Search Strategies For 4th Generation Quarks at the LHC; Beyond the SM4

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Outline

The SM4 setup

- SM4: One of simplest extensions of the SM - adding a fourth chiral generation.
- Supports a heavy Higgs in accordance with current data and provides hints for dynamic EWSB / Compositeness.
- Addresses several tensions in flavor physics
- Provides new CP violating phases that may become handy for Baryogenesis.

Current Mass Limits (the SM4 case)

- Within SM4, the current limit is $M_{t'} > 450 GeV$ (CMS), replacing the earlier $M_{t'} > 358 GeV$ (CDF).
  - *[Luk, arXiv:1110.3246]*
  - *[Ivanov for CDF, D0 Collaborations, arXiv:1109.1025]*
- The limits are achieved assuming $t' \rightarrow Wb$ (SM4) and looking in the semileptonic channel:

$$pp \rightarrow t'\overline{t'} \rightarrow \left[W^+\right]_{hadronic} b \left[W^-\right]_{leptonic} \overline{b} \rightarrow l\nu bq\overline{q}\overline{b}$$

BSM4

- In the past few years several BSM4 models were proposed:
  - Extended Higgs sector: multi Higgs frameworks.

    [S. Bar-Shalom, S. Nandi, A. Soni, arXiv:1105.6095]

    [Hashimoto Phys.Rev. D81 (2010) 075023]

    [Hung, Xiong Nucl.Phys. B847 (2011)]

    [Luty, Phys. Rev. D41, 2893 (1990)]

    [De Pree, Marshall, Sher, Phys. Rev. D80, 037301 (2009)]
    - MSSM with 4 generations

      [S. Dawson, P. Jaiswal, JHEP 1102 (2011) 055]
    - Warped Extra Dimension with 4 generations

      [M. Frank, B. Korutlu, M. Toharia, CUMQ-HEP-162.]
- In some of these models new decay modes for the t' may emerge, e.g., $t' \to ht$, $t' \to H^+ b$, $t' \to Wb'$, that potentially alter the standard SM4 phenomenology of t' decay.

The 4G2HDM example

- t' decay patterns:
  1. $t' \longrightarrow W^+ b$ (SM4 -like)
  2. $t' \longrightarrow W^+ b'$
  3. $t' \longrightarrow ht$
  4. $t' \longrightarrow H^+ b$

- h decays
  1. $h \longrightarrow b\overline{b}$
  2. $h \longrightarrow W^+W^-, ZZ$
- H^+ decays
  1. $H^+ \longrightarrow t\overline{b}$
  2. $H^+ \longrightarrow t'\overline{b}$
  3. $H^+ \longrightarrow hW^+$

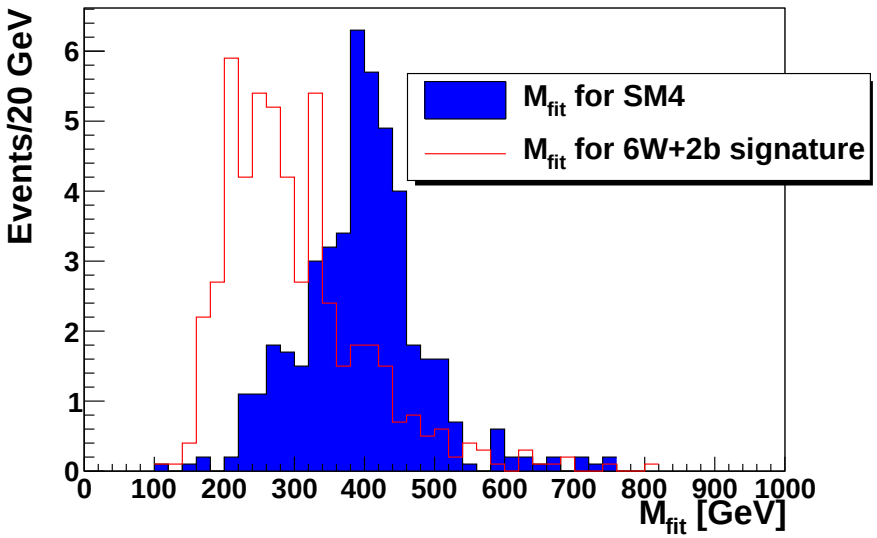
The LHC signatures for t' pair production

$pp \longrightarrow t'\overline{t'} \longrightarrow n_W W + n_b b$

- 2W+2b (SM4 - like ; $n_W = n_b = 2$)
- 6W+2b ($n_W = 6$, $n_b = 2$)
- 2W+6b ($n_W = 2$, $n_b = 6$)

Handling the New Signatures @ The LHC

- For the BSM4 case, the fit to the SM4 $l\nu bq\bar{q}\bar{b}$ signature may fail
- e.g. for $BR(t' \to ht \to WWt) \sim 1$, $M_{fit} = m(l\nu b) = m(\bar{q}q\bar{b})$ is substantially lower - exactly where the $t\bar{t}$ background peak is located.

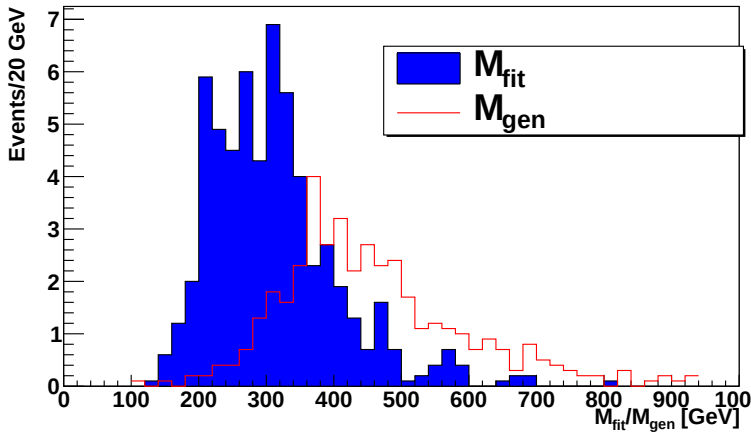


Mass Reconstruction in the General Case

- We use a reconstruction strategy that is general to the 1lepton+nj+$\not{E}_T$ events.
- We choose the correct partition of the event:

$$m(l\nu) = M_W$$
$$m(\textit{Left Side}) = m(\textit{Right Side}) \equiv M_{gen}$$

- M_{gen} replacing the "standard" M_{fit} used by CMS.

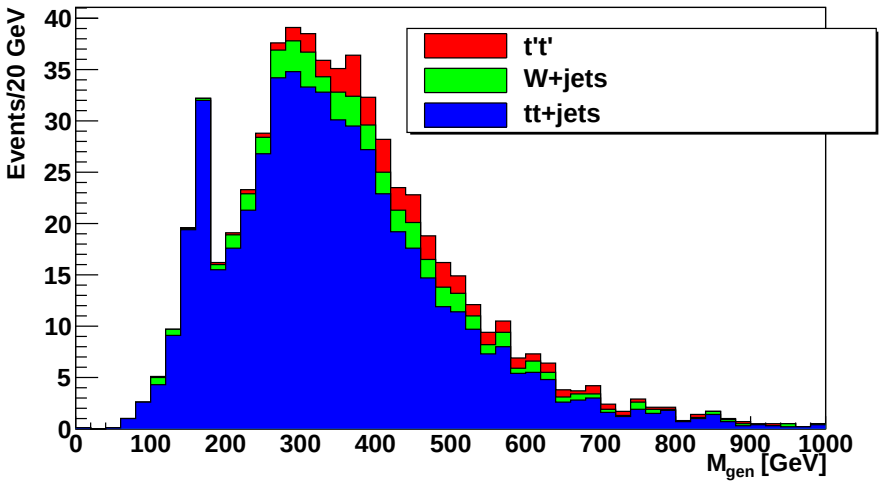


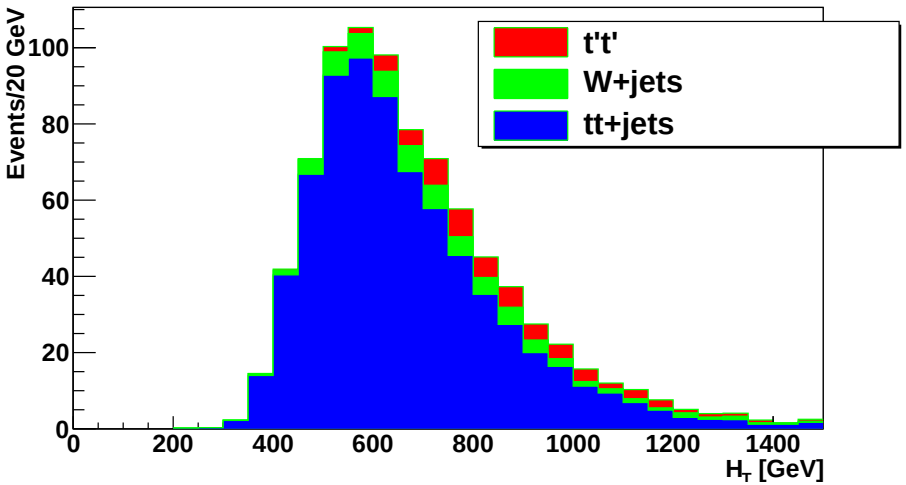
Full Simulation

- We use Madgraph/MadEvent to generate signal and two $\int Ldt = 1$ fb^{-1} sets of background events of: W+jets, $t\bar{t}$+jets.
- K-factors:
  - 1.5 for the signal and $t\bar{t}$+jets background
  - 1.3 for W+jets background
- MLM parton-jet matching method for the background.
- BRIDGE for the decay of the new particles in the signal
- Pythia for the decay of the SM particles, shower, fragmentation and hadronizations.
- PGS with the LHC card for the detector simulation

Results: M_{gen} and H_T distributions

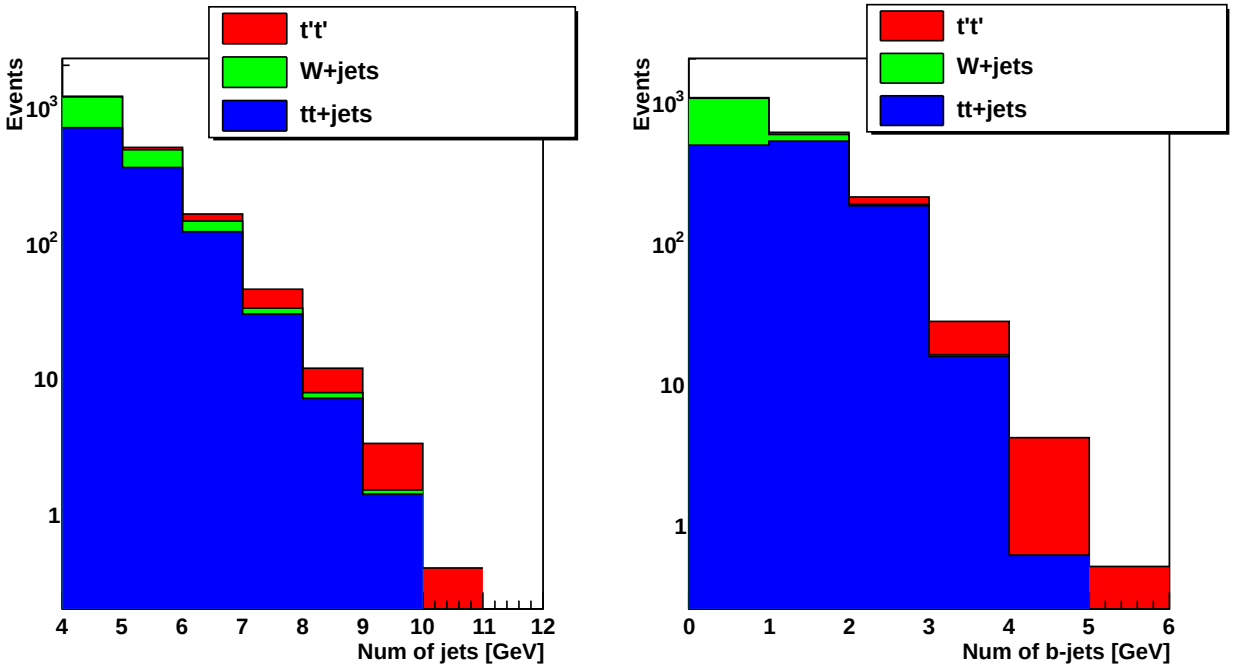
- M_{gen} and $H_T = \sum \mid p_T \mid$ for the $pp \rightarrow t'\overline{t'} \rightarrow 2W + 6b$ signature with $M_{t'} = 450\ GeV$.





Results: Excess of jets and b-jets

- 2W+6b exhibits a higher number of jets and b-jets with respect to the background and with respect to the SM4 2W+2b (not shown)



- Gives an extra handle for isolating the signal.

Detection Sensitivity

- We thus use the following cuts:
  1. $M_{gen} > 300\ GeV$
  2. $H_T > 600\ GeV$
  3. $n_{j+bj} \equiv n_{jets} + n_{b-jets} > 6$

Process	without cuts	n_{j+bj}	M_{gen}	H_T	all cuts combined	$\frac{S}{\sqrt{B}}$
$t\bar{t} + jets$	1206	179	536	678	93	
$W + jets$	626	9	353	443	5	
6W+2b $M_{t'} = 350\ GeV$	168	80	87	135	46	4.65
2W+6b $M_{t'} = 350\ GeV$	172	99	93	138	56	5.66
6W+2b $M_{t'} = 400\ GeV$	113	58	60	99	34	3.43
2W+6b $M_{t'} = 400\ GeV$	119	74	69	104	45	4.55
6W+2b $M_{t'} = 450\ GeV$	77	43	40	74	23	2.32
2W+6b $M_{t'} = 450\ GeV$	70	46	43	65	29	2.93

- In contrast, with the "standard" CMS method $\frac{S}{\sqrt{B}} \sim 1.7$ for $M_{t'} = 450\ GeV$ and ~ 2.6 for $M_{t'} = 350\ GeV$.

Current CMS Limit and the BSM4 Case

- CMS Method: performing a 2d (M_{fit} and H_T) likelihood fit to the data under the hypothesis of S+B and B only. They find an 95% CL exclusion of $M_{t'} < 450 GeV$.
- We simulate the CMS analysis by imposing cuts on M_{fit} and H_T and counting the number of events (N_{SM4}) that survive, assuming the SM4 signature $\overline{t'}t' \rightarrow 2b + 2W$ with $M_{t'} = 450\ Gev$.
- We use N_{SM4} as our reference value for a 95% CL exclusion.
- Thus, we interpret the case of $N_{BSM4} < N_{SM4}$ to have a weaker bound on the t' mass in the BSM4 framework.

Bounds for BSM4

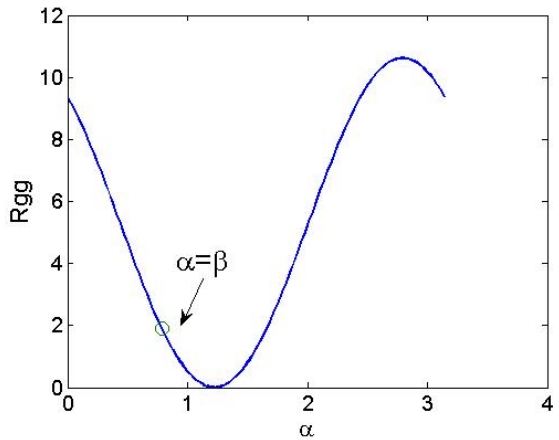
Process	# events after cuts
SM4 2W+2b $M_{t'} = 450\ GeV$	$N_{SM4} = 38$
BSM4 6W+2b $M_{t'} = 350\ GeV$	$N_{BSM4} = 32 < N_{SM4}$
BSM4 2W+6b $M_{t'} = 350\ GeV$	$N_{BSM4} = 42 \sim N_{SM4}$
BSM4 6W+2b $M_{t'} = 400\ GeV$	$N_{BSM4} = 26 < N_{SM4}$
BSM4 2W+6b $M_{t'} = 400\ GeV$	$N_{BSM4} = 33 < N_{SM4}$
BSM4 6W+2b $M_{t'} = 450\ GeV$	$N_{BSM4} = 20 < N_{SM4}$
BSM4 2W+6b $M_{t'} = 450\ GeV$	$N_{BSM4} = 28 < N_{SM4}$

- Based on the table above we estimate the current CMS limit on the t' mass to be around 350 GeV in the BSM4 case.

Higgs Bounds: Another Success of BSM4

- CMS recently reported a $120 - 600$ GeV exclusion of SM4 Higgs.

  [Koryton, CMS Collaboration, EPS-HEP 2011, July 21 -27, 2011; Grenoble, Rhone-Alpes France]
- SM4: Higgs production by gluon fusion is enhanced by a factor of ~ 10 (t' and b' loops).
- In 4G2HDM Higgs production by gluon fusion depends on α and β, through the intereference between the heavy quark loops.
- Either Higgs production or Higgs decay to W^+W^- can be suppressed in some areas of parameter space leading to an invisible Higgs.



Summary

- Standard search strategies for 4th gen quarks which assume the simplest SM4 framework fail for generic BSM4 scenarios for 4th gen dynamics, resulting in a lower limit for t' and b' masses.
- We discussed a method that is suitable for more complex t' decay patterns, in particular, the 6W+2b & 2W+6b signatures that can emerge in BSM4 frameworks that have e.g. $BR\,(t' \rightarrow th) \sim 1$.
- We estimate that the current best limit on the t' mass in this case to be 350 GeV instead of the 450 GeV recently reported by CMS.