Search for Fourth Family Quarks at ATLAS

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Flavour in the era of LHC workshop
Oct 9-11, 2006, CERN

Motivation: Yukawa Couplings in SM

- Masses of fermions introduced by couplings to Higgs field:

$$m_f = g_f \cdot \eta \qquad (\eta = \langle H \rangle \approx 245 \text{ GeV})$$

- Couplings vary by orders of magnitude:
  - Even among same type fermions:

$$g_t / g_u \approx 35000 \div 175000$$

$$g_b / g_d \approx 300 \div 1500 \qquad g_\tau / g_e \approx 3500$$

  - Or within 3rd family:

$$g_t / g_b \approx 40 \quad g_t / g_\tau \approx 100 \qquad g_t / g_{\nu\tau} > 10000$$

- Three-family case not particularly natural.

See talk by S. Sultansoy at Feb’06 FlavLHC.

Flavor Democracy

- Before spontaneous symmetry breaking, all fermions are massless. Fermions with same quantum numbers are indistinguishable.
- No reason why Yukawa couplings for fermions of a given type should be different.

$$a_{ij}^{d} \cong a^{d}, \quad a_{ij}^{u} \cong a^{u}, \quad a_{ij}^{l} \cong a^{l}, \quad a_{ij}^{\nu} \cong a^{\nu}.$$

=> For each type of fermion (f = u, d, l, ν), (n-1) massless particles and a single massive particle with $m = n \cdot a^{f} \cdot \eta / \sqrt{2}$.

Flavor Democracy II

- With a single Higgs doublet responsible for all the masses, assume couplings for different types of fermions are comparable to each other and lies somewhere between the other couplings of EW unification:

$$a^d \approx a^u \approx a^l \approx a^\nu \approx a$$

$$e = g_W \sin\theta_W \; < \; a/\sqrt{2} \; < \; g_Z = g_W/\cos\theta_W$$

- With these assumptions, flavor democracy predicts a fourth family with quasi-degenerate up-type u_4 and down-type d_4 quarks in the mass range ~300 to ~700 GeV (Ciftci, Ciftci, Sultansoy, PRD 72, 053006, 2005). This range is consistent with partial-wave unitarity at high energies.

Event Generation

- 12k signal events each generated for three choices of mass 250, 500, 750 GeV. (CompHEP v4.4.3)

$$pp \to d_4 \bar{d}_4 \to W^+ W^- jj \quad , \quad j = u, c$$

- Assume that mixing is predominantly to light (1st & 2nd) generations. Taking into account the current limits on the mixing parameters:

$$|V_{ud_4}| < 0.004 \qquad |V_{cd_4}| < 0.044 \qquad |V_{u_4 d}| < 0.08 \qquad |V_{u_4 s}| < 0.11$$

A common mixing parameter of 0.001 is chosen for event generation (relative magnitudes not important).

M_{d4} (GeV)	250	500	750
Γ (MeV)	0.01	0.08	0.28
σ (pb)	99.8	2.59	0.25

Event Generation II

- SM background events generated with MadGraph (v3.95). For $|\eta_{jet}|<2.5$, $\Delta R_{jj}>0.4$, $P_T^{jet}>20GeV$, the cross-sections are:

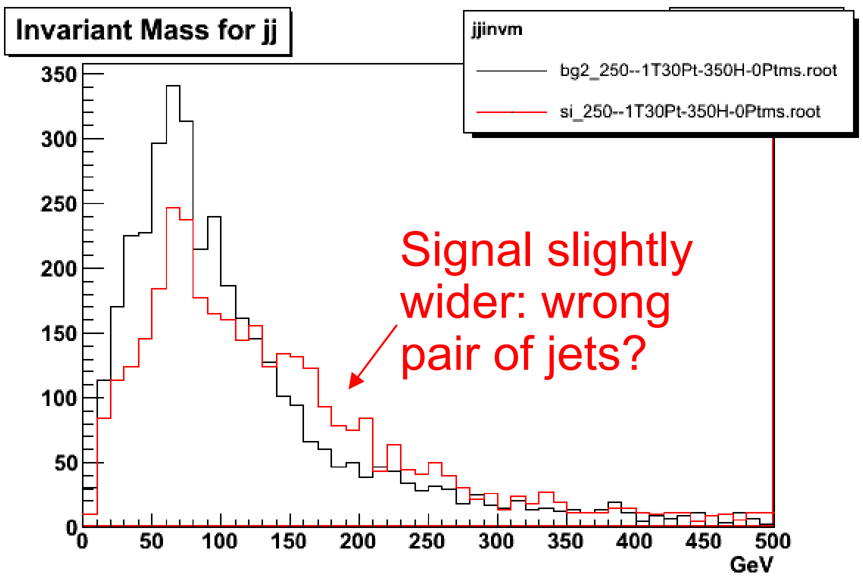
  pp > w+w-bb~ σ~612 pb

  pp > w+w-jj (j=u,d,s,c) σ~24 pb

  (Backgrounds with same-charge Ws negligible: σ<1pb.)
- All ntuples produced with ATLAS fast simulation ATLfast interfaced to Pythia in ATLAS framework, Athena release 11.0.4.1.
- CTEQ6L1 set of pdfs used.

Event Reconstruction

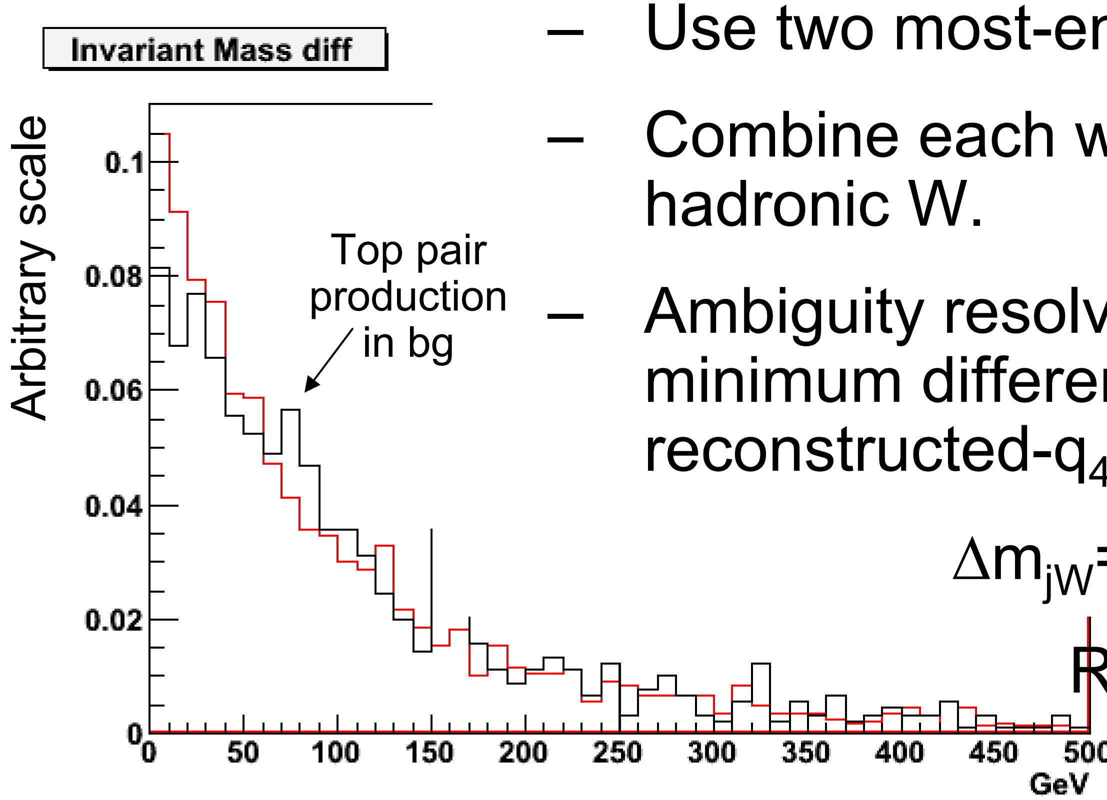
- Reconstruct one leptonic W:
  - Require exactly one lepton. P_T>15 GeV
  - Use missing E_T to reconstruct neutrino.



- Reconstruct one hadronic W:
  - Take 3rd and 4th most-energetic jets
  - Reject if m_{jj}>200GeV.

Event Reconstruction II

- Reconstruct q_4:
  - Use two most-energetic jets. P_T>30 GeV
  - Combine each with either leptonic or hadronic W.
  - Ambiguity resolved by requiring minimum difference between two reconstructed-q_4 masses:

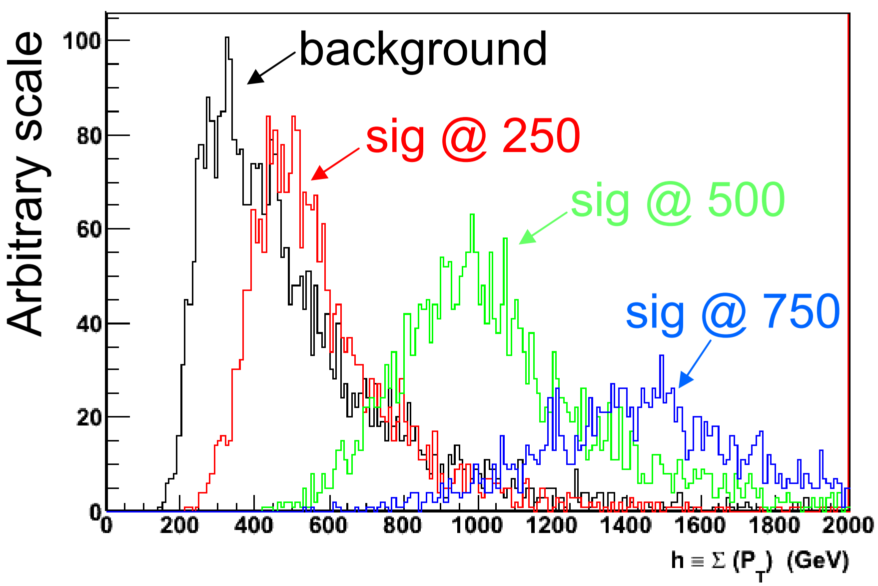


$$\Delta m_{jW} = m^1_{q4} - m^2_{q4}$$

Require Δm_{jW}<100GeV

Background Rejection

- ATLfastB results for jet-tagging used. Reject if either of hard jets is b-tagged. ~40% reduction in background, with insignificant loss in signal.
- Scalar sum of all transverse momenta:



$$H_T \equiv \sum_{jet=1}^{4} P_T^{jet} + P_T^{lept} + P_T^{miss}$$

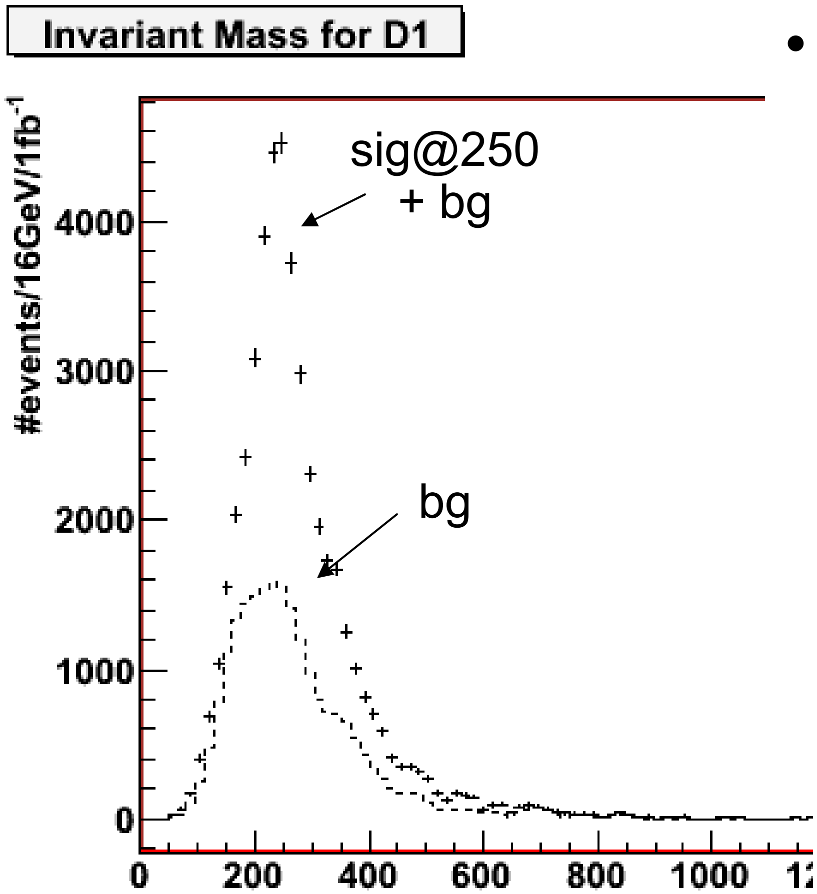
– Reject events if $H_T < H_T^{min}$ with H_T^{min} = 350 GeV chosen for 250GeV signal.

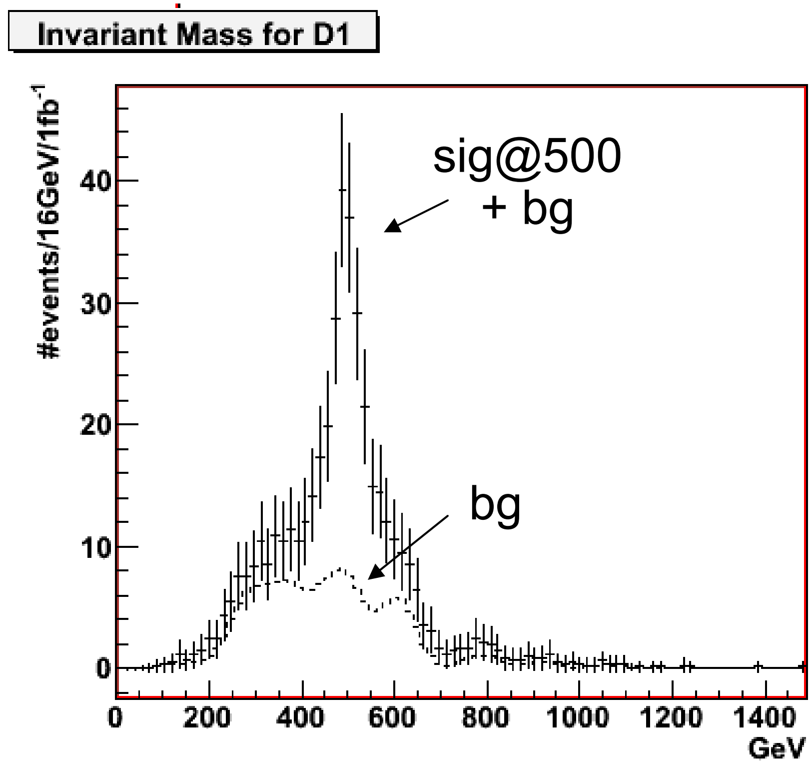
– H_T^{min} can be increased for scans of higher-mass signals.

Results

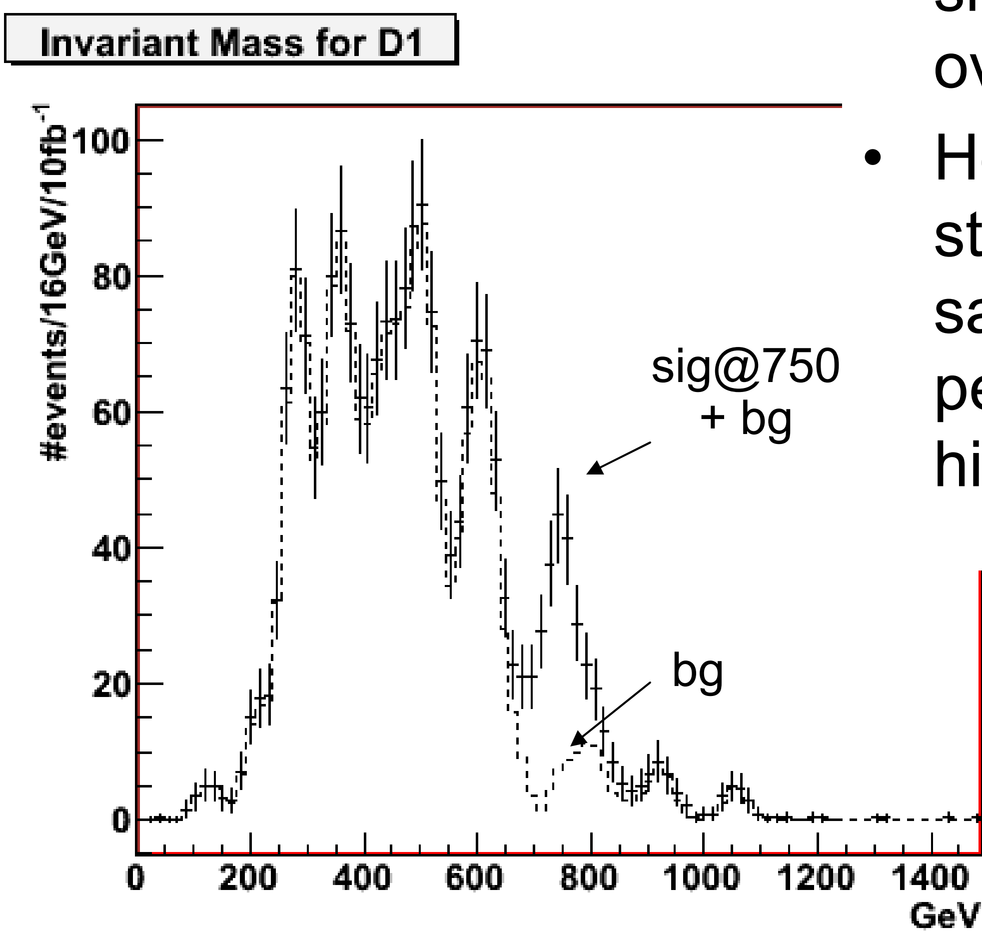
With 1fb^{-1} of data:

- For m_{q4}=250 GeV, a total of about 50k events expected with S/B≈1.25. (S/√B~175)
- For m_{q4}=500 GeV, a total of about 430 events expected with S/B≈1.38. (S/√B~18.5)





Results II



With 10fb^{-1} of data:

- For m_{q4}=750 GeV, a clear signal peak can be seen over the background.
- However, due to limited statistics of our WWbb sample, there are other peaks in the final histogram.

Conclusions

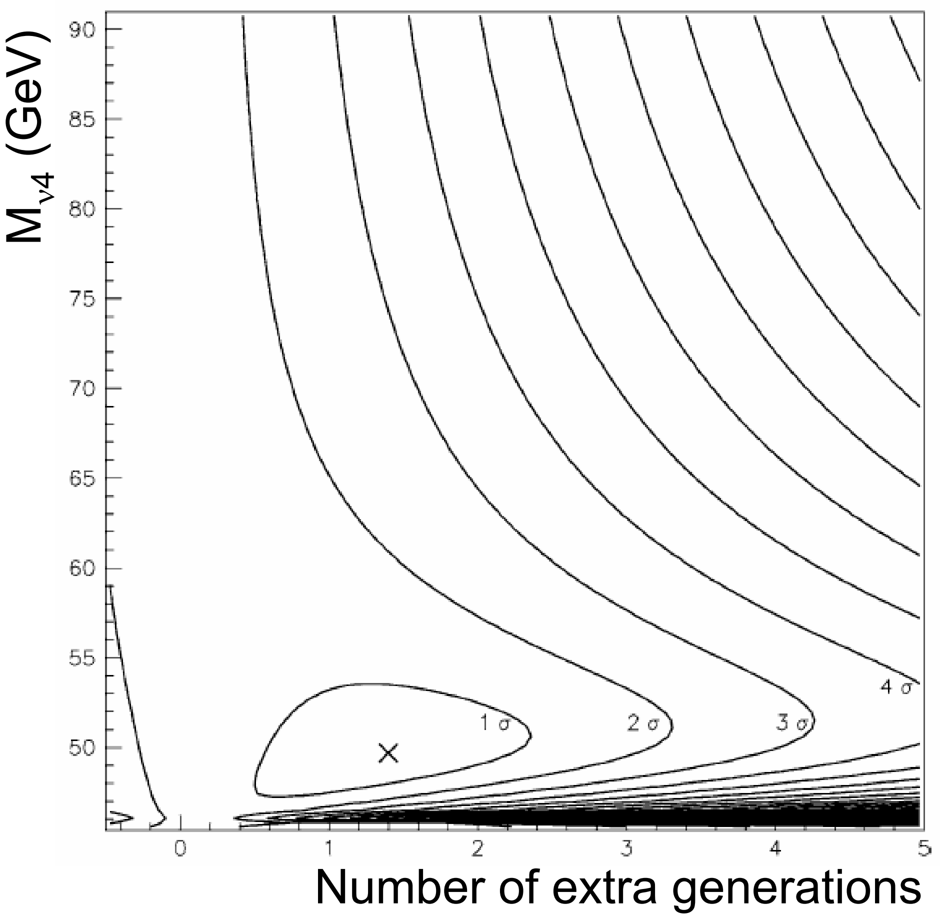
- 4^{th} family interactions modeled in CompHEP and signal and SM background Monte Carlo generated.
- First pass on the reconstruction and background rejection shows encouraging results for low-mid m_{q4}:
  - Top pair production will be the main background for 250 GeV, but even with very low integrated luminosity, thousands of events will be reconstructed, leaving way for further improvements.
  - For 500 GeV, the background is mostly flat continuum, but a clear peak observed with only $1fb^{-1}$ of data.
- For the higher m_{q4}, to draw concrete conclusions more MC statistics for the SM background will be needed.
- No optimizations yet performed on any of the selection criteria.

Future Steps

- In the short term:
  - Generate larger background samples with higher P_T hard jets.
  - Also look for background from W+W-jjj & W+W-bbj events.
  - Optimize selection criteria.
  - Explore smarter selection for hadronic W jets.
  - Determine minimum integrated luminosity necessary for 3σ and 5σ observation, as a function of q_4 mass.
- In the longer term:
  - Explore reconstruction for events with both Ws decaying leptonically.
  - Study how the signal would be distinguished from other models.

Backup Slides

Possible?



Precision EW data consistent with fourth generation (which has a heavy neutrino).

Example exclusion plot from Novikov, Okun, Rozanov, Vysotsky, PLB 529, 2002, for:

M_{d4} = 200 GeV
M_{u4} = 220 GeV
M_{e4} = 100 GeV

Selection Efficiencies (%)

	sig@250	WWjj	WWbb
Single lepton	34.5	30.9	36.3
4 jets	94.6	92.2	92.3
P_T^{lept}>15GeV	91.3	90.3	89.8
m_{jj}<200 GeV	75.7	79.3	83.5
Hard jets tag≠b P_T>30GeV	96.3	85.9	48.1
h>350GeV	95.0	67.9	64.9
Δm<100GeV	66.1	55.0	63.1