Beyond the Standard Model explorations
From theory to data.

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Theory: with N. Christensen and C. Duhr.
CMS: with J. Andrea and E. Conte.
ATLAS: with S. Calvet, Ph. Gris, A. Renaud, L. Valery and D. Zerwas.

High-energy physics seminar @ LPC, Clermont-Ferrand
February 15, 2012

Outline

1. Monte Carlo tools and New Physics investigations at the LHC.
2. A comprehensive approach for BSM simulations.
3. Monotop production at hadron colliders
4. Sgluon induced multitop production at hadron colliders
5. Summary - outlook.

Monte Carlo tools and discoveries at the LHC.

- **One of the goals of the LHC: which New Physics theory is the correct one?**

Confront data and theory.

- **Establishing of an excess over the SM backgrounds**.
  - * **Difficult task**.
  - * Use of **Monte Carlo generators** (backgrounds, signals).
- **Confirmation of the excess**.
  - * **Model building activities**.
    - ◇ Bottom-up and top-down approach.
  - * **Implementation** of the new models in the Monte Carlo tools.
- **Clarification of the new physics**.
  - * **Measurement of the parameters**.
  - * Use of **precision predictions**.
  - * **Sophistication of the analyses ⇔ new physics and detector knowledge**.

Monte Carlo tools play a key role!
But how is new physics presently investigated in particle physics?

A framework for LHC analyzes (1).

Idea ⇔

Model building

* **Pen&pencil stage.**
* Leading order, loop calculations, ...
* Electroweak, low energy constraints,...

⇒ **Publications**

⇓

Phenomenology

* **Monte Carlo event generator.**
* Matrix element calculation.
* Parton showering / hadronization.
* Generic detector simulation.

⇒ **Publications**

⇓

Experiment

* **Experimental framework.**
* Matrix elements, parton showering, hadronization.
* Realistic detector simulation.
* **Comparison with data**.

⇒ **Publications**

A framework for LHC analyzes (2).

- **New physics theories**.
  - * A **lot of different** theories.
  - * Based on very **different ideas**.
  - * **In evolution** (especially regarding the discoveries).

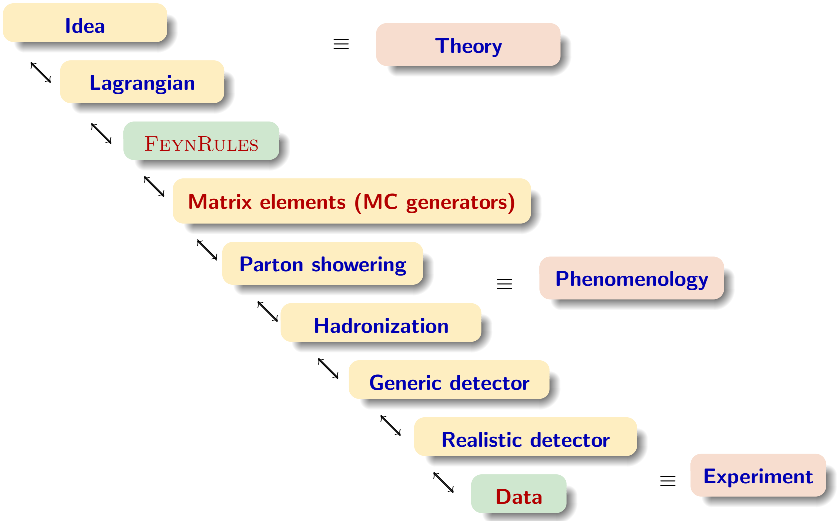
Implementation in Monte Carlo tools.

- A model consists in:
  - * **particles**,
  - * **parameters**,
  - * **interactions** ($\equiv$ Feynman rules).
- The Feynman rules **have to be derived (from a Lagrangian)**.
  - * Must be **translated in a programming language**.
  - * **Tedious, time-consuming, error prone**.
  - * We need to iterate for each considered model.
  - * We need to iterate for each considered MC tool.
  - * Beware: **allowed Lorentz and color structures**.
  - * Beware: **validation**.

Redundancies of the work.

A framework for LHC analyzes (3).

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



Outline

The FeynRules approach (1).

- **Starting from physical quantities**.
  * All the physics is included in the model **Lagrangian**.
    - ◇ The Lagrangian is **absent in the MC implementation**.
  * **Traceability.**
    - ◇ **Univocal definition of a model**.
    - ◇ **No dependence on the conventions used** by the MC tools.
  * **Flexibility.**
    - ◇ A modification of a model $\equiv$ change in the Lagrangian.

Aims.

* A **general environment** to implement any Lagrangian-based model.
* To interface **several Monte Carlo generators**.
* **Robustness, easy validation and maintenance**.
* Easy integration in **experimental software frameworks**.
* Allowing for both **top-down and bottom-up approaches**.

The FEYNRULES approach (2).

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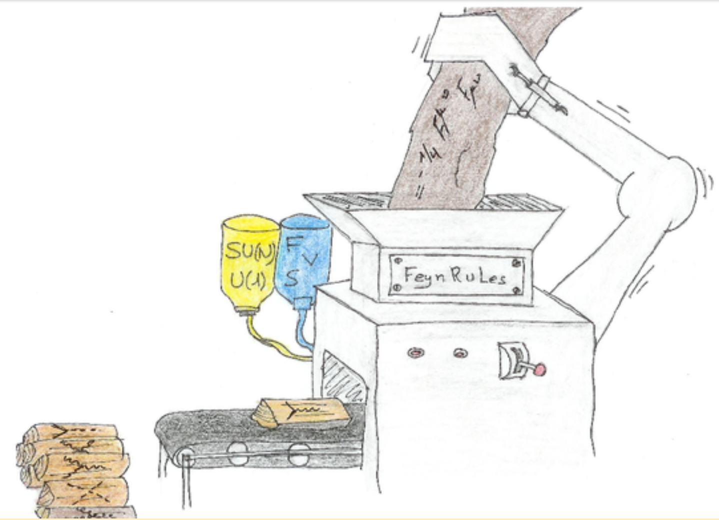
The FeynRules approach (3).



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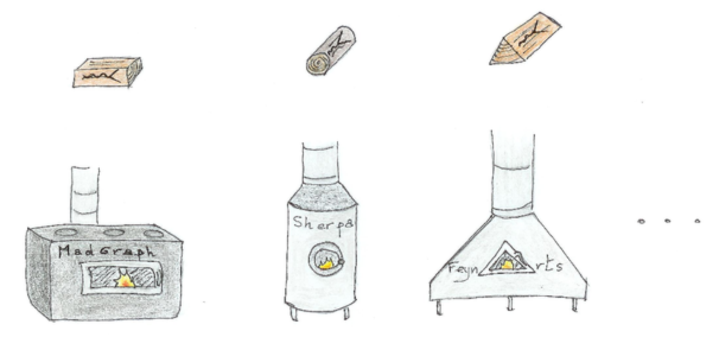
The FeynRules approach (4).

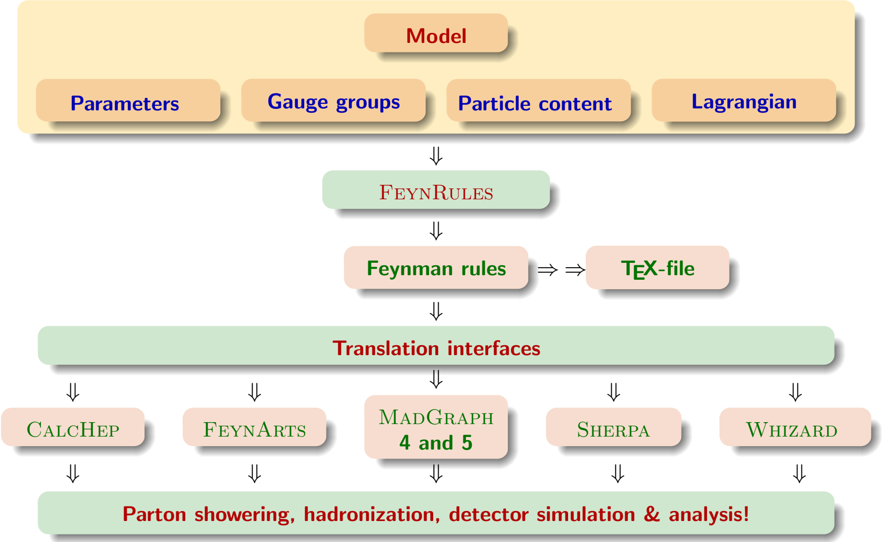


FeynRules in a nutshell.

[Christensen, Duhr (CPC '09); Christensen, Duhr, BenjF (in prep)]

- **A framework for LHC analyzes based on FeynRules to**:
  - * **Develop new models**.
  - * **Implement (and validate)** new models in Monte Carlo tools.
  - * Facilitate **phenomenological** investigations of the models.
  - * **Test** the models against data.
- **Main features**
  - * FeynRules is a Mathematica package.
  - * FeynRules derives **Feynman rules from a Lagrangian**.
  - * **Requirements**: locality, Lorentz and gauge invariance.
  - * **Supported fields**: scalar, fermion, vector, tensor, ghost, superfield.
  - * **Interfaces**: export the Feynman rules to Monte Carlo generators.

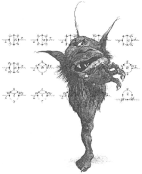
The FeynRules scheme.



Latest developments (1).

- **The UFO** [Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter CPC '12].
  - UFO ≡ Universal FeynRules output (**not tied** to any Monte Carlo tool).
  - Allows for **generic** color and Lorentz structures.
  - Used by MadGraph**5, GoSam and (in the future by)** Herwig**++**.
  - FeynRules interface: creates a Python **module** to be linked.
  - The module contains **all** the model information.
- **ALOHA** [de Aquino, Link, Maltoni, Mattelaer, Stelzer (2011)].
  - ALOHA ≡ Automatic Libraries Of Helicity Amplitudes.
  - Exports the UFO; **produces the related** Helas **routines** (C++/Python).
    ⇒ to be used for **Feynman diagram computations**.
  - Used by MadGraph**5** / as a standalone package.

Latest developments (2).



- **A superspace module for** FEYNRULES [Duhr, BenjF (CPC '11)].
  - * Full support for **Weyl fermions and superfields**.
  - * Series expansion in terms of **component fields**.
  - * **Automatic derivation** of supersymmetry-conserving Lagrangians.
  - * **Automatic solution** of the equations of motion for the auxiliaries.
  - * Can be used for **many calculations in superspace**.
- **A new** FEYNARTS **interface** [Degrande, Duhr].
  - * Allows for **generic** Lorentz structures.
  - * Creates both the **model dependent and independent** FEYNARTS files.
  - * New version of FORMCALC $\Rightarrow$ **multifermion interactions**.

FeynRules-1.6 - status.

- **Current public version: 1.6.0**.
  - * **To be download on http://feynrules.irmp.ucl.ac.be/**.
  - * Contains the **superspace module**.
  - * Contains the **UFO interface** $\Rightarrow$ MadGraph5, GoSam.
  - * Contains the new FeynArts **interface**.
  - * Interfaced to Whizard. [Christensen, Duhr, BenjF, Reuter, Speckner (2010)]
  - * Supports **color sextets**.
  - * Other interfaces: CalcHep/CompHep, MadGraph4, Sherpa.
  - * **Manual currently being updated** [Christensen, Duhr, BenjF (in prep)].
- **Current online model database**.
  - * **http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage/** .
  - * Standard Model and simple extensions (10).
  - * Supersymmetric models (4).
  - * Extra-dimensional models (4).
  - * Strongly coupled and effective field theories (4).

The top-down approach vs. the bottom-up approach (1).

- **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 ⇔ new Majorana state.

The top-down approach vs. the bottom-up approach (2).

- **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**.

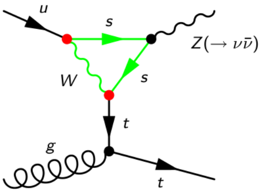
The bottom-up approach: we start from a signature.

Outline

Monotop production at the hadron colliders.

- **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:



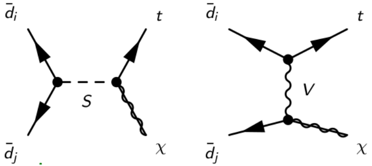
- **Observing monotops** $\Leftrightarrow$ **Beyond the Standard Model physics**.

Classes of models yielding monotop signatures (1).

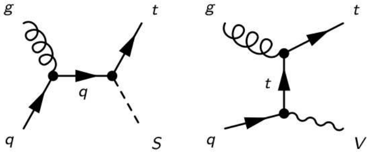
- **Main features of monotop signatures**.
  - * **Final state flavor** is fixed.
    - ◇ One top quark.
    - ◇ Missing energy.
      - ►Bosonic or fermionic state.
      - ►One particle or n-particle state.
      - ►Neutral, weakly-interacting, long-lived/stable/invisible.
  - * **Initial state possibilities**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

Classes of models yielding monotop signatures (2).

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



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



Chain of simulation tools.

Effective model

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

⇓

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

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Feynman rules

⇓

Translation ⇒ UFO files
[Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter, CPC '12]

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

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Parton-level analysis ⇒ conclusions.

Signal and background descriptions.

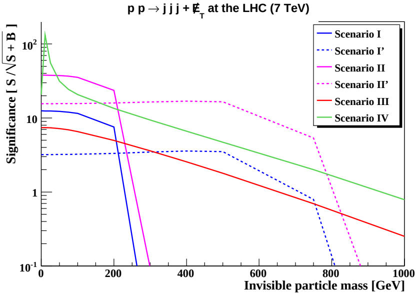
- **Signal**.
  - * **Leptonic top decay**.
    - ◇ Signature: **1 lepton + 1 b jet + missing energy**.
    - ◇ **No top mass reconstruction**.
    - ◇ **More challenging** ⇒ not considered.
  - * **Hadronic top decay**.
    - ◇ Signature: **2 light jets + 1 b jet + missing energy**.
    - ◇ The top is **fully reconstructed**.
- **Sources of background**.
  - * Z **(**$\rightarrow \nu\bar{\nu}$**) + 3 jets**.
    ►Irreducible background.
  - * **QCD multijet**.
    ►Misreconstructed jet $\rightarrow$ 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.

- **A proper analysis requires**:
  * **Parton showering**.
  * **Hadronization**.
  * **A proper detector simulation**.
  * **Data-driven methods for background estimation.**
  * This is a **prospective parton-level study.**
- **We rely on existing experimental studies at the LHC**.
  * CMS: JHEP **1108** (2011) 155.
  * 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**.

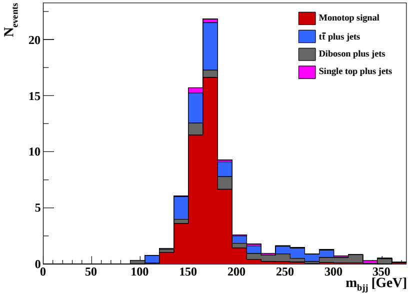
LHC sensitivity to monotop signatures at 10 fb^{-1}.



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.

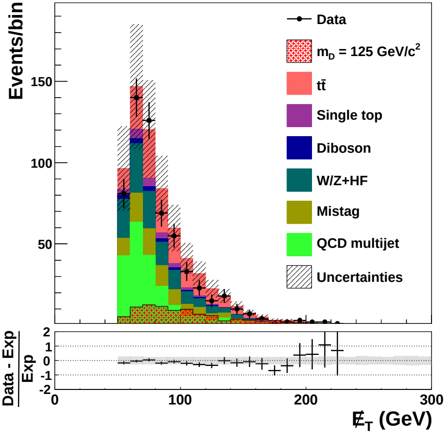


BenjF (to appear in MPLA).

Andrea, Conte, BenjF (in prep.).

- ***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 $\mathbf{fb}^{-1}$**.
  - ▶ **TeV scale squarks**
  - ▶ **Moderate RPV couplings**
  - ▶ **Possible discovery**.

From theory to data: CDF exclusions.



BenjF, CDF collaboration (submitted to PRL).

- **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.**

Outline

Multiple top quark production at hadron colliders.

- **PRoduction of four top quarks in the Standard Model**.
  - * **Phase-space suppressed**.
  - * Total cross section @ 7 TeV: 0.3 fb.

- **Multitop events (at a large rate)** $\Leftrightarrow$ **Beyond the Standard Model physics**.

- **Theoretical framework:** ***R*-symmetric supersymmetric models**.
  - * Predict a scalar color-octet field, the **sgluon**.
  - * **Strong couplings** to gluons.
  - * **Effective couplings** to quarks and gluons through squark loops.

- **Important production through usual gauge couplings.**

- **Decays to quark or gluon pairs.**

- **Benchmark scenarios.**
  - * Sgluon decays to an associated **top plus light jet** pair.
  - * Sgluon decays to a **top-antitop** pair.

Chain of simulation tools.

Effective model

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

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

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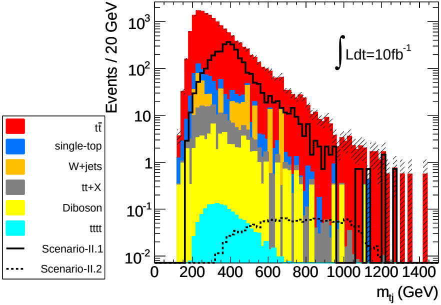
Pythia / Delphes ⇒ **Analysis.**

Signal and background descriptions.

- **Decay chain 1:** $pp \to \sigma\sigma \to tjtj, \bar{t}jtj, \bar{t}j\bar{t}j$.
- **Decay chain 2:** $pp \to \sigma\sigma \to t\bar{t}t\bar{t}$.
  - * **Two leptonic top decays**.
    - ◇ **2 (possibly same-sign) leptons + 2 b-jets + $\not{E}_T$ + jets**.
  - * **One leptonic top decay**.
    - ◇ **1 lepton + 1 b-jet + $\not{E}_T$ + jets**.
- **Sources of background**.
  - * **High multiplicity** final states.
    ►**Many jets** ($n \geq 4$).
    ►**Important hadronic energy**.
  - * **Main sources of background (after basic cuts).**
    - ◇ $t\bar{t}$ **plus jets**.
    - ◇ $t\bar{t} + V$ **plus jets**.
    - ◇ $t\bar{t} + VV$ **plus jets**.

LHC sensitivity to sgluon production at 10 fb^{-1}.



Calvet, BenjF, Gris, Renaud, Valery, Zerwas, LH'11.

- ***tjtj* channel; one lepton analysis.**
  - ►**One single lepton:** $\not{p}_T > 25$ **GeV**.
  - ►**Six jets:** $\not{E}_T > 25$ **GeV**.
  - ►**At least one** b**-tag**.
  - ►$\not{E}_T > 40$ **GeV**.
  - ►**Moderate** $M_T^W > 25$ **GeV**.
- **Sgluon scenarii**.
  - ►$m_\sigma = 400$ **or** $1000\,GeV$.
  - ►**BR(**$\sigma \to tj$**) = 100 %.**
- **Results for 10 fb**$^{-1}$.
  - ►Sensitivity: **334 and 228 fb**.

Outline.

Conclusions.

- **Simplified effective theory approach**.
  * **Monotop signatures**.
  * **Multitop signatures**.
- **Prospective phenomenological studies**.
  * Fast Monte Carlo studies.
  * Motivations for a complete full simulation.
  * Motivations for a data analysis.
  * **Well tested chain of tools**.
- **From the theory to the data**.

New interesting signatures?

► **Speak!**