Monotop and multitop production at hadron colliders
From effective field theory to data

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J. Andrea, BenjF & F. Maltoni, PRD **84** (2011) 074025

BenjF + CDF collaboration, PRL **108** (2012) 201802

BenjF, IJMPA **27** (2012) 1230007

S. Calvet, BenjF, P. Gris & L. Valéry, arXiv:1212.3360

J. Andrea, E. Conte & BenjF, in preparation

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Outline.

1. The bottom-up approach for new physics at the LHC
2. Effective field theories for the top sector and simulation setup
3. Monotop production at hadron colliders
4. Sgluon-induced multitop production at the LHC
5. Summary

The top-down approach.

- **Motivations**.
  - * **Theoretical ideas**.
    - ►*e.g.*, **symmetry principles** as for Grand Unified Theories.
  - * **Addresses one or several issues** of the Standard Model.
    - ►*e.g.*, **hierarchy problem** as in Universal Extra Dimensional models.
  - * **Predictions** can be made through perturbation theory.
    - ►*e.g.*, **test at colliders**.
- **Benchmark scenarios**.
  - * Many **new parameters** enter in new theories:
    - ►*e.g.*, **hundreds of parameters** in supersymmetric models.
  - * Experimental data **constrains some of them**.
    - ►*e.g.*, **electroweak precision observables**.
  - * **Viable benchmark scenarios**.
- **Signatures at colliders**.
  - * **Driven by the benchmark scenarios**.
    - ►*e.g.*, **same sign leptons** $\Leftrightarrow$ **new Majorana state**.

The top-down approach: limitations.

- **Signatures at colliders**.
  - * Not typical from a **given benchmark of a specific model**.
    ► **Various benchmarks for gravity-mediated supersymmetry breaking**.
  - * Not typical from a **specific model**.
    ► **Extra Dimensions and supersymmetry imply both cascade decays**.

- **Theory and data**.
  - * **How to relate** observations to a given model/benchmark?
  - * **How to disentangle** models and benchmarks?

- **Bias in the expectations**.
  - * Are we **missing** some signatures in those investigated?
    ► **Phenomenologically and experimentally**.

The bottom-up approach: we start from a signature.

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Monotop production at the LHC: general features.

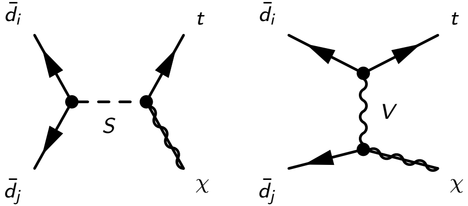
- **Bottom-up approach: we propose a final state signature.**
  - One top quark in association with missing energy.

- **Monotop production in the Standard Model.**
  - * **Loop-suppressed** and **CKM-suppressed**.
  - ⇒ **Observing monotops at the LHC ⇒ new physics**.

- **Main features of monotop signatures.**
  - * **Final state flavor** is fixed.
    - ◇ One top quark.
    - ◇ **Missing energy**.
      - Bosonic or fermionic state.
      - One particle or *n*-particle state.
      - Neutral, weakly-interacting, long-lived/stable/invisible.
  - * **Initial state possibilities** are then reduced.
    - Down-type antiquark pair ⇒ **baryon-number-violating process**.
    - Up-type quark/gluon ⇒ **flavor-changing process**.
  - * **Enhanced coupling between the 3rd generation and the others**.

Classes of models yielding monotop signatures (1).

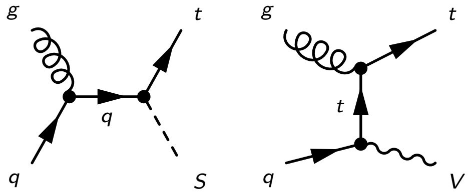
- **Fermionic missing energy state** χ (initial antiquark pairs).
  - $s-$, $t-$ **and** $u-$**channel exchanges of a new state**.
    - ◇ **Scalar** or **vector**, in the **fundamental representation of** $SU(3)_c$.



  - **Concrete examples**.
    - ◇ R**-parity-violating supersymmetry** ($S \equiv \tilde{t}/\tilde{q}$ and $\chi \equiv \tilde{\chi}^0$).
    - ◇ $SU(5)$ **theories** ($V \equiv$ leptoquark and $\chi \equiv \nu$).
    - ◇ $\chi \equiv$ **composite state (*e.g.*, scalar + fermion)**.
    - ◇ $\chi \equiv$ **spin-3/2 particle**.
    - ◇ *etc* (including four-fermion interactions)...

Classes of models yielding monotop signatures (2).

- **Bosonic missing energy state** (initial quark/gluon pairs).
  - * **Flavor-changing interactions** of the top quark.
    - ◇ With a **charm or up quark**.
    - ◇ With a new neutral **scalar, vector or tensor field**.



  - * **Concrete examples**.
    - ◇ *R*-**parity-conserving supersymmetry** ($pp \to \tilde{q}\tilde{\chi}^0 \to t\tilde{\chi}^0\tilde{\chi}^0$).
    - ◇ **Flavor-violating graviton couplings**.
    - ◇ *etc...*

Multiple top quark production at hadron colliders.

- **Production of four top quarks in the Standard Model.**
  * **Phase-space suppressed.**
  * Inclusive cross sections: @ 7 TeV: 0.3 fb; @ 8 TeV: 0.7 fb.

  $\Rightarrow$ **Multitop events (at a large rate) $\Rightarrow$ new physics.**

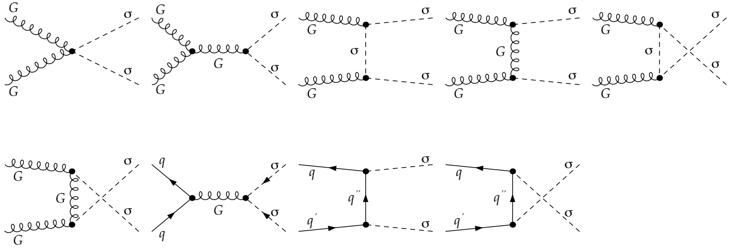
- **Theoretical framework inspired by R-symmetric supersymmetry.**
  * Predict a scalar color-octet field, the **sgluon**.
  * **QCD couplings** to gluons.
  * **Effective couplings** to quarks and gluons through supersymmetric loops.
    - **Quark - antiquark - sgluon** $\Rightarrow \mathcal{O}\left(\frac{m_q}{M_{\rm SUSY}}\right)$.
    - **Gauge boson pair - sgluon** $\Rightarrow \mathcal{O}\left(\frac{1}{M_{\rm SUSY}}\right)$.

  $\Rightarrow$ **Important for the top quark.**

- **Sgluon fields also appear in:**
  * $N\!=\!1/N\!=\!2$ hybrid supersymmetric theories.
  * Vector-like confining theories (colorons).
  * Extra-dimensional theories (with $D \geq 6$).

Simplified model for sgluon production and decay

- **Signatures.**
  - * Sgluon **pair-production**.



  - * **Decays** to 2, 3 or 4 top quarks.

Simulation setup.

Based on [Christensen, de Aquino, Degrande, Duhr, BenjF, Herquet, Maltoni, Schumann (EPJC '11)].

1. Implementation of the simplified models in FeynRules.
   [Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BenjF (in prep)]
2. **UFO** files. [Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter (CPC '11)]
3. Event generation with MadGraph **5**. [Alwall, Herquet, Mattelaer, Stelzer (JHEP '11)]
4. Parton showering and hadronization with Pythia.
   [Sjostrand, Mrenna, Skands (JHEP '06; CPC '08)]
5. Fast detector simulation with Delphes. [Ovyn, Rouby, Lemaitre ('09)]
6. Phenomenological analysis.
   * Monotops: relying on MadAnalysis 5. [Conte, BenjF, Serret (CPC '13)]
   * Multitops: home-made program using the MCLimit **package**.
     [http://www-cdf.fnal.gov/∼trj/mclimit/production/mclimit.html]

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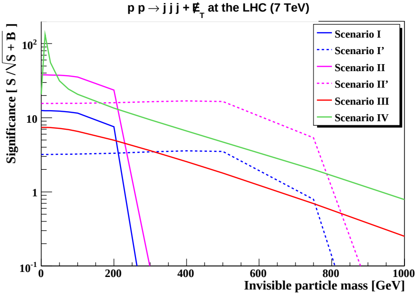
Signal and background descriptions.

- **Signal**.
  - **Leptonic top decay**.
    - Signature: **1 lepton + 1 b jet + missing energy**.
    - **No top mass reconstruction**.
    - **More challenging** ⇒ not considered.
  - **Hadronic top decay**.
    - Signature: **2 light jets + 1 b jet + missing energy**.
    - The top is **fully reconstructed**.

- **Sources of background**.
  - **Z ($\to \nu\bar{\nu}$) + 3 jets**.
    ►Irreducible background.
  - **QCD multijet**.
    ►Misreconstructed jet → fake missing energy.
  - **W + jets, $t\bar{t}$ and diboson**.
    ►Missing energy: leptonic W decay with nonreconstructed lepton.
  - **Single top**.
    ►Non- or misreconstructed leptons.

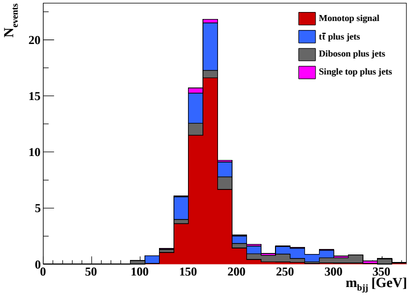
Prospective parton-level analysis at 1 fb^{-1}.



[Andrea, BenjF, Maltoni (PRD '11)]

- **Basic selection cuts.**
  - ▶Exactly **3 parton-level jets**.
  - ▶$p_T > 50$ **GeV**; $|\eta| < 2.5$.
  - ▶ΔR**(jet,jet)** > 0.5.
- **Exploiting the reconstructed top.**
  - ▶$\not{p}_T > 150$ **GeV**.
  - ▶**One** b**-tag; no isolated leptons**.
  - ▶$M_{jj} \in [m_w - 20, m_w + 20]$ **GeV**.
  - ▶$M_{bjj} \in [m_t - 30, m_t + 30]$ **GeV**.
- **Efficiencies.**
  - ▶b-tag: 60%; c/j-mistag: 10/1%.
- **Results**.
  - ▶**Flavor-changing modes** more optimistic (cf. parton densities).
  - ▶**Resonant modes** depend on the resonance mass.
  - ▶**Fairly large invisible mass reachable**.

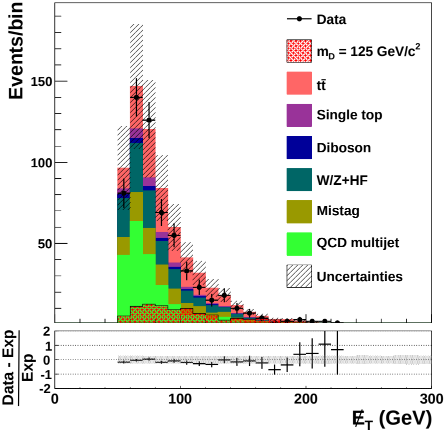
Complete Monte Carlo study including detector simulation.



[BenjF (IJMPA '12)]

- *R*-parity violating **SUSY.**
- **Basic cuts.**
  - ► $\not{E}_T > 200$ **GeV**.
  - ► **Lepton veto**.
- **Exploiting the reconstructed top.**
  - ► **Exactly one** *b***-jet**.
  - ► **Exactly two light jets**.
  - ► $M_{jj} \in [m_w - 15, m_w + 15]$ **GeV**.
- **Results at 4 fb**$^{-1}$.
  - ► **TeV scale squarks**
  - ► **Moderate RPV couplings**
  - ► **Possible discovery**.

From theory to data: CDF exclusions.



[BenjF + CDF collaboration (PRL '12)]

- **Flavor changing monotop events.**
  - ► Z' **with a mass of 125 GeV.**
- **Basic set of cuts.**
  - ► $\not{E}_T > 50$ **GeV**.
  - ► **Exactly three jets with one** b**-jet**.
  - ► $E_T^{j_1} > 35$ **GeV**.
  - ► $E_T^{j_2,j_3} > 25$ **GeV**.
  - ► **One jet with** $|\eta| < 0.9$.
  - ► **Other jets with** $|\eta| < 2.4$.
  - ► **Lepton veto**.
- **Exploiting the top quark.**
  - ► $\Delta\phi(\not{E}_T, j_2) > 0.7$.
  - ► m_{bjj} **compatible with** m_t.
  - ► **Large** $\not{E}_T$ **significance**.
- **Results with 7.7 fb^{-1} of data.**
  - ► **Compatible with the SM.**

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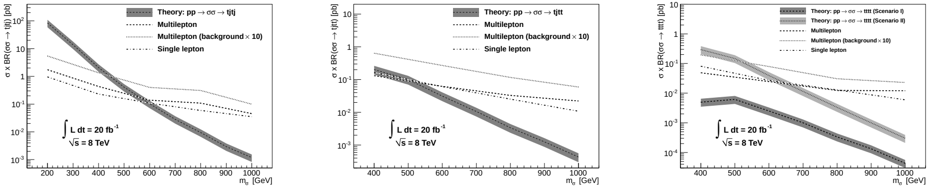
Single lepton analysis.

- **Object selection.**
  - * **Jets**: $E_T^{(\mathrm{cal.})} > 20$ GeV; $\eta < 2.5$.
  - * **b-tagging**: efficiency: 60%; mistag: 10% (charm) and 1% (light).
  - * **Jet removal**: if $\Delta R(j, e^\pm) \leq 0.1$.
  - * **Lepton removal**: if $\Delta R(\ell^\pm, j) \leq 0.4$.
- **Selection cuts.**
  - * **One single lepton**: $p_T \geq 25$ GeV.
  - * **Missing energy**: $\not{E}_T \geq 40$ GeV.
  - * W **transverse mass**: $M_T^W \geq 25$ GeV.
    $\Rightarrow$ **good control of multijet backgrounds** (ATLAS: EPJC **72** (2012) 2083).
  - * **Jet multiplicity cuts.**
    - ► **tjtj**: $N_j \geq 5$; $N_b \geq 1$; $p_T^j \geq 25$ GeV $\Rightarrow$ Main bgd $\equiv t\bar{t}$ + **jets**.
    - ► **tjtt**: $N_j \geq 7$; $N_b \geq 2$; $p_T^j \geq 25$ GeV $\Rightarrow$ Main bgd $\equiv t\bar{t}$ + **jets**.
    - ► **tttt**: $N_j \geq 8$; $N_b \geq 2$; $p_T^j \geq 25$ GeV $\Rightarrow$ Main bgd $\equiv t\bar{t} + V(V')$ + **jets**.
- **Large hadronic activity for the signal**: use H_T as a discriminating variable.
- **The ditop case**: the **sgluon mass** can be reconstructed.

Multilepton analysis.

- **Object selection**: same as before.
- **Selection cuts.**
  * $N_\ell \geq 2$ **leptons with** $p_T^\ell > 20$ **GeV**.
  * $m_{\ell\ell} \geq 50$ **GeV**$\Rightarrow$ **rejection of hadronic resonances**.
  * **Missing energy**: $\not{E}_T \geq 40$ GeV$\Rightarrow$ **good rejection of the Z backgrounds**.
  * **Jet multiplicity cuts.**
    - **tjtj**: $N_j \geq 3$; $N_b \geq 1$; $p_T^j \geq 25$ GeV $\Rightarrow$ Main bgd $\equiv t\bar{t}$ **+ jets**.
    - **tjtt**: $N_j \geq 4$; $N_b \geq 2$; $p_T^j \geq 25$ GeV $\Rightarrow$ Main bgd $\equiv t\bar{t}$ **+ jets**.
    - **tttt**: $N_j \geq 5$; $N_b \geq 3$; $p_T^j \geq 25$ GeV $\Rightarrow$ Main bgd $\equiv t\bar{t} + V(V')$ **+ jets**.
- **Multijet background + fakes.**
  * If $N_\ell = 2$: we ask for **same sign leptons**.
  * After cuts, mulitjet is **10 x larger** than the rest (ATLAS-CONF-2012-130).
  * **Two considered cases** (the truth should be in between).
    - Without multijet + fakes .
    - Without multijet + fakes but after multiplying the bgd by 10.
- **Large hadronic activity for the signal**: use H_T as a discriminating variable.

Extracting the LHC sensitivity.



[Calvet, BenjF, Gris, Valéry '12]

- **Signatures**: *tjtj* (left) *tjtt* (middle) and *tttt* (right); LHC @ 8 TeV; 20 fb^{-1}.
- **Gray bands: theory curves for all our scenarios** (with scale uncertainties).
- **Expectations** for 8 fb^{-1} (using MCLIMIT).
- **LHC sensitivity**.

	Single lepton analysis	Multilepton analysis	Multilepton analysis (background $\times 10$)
tjtj	$590\ ^{+40}_{-30}$ GeV	$570\ ^{+30}_{-50}$ GeV	$440\ ^{+40}_{-15}$ GeV
tjtt	$480\ ^{+70}_{-80}$ GeV	$520\ ^{+35}_{-90}$ GeV	-
tttt (S-I)	-	-	-
tttt (S-II)	$640\ ^{+40}_{-30}$ GeV	$650\ ^{+30}_{-40}$ GeV	$520\ ^{+50}_{-110}$ GeV

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Summary.

- **We exploit the FeynRules - UFO - MadGraph - Pythia - Delphes chain.**
  - * We **develop** simplified models.
    - ◇ **Monotop signatures**.
    - ◇ **Multitop signatures**.
  - * Investigate their **phenomenology** at the LHC (7 TeV and 8 TeV).
- **Monotops**.
  - * **One hadronic top quark and missing energy**.
  - * The LHC can probe **fairly large missing mass**.
  - * The LHC can constrain **the coupling strengths**.
- **Sgluon-induced multitops**.
  - * ***tjtj*, *tjtt* and *tttt* topologies** with **at least one lepton** after top decays.
  - * Large **final state hadronic activity** ⇒ discriminating variable: H_T.
  - * Single lepton and *tjtj*: **the sgluon mass can be reconstructed**.
  - * Sgluons up to **700 GeV** can be probed.