SEARCH FOR FOURTH GENERATION T’ QUARK AT THE TEVATRON

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On behalf of the CDF and D0 Collaborations
Presenting today

9 fb⁻¹ last week
Another Quark Generation?

- Not forbidden by EWK precision data
  - Mass order few hundred GeV
  - Small mass splitting preferred: $M(t') - M(b') < M(W)$
- Would have big effect on Higgs sector
  - Oblique corrections could drive mass up to $\sim 500$ GeV
- Could be lepton too if $m(\nu_4) > \sim 50$ GeV

For $b'$ search see L. Scodellaro
Sat. 15:20 track 10
Why not 4 generations?

- Z-width measurements from LEP
- Constraint
  - $M(\nu_4) > \frac{1}{2} M(Z)$
Why not 4 generations?

- **Generation Mixing**
  - CKM Matrix

- **Constraint**
  - Flavour physics measurements and unitarity triangle sets limits on 4\(^{\text{th}}\) generation models

- **BUT**
  - Mixing between 3\(^{\text{rd}}\) and 4\(^{\text{th}}\) generation only weakly constrained
Why not 4 generations?

- Electroweak Effects
- Constraints
  - \( S, T \) fits to SM constrain available phase-space for 4\(^{th}\) generation
- But
  - Possible with electroweak radiative corrections
  - Could even argue would agree better 😊

<table>
<thead>
<tr>
<th>parameter set</th>
<th>( m_{u_4} )</th>
<th>( m_{d_4} )</th>
<th>( m_H )</th>
<th>( \Delta S_{\text{tot}} )</th>
<th>( \Delta T_{\text{tot}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>310</td>
<td>260</td>
<td>115</td>
<td>0.15</td>
<td>0.19</td>
</tr>
<tr>
<td>(b)</td>
<td>320</td>
<td>260</td>
<td>200</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>(c)</td>
<td>330</td>
<td>260</td>
<td>300</td>
<td>0.21</td>
<td>0.22</td>
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<tr>
<td>(d)</td>
<td>400</td>
<td>350</td>
<td>115</td>
<td>0.15</td>
<td>0.19</td>
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<tr>
<td>(e)</td>
<td>400</td>
<td>340</td>
<td>200</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>(f)</td>
<td>400</td>
<td>325</td>
<td>300</td>
<td>0.21</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Looks like a Top... but not quite...

Assume SM production for limits

Tevatron
~85% qq
~15% gg

Also: Generic search for events in this final state in the tails of some distributions....
Our Search: Lepton + Jets + MET

Good compromise between BR and background rates
Event Selection

**Event Counts:**
- 1809 (3724) events
- 1002 (1677) electrons
- 807 (2047) muons

**Trigger:**
- on electron or muon
- CDF: new: muons from jets + MET trigger
- D0: some triggers with ≥1 jets too

**Missing Transverse Energy:**
- > 20 / 25 GeV

**4 jets (no b-tagging):**
- corrected $E_T > 20$ GeV
- D0: leading jet > 40 GeV

**1 isolated electron or muon $p_T > 20$ (25) GeV**

**Mis-measured muon removal**

**QCD Removal cuts**
Sample Composition

- Signal modelled as $g \rightarrow t't'b$:
  - 100% BR to $Wb$
  - Width < detector resolution

- Dominant backgrounds:
  - $t\bar{t}$
    - 100% BR to $Wb$
    - Constrained to NLO cross section
  - $W+jets$
    - Merged from $W+0…3p$ exclusive + $W+4p$ inclusive
  - QCD (1 jet fakes a lepton)
    - Shapes from jet-triggered data
    - Require limit on fraction of energy in EM calorimeter
    - Normalisation from fit with Missing $E_T$ cut relaxed
  - Other: single top, diboson, Drell-Yan, $Z+jets$
    - From MC

All MC samples are run through CDF detector simulation
Discriminating Variables

- Total transverse reconstructed energy ($H_T$)

\[ H_T = \sum_{jets} E_{T,jets} + E_{T,lepton} + E_T \]

$t'$ normalisation arbitrary
Discriminating Variables

- Reconstructed top mass ($M_{\text{reco}}$ CDF, $M_{\text{fit}}$ D0)
  - From the combination with the lowest $\chi^2$
    - e.g CDF

$$
\chi^2 = \sum_{i=l,4jets} \left( \frac{p_T^{i,\text{fit}} - p_T^{i,\text{meas}}}{\sigma_i} \right)^2 + \sum_{j=x,y} \left( \frac{p_{j}^{UE,\text{fit}} - p_{j}^{UE,\text{meas}}}{\sigma_j} \right)^2 + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{t\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b,jj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b,t\nu} - M_t)^2}{\Gamma_t^2}
$$

- $t'$ normalisation arbitrary
Discriminating Variables

- 
  \( t\bar{t} \) production
  \( m(t') = 300 \text{ GeV} \)

- 
  multijet background

- 
  W+jets
The Fit

- ‘3D’ fit: $H_T$ vs $M_{\text{reco}}$ vs $N_{\text{jet}}$ / good-bad $\chi^2$
  - New: separate into 4 and $\geq 5$ jets and into $\chi^2 < 8$ and $\chi^2 > 8$

- Binned Poisson Likelihood approach
  - Systematics represented as nuisance parameters
    - Remove by profiling
  - Obtain posterior in signal cross section
    - Using Bayes Theorem and uniform prior
The Fit

- 2D fit: $H_T$ vs $M_{\text{fit}}$
- Fit for background only
  - 3 parameter fit: ttbar, QCD and W-like (mostly $W+\text{jets}$)
- Fit for background + signal
  - 4 parameter fit: also $t't'\text{bar}$ (free)
- Likelihood ratio as test statistic
- Set limits using $C L_S$ method
  - $1 - C L_{S+B} / C L_B = 0.95 \rightarrow 95\% \ C L \ exclusion$
Systematics

- **CDF**
  - Three types
    - All Gaussian-constrained
  - Normalization uncertainties
    - Integrated luminosity, ID scale factors, background cross sections
  - Shape (+normalization) uncertainties
    - Jet energy scale, $Q^2$ scale, ISR/FSR
  - MC statistics
    - Handled using “Barlow-Beeston lite” method
    - Bins combined automatically to ensure accuracy

- **D0**
  - Profiling all systematics
    - Same code as used for Higgs exclusion
No signal model other than “something that is in the high $M_{\text{reco}}$, high $H_T$ region”

- Starting from highest $H_T$ and $M_{\text{reco}}$ bin
  - Get p-value of that bin
  - Extend by 1 bin in each dimension and repeat fit

- Largest excess
  - $M_{\text{reco}} > 250$ MeV/c$^2$, $H_T > 550$ MeV
  - 29 events, 18.03 expected
    - p-value 0.01

- Global p-value takes into account trials factor
  - Excess $\sim$2 sigma

P-value: Probability that the number of observed events in that range is compatible with the background only hypothesis

Alison Lister, ICHEP2010, 23rd July 2010
The Variables in Data
Limits

- Assume $\text{BR}(t' \rightarrow Wb) \approx 100\%$
- Assume strong SM production ($g \rightarrow t't'\bar{t}\bar{b}$)

Exclude $M(t') < 335 (296) \text{ GeV} @ 95\% \text{ CL at CDF (D0)}$
Conclusions

- Search for 4\textsuperscript{th} generation top-like quark
- No significant excess seen in high $H_T$, high $M_{\text{reco}}$
  - Largest excess order 2 sigma
    - Seen by both experiments
      - Not going away and not getting larger… most frustrating 😊
- Exclude 4\textsuperscript{th} generation $t'$ with 100\% BR to $Wq$ up to $M(t') < 335$ (296) GeV @ 95\% CL at CDF (D0)
Likelihood Functions

CDF Run 2 (4.6 fb$^{-1}$) - $t'$ Search Likelihoods - Preliminary

- $m(t') = 200$ GeV
- $m(t') = 220$ GeV
- $m(t') = 240$ GeV
- $m(t') = 260$ GeV
- $m(t') = 280$ GeV
- $m(t') = 300$ GeV
- $m(t') = 320$ GeV
- $m(t') = 340$ GeV
- $m(t') = 350$ GeV
- $m(t') = 380$ GeV
- $m(t') = 380$ GeV
- $m(t') = 400$ GeV
- $m(t') = 450$ GeV
- $m(t') = 500$ GeV

(CDF Run 2 (4.6 fb$^{-1}$) - $t'$ Search Likelihoods - Preliminary)
The Variables in Data

D0 Run II preliminary 4.3 fb⁻¹

CDF Run 2 (4.6 fb⁻¹) Preliminary

Events/25 GeV

H_T (GeV)

M_reco (GeV)

difference

Observed

tt
W+jets, EW
QCD

Events/25 GeV

Observed

tt
W+jets, EW
QCD
Previous Results

Limit: $M(t') > 256$ GeV/c$^2$
Limit: $M(t') > 284$ GeV/c$^2$
Limit: $M(t') > 311$ GeV/c$^2$

1118 events
Better QCD model
Better QCD removal cuts
New W+jets modelling