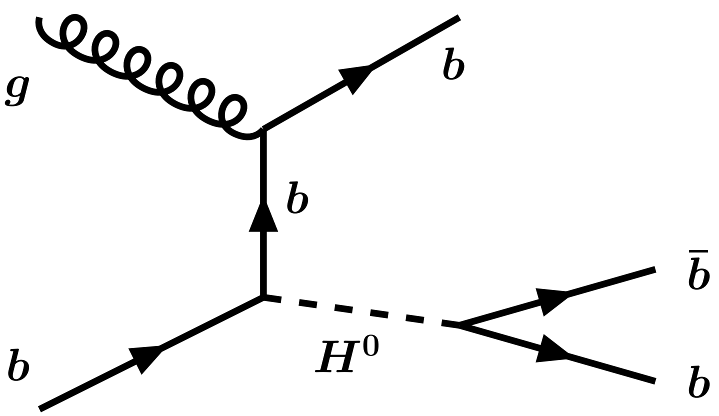
Blue lines: $G' \to \Theta\Theta \to (Wbb)(jj)$ *(work with Gordan Krnjaic 1104.2893)*

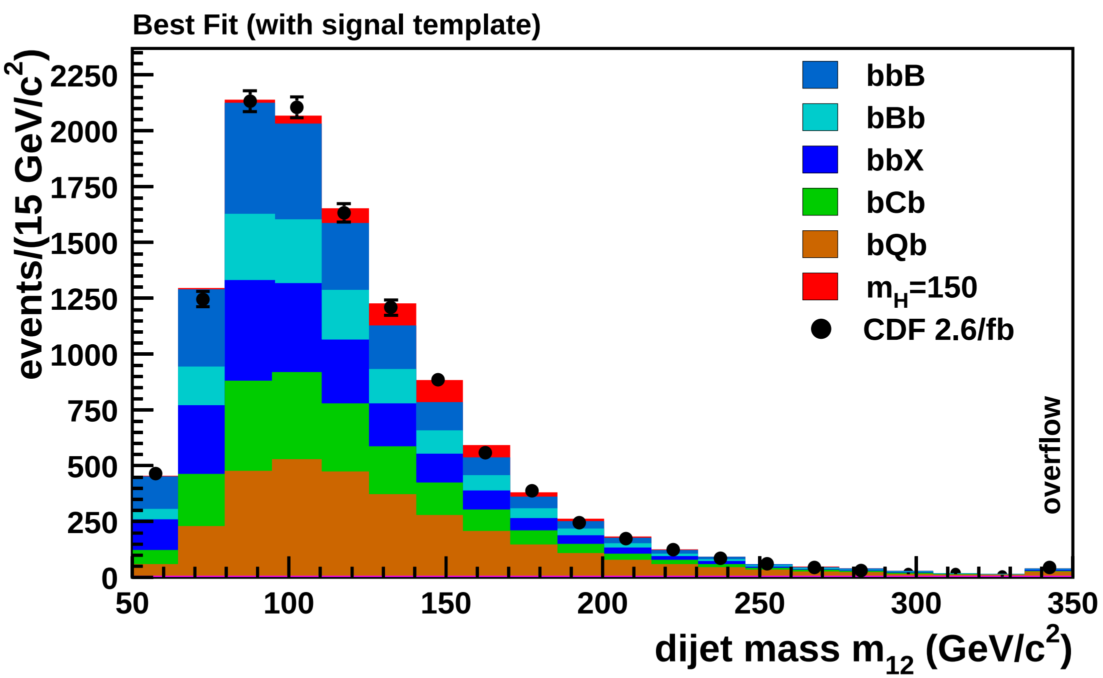
Deviations from the SM are consistent with a new particle of mass ~ 160 GeV.

Various tests that remain to be done related to the Wjj excess:

- increase the jet p_T cut (signal should decrease slower than backgrounds)
- search for $\gamma + jj$ (test of the leptophobic Z' explanation)
- search for a pair of jj resonances at ~ 160 GeV
  (test of resonant production of scalar pairs)
- search for jj resonances in the 300 - 400 GeV range
  (current limits from CDF with 1 fb^{-1})
- search for jj resonances in the 150 - 170 GeV
  (current limits from UA1 with 10 pb^{-1})
- CMS and ATLAS: Wjj searches with ~ 10 fb^{-1}
- ....

CDF search for $3b$ signal predicted in the MSSM at large $\tan\beta$: 1106.4782



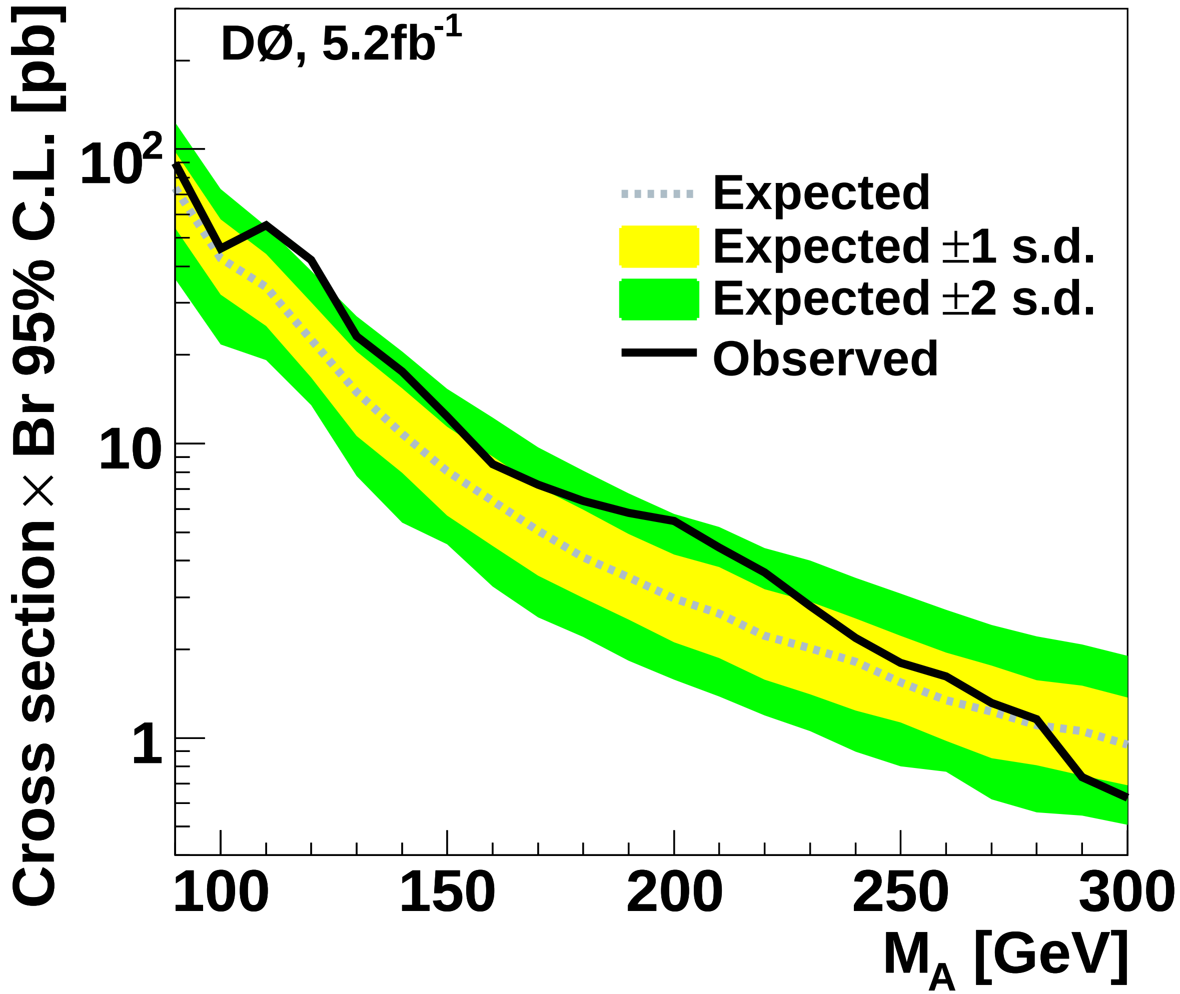


Excess of events with $m_{12} \approx 130 - 160$ GeV (consistent with $M_H \approx 150$ GeV).

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.

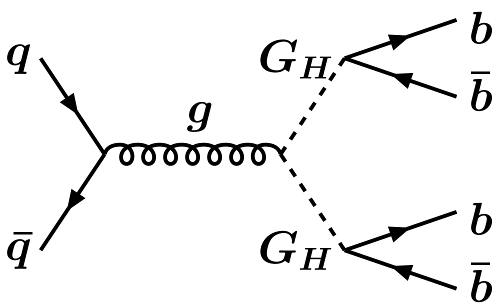
D0 search in the $3b$ channel with 5.2 fb^{-1} is optimized for the MSSM Higgs bosons through the use of a likelihood discriminant $\Rightarrow$ may not apply to a $G_H G_H \to bbb(b)$ signal.

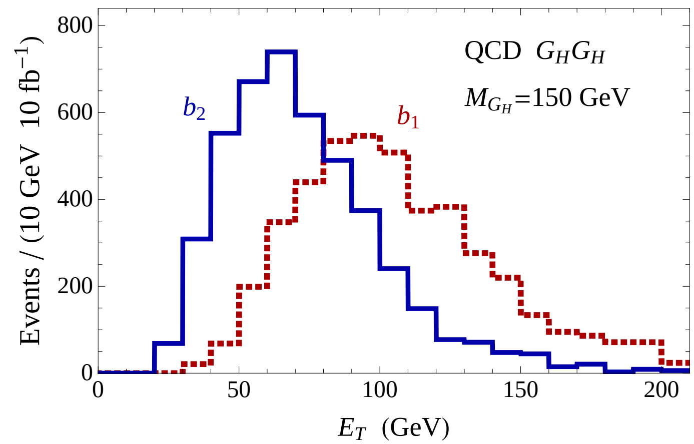
.

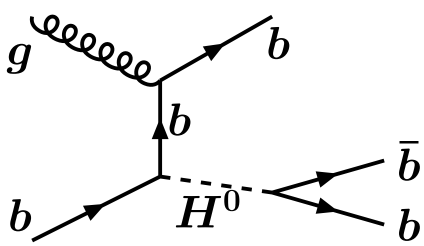


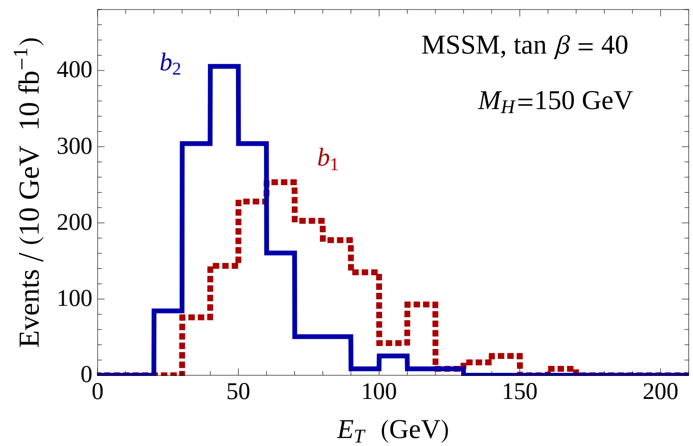
Use kinematic distributions to differentiate between models

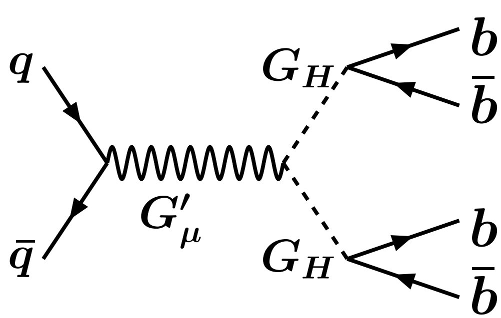
Transverse energy (E_T) distributions of the two leading b-jets:

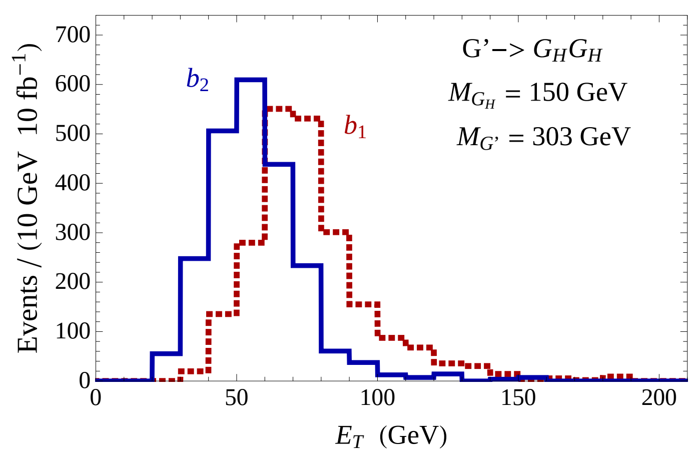












CDF near-future results/updates

- *Some new physics searches (monojets, DM, delayed photons, ...)*
- *Search for the Higgs boson (updates of all channels)*
- *Diboson measurements*
- *Updated non-SM results on bbb final state*
- *Measurement of* M_W *with* ~ 20 *MeV precision*
- *Top quark properties:* *single top production and* V_{tb}
  $t-\bar{t}$ *asymmetry (currently,* $> 3.4\sigma$ *away from SM) ;*
  updated measurements of m_t, $\sigma_{t\bar{t}}$
  measurement of polarization/spin correlation in top decays
- $B \to \mu\mu$ *search*
- *Measurements of:* $B \to K^*\mu\mu$ *angular distributions;*
  B_s *mixing phase and* $\Delta\Gamma_s$ *using* $J/\psi\Phi$
  $\Delta\Gamma_s$ *using* $B_s \to D_s D_s$
  BR and CP-violating asymmetries of $B \to hh$ *decays*
- *Production and decay of c quarks:*
  $A_{CP}(D^0)$ — *test of* 3.5σ *evidence from LHCb ;*
  3D measurement of Y(nS) polarization and production x-section
  Measurement of CP violation in $D \to K_s\pi\pi$ *decays*
  Low-p_t *charm production cross-section*
- *High-*p_T *QCD:* $Z+j$, $Z+b$, $W+c$, $\gamma+j$, $\gamma+b$, $\gamma\gamma$ *production*
  exclusive di-photon production
  measurements of inclusive distributions at $\sqrt{s} = 300$ *and 900 GeV*

D0 plans

- *Higgs*

Searches in all channels
Measurements of W+jets, W+b-jets, $t\bar{t}$ cross sections, di-boson production, etc.

- *Top quark*

Precision measurement of top quark mass with below 1 GeV precision
Precision measurement of top/anti-top quarks mass difference
Measurements of top quark production properties, including cross sections
Measurements of top quark decay properties
Measurements of s- and t-channels single top quark production

- *Electroweak*

W boson mass measurement with ~ 20 *MeV precision*
Production and decay properties of di-bosons: $WW, WZ, ZZ, W\gamma, Z\gamma$, *etc.*
Precision measurement of $\sin\theta_W$

- *B physics*

Studies of di-muon production asymmetry and CP violation (3.9σ away from SM)
Measurements of b-baryons and b-mesons production, properties and lifetimes

- *QCD*

Precision measurements of single, double and triple jets cross sections
Precision measurement of angular correlations in jets production
Extraction of α_s *and PDFs*

- *New Phenomena*

Model independent search for new physics
Supersymmetry searches, including MSSM Higgs

- *Detectors performance over 10 years and 10 fb-1 of data*

Synergy between "frontiers" (energy, intensity, cosmic)

Neutrino masses require the coupling of ν's to whatever breaks the electroweak symmetry (Higgs doublet in the SM).

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

Good agreement with the standard model predictions, so far, with a few possible exceptions: Wjj (CDF), like-sign $\mu\mu$ asymmetry (D0), $A_{\rm FB}^{t\bar{t}}$, ...

Great push forward by CMS and ATLAS.
Several important searches remain to be done by D0 and CDF where LHC has too large backgrounds.

Unitarity of the longitudinal WW scattering requires a Higgs boson or something else below the TeV scale!

New particles with masses in the 100 GeV – 5 TeV may exist (including exotic ones: color-octet scalars, gluon-prime bosons, W' bosons, non-chiral fermions, ...)

Discovering such objects at the LHC, Tevatron, or future colliders would point to new symmetries or deeper organizing principles.