New colored particle production at the NLO in QCD

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Outline

1. Framework for new physics event generation with MADGRAPH5_aMC@NLO

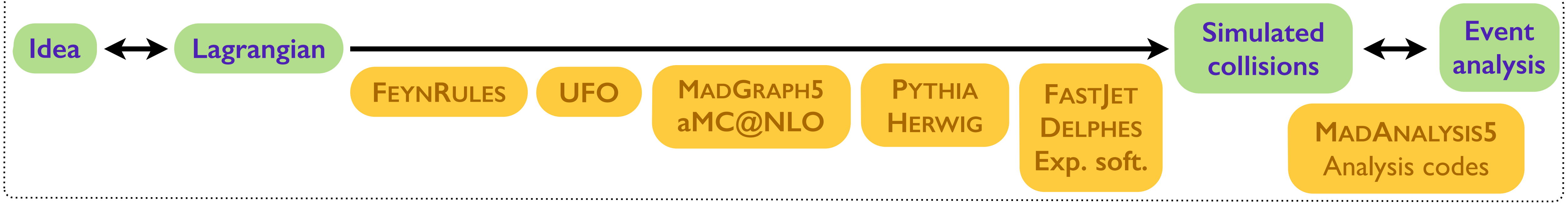
2. Stop and sgluon pair production at the next-to-leading order in QCD

3. Perspectives

Automated LO calculations with MadGraph5_aMC@NLO

✦ A comprehensive approach to Monte Carlo simulations

[Example based on FeynRules and MadGraph5_aMC@NLO]



Idea ↔ Lagrangian → Simulated collisions ↔ Event analysis

FeynRules

UFO

MadGraph5 aMC@NLO

Pythia Herwig

FastJet Delphes Exp. soft.

MadAnalysis5 Analysis codes

✦ Streamline the chain from the model Lagrangian to analyzed simulated collisions

✤ Works at the leading order

- ★ Implementation of the new physics Lagrangian into FeynRules [Alloul, Christensen, Degrande, Duhr & BF (CPC'14)]
- ★ Generation of a UFO model file [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
- ★ Import of the model into MadGraph5_aMC@NLO [Alwall, Frederix, Frixione, Hirschi, Mattelaer, Shao, Stelzer, Torrielli & Zaro (JHEP'14)]
- ★ Hard scattering process with MadGraph5_aMC@NLO
- ★ Matching to parton showering, multiparton matrix element merging, hadronization, detector simulation, *etc.*

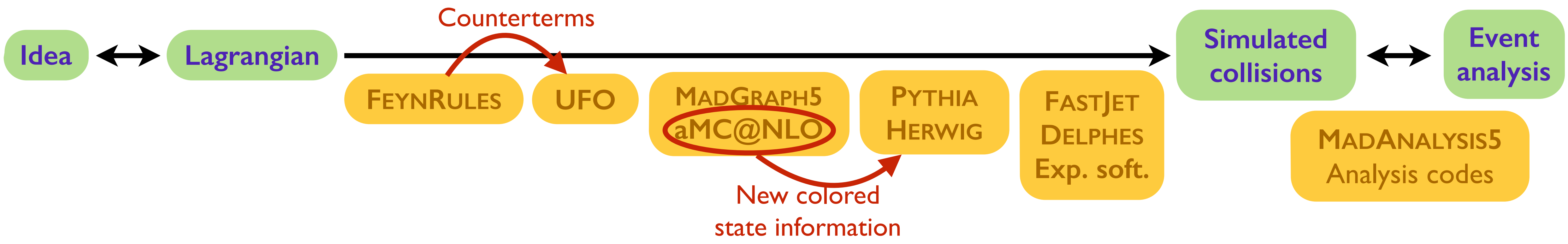
✤ Fully tested and validated in the context of large classes of new physics models

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

What about new physics event generation
at the next-to-leading order in QCD?

Automated NLO calculations with MadGraph5_aMC@NLO

✦ A comprehensive approach to Monte Carlo simulations



Counterterms

Idea ↔ Lagrangian → Simulated collisions ↔ Event analysis

FeynRules

UFO

MadGraph5 aMC@NLO

Pythia Herwig

FastJet Delphes Exp. soft.

MadAnalysis5 Analysis codes

New colored state information

✦ Streamline the chain from the model Lagrangian to analyzed simulated collisions

- ✤ FeynRules is linked to the NLOCT module [Degrande ('14)]
  - ★ Calculation of UV and R_2 counterterms
  - ★ Export of the information to the UFO
- ✤ Matching to parton showers
  - ★ Monte Carlo counterterms associated with the new colored states are included
  - ★ Restrictions on the parton shower code to employ (Pythia 8, Herwig++)

✦ Analytical and numerical validation: on-going

- ✤ BSM models will be released as soon as validated
  - ★ Starting point: simplified models
- ✤ Currently:
  - ★ one stop simplified model
  - ★ the sgluon simplified model

[http://feynrules.irmp.ucl.ac.be/wiki/NLOModels]

The stop simplified model: description

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15)]

✦ Motivations

- First use of FeynRules/aMC@NLO for a BSM model with an extended colored sector
- Simple: calculation of many quantities (UV & R_2, loop matrix elements, *etc.*) analytically
- Physics cases: stop searches with a t-tbar-met signature

✦ The stop (σ_3) / bino (χ) model

$$\mathcal{L}_3 = \underbrace{D_\mu\sigma_3^\dagger D^\mu\sigma_3 - m_3^2\sigma_3^\dagger\sigma_3}_{\text{Production}} \underbrace{+ \frac{i}{2}\bar\chi\not\partial\chi - \frac{1}{2}m_\chi\bar\chi\chi + \Big[\sigma_3\bar t(\tilde g_L P_L + \tilde g_R P_R)\chi + \text{h.c.}\Big]}_{\text{Decay}}$$

- One scalar field in the fundamental representation (σ_3)
- One gauge-singlet Majorana fermion (χ) coupling the stop to the top

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

- Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{96\pi^2}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$\delta Z_{\sigma_3} = 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_s^2 m_3^2}{12\pi^2}\left[\frac{3}{\bar\epsilon} + 7 - 3\log\frac{m_3^2}{\mu_R^2}\right]$$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar\epsilon}\left[\frac{n_f}{3} - \frac{11}{2}\right] + \frac{\alpha_s}{6\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_t^2}{\mu_R^2}\right] + \frac{\alpha_s}{24\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$R_2^{\sigma_3^\dagger\sigma_3} = \frac{ig_s^2}{72\pi^2}\delta_{c_1c_2}\Big[3m_3^2 - p^2\Big]$$

$$R_2^{g\sigma_3^\dagger\sigma_3} = \frac{53ig_s^3}{576\pi^2}T^{a_1}_{c_2c_3}\left(p_2 - p_3\right)^{\mu_1}$$

$$R_2^{gg\sigma_3^\dagger\sigma_3} = \frac{ig_s^4}{1152\pi^2}\eta^{\mu_1\mu_2}\left[3\delta^{a_1a_2} - 187\{T^{a_1},T^{a_2}\}\right]_{c_3c_4}$$

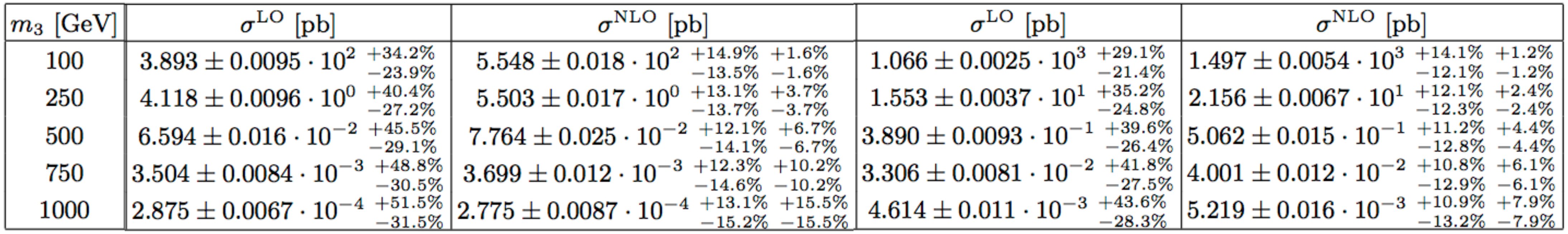
Neutralino couplings also checked
Unlike in full models, non-trivial behavior

The stop simplified model: total rates

[Degrande, BF, Hirschi, Proudom & Shao (to appear)]

✦ Total rates at 8 TeV and 13 TeV

Numerically validated



m_3 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$3.893 \pm 0.0095 \cdot 10^{2}\ {}^{+34.2\%}_{-23.9\%}$	$5.548 \pm 0.018 \cdot 10^{2}\ {}^{+14.9\%}_{-13.5\%}\ {}^{+1.6\%}_{-1.6\%}$	$1.066 \pm 0.0025 \cdot 10^{3}\ {}^{+29.1\%}_{-21.4\%}$	$1.497 \pm 0.0054 \cdot 10^{3}\ {}^{+14.1\%}_{-12.1\%}\ {}^{+1.2\%}_{-1.2\%}$
250	$4.118 \pm 0.0096 \cdot 10^{0}\ {}^{+40.4\%}_{-27.2\%}$	$5.503 \pm 0.017 \cdot 10^{0}\ {}^{+13.1\%}_{-13.7\%}\ {}^{+3.7\%}_{-3.7\%}$	$1.553 \pm 0.0037 \cdot 10^{1}\ {}^{+35.2\%}_{-24.8\%}$	$2.156 \pm 0.0067 \cdot 10^{1}\ {}^{+12.1\%}_{-12.3\%}\ {}^{+2.4\%}_{-2.4\%}$
500	$6.594 \pm 0.016 \cdot 10^{-2}\ {}^{+45.5\%}_{-29.1\%}$	$7.764 \pm 0.025 \cdot 10^{-2}\ {}^{+12.1\%}_{-14.1\%}\ {}^{+6.7\%}_{-6.7\%}$	$3.890 \pm 0.0093 \cdot 10^{-1}\ {}^{+39.6\%}_{-26.4\%}$	$5.062 \pm 0.015 \cdot 10^{-1}\ {}^{+11.2\%}_{-12.8\%}\ {}^{+4.4\%}_{-4.4\%}$
750	$3.504 \pm 0.0084 \cdot 10^{-3}\ {}^{+48.8\%}_{-30.5\%}$	$3.699 \pm 0.012 \cdot 10^{-3}\ {}^{+12.3\%}_{-14.6\%}\ {}^{+10.2\%}_{-10.2\%}$	$3.306 \pm 0.0081 \cdot 10^{-2}\ {}^{+41.8\%}_{-27.5\%}$	$4.001 \pm 0.012 \cdot 10^{-2}\ {}^{+10.8\%}_{-12.9\%}\ {}^{+6.1\%}_{-6.1\%}$
1000	$2.875 \pm 0.0067 \cdot 10^{-4}\ {}^{+51.5\%}_{-31.5\%}$	$2.775 \pm 0.0087 \cdot 10^{-4}\ {}^{+13.1\%}_{-15.2\%}\ {}^{+15.5\%}_{-15.5\%}$	$4.614 \pm 0.011 \cdot 10^{-3}\ {}^{+43.6\%}_{-28.3\%}$	$5.219 \pm 0.016 \cdot 10^{-3}\ {}^{+10.9\%}_{-13.2\%}\ {}^{+7.9\%}_{-7.9\%}$

8 TeV

13 TeV

- ✤ NNPDF2.3; scales set to the stop mass
- ✤ Agrees with PROSPINO [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]
- ✤ Scale varied by a factor of two up and down
- ✤ PDF variations obtained with the 100 NNPDF replica provided with the central set of densities

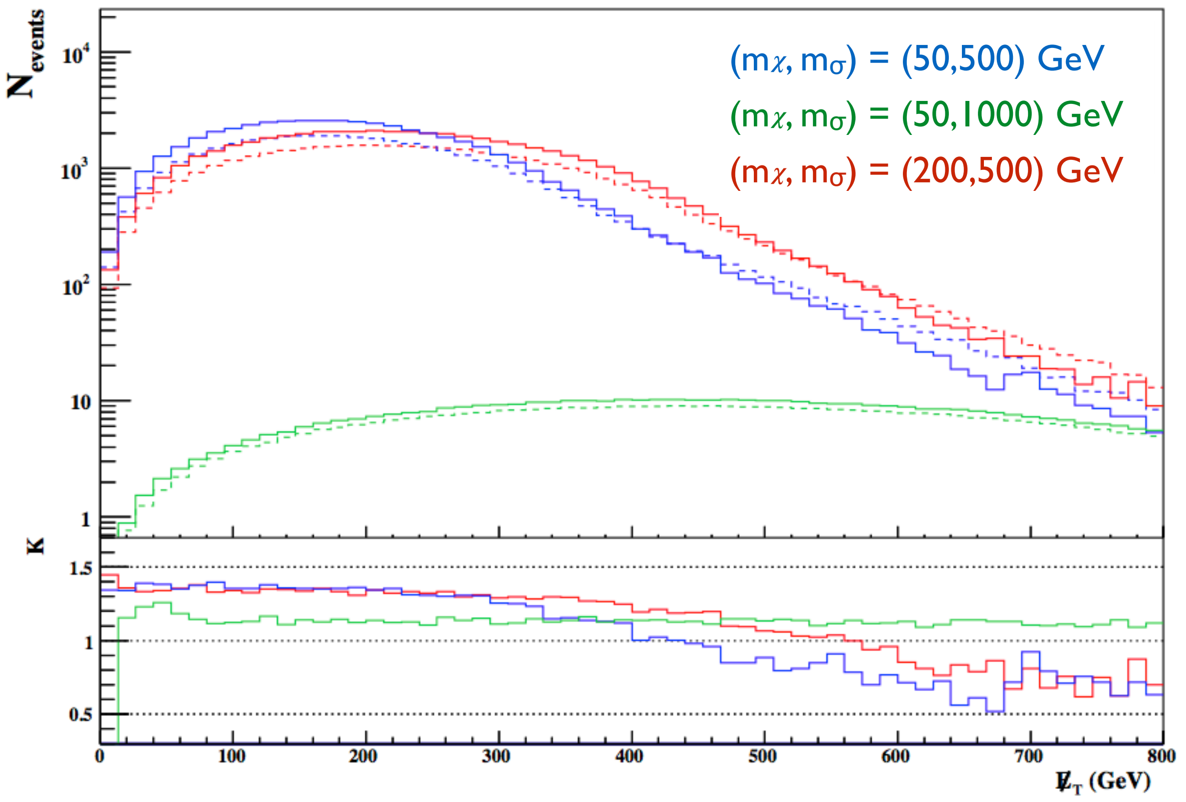
The stop simplified model: kinematical distributions

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15)]

✦ Differential distributions at NLO

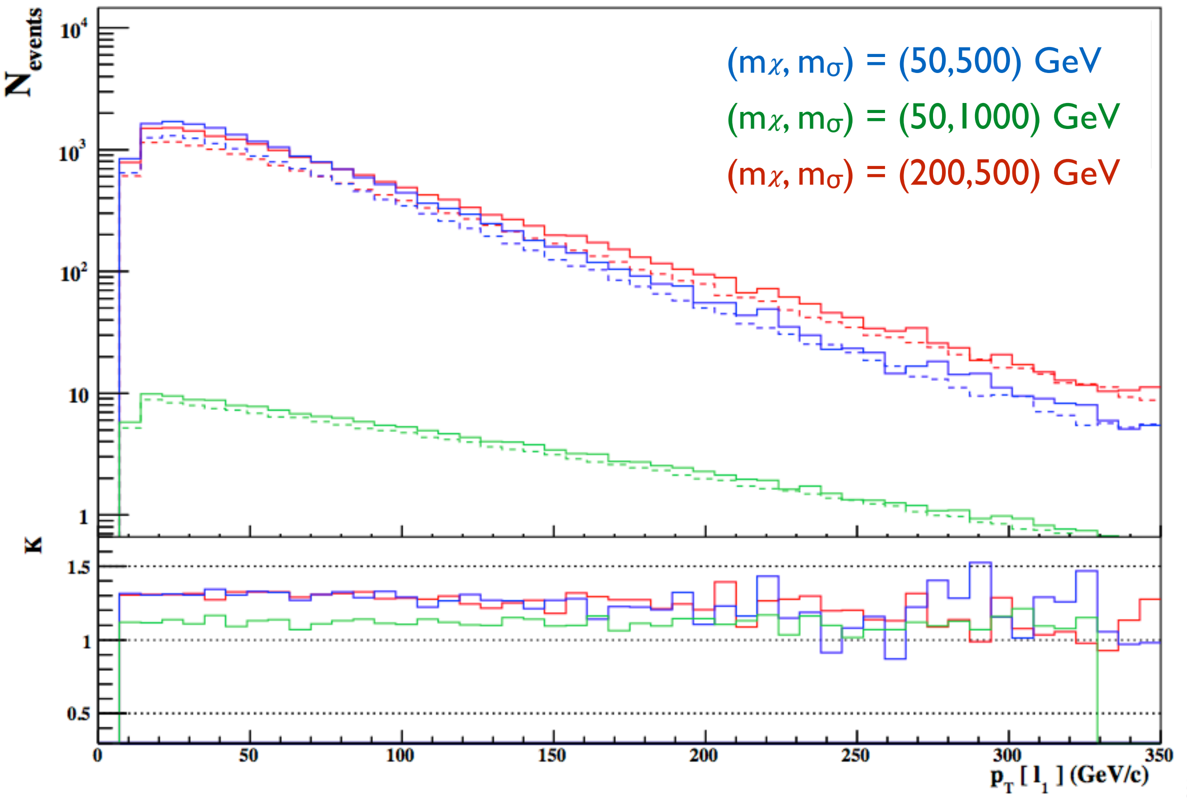
- Test case: 500/1000 GeV stop; 50/200 GeV bino; 13 TeV collisions
- Standard coupling strengths for a maximally mixing stop and a bino
- Shower: Pythia 8.2 [Sjostrand, Mrenna & Skands (CPC'08)]
- Jet reconstruction: anti-k_T & FastJet [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
- Analysis (single lepton case) & figures: MadAnalysis 5 [Conte, BF, Serret (CPC'13)]

Missing transverse energy



- ★ Constant *K*-factors not suitable
- ★ The K-factor is depending on the scenario

Leading lepton transverse momentum (single lepton signature)



- ★ Constant *K*-factors not suitable
- ★ The K-factor depends on the scenario

Validation: hundreds of figures (Root files) are available on the web

How are experimental results depending on the NLO effects?
[Internship of A. Molter]

The sgluon simplified model: description

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15)]

✦ Motivations

- First use of FEYNRULES/aMC@NLO for a BSM model with an extended colored sector
- Simple: calculation of many quantities (UV & R$_2$, loop matrix elements, *etc.*) analytically
- Physics cases: sgluon searches (relying on pair-production)

✦ The sgluon (σ_8) model

$$\mathcal{L}_8 = \underbrace{\frac{1}{2}D_\mu\sigma_8 D^\mu\sigma_8 - \frac{1}{2}m_8^2\sigma_8\sigma_8}_{\text{Production}} + \underbrace{\frac{\hat{g}_g}{\Lambda}\sigma_8 G_{\mu\nu}G^{\mu\nu} + \sum_{q=u,d}\Big[\sigma_8\bar{q}\big(\hat{g}^L_q P_L + \hat{g}^R_q P_R\big)q + \text{h.c.}\Big]}_{\text{Decay}}$$

- One scalar field in the adjoint representation (σ_8)
- Effective couplings ($\hat{g}$): only for the decay that is enforced to be at the leading order
- $\hat{g}$ couplings at NLO: a consistent effective theory is required for a proper renormalization

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

- Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{32\pi^2}\left[\frac{1}{\bar\epsilon} - \log\frac{m_8^2}{\mu_R^2}\right]$$

$$\delta Z_{\sigma_8} = 0 \quad \text{and} \quad \delta m_8^2 = -\frac{3g_s^2 m_8^2}{16\pi^2}\left[\frac{3}{\bar\epsilon} + 7 - 3\log\frac{m_8^2}{\mu_R^2}\right]$$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar\epsilon}\left[\frac{n_f}{3} - \frac{11}{2}\right] + \frac{\alpha_s}{6\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_t^2}{\mu_R^2}\right] + \frac{\alpha_s}{8\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_8^2}{\mu_R^2}\right]$$

$$\begin{aligned}
R_2^{\sigma_8\sigma_8} &= \frac{ig_s^2}{32\pi^2}\delta_{a_1a_2}\Big[3m_8^2 - p^2\Big]\\
R_2^{g\sigma_8\sigma_8} &= \frac{7g_s^3}{64\pi^2}f_{a_1a_2a_3}\left(p_2 - p_3\right)^{\mu_1}\\
R_2^{gg\sigma_8\sigma_8} &= \frac{ig_s^4}{384\pi^2}\eta^{\mu_1\mu_2}\Big[72(d_{a_1a_4e}d_{a_2a_3e} + d_{a_1a_3e}d_{a_2a_4e})\\
&\qquad - 141d_{a_1a_2e}d_{a_3a_4e} - 92\delta_{a_1a_2}\delta_{a_3a_4}\\
&\qquad + 50(\delta_{a_1a_3}\delta_{a_2a_4} + \delta_{a_1a_4}\delta_{a_2a_3})\Big]
\end{aligned}$$

The sgluon simplified model: results

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15)]

✦ Total rates at 8 TeV and 13 TeV

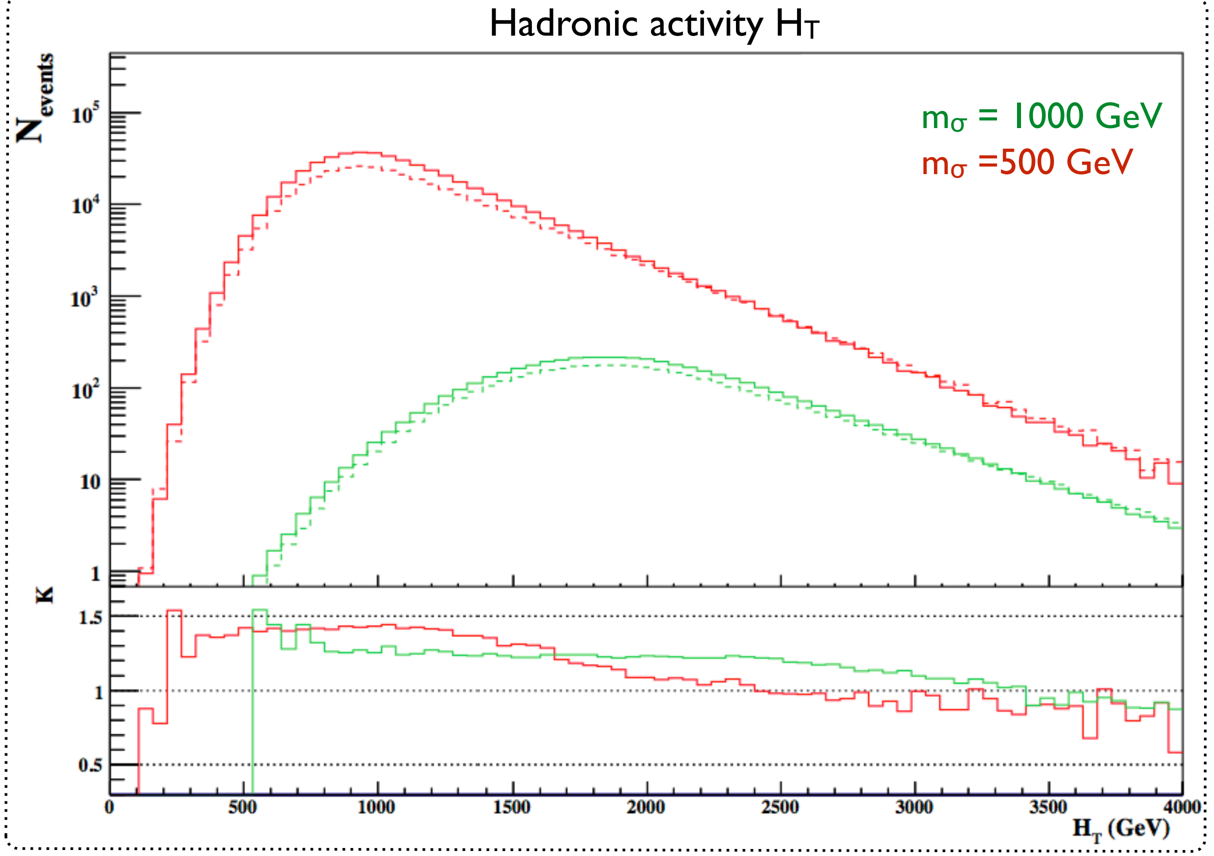
Numerically validated

m_8 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$3.854 \pm 0.0094 \cdot 10^{3}\ ^{+34.4\%}_{-24.1\%}$	$5.573 \pm 0.02 \cdot 10^{3}\ ^{+14.9\%}_{-13.6\%}\ ^{+1.6\%}_{-1.6\%}$	$1.056 \pm 0.0029 \cdot 10^{4}\ ^{+29.2\%}_{-21.5\%}$	$1.470 \pm 0.0058 \cdot 10^{4}\ ^{+13.6\%}_{-11.9\%}\ ^{+1.2\%}_{-1.2\%}$
250	$3.889 \pm 0.010 \cdot 10^{1}\ ^{+41.3\%}_{-27.7\%}$	$5.432 \pm 0.019 \cdot 10^{1}\ ^{+14.5\%}_{-14.6\%}\ ^{+3.9\%}_{-3.9\%}$	$1.504 \pm 0.0034 \cdot 10^{2}\ ^{+35.7\%}_{-25.1\%}$	$2.145 \pm 0.0077 \cdot 10^{2}\ ^{+12.9\%}_{-12.9\%}\ ^{+2.5\%}_{-2.5\%}$
500	$5.878 \pm 0.015 \cdot 10^{-1}\ ^{+47.6\%}_{-30.0\%}$	$7.431 \pm 0.028 \cdot 10^{-1}\ ^{+15.8\%}_{-16.2\%}\ ^{+7.6\%}_{-7.6\%}$	$3.619 \pm 0.0079 \cdot 10^{0}\ ^{+40.8\%}_{-27.0\%}$	$4.977 \pm 0.018 \cdot 10^{0}\ ^{+13.3\%}_{-14.1\%}\ ^{+4.7\%}_{-4.7\%}$
750	$2.977 \pm 0.0073 \cdot 10^{-2}\ ^{+52.0\%}_{-31.9\%}$	$3.353 \pm 0.012 \cdot 10^{-2}\ ^{+17.2\%}_{-17.3\%}\ ^{+12.1\%}_{-12.1\%}$	$2.951 \pm 0.0065 \cdot 10^{-1}\ ^{+43.6\%}_{-28.4\%}$	$3.817 \pm 0.015 \cdot 10^{-1}\ ^{+14.0\%}_{-14.8\%}\ ^{+6.9\%}_{-6.9\%}$
1000	$2.328 \pm 0.0058 \cdot 10^{-3}\ ^{+55.9\%}_{-33.4\%}$	$2.398 \pm 0.0099 \cdot 10^{-3}\ ^{+19.0\%}_{-18.4\%}\ ^{+19.1\%}_{-19.1\%}$	$3.983 \pm 0.0087 \cdot 10^{-2}\ ^{+46.1\%}_{-29.5\%}$	$4.822 \pm 0.017 \cdot 10^{-2}\ ^{+15.1\%}_{-15.6\%}\ ^{+9.3\%}_{-9.3\%}$

8 TeV

13 TeV

- ✤ NNPDF2.3; scales set to the sgluon mass; uncertainties evaluated as for the stop case
- ✤ Validation with MADGOLEM
  - ★ Discrepancy of a 1-3 % for central scale choices; larger for other scale setups
  - ★ MADGOLEM is overestimating the numerical uncertainties



✦ Differential distributions at NLO

- ✤ Test case: 500/1000 GeV sgluons; 13 TeV collisions
- ✤ Tetratop decays
- ✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands (CPC'08)]
- ✤ Jet reconstruction: anti-k_T & FASTJET
  [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
- ✤ Analysis & figure: MADANALYSIS 5
  [Conte, BF, Serret (CPC'13)]

★ Constant *K*-factors not suitable
★ The K-factor is depending on the scenario

(Re-)starting now…

✦ aMC@NLO is ready for NLO simulations of simplified models

- ✤ Stop/sgluon models available
- ✤ Gluino and SUSY-QCD on their way
  - ★ Gluino tests (started last week): first matching of gluon production at NLO to parton showers!
  - ★ OS subtraction (ready?)
- ✤ Electroweakinos: easy
- ✤ Goal: Full MSSM, NMSSM (including ggH vertices)

[Degrande, BF, Hirschi, Proudom & Shao]
[BF, Hirschi & Mattelaer]

✦ Phenomenology

- ✤ Recasting LHC results with NLO predictions [Ambrogi, BF, Kulkarni & Molter]
- ✤ Single sgluon production at the NLO [BF, Maltoni, Mawatari & Tziveloglou]
- ✤ R-parity violating supersymmetry and monotops [Cacciapaglia, Deandrea, BF, Proudom & Shao]
- ✤ Vector like top partners (on the Les Houches to-do list) [Basso, Cacciapaglia, Deandrea & BF]