Monotops at the Large Hadron Collider.

Benjamin Fuks (IPHC Strasbourg / Université de Strasbourg).

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With J. Andrea and F. Maltoni.

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Outline.

1. The bottom-up approach for new physics at the LHC.
2. Monotop signatures at the LHC.
3. LHC sensitivity to monotops.
4. Summary - outlook.

Classifying Beyond the Standard Model theories.

- **New physics theories**.
  - * There are a **lot of different** theories.
  - * Based on very **different ideas**.
  - * **In evolution** (especially regarding the discoveries [or exclusions!]).

- **New physics theories can be classified into two main categories**.
  - * Built from a **top-down** approach.
  - * Built from a **bottom-up** approach.

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 **constraints some of them**.
    - ►*e.g.*, **electroweak precision observables**.
  - * **Viable benchmark scenarios**.
- **Signatures at colliders**.
  - * **Driven by the benchmark scenarios**.
    - ►*e.g.*, **same sign leptons** ⇔ **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**.

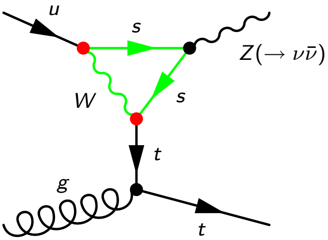
The bottom-up approach: we start from a signature.

Outline.

Monotop production at the LHC.

- **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**.
  * **CKM-suppressed**.
  * Representative Feynman diagram:



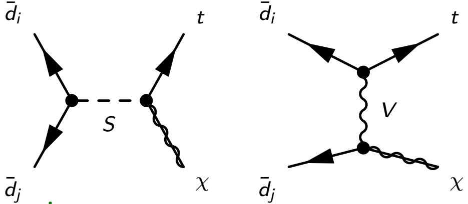
- **Observing monotops at the LHC ⇔ Beyond the Standard Model physics**.

Classes of models yielding monotop signatures (1).

- **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 (2).

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



  * **Concrete examples**.
    - ***R*-parity-violating supersymmetry** ($S \equiv \tilde{t}/\tilde{q}$ and $\chi \equiv \tilde{\chi}^0$).
      ►Heavy neutralinos: [Desai, Mukhopadhyaya, JHEP '10].
    - **$SU(5)$ theories** ($V \equiv$ leptoquark and $\chi \equiv \nu$).
    - **$\chi \equiv$ composite state (*e.g.*, scalar + fermion)**.
      ►[Davoudiasl, Morrisey, Sigurdson, Tulin, '11].
    - **$\chi \equiv$ spin-3/2 particle**.
    - *etc...*

Toy scenarios I and II.

- **Scenario I**.
  - Standard Model plus **one additional Majorana fermion χ**.
  - **One additional new colored scalar state φ**.
  - Simplifications: no new pseudoscalar interactions.

$$\mathcal{L} = \epsilon^{ijk} \varphi_i \bar{d}^c_j \left[a^q_{SR} \right] d_k + \varphi_i \bar{u}^i \left[a^{1/2}_{SR} \right] \chi + \text{h.c.}\ .$$

$\Rightarrow$ **Monotop resonant production** (with $a = 0.1$).

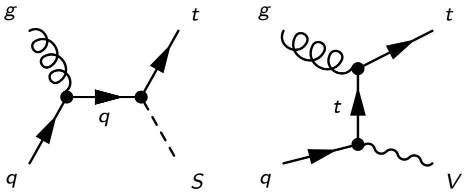
- **Scenario II**.
  - Standard Model plus **one additional Majorana fermion χ**.
  - **One additional new colored vector state X**.
  - Simplifications: no new pseudovector interactions.

$$\mathcal{L} = \epsilon^{ijk} X_{\mu,i}\ \bar{d}^c_j \left[a^q_{VR} \gamma^\mu \right] d_k + X_{\mu,i}\ \bar{u}^i \left[a^{1/2}_{VR} \gamma^\mu \right] \chi + \text{h.c.}\ .$$

$\Rightarrow$ **Monotop resonant production** (with $a = 0.1$).

Classes of models yielding monotop signatures (3).

- **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** (two-particle missing energy).
      ► $pp \to \tilde{q}\tilde{\chi}^0 \to t\tilde{\chi}^0\tilde{\chi}^0$: [Allanach, Grab, Haber, JHEP '11].
    - ◇ **Anomalous** $Z - q - q'$ **interactions**.
      ►[del Aguila, Aguilar-Saavedra, Ametller, PLB '99].
    - ◇ **Flavor-violating graviton couplings**.
      ►[Degrassi, Gabrielli, Trentadue, PRD '09].
    - ◇ *etc...*

Toy scenarios III and IV.

- **Scenario III**.
  * Standard Model plus **one additional real scalar ϕ**.
  * Simplifications: no new pseudoscalar interactions.

$$\mathcal{L} = \phi \bar{u} \Big[a^0_{FC} \Big] u + \text{h.c.} \ .$$

$\Rightarrow$ **Flavor-changing monotop production** (with $a = 0.1$).

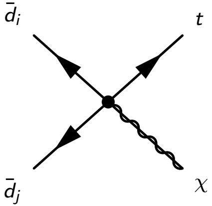
- **Scenario IV**.
  * Standard Model plus **one real vector field V**.
  * Simplifications: no new pseudovector interactions.

$$\mathcal{L} = V_\mu \bar{u} \Big[a^1_{FC} \gamma^\mu \Big] u + \text{h.c.} \ .$$

$\Rightarrow$ **Flavor-changing monotop production** (with $a = 0.1$).

Classes of models yielding monotop signatures (4).

- **Fermionic missing energy state** χ.
  - * **Four-fermion interactions**.



  - * **Concrete examples**.
    - ◇ **From** $SU(2) \times SU(2)$.
      ►[Morrisey, Tait, Wagner, PRD '05].
    - ◇ **Model-independent study.**
      ►[Dong, Durieux, Gerard, Han, Maltoni, '11].

Toy scenario V.

- **Scenario V**.
  - Standard Model plus **one additional Majorana fermion χ**.
  - **Modeling through s, t, u exchanges of very heavy scalars**.
  - Simplifications: no new pseudoscalar interactions.

$$\mathcal{L} = \epsilon^{ijk}\varphi_i \bar{d}^c_j \left[a^q_{SR}\right] d_k + \varphi_i \bar{u}^i \left[a^{1/2}_{SR}\right]\chi + \epsilon^{ijk}\tilde{\varphi}_i \bar{d}^c_j \left[\tilde{a}^q_{SR}\right] u_k + \tilde{\varphi}_i \bar{d}^i \left[\tilde{a}^{1/2}_{SR}\right]\chi + \text{h.c.}\ .$$

(with $a = \tilde{a} = 0.1$).

Outline.

Chain of simulation tools.

Model

Parameters | **Gauge groups** | **Particle content** | **Lagrangian**

⇓

FeynRules **1.6** [Christensen, Duhr, BenjF (in prep.)]

⇓

Feynman rules

⇓

Translation ⇒ UFO files
[Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter, '11]

⇓

MadGraph **5** [Alwall, Herquet, Mattelaer, Stelzer, JHEP '11]

⇓

Parton-level analysis ⇒ conclusions.

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**.
  - * $Z\ (\rightarrow \nu\bar{\nu}) + 3$ **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.

Background rejection (1).

- **A proper analysis requires**:
  - * **Parton showering**.
  - * **Hadronization**.
  - * **A proper detector simulation**.
  - * **Data-driven methods for background estimation.**
- **We rely on existing experimental studies**.
  [Disclaimer: this is a prospective study].
  - * CMS: CERN-PH-EP-2011-065.
  - * ATLAS: PLB **701** (2011) 186.
- **First set of selection cuts.**
  - * Large **missing transverse momentum** ($\not{p}_T > 150$ GeV).
  - * p_T**(jet)** > 50 **GeV** for three high quality jets.
  - * H_T**(jet)** > 300 **GeV**.

$\Rightarrow$ **comparable amount of QCD, $t\bar{t}$, Z and W events**.
$\Rightarrow$ **diboson and single top highly reduced**.

Background rejection (2).

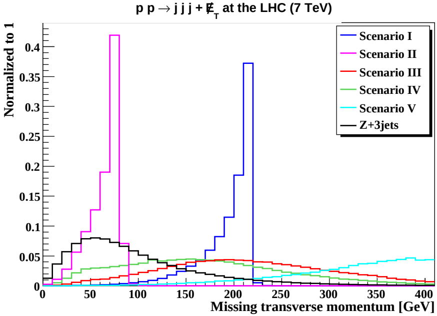
- **Second set of selection cuts: exploiting the presence of a top quark.**
  * Exactly **three jets**.
  * **Lepton veto**.
  * One b-**tagged** jet.
  * Three-jet invariant mass compatible with the **top mass**.
  * Two non-b-jet invariant mass compatible with the W **mass**.

$\Rightarrow$ **all instrumental backgrounds are expected to be highly suppressed**.
$\Rightarrow$ **the only considered source of background consists in** $Z(\to \nu\bar{\nu}) + 3$ **jets**.

Remainder.

- This is a **prospective study**.
- Promising results $\Rightarrow$ **motivation for a more complete study**.
  ►Parton showering & hadronization.
  ►Detector simulation.

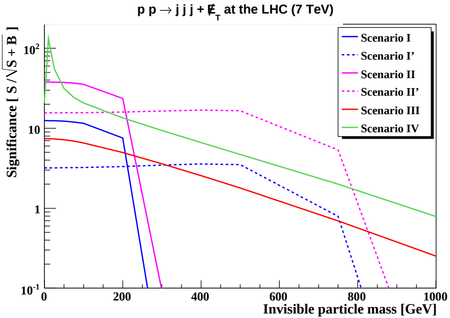
Missing transverse momentum distribution.



- **Our selection cuts.**
  - ▶Exactly **3 parton-level jets**.
  - ▶$p_T > 50$ **GeV**; $|\eta| < 2.5$.
  - ▶ΔR**(jet,jet)** > 0.5.
- **Resonant behavior**.
  - ▶Scenarios I and II.
  - ▶Spectra with an **edge**.
  - ▶Depends on the **invisible mass**.
- **Flavor-changing production modes**.
  - ▶Scenarios III and IV.
  - ▶**Flatter spectra**.
  - ▶**Peak at high** p_T**-value**.
- **Four-fermion interactions**.
  - ▶Scenario V.
  - ▶**Monotonically growing spectrum**.

Simple cuts ⇒ Reject the major background contributions.

LHC sensitivity to monotop signatures at 1 fb^{-1}.



- **Additional cuts.**
  - ▶ $\not{p}_T > 150$ **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-tagging: 60%.
  - ▶ c-mistagging: 10%.
  - ▶ light jet-mistagging: 1%.
- **Resolution ⇒ smearing**.
- **Results**.
  - ▶ **Flavor-changing modes** more optimistic (cf. parton densities).
  - ▶ **Resonant modes** depend on the resonance mass.
  - ▶ **Fairly large invisible mass reachable**.

Outline.

Conclusions.

- **We have investigated monotop production at the LHC**.
  - **One hadronic top quark**.
  - **Missing energy**.
- **Simplified effective theory approach**.
- **Basic selection cuts were performed**.
  - The LHC can probe **fairly large missing mass**.
  - The LHC can constrain **the coupling strengths**.
  - **The results are encouraging**.
  - We need furter studies **to understand the instrumental backgrounds**.

Further studies.

- **More complete simulation**.
- **More advanced analysis techniques**.
- **CMS and CDF analyses are on their way**.