Experimental Constraints on 4th generation quark masses

- Work done with PQ Hung, arxiv:0711.4353 (PRD, 2008)

CDF -- PRD 76, 072006 (2007)

We present the results of a search for new particles that lead to a Z boson plus jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the Collider Detector at Fermilab (CDF II). A data sample with a luminosity of 1.06 fb^{-1} collected using Z boson decays to ee and $\mu\mu$ is used. We describe a completely data-based method to predict the dominant background from standard-model Z+jet events. This method can be similarly applied to other analyses requiring background predictions in multi-jet environments, as shown when validating the method by predicting the background from W+jets in $t\bar{t}$ production. No significant excess above the background prediction is observed, and a limit is set using a fourth generation quark model to quantify the acceptance. Assuming $BR(b' \to bZ) = 100\%$ and using a leading-order calculation of the b' cross section, b' quark masses below 268 GeV/c^2 are excluded at 95% confidence level.

- But…..
- B(b’ --> bZ) depends on $|V_{34}|^2$ and is a one-loop process
- B(b’ --> tW) depends on $|V_{34}|^2$ and is tree level, so for M(b’) > 255 GeV, will completely dominate. Even for smaller M(b’), the three-body decay might dominate the loop (note that the loop depends on the t’ mass)
- Thus the conditions listed in the abstract will never be met (for a sequential 4th generation). In addition, if the t’ is lighter, then b’ --> t’W* or t’*W will not have the V_{34} factor.

- This prompted an analysis of the experimental constraints, without such assumptions. For b' decays, the free parameters are the t' mass and V_{34}; for t' decays, the free parameters are the b' mass and V_{43}.

- What are plausible values of the CKM mixing angles? The analysis shouldn't depend on what a theorist says, but ….

- Suppose a Z_2 symmetry distinguishes the 4th family from the other three. Then, $V_{34} = V_{43} = 0$. But one expects all non-gauge symmetries to be broken by Planck scale effects, giving $V_{34} = V_{43} = (M_W/M_{Pl}) = 10^{-17}$. This gives typical decay lengths for b' and t' quarks of a few centimeters.
- Perhaps not likely, but certainly the possibility of VERY small mixing angles should be considered.

- In addition, CDF reported a lower bound on the t' mass of 258 GeV.
- This assumes that t' -> q + W
- If the b' mass is smaller than m(t')-m(W), this assumption is false. Even if it is larger, but less than that of the t', the 3-body decay will dominate if V_{43} is small.

- Thus, we re-examine the bounds, without assumptions. With only two free parameters in each case, the results can be easily presented.
- Since this work was in February, it is already outdated. Thus, the results should be considered illustrative.

- For simplicity, we ignore the heavy quark and W widths, and ignore virtual heavy quarks.   A better analysis would include these---see the poster of George Hou from ICHEP.
- The formulae, including the widths, are not difficult, and thus experimentalists are urged to include all of these effects.
- We begin with the t’ bounds. They depend on V_{43} and the b’ mass.

- CDF -- PRL 100, 161803 (2008)

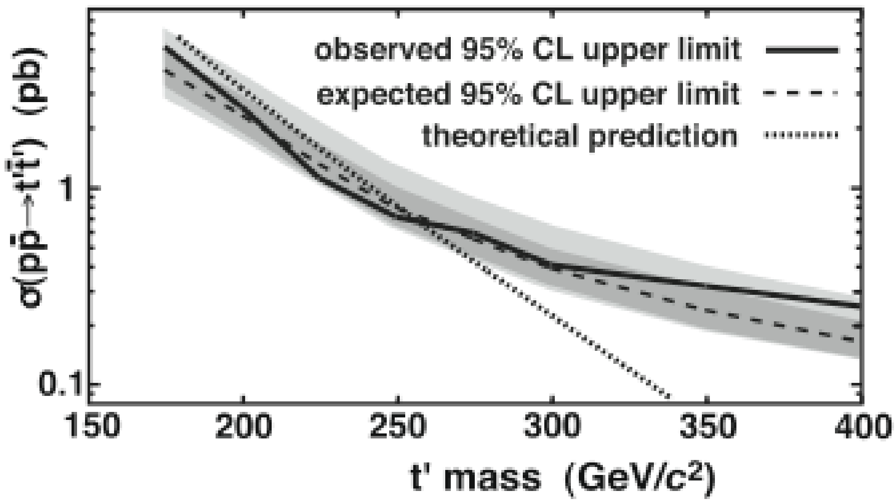
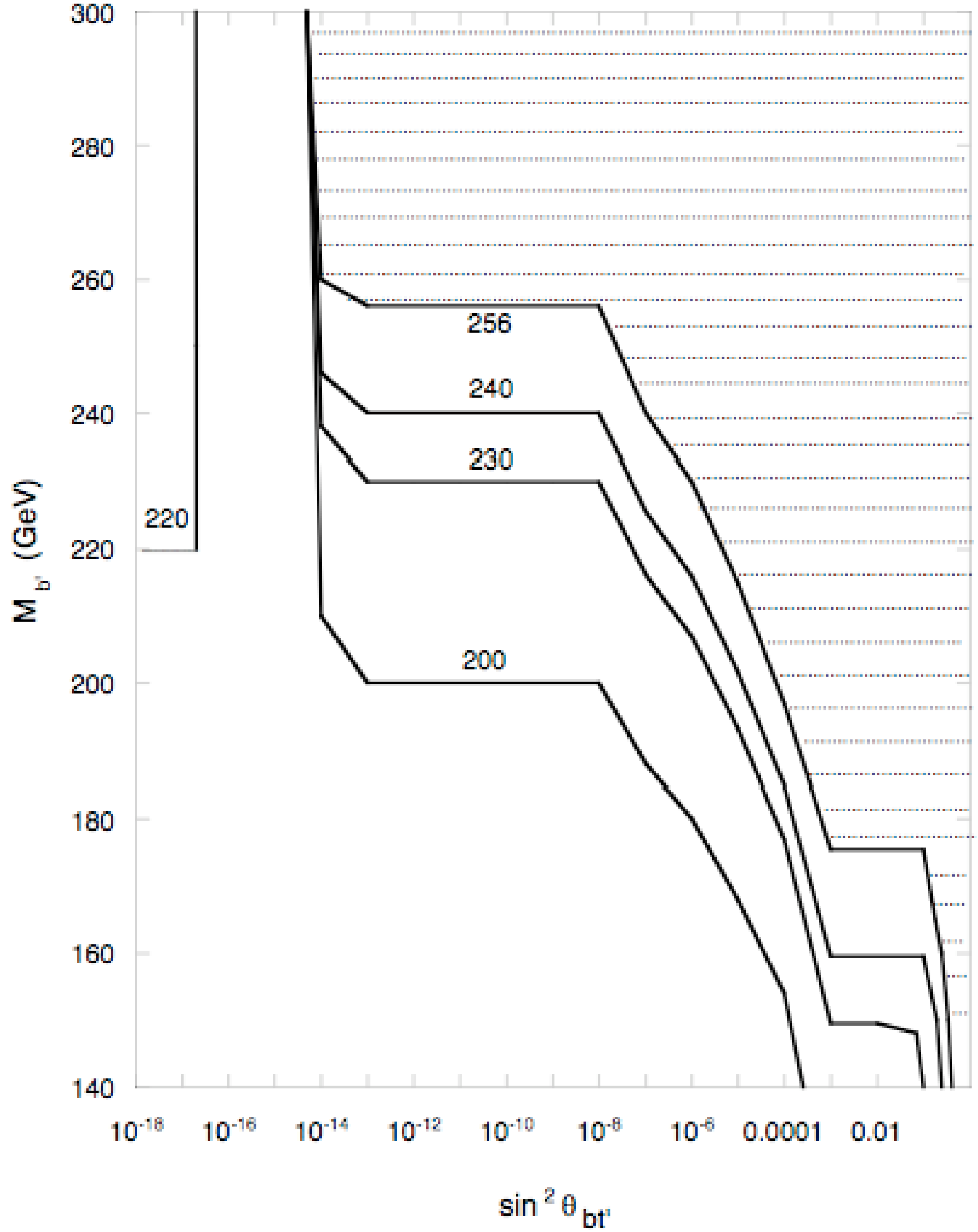


FIG. 2: Observed and expected 95% C.L. upper limits on the cross section for $t'\bar{t}'$ production as a function of t' mass. The grey bands around the median expected limit show the ±1- and ±2-standard-deviation ranges. The theoretical prediction is also shown (assuming a 100% branching ratio to Wq).

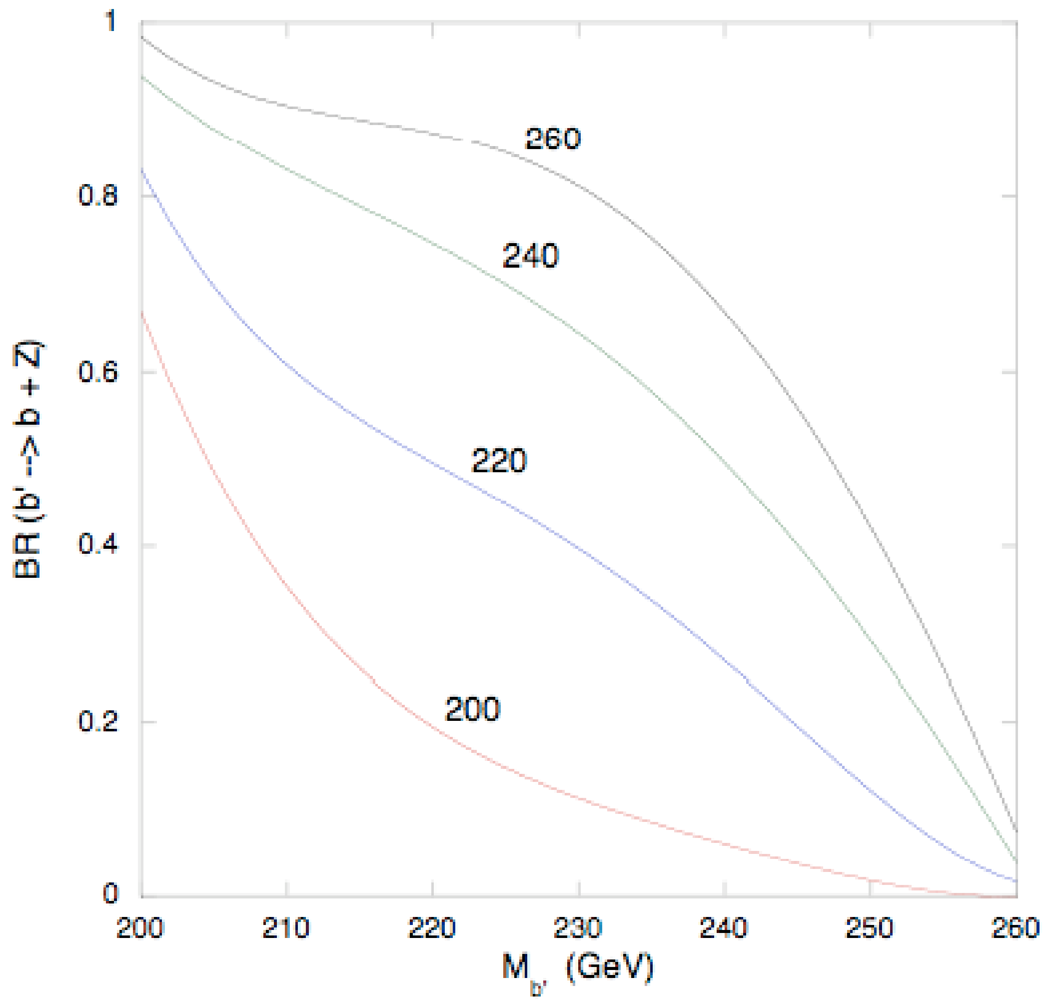
The 95% confidence level bound gives 256 GeV. If the branching ratio is smaller, the bound is weakened substantially.

- If m(b’) < m(t’) - m(W), then the BR(t’ -> qW) becomes very small unless V_{43} is very large (O(1)).
- If m(t’)-m(W) < m(b’) < m(t’), then the BR(t’--> qW) becomes a tradeoff of V_{43} vs. 3-body phase space.
- Even if m(b’) > m(t’), the decay length of the t’ must be smaller than about a centimeter. But if it is larger than a few meters, stable particle searches give a bound of 220 GeV on the t’ mass.
- Putting this all together….

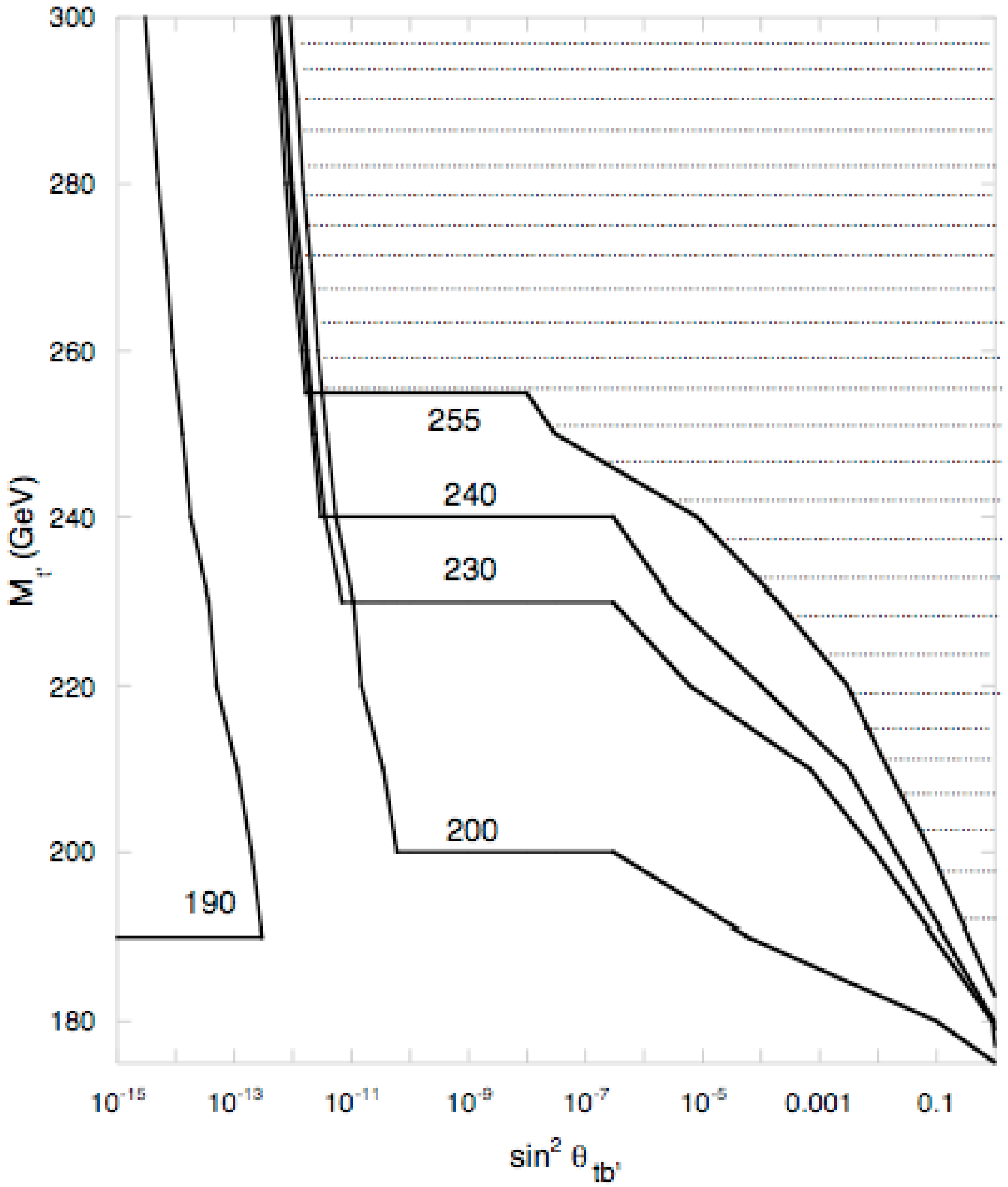


300
280
260
240
220
200
180
160
140
256
240
230
220
200
$M_{b'}$ (GeV)
10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 0.0001 0.01
$\sin^2\theta_{bt'}$

- Turning to the b’ bounds, CDF looked for b’ --> b + Z, which will never dominate for b’ masses above 255 GeV.
- The rate for b’ --> b + Z depends sensitively on the t’ mass.   In fact, for m(t’) = m(top), the rate vanishes due to a GIM mechanism.



BR (b' --> b + Z)
M_b' (GeV)
260
240
220
200
0
0.2
0.4
0.6
0.8
1
200
210
220
230
240
250
260



300
280
260
240
220
200
180
$M_{t'}$ (GeV)
255
240
230
200
190
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
0.001
0.1
$\sin^2\theta_{tb'}$

Conclusion

- Bounds on fourth generation quark masses should emphasize the assumptions made.
- Assumption-free results for b' and t' can be made by plotting results as a function of the other quark mass and the mixing angle.
- In both cases, there is a gap for decay lengths between 1 and a few hundred centimeters, and reasonable models give precisely these decay lengths.

Addendum:

- CDF and D0 place no bounds on the charged heavy lepton of a 4th family.
- If the heavy neutrino is heavier (or the mixing angle is not small), the primary decay is L --> ν_τ W.   The signature of L^+L^- is thus a W-pair and missing energy. Backgrounds are large.

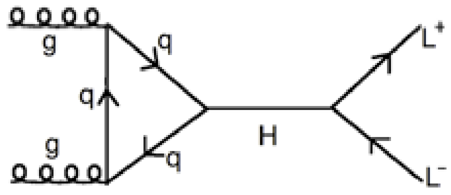


Figure 1: $gg \to H \to L^+L^-$

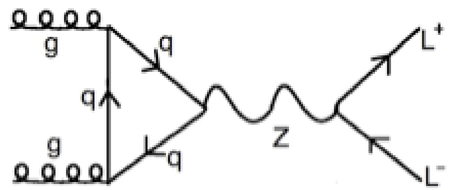


Figure 2: $gg \to Z \to L^+L^-$

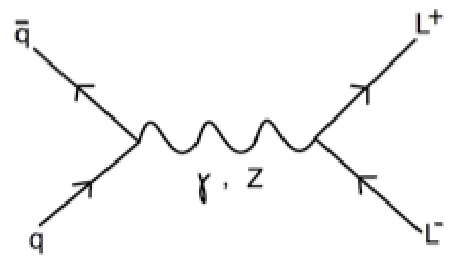


Figure 3: $q\bar{q} \to \gamma, Z \to L^+L^-$

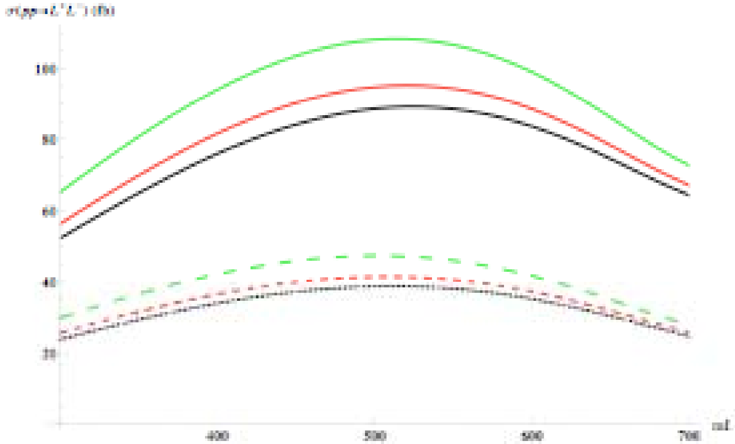


Figure 4: σ_{total} (fb) vs m_L (GeV). Solid lines: $m_{Up} = m_{Down} = 500$ GeV; dashed lines: $m_{Up} = m_{Down} = 300$ GeV. Green: $m_H = 550$ GeV; red: $m_H = 530$ GeV; black: $m_H = 550$ GeV.

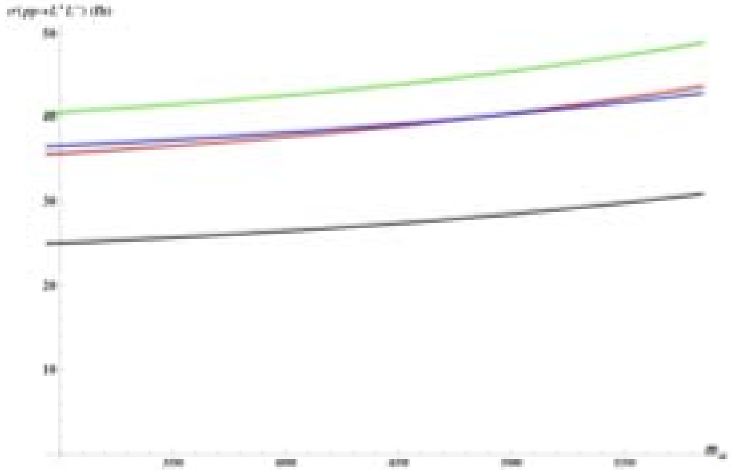


Figure 5: σ_{total} (fb) vs m_H (GeV). Green: $m_L = 600$ GeV; blue: $m_L = 500$ GeV; red: $m_L = 400$ GeV; black: $m_L = 300$ GeV. $m_H = 150$ GeV for all.

- Cross sections typically of O(50) fb, leading to O(10000) events. But W-pair backgrounds are huge.
- There is (AFAIK) NO analysis of the charged heavy lepton production reach at a hadron collider since 1988 (for the SSC).
- Then, Hinchliffe required that the angle between the W’s be greater than 2 radians. This eliminated the background, and left a handful of events, if the lepton mass was 250 GeV or less.

- Needed:

An analysis of charged heavy lepton production at ATLAS/CMS.

It may very well be that these heavy leptons are unobservable at the LHC.