Next-to-leading order predictions matched to parton showers for new physics

Fuks Benjamin

LPTHE - CNRS - UPMC

Theory seminar @ Fermilab

16 December 2015

Outline

New physics at the LHC

✦ The quest for physics beyond the Standard Model at the LHC has started!

- How to get hints of new physics?
  - ★ Confront data to the Standard Model expectation in search channels
  - ★ Observe unexplained deviations at a good confidence level
- Nature of non standard effects?
  - ★ Fitting deviations by new physics signals
  - ★ Leading order Monte Carlo tools and techniques do a proper job
  - ★ Reinterpretation of the signals in different theoretical frameworks
- Final words on the nature of new physics
  - ★ Accurate measurements of the model parameters
  - ★ The most precise predictions are mandatory

Predictions at the LHC using QCD

- Distribution of an observable ω at hadron colliders
  - Predictions relies on the QCD factorization theorem

$$\frac{d\sigma}{d\omega} = \sum_{ab} \int dx_a \, dx_b \, \mathbf{f_{a/p_1}}(x_a;\mu_F) \, \mathbf{f_{b/p_2}}(x_b;\mu_F) \, \frac{d\sigma_{\mathbf{ab}}}{d\omega}(\dots,\mu_F)$$

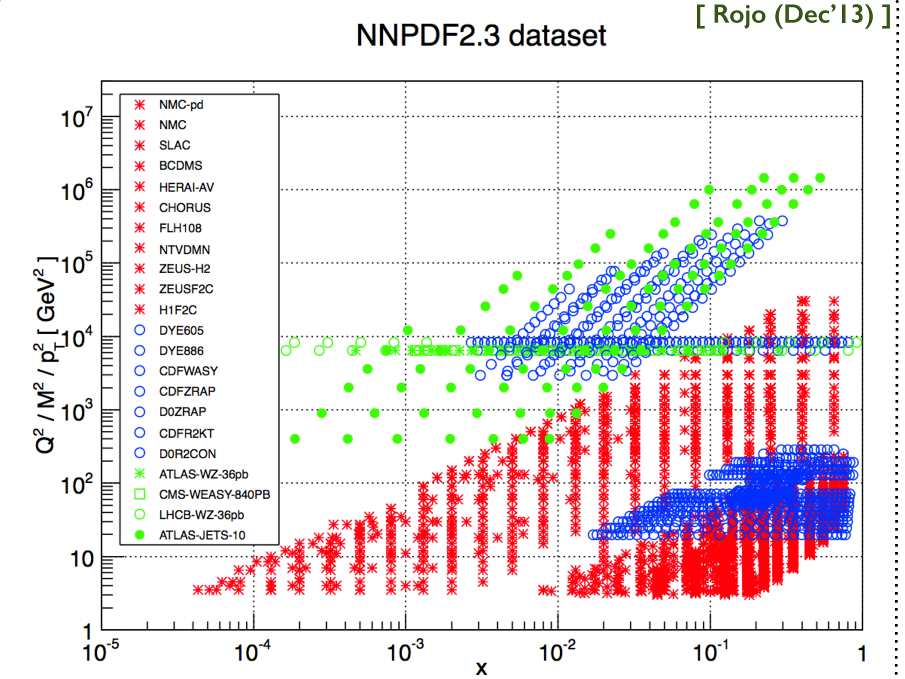
  - Long distance physics: the parton densities
  - Short distance physics: the differential parton cross section $d\sigma_{ab}$
  - Separation of both regimes through the factorization scale μ_F
    - ★ Choice of the scale: theoretical uncertainties on the predictions

The QCD factorization theorem

✦ Long distance physics: parton densities

- ✤ Relate the colliding hadrons to their content
- ✤ Depend on the momentum fraction *x* of the parton in the proton and on a scale *Q*
- ✤ Fitted from experimental data in some kinematical regimes (*x*,*Q*)
- ✤ QCD evolution (DGLAP/BFKL equations)

[Rojo (Dec'13)]



✦ Short distance physics: the partonic cross section

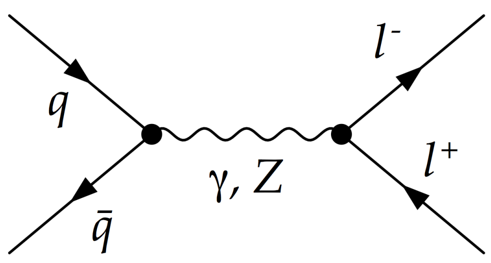
- ✤ Can be calculated order by order in perturbative QCD: $d\sigma = d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)} + \ldots$
  - ★ The more orders included, the more precise are the predictions
  - ★ α_s is also series-expanded (renormalization scale dependence)
  - ★ Truncation of the series and α_s: theoretical uncertainties on the predictions

Fixed-order predictions (1)

✦ Leading-order (LO): $d\sigma \approx d\sigma^{(0)}$

- ✤ Easily calculable
  - ★ Automated for any theory and any process (MADGRAPH, *etc.*)
- ✤ Very naive
  - ★ Rough estimate for many observables (large uncertainties)
  - ★ Cannot be used for any observable (e.g., dilepton p_T)

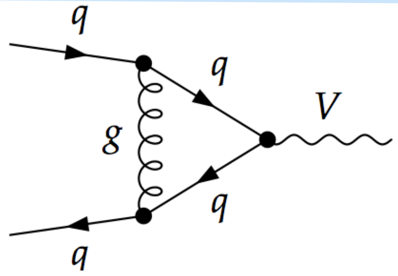
The Drell-Yan example



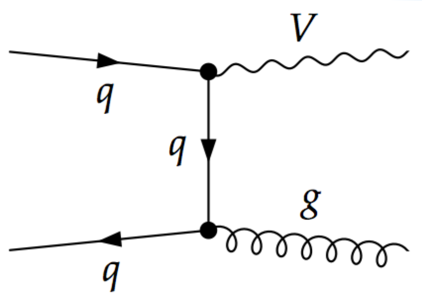
✦ Next-to-leading-order (NLO): $d\sigma \approx d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)}$

- ✤ Two contributions: virtual loop and real emission
  - ★ Both divergent
  - ★ The sum is finite (KLN theorem)
- ✤ Reduction of the theoretical uncertainties
  - ★ First order where loops compensate the scale dependence
- ✤ Better description of the process
  - ★ Impact of extra radiation
  - ★ More initial states included
  - ★ Sometimes not precise enough

The Drell-Yan example:
Representative virtual

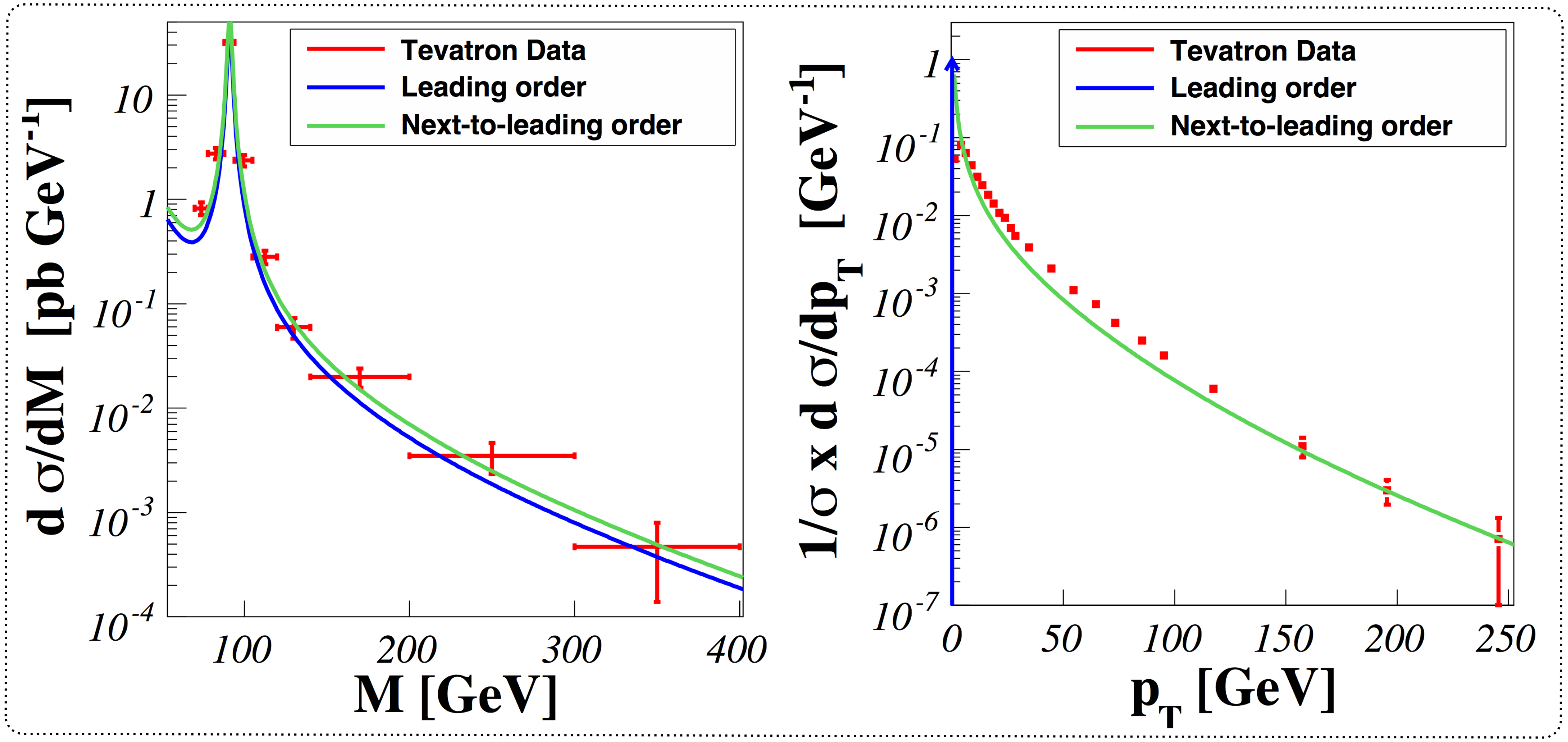


Representative real



Fixed-order predictions (2)

✦ Tevatron predictions and data



- ✤ Fair agreement for the invariant-mass spectrum both at LO and NLO
- ✤ Transverse-momentum spectrum
  - ★ The NLO is actually the LO…
  - ★ Divergent predictions at small p_T; underestimation at medium p_T

Improving the predictions

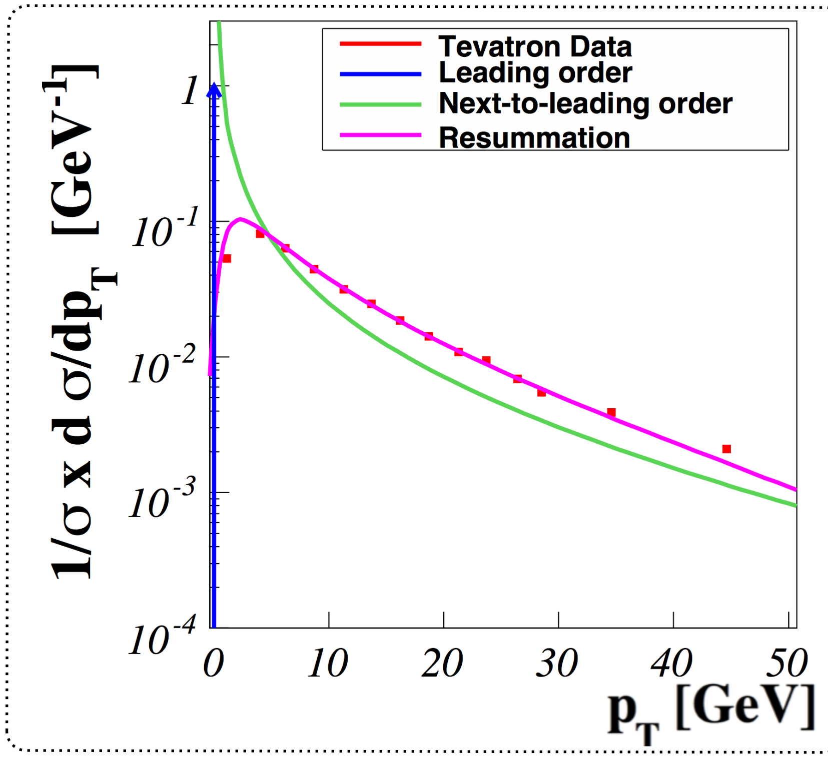
✦ Improving the NLO results

- ✤ NLO calculations involve logarithmic terms
  - ★ Related to soft and collinear radiation
  - ★ Can be large in some phase space regions
  - ★ Spoil the convergence of the perturbative series
- ✤ Matching with parton showers
  - ★ Resummation of the soft and collinear radiation
  - ★ Predictions of fully exclusive description of collisions
  - ★ Suitable for going beyond the parton level (hadronization, detector simulation)

Need for NLO
Monte Carlo generators

✦ Back to the Drell-Yan example @ the Tevatron

- ✤ Confronting resummed spectra and data
  - ★ Very good agreement
  - ★ Resummation cures fixed-order instabilities



Outline

1. Need for precision Monte Carlo event generators

2. **Automating NLO calculations in QCD with MADGRAPH5_aMC@NLO**

3. Stop pair-production at the LHC

4. Supersymmetric QCD @ NLO

5. Summary - conclusions

NLO calculations in a nutshell

✦ Contributions to an NLO result in QCD

✤ Three ingredients: the Born, virtual loop and real emission contributions

$$\sigma_{NLO} = \int d^4\Phi_n \mathcal{B} + \int d^4\Phi_{n+1} \mathcal{R} + \int d^4\Phi_n \mathcal{V}$$

Born

Reals: one extra power of α_s and divergent

Virtuals: one extra power of α_s and divergent

✤ KLN theorem: the divergences cancel for infrared-safe observables

★ If no distinction between soft-and-collinear emission from the no-emission case

How to compute the real and virtual pieces with MADGRAPH5_aMC@NLO?

The virtual contributions

✦ Loop diagram calculations

✤ Calculations done in *d=4-2ε* dimensions

★ Divergences made explicit ($1/\varepsilon^2$, $1/\varepsilon$)

✤ Loop integral rewritten with scalar integrals

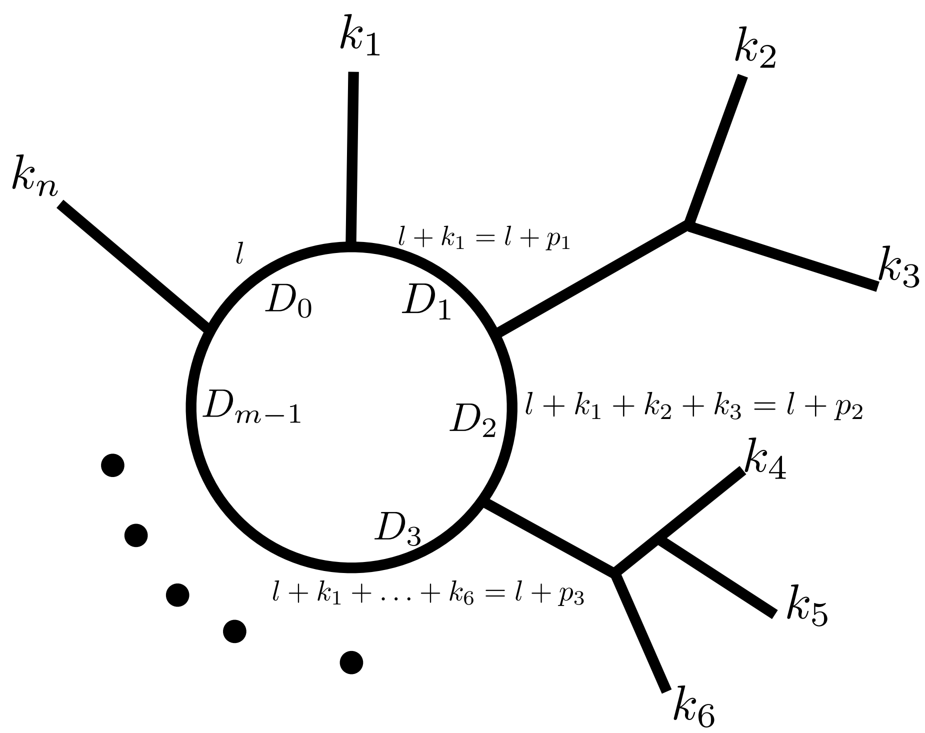
$$\int d^d l \frac{N(l)}{D_0 D_1 \ldots D_{m-1}} = \sum \text{coeff}_i \int d^d l \frac{1}{D_{i_0} D_{i_1} \ldots}$$

★ Involves integrals with up to four denominators

★ The decomposition basis is finite

★ The coefficients depend on the external momenta

m-point diagram with *n* external momenta



✤ The Ossala-Papadopoulos-Pittau (OPP) technique [Ossala, Papadopoulos, Pittau (NPB'07)]

★ Reduction made at the level of the integrand

★ Used in MadLoop (the loop module of aMC@NLO) [Hirschi *et al.* (JHEP'11)]

The Ossala-Papadopoulos-Pittau technique (I)

✦ Apparition of spurious terms in the reduction

✤ An integral equality does not mean an integrand equality

$$\int d^d l \frac{N(l)}{D_0 D_1 \dots D_{m-1}} = \sum \mathrm{coeff}_i \int d^d l \frac{1}{D_{i_0} D_{i_1} \dots} \quad \not\Rightarrow \quad \frac{N(l)}{D_0 D_1 \dots D_{m-1}} = \sum \mathrm{coeff}_i \, \frac{1}{D_{i_0} D_{i_1} \dots}$$

✤ Spurious terms appears

$$\frac{N(l)}{D_0 D_1 \dots D_{m-1}} = \sum \left(\mathrm{coeff}_i + \mathrm{spurious}_i(l)\right) \frac{1}{D_{i_0} D_{i_1} \dots}$$

★ Their integral vanishes

★ Their momenta dependence is known [del Aguila, Pittau (JHEP'04)]

✤ The integrand numerator can be decomposed

$$N(l) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0 i_1 i_2 i_3} + \tilde{d}_{i_0 i_1 i_2 i_3}(l)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i + \sum_{i_0<i_1<i_2}^{m-1} \left[c_{i_0 i_1 i_2} + \tilde{c}_{i_0 i_1 i_2}(l)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b_{i_0 i_1} + \tilde{b}_{i_0 i_1}(l)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i + \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i \neq i_0}^{m-1} D_i + \tilde{P}(l) \prod_i D_i + \mathcal{O}(\varepsilon)$$

The Ossala-Papadopoulos-Pittau technique (2)

- The numerator is computed from specific choices for the loop momentum

$$N(l) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0 i_1 i_2 i_3} + \tilde{d}_{i_0 i_1 i_2 i_3}(l)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i + \sum_{i_0<i_1<i_2}^{m-1} \left[c_{i_0 i_1 i_2} + \tilde{c}_{i_0 i_1 i_2}(l)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b_{i_0 i_1} + \tilde{b}_{i_0 i_1}(l)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i + \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i\neq i_0}^{m-1} D_i + \tilde{P}(l) \prod_i D_i + \mathcal{O}(\varepsilon)$$

  - One chooses l^μ so that several denominators vanish
  - The equation simplifies
  - One gets a system of equations to (numerically) solve

- OPP at works
  - For each phase-space point, the system must be solved
  - Example for a box diagram, there are typically 50 equations to solve

OPP - the rational terms (1)

- The loop momentum lives in a *d*-dimensional space
  - The OPP decomposition must be done in *d* dimensions

$$\int d^d l \frac{N(l,\tilde{l})}{\bar{D}_0 \bar{D}_1 \ldots \bar{D}_{m-1}} \quad \text{with} \quad \underbrace{\bar{l}}_{d\text{-dim}} = \underbrace{l}_{\text{4-dim}} + \underbrace{\tilde{l}}_{(-2\varepsilon)\text{-dim}}$$

  - Need for rational terms (that finds their origin in the ultraviolet): the R_1 and R_2 terms

- The R_1 terms originates from the denominator

$$\frac{1}{\bar{D}_i} = \frac{1}{D_i}\left(1 - \frac{\tilde{l}^2}{D_i}\right)$$

  - The denominator structure in the reduction is known
  - These terms can be calculated generically

$$\int d^d l \frac{\tilde{l}^2}{\bar{D}_i \bar{D}_j} = -\frac{i\pi^2}{2}\left[m_i^2 + m_j^2 - \frac{(p_i - p_j)^2}{2}\right] + \mathcal{O}(\varepsilon)$$

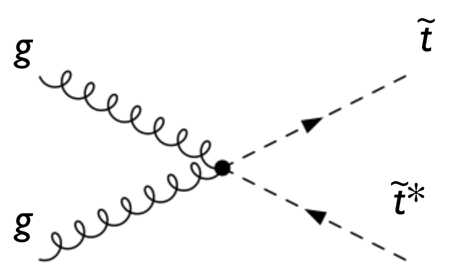
$$\int d^d l \frac{\tilde{l}^2}{\bar{D}_i \bar{D}_j \bar{D}_k} = -\frac{i\pi^2}{2} + \mathcal{O}(\varepsilon)$$

$$\int d^d l \frac{\tilde{l}^2}{\bar{D}_i \bar{D}_j \bar{D}_k \bar{D}_l} = -\frac{i\pi^2}{6} + \mathcal{O}(\varepsilon)$$

OPP - the rational terms (2)

- The R_2 terms originates from the numerator
  - Contributions proportional to $\tilde{l}^2$ can arise
  - Process dependent ➢ cannot be included directly in the OPP reduction formula
  - In a renormalizable theory, there is a finite number of such R_2 pieces
    - ★ They can be calculated once and for all for a specific model
    - ★ They can be casted under the form of R_2 counterterm Feynman rules

Example: g-g-t̃-t̃* vertex



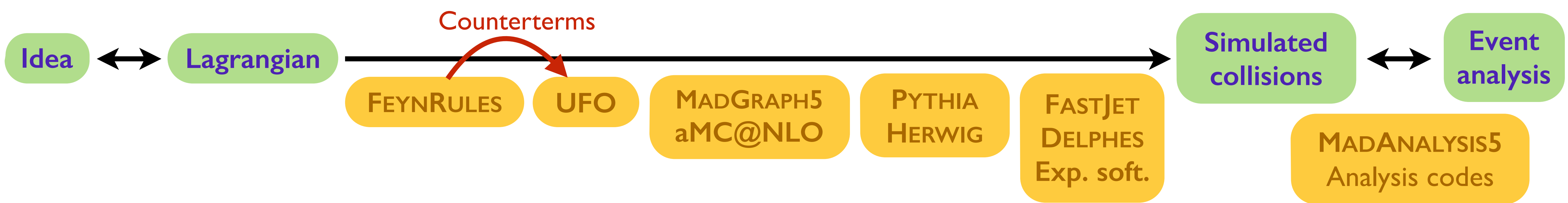
$$\frac{i g_s^4}{1152\pi^2}\eta^{\mu_1\mu_2}\left[3\delta^{a_1a_2} - 187\{T^{a_1}, T^{a_2}\}\right]$$

- The R_2 calculation for a model has been automated in NLOCT [Degrande (CPC'15)]
  - Included in UFO model files [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)] [Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]
  - NLOCT also renormalize the theory and include the UV counterterms in the UFO
    - ★ On-shell or $\overline{\text{MS}}$ schemes only

Automating NLO event generation

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

✦ A comprehensive approach to Monte Carlo simulations



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

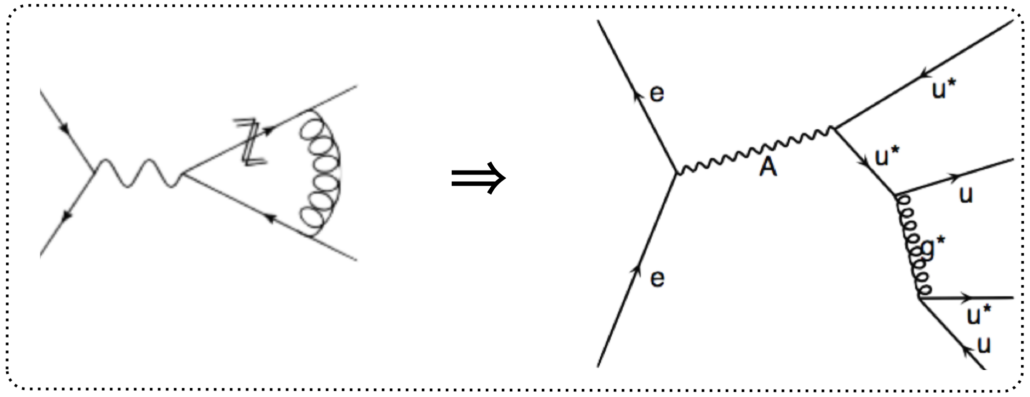
✤ FEYNRULES is linked to the NLOCT module [Alloul, Christensen, Degrande, Duhr & BF (CPC'14); Degrande (CPC'15)]

★ Calculation of UV and R_2 counterterms [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]

★ Export of the information to the UFO [Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

Loop calculations with MadLoop

- MadLoop uses MadGraph tree-level capabilities for loop calculations
  - Loop-diagrams with *n* external legs are cut: tree-level diagrams with *n*+2 external legs



    - ★ All diagrams with 2 extra parton in the final states are generated
    - ★ A first filter removes the non-necessary ones (including permutations, mirror graphs, *etc.*)
    - ★ A second filter removes the external line tadpoles and bubbles graphs

- MadLoop then calculates the virtual contributions
  - Contraction with Born diagrams, color traces calculated, … performed
  - Internal propagator denominators are removed
    - ★ We have the loop integrand numerator
    - ★ The OPP method is used for its evaluation
  - UV and R_2 counterterm diagrams added

Infrared divergences (I)

✦ Properties of the NLO cross section

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \; \mathcal{B} + \int \mathrm{d}^d\Phi_{n+1} \; \mathcal{R} + \int \mathrm{d}^4\Phi_n \int_{\mathrm{loop}} \mathrm{d}^d\ell \; \mathcal{V}$$

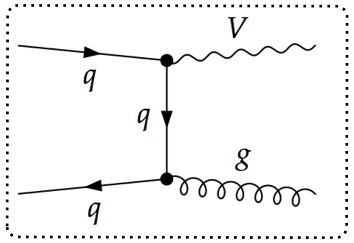
- ✤ All the individual pieces are infrared-divergent
  - ★ Issues for a numerical code
- ✤ The sum is finite (KLN theorem)
  - ★ The divergences have the same origin and cancel
  - ★ Numerically, their cancellation must be dealt explicitly
  - ★ Introduction of a subtraction method

Infrared divergences (2)

✦ Divergences are related to soft and collinear radiation

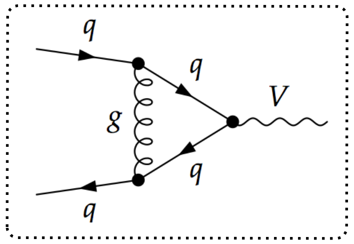
- Real emission (in the soft limit)

$$iM \approx g_s T^a \left[\frac{\epsilon^* \cdot k_2}{k_2^0 \mathbf{k_g^0}(\mathbf{1} + \cos\theta)} - \frac{k_1 \cdot \epsilon^*}{k_1^0 \mathbf{k_g^0}(\mathbf{1} - \cos\theta)}\right] \mathbf{iM}^{\mathrm{Born}}$$



- Virtual corrections (in the soft limit)

$$iM \approx (i\, g_s^2) \int \mathrm{d}k_g \frac{k_1 \cdot k_2}{k_g^2\, (k_1^0 \mathbf{k_g^0}(\mathbf{1} - \cos\theta))(k_2^0 \mathbf{k_g^0}(\mathbf{1} + \cos\theta))} \mathbf{iM}^{\mathrm{Born}}$$



- If we cannot distinguish the “no branching” from the “soft-collinear emission” case
  - ★ Cancellation occurs
  - ★ Infrared safety: observables are not sensitive to soft-collinear emissions

✦ Structure of the poles

- Real emission: poles appears after integration over the *d*-dimensional phase space
- Virtual contributions: in dimensional regularization, the poles appears as poles in the regularization parameter

Subtraction methods

✦ Subtracting the poles

- The structure of the poles is known ➢ subtraction methods

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \, \mathcal{B} + \int \mathrm{d}^4\Phi_{n+1} \Big[\mathcal{R} - \mathcal{C}\Big] + \int \mathrm{d}^4\Phi_n \Big[\int_{\rm loop} \mathrm{d}^d\ell \, \mathcal{V} + \int \mathrm{d}^d\Phi_1 \mathcal{C}\Big]$$

- The subtraction terms $\mathcal{C}$ contains the pole structure
  - ★ Subtracted from the reals ➢ makes them finite
  - ★ Added back to the virtuals ➢ makes them finite
  - ★ All individual pieces are finite
  - ★ Integrals can be made numerically in four dimensions

✦ Choice of the subtraction terms

- Must match the infrared structure of the real
- Should be integrable over the one-body phase space conveniently
  - ★ To get the soft and collinear pieces of the virtuals
- Should be integrable numerically conveniently

The Frixione-Kunszt-Signer subtraction (1)

[Frixione, Kunszt, Signer (NPB'96)]

✦ Division of the phase space

- ✤ Decomposition of the matrix element: at most one singularity per term

  $\mathrm{d}\sigma^{(n+1)} = \sum_{ij} \mathcal{S}_{ij} \mathrm{d}\sigma_{ij}^{(n+1)}$ where *(i,j)* denotes a parton pair that yields an IR divergence

- ✤ The behavior of $\mathcal{S}_{ij}$ is such that:
  - ★ $\mathcal{S}_{ij} \to 1$ if the partons *i* and *j* are collinear
  - ★ $\mathcal{S}_{ij} \to 1$ if the partons *i* is soft
  - ★ $\mathcal{S}_{ij} \to 0$ for all other infrared limits

The Frixione-Kunszt-Signer subtraction (2)

[Frixione, Kunszt, Signer (NPB'96)]

✦ The FKS formula

✤ The infrared (IR) singularities are separated

$$\mathrm{d}\sigma^{(n+1)} = \sum_{ij} \mathcal{S}_{ij} \mathrm{d}\sigma_{ij}^{(n+1)}$$

✤ The divergent behaviour of σ_{ij} reads

$$\mathrm{d}\sigma_{ij}^{(n+1)} \propto \frac{1}{E_i^2}\,\frac{1}{1-\cos\theta_{ij}} \propto \frac{1}{\xi_i^2}\,\frac{1}{1-y_{ij}} \quad \text{with} \quad \begin{aligned} \xi_i &= E_i\sqrt{\hat{s}} \\ y_{ij} &= \cos\theta_{ij} \end{aligned}$$

Controls the soft pieces

Controls the collinear pieces

✤ This naturally defines the divergence-free quantity

$$\mathrm{d}\sigma_{ij}^{(n+1)} = \left[\frac{1}{\xi_i}\right]_c \left[\frac{1}{1-y_{ij}}\right]_\delta \left[\xi_i^2(1-y_{ij})\left|M_{ij}^{(n+1)}\right|^2\right] \mathrm{d}\xi_i \mathrm{d}y_{ij} \mathrm{d}\phi_i \mathrm{d}\Phi_n^{ij}$$

Regulators: "plus-distribution"

No more IR divergencies

Factorized phase space

✤ The regulators introduce two free parameters (δ and $\xi_{\rm cut}$) and are defined as

$$\int_0^{\xi_{\max}} d\xi_i f(\xi_i) \left(\frac{1}{\xi_i}\right)_c = \int_0^{\xi_{\max}} d\xi_i \frac{f(\xi_i) - f(0)\Theta(\xi_{cut}-\xi_i)}{\xi_i}\,; \quad \int_{-1}^{1} dy_{ij} g(y_{ij}) \left(\frac{1}{1-y_{ij}}\right)_\delta = \int_{-1}^{1} dy_{ij} \frac{g(y_{ij}) - g(1)\Theta(y_{ij}-1+\delta)}{1-y_{ij}}$$

Events and counterevents

✦ The regulators define events and counterevents

✤ Integrating over the regulators gives

$$\mathrm{d}\sigma_{ij}^{(n+1)} = \left[\frac{1}{\xi_i}\right]_c \left[\frac{1}{1-y_{ij}}\right]_\delta \Sigma_{ij}(\xi_i, y_{ij}) d\xi_i dy_{ij}$$

$$= \int_0^{\xi_{\max}} d\xi_i \int_{-1}^{1} dy_{ij} \frac{1}{\xi_i(1-y_{ij})} \Big[\underbrace{\Sigma_{ij}(\xi_i, y_{ij})}_{\text{Event}} \underbrace{- \Sigma_{ij}(\xi_i, 1)\Theta(y_{ij} - 1 + \delta)}_{\text{Counterevent}}$$

$$\underbrace{- \Sigma_{ij}(0, y_{ij})\Theta(\xi_{cut} - \xi_i) + \Sigma_{ij}(0,1)\Theta(\xi_{cut} - \xi_i)\Theta(y_{ij} - 1 + \delta)}_{\text{Counterevent}} \Big]$$

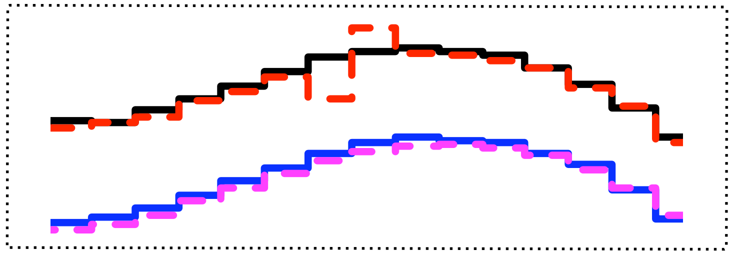
✦ Properties of events and counterevents

✤ If *i* and *j* are on-shell (event), the combined *ij* parton is on-shell (counterevent)

★ This leads to a reshuffling of all particle momenta

✤ An event and the associated counterevent can fill different histogram bins

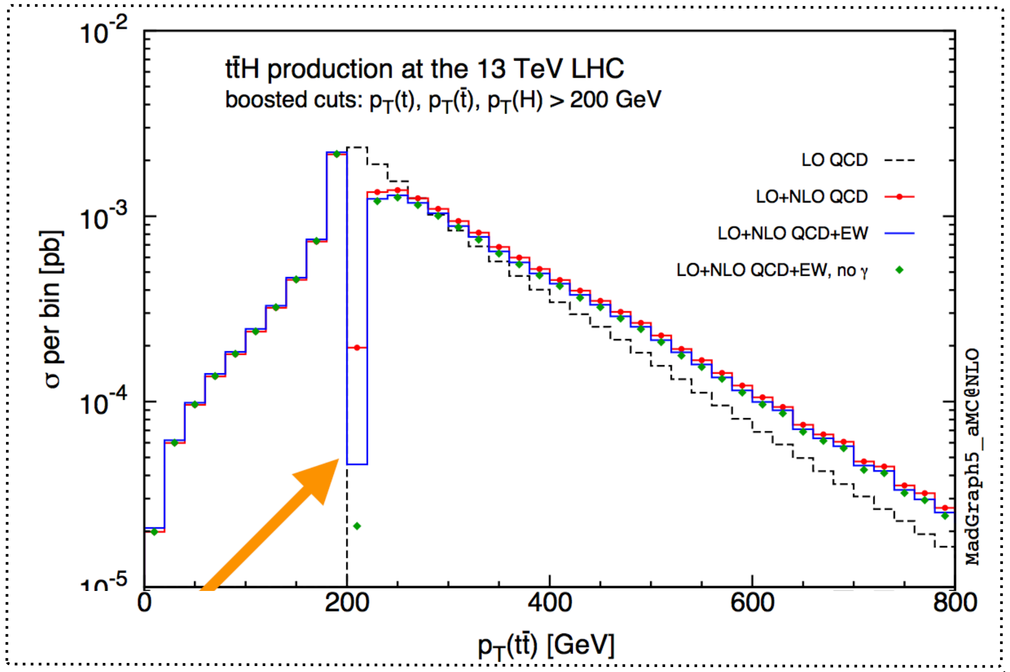
★ Peak-dip structure for the fixed-order distributions
(even for IR safe observables and for any binning resolution)



Fixed order event generation

- Unweighting is not possible at the fixed order
  - Kinematic mismatch of events and counterevents
    - The (n)-body and ($n+1$)-body contributions are not bounded from above
    - Only weighted events can be used
- FKS subtraction is taken care of by MADFKS [Frederix *et al.* (JHEP'09)]
  - Two sets of momenta are generated
    - (n)-body: Born, virtuals and counterterms
    - ($n+1$)-body: real emission
  - Histograms are filled and cuts are applied on the fly
    - Using different weights for the different terms

- Fixed-order instabilities
  - (n)-body kinematical constraints relaxed in the ($n+1$)-body case
    - Weird behavior of the distributions

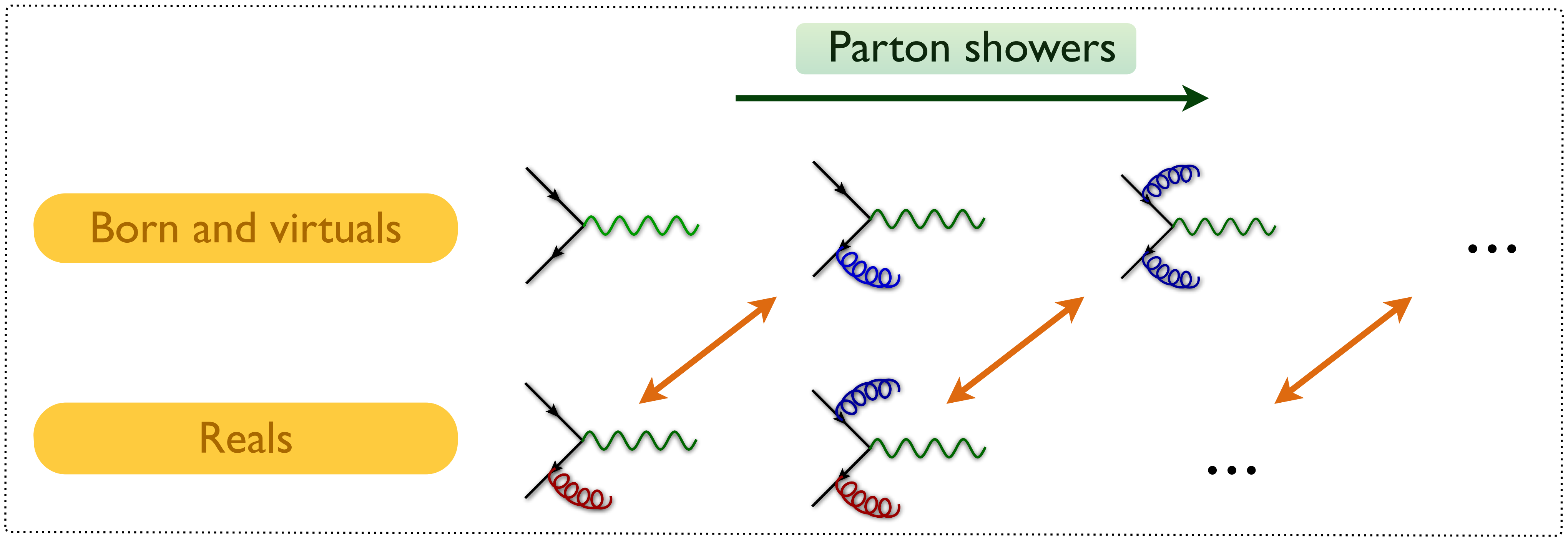


Matching NLO calculations to parton showers

✦ Parton shower / hadronization effects

- ✤ Evolution of hard partons down to more realistic final states made of hadrons
  - ★ Fully exclusive description of the events
- ✤ Resummation of the soft-collinear QCD radiation
  - ★ Cures the fixed-order instabilities

✦ Problem: double counting of several contributions



- ✤ Two sources of double counting
  - ★ Radiation: both at the level of the reals and of the shower
  - ★ No radiation: both in the virtuals and in the no-emission probability

The MC@NLO prescription (I)

[Frixione, Webber (JHEP'02)]

✦ Solution to the double counting issue

- ✤ The shower is unitary
  - ★ What is double counted in the virtuals is (minus) what is double counted in the reals
- ✤ Adding and subtracting identical contributions

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \Big[\mathcal{B} + \int_{\text{loop}} \mathrm{d}^d\ell\, \mathcal{V} + \int \mathrm{d}^4\Phi_1 \boxed{\mathcal{MC}}\Big] \mathcal{I}_{\text{MC}}^{(n)} + \int \mathrm{d}^4\Phi_{n+1} \Big[\mathcal{R} \boxed{- \mathcal{MC}}\Big] \mathcal{I}_{\text{MC}}^{(n+1)}$$

Monte Carlo counterterms

- ★ $\mathcal{I}_{\text{MC}}^{(n)}$ represents the shower operator for a (*n*)-body final state
- ★ The MC counterterms: how the shower gets from an (*n*)-body to a (*n*+1)-body final state

$$\mathcal{MC} = \left| \frac{\partial \left(t^{MC}, z^{MC}, \phi\right)}{\partial \Phi_1} \right| \frac{1}{t^{MC}} \frac{\alpha_s}{2\pi} \frac{1}{2\pi} P\left(z^{MC}\right) \mathcal{B}$$

The MC@NLO prescription (2)

[Frixione, Webber (JHEP'02)]

✦ Properties of the Monte Carlo counterterms

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \left[\mathcal{B} + \int_{\text{loop}} \mathrm{d}^d\ell\ \mathcal{V} + \int \mathrm{d}^4\Phi_1 \mathcal{MC}\right] \mathcal{I}_{\text{MC}}^{(n)} + \int \mathrm{d}^4\Phi_{n+1}\ \left[\mathcal{R} - \mathcal{MC}\right] \mathcal{I}_{\text{MC}}^{(n+1)}$$

- They allows for maintaining the NLO normalization of the cross section
  - After expanding the shower operator at order α_s
- They match the real emission IR behavior (by definition of the shower)
  - The MC counterterms and the reals have the same kinematics by construction (no need for momentum reshuffling; the cancellation is exact)
  - Weights for the (n)-body and (n+1)-body are now bounded from above
  - Unweighting is possible
- They ensure a smooth transition between the hard and soft-collinear regions
  - Soft-collinear region: $\mathcal{R} \approx \mathcal{MC}$ and the shower dominates
  - Hard region: $\mathcal{MC} \approx 0, \quad \mathcal{I}_{\text{MC}}^{(n)} \approx 0, \quad \mathcal{I}_{\text{MC}}^{(n+1)} \approx 1$ and the hard emission dominates
- They are shower-dependent

Monte Carlo and FKS counterterms

✦ MC and FKS counterterms

- ✤ The MC counterterms cannot be integrated numerically
  - ★ Issue with the pole cancellation in the virtuals
  - ★ Using both FKS and MC counterterms

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \Big[\mathcal{B} + \Big(\int_{\mathrm{loop}} \mathrm{d}^d\ell\ \mathcal{V} + \int \mathrm{d}^d\Phi_1 \mathcal{C}\Big) + \int \mathrm{d}^4\Phi_1 \Big(\mathcal{MC} - \mathcal{C}\Big)\Big] \mathcal{I}_{\mathrm{MC}}^{(n)} + \int \mathrm{d}^4\Phi_{n+1} \Big[\mathcal{R} - \mathcal{MC}\Big] \mathcal{I}_{\mathrm{MC}}^{(n+1)}$$

S-events H-events

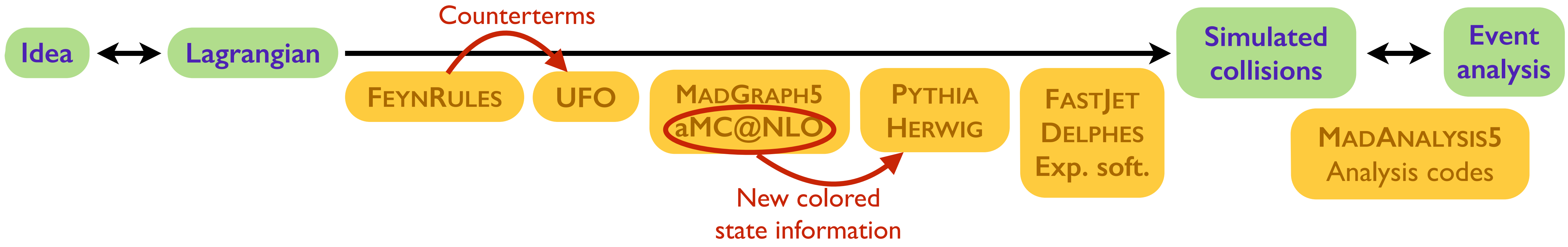
- ✤ In practice, S-events and H-events are generated separately
  - ★ The related contribution can carry a negative weight
  - ★ The sign of the weight has to be included in the unweighting procedure

Outline

1. Need for precision Monte Carlo event generators
2. Automating NLO calculations in QCD with MADGRAPH5_aMC@NLO
3. **Stop pair-production at the LHC**
4. Supersymmetric QCD @ NLO
5. Summary - conclusions

Automating NLO event generation

✦ A comprehensive approach to Monte Carlo simulations



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

✤ FEYNRULES is linked to the NLOCT module [Alloul, Christensen, Degrande, Duhr & BF (CPC'14); Degrande (CPC'15)]

★ Calculation of UV and R_2 counterterms [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]

★ Export of the information to the UFO [Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

✤ Matching to parton showers with MADGRAPH5_aMC@NLO

[Alwall, Frederix, Frixione, Hirschi, Mattelaer, Shao, Stelzer, Torrielli & Zaro (JHEP'14)]

★ Monte Carlo counterterms associated with the new colored states are included (for standard colored states)

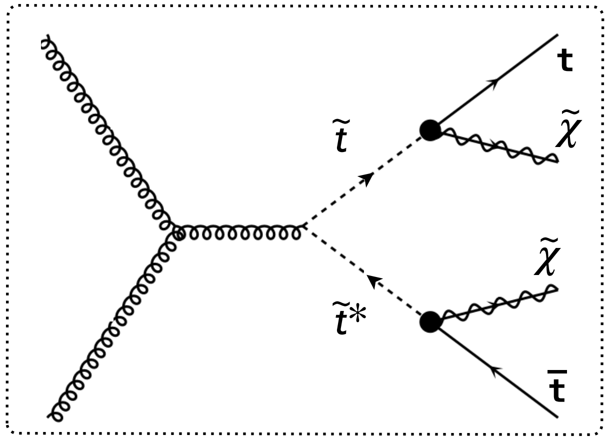
★ Restrictions on the parton shower code to employ (PYTHIA 8, HERWIG++)

Case 1: a stop simplified model

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

✦ Motivations

- ✤ A brand new machinery must be tested and validated
  - ★ Simple cases with physics motivation come first
  - ★ Many quantities can be calculated analytically (UV and R_2 counterterms, *etc.*)
- ✤ First use of FeynRules/aMC@NLO for a model with an extended colored sector
- ✤ Physics case: stop searches in the top+antitop+MET channel



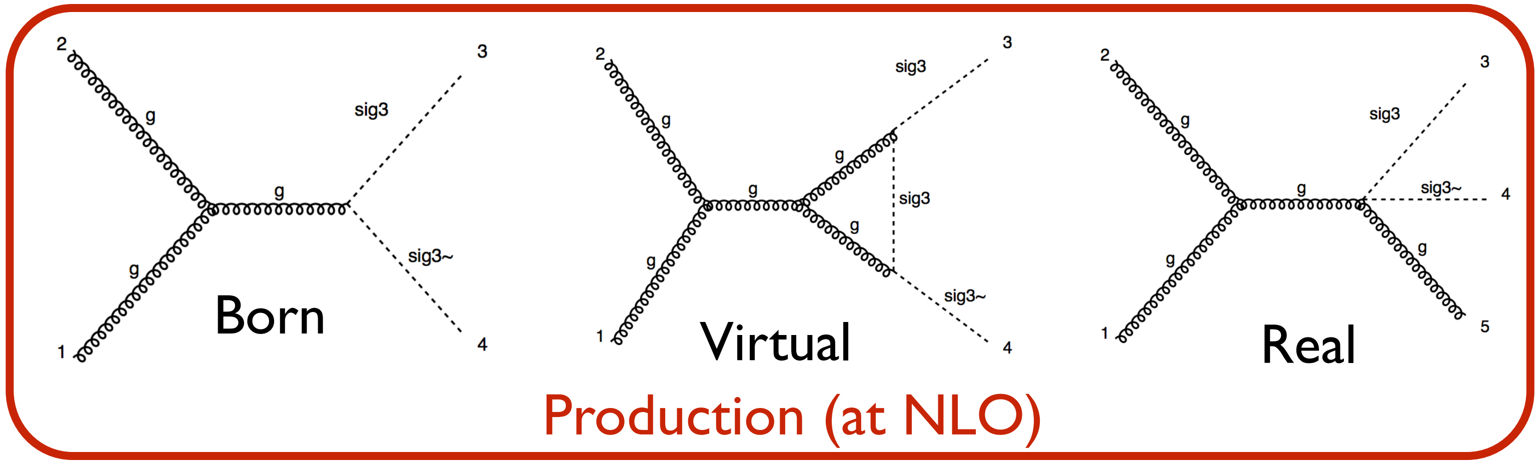
A stop simplified model: model description

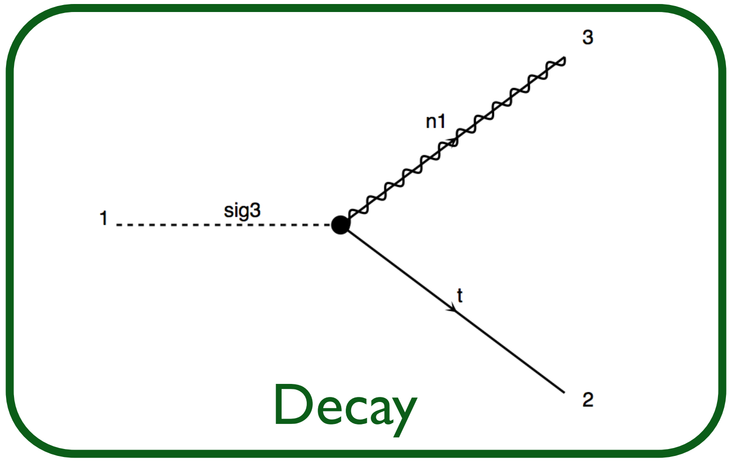
✦ We supplement the Standard Model with a stop (σ_3) and a bino (χ)

$$\mathcal{L}_3 = \underbrace{D_\mu\sigma_3^\dagger D^\mu\sigma_3 - m_3^2\sigma_3^\dagger\sigma_3}_{\text{Production}} + \underbrace{\frac{i}{2}\bar\chi\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar\chi\chi + \Big[\sigma_3\bar t(\tilde g_L P_L + \tilde g_R P_R)\chi + \text{h.c.}\Big]}_{\text{Decay}}$$

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

✦ Representative Feynman diagrams (*cf.* a top+antitop+MET signature)





Analytical validation of the UFO model

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

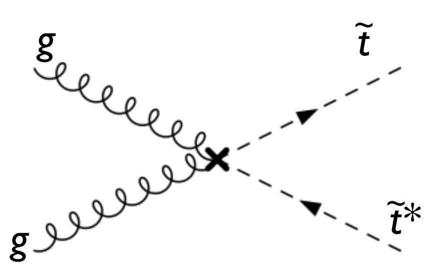
- The UV behavior of the model has been extensively checked analytically
  - Wave function and mass renormalization constants in the on-shell scheme

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{96\pi^2}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right] \qquad \delta Z_{\sigma_3} = 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_s^2 m_3^2}{12\pi^2}\left[\frac{3}{\bar\epsilon} + 7 - 3\log\frac{m_3^2}{\mu_R^2}\right]$$

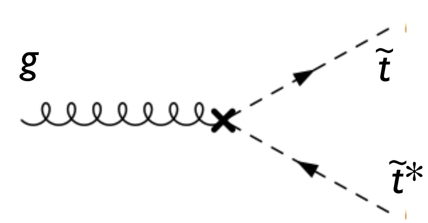
  - Strong coupling renormalization: zero-momentum subtraction
    - ★ Heavy particle contributions subtracted from the gluon self-energy

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

  - New physics UV counterterms
    - ★ Non-trivial (non-supersymmetric) behavior of the neutralino couplings verified
  - New physics R_2 counterterms



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



$$\frac{53ig_s^3}{576\pi^2}T^{a_1}_{c_2c_3}(p_2-p_3)^{\mu_1}$$

$$\frac{ig_s^2}{72\pi^2}\delta_{c_1c_2}\left[3m_3^2 - p^2\right]$$

Numerical validation of the UFO model - total rates

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

- ✦ The IR behavior of the model has been extensively checked numerically
  - ✤ Universality of QCD predicts it

- ✦ Total rates at 13 TeV

m_3 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$1.066 \pm 0.0025 \cdot 10^{3}$ $^{+29.1\%}_{-21.4\%}$	$1.497 \pm 0.0054 \cdot 10^{3}$ $^{+14.1\%}_{-12.1\%}$ $^{+1.2\%}_{-1.2\%}$
250	$1.553 \pm 0.0037 \cdot 10^{1}$ $^{+35.2\%}_{-24.8\%}$	$2.156 \pm 0.0067 \cdot 10^{1}$ $^{+12.1\%}_{-12.3\%}$ $^{+2.4\%}_{-2.4\%}$
500	$3.890 \pm 0.0093 \cdot 10^{-1}$ $^{+39.6\%}_{-26.4\%}$	$5.062 \pm 0.015 \cdot 10^{-1}$ $^{+11.2\%}_{-12.8\%}$ $^{+4.4\%}_{-4.4\%}$
750	$3.306 \pm 0.0081 \cdot 10^{-2}$ $^{+41.8\%}_{-27.5\%}$	$4.001 \pm 0.012 \cdot 10^{-2}$ $^{+10.8\%}_{-12.9\%}$ $^{+6.1\%}_{-6.1\%}$
1000	$4.614 \pm 0.011 \cdot 10^{-3}$ $^{+43.6\%}_{-28.3\%}$	$5.219 \pm 0.016 \cdot 10^{-3}$ $^{+10.9\%}_{-13.2\%}$ $^{+7.9\%}_{-7.9\%}$

- ★ NNPDF 2.3
- ★ Scales set to the stop mass
- ★ Scale uncertainties: factor of 2 up and down
- ★ PDF uncertainties: 100 NNPDF replica

- ✤ Agreement with PROSPINO [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]
- ✤ Enhancement of the cross section of 25% (heavy stops) - 50% (light stops)
  - ★ Genuine NLO contributions
- ✤ Sizeable reduction of the scale uncertainties

Kinematical distributions

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

✦ Differential distributions at NLO (illustrative example)

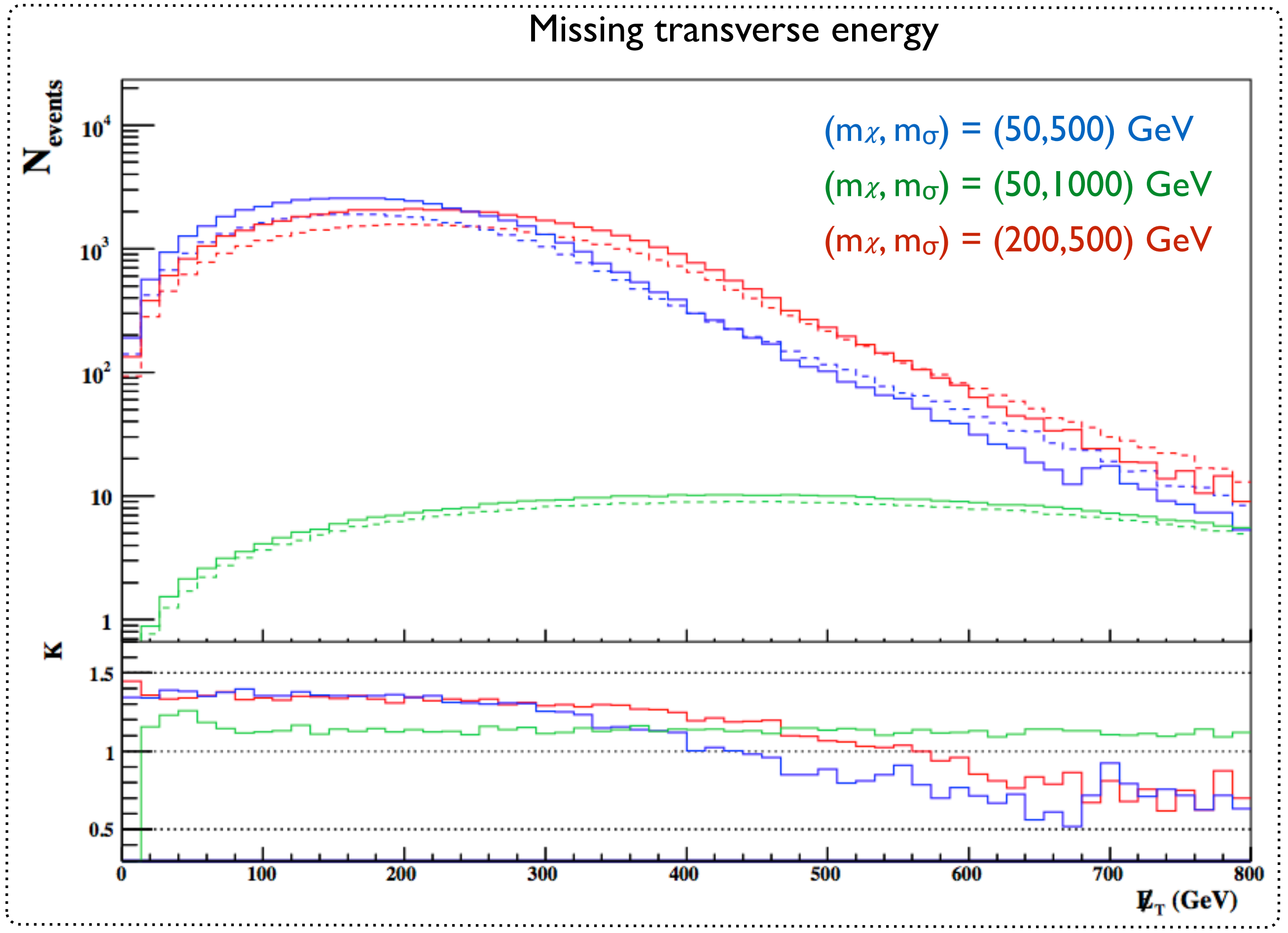
✤ Setup:

- ★ Benchmarks: 500/1000 GeV stop; 50/200 GeV bino
- ★ Semileptonic decay (single lepton signal)
- ★ 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): MADANALYSIS 5
  [Conte, BF, Serret (CPC'13)]

✤ Comparing LO+PS and NLO+PS

- ★ Constant *K*-factors not always accurate
- ★ The *K*-factors depend on the scenario

How do the experimental results depend on the NLO effects?



The CMS-SUS-13-011 stop search

- The CMS-SUS-13-011 study relies on LO simulation and MLM merging
  - Simulated signal: $p\, p \to \tilde{t}\, \tilde{t}^*$ + 0,1,2 jets at the LO, and MLM-merged
  - Parton showering: PYTHIA 6 with the Z_2 tune [Field (APPB '11)]
- Analysis of the single-leptonic (plus MET) decay of the stop pair
  - One single lepton and 4 jets (mainly issued from the stop-antistop system decay)
  - Large missing energy
  - At least one *b*-jet
  - Top reconstruction quality
  - Transverse variable constraints

- Feature
  - The selection does not really depend on the extra jets
    - The main hadronic activity comes from the decay products
  - The limit should be agnostic of the merging, of the NLO corrections, *etc.*
  - The uncertainties should not!

Merging effects on the CMS-SUS-13-011 results

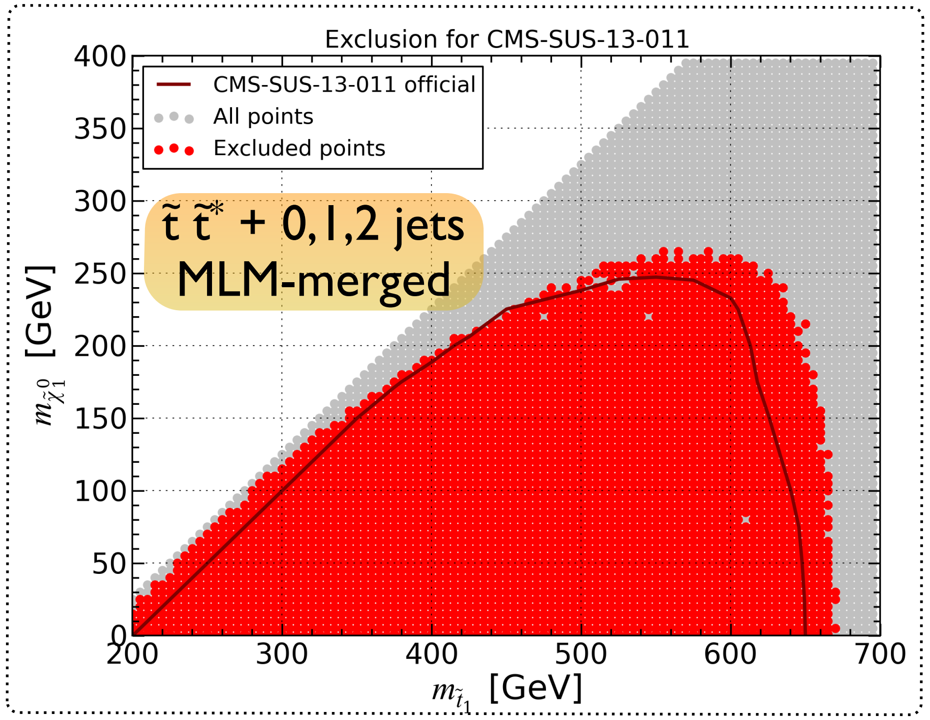
[Ambrogi, Conte, BF, Kulkarni & Molter (in preparation)]

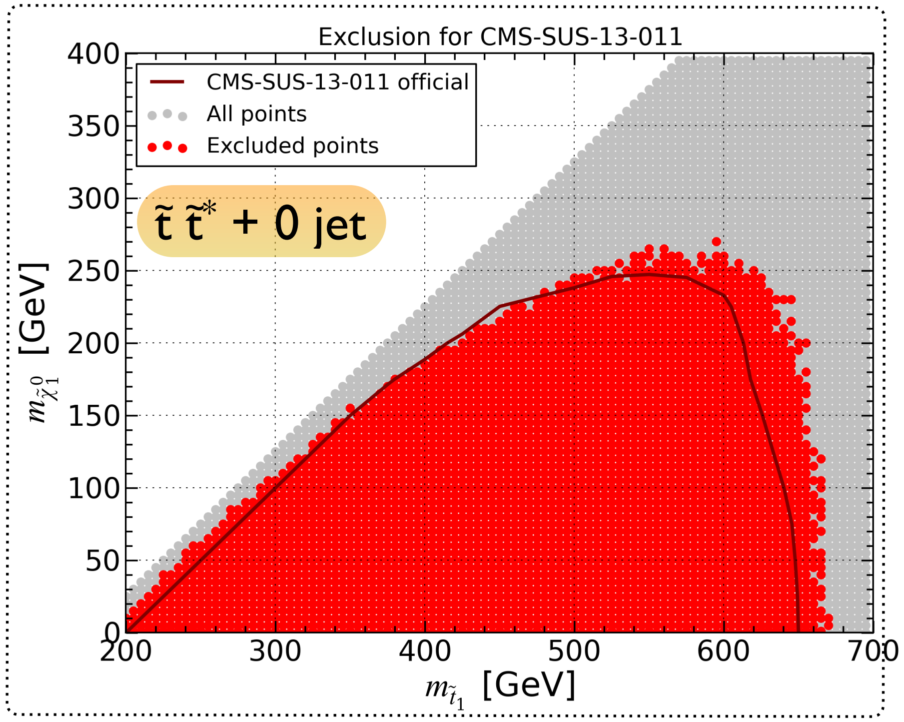
- Relies on leading order simulation and MLM merging
  - Simulated signal: $p\,p \to \tilde{t}\,\tilde{t}^* + 0,1,2$ jets @LO ; PYTHIA 6 with the Z_2 tune
- Feature: the limit should be agnostic of the merging

- Verification with MADANALYSIS 5

[Conte, BF, Serret (CPC'13); Conte, Dumont, BF, Wymant (EPJC'14)]
[Dumont, BF, Kraml *et al.* (EPJC'15)]

  - Good agreement with the official exclusion at the 20 GeV level
  - The limit does not depend on the merging





Effects of the shower

[Ambrogi, Conte, BF, Kulkarni & Molter (in preparation)]

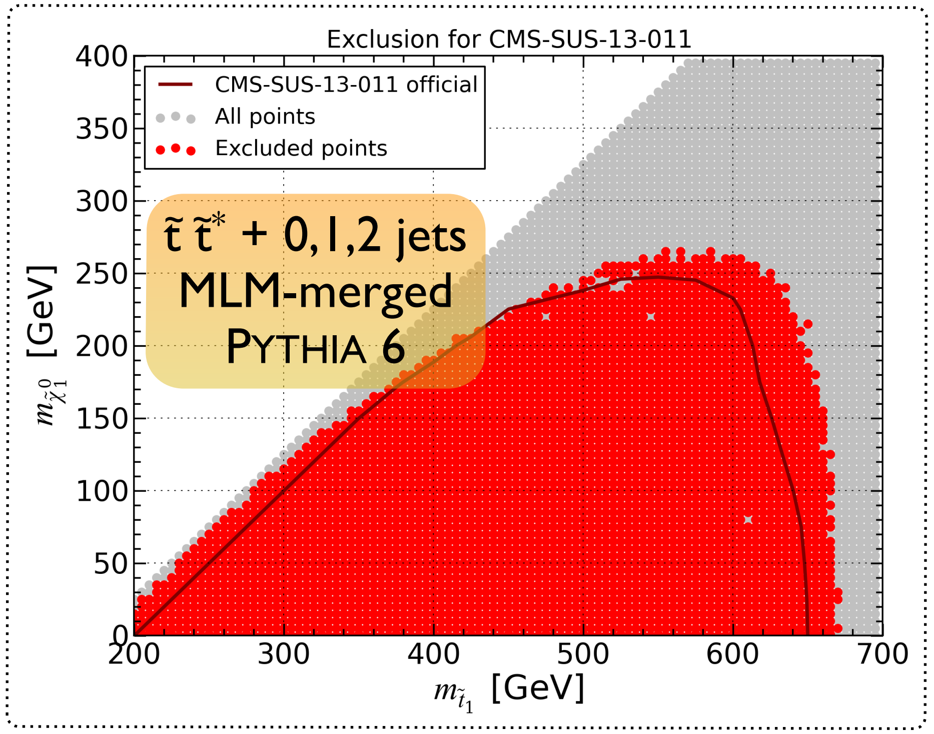
✦ Moving towards more modern tools

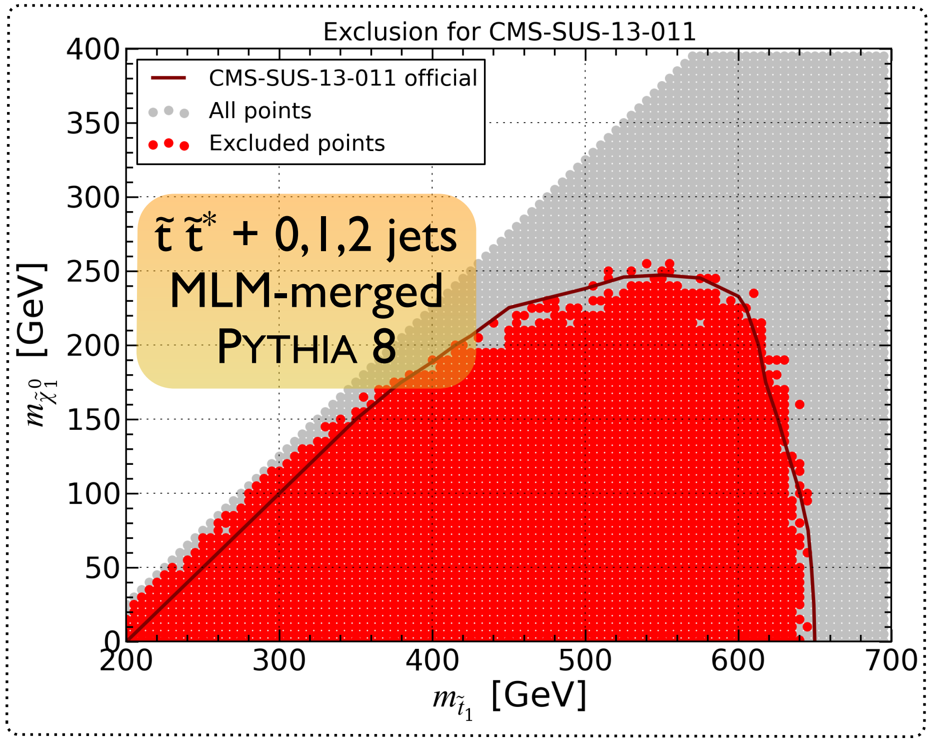
1. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0,1,2 jets @LO ; PYTHIA 6 with the Z_2 tune
2. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0,1,2 jets @LO ; PYTHIA 8 with the MONASH tune

[Skands, Carrazza & Rojo (EPJC '14)]

✦ How are the limits changing?

- ✤ Limits stable at the 20-40 GeV level (better agreement with the official limit…)
- ✤ What would be the effect of a more modern PYTHIA and tune on the limits?!





NLO effects

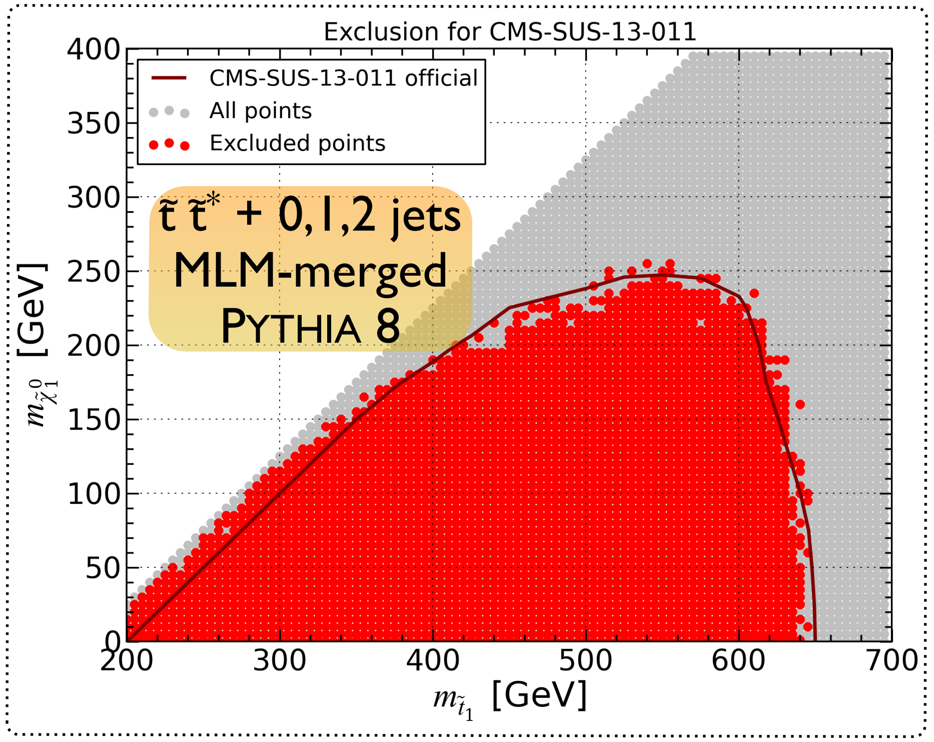
[Ambrogi, Conte, BF, Kulkarni & Molter (in preparation)]

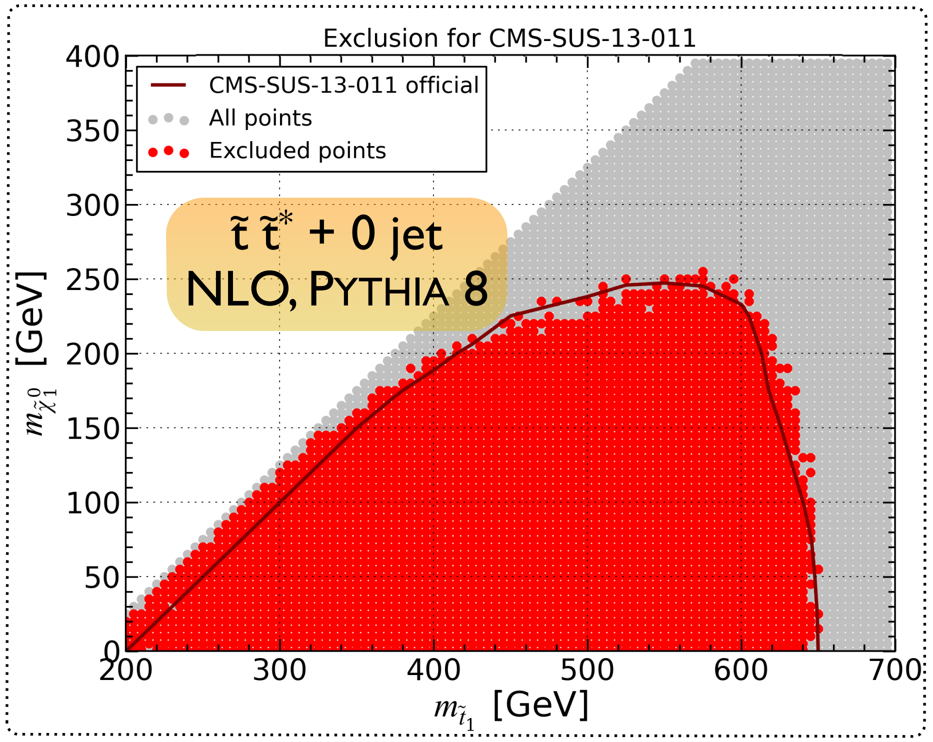
✦ LO and NLO

1. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0,1,2 jets @LO ; PYTHIA 8 with the MONASH tune
2. Simulated signal: p p → $\tilde{t}\,\tilde{t}^*$ + 0 jet @NLO ; PYTHIA 8 with the MONASH tune

✦ How are the limits changing?

✤ Stable constraints (due to the many jets already there at the LO)





This is an analysis dependent statement
NLO effects could be crucial for some analyses!!!
Better control of the uncertainties in all cases!

NLO effects

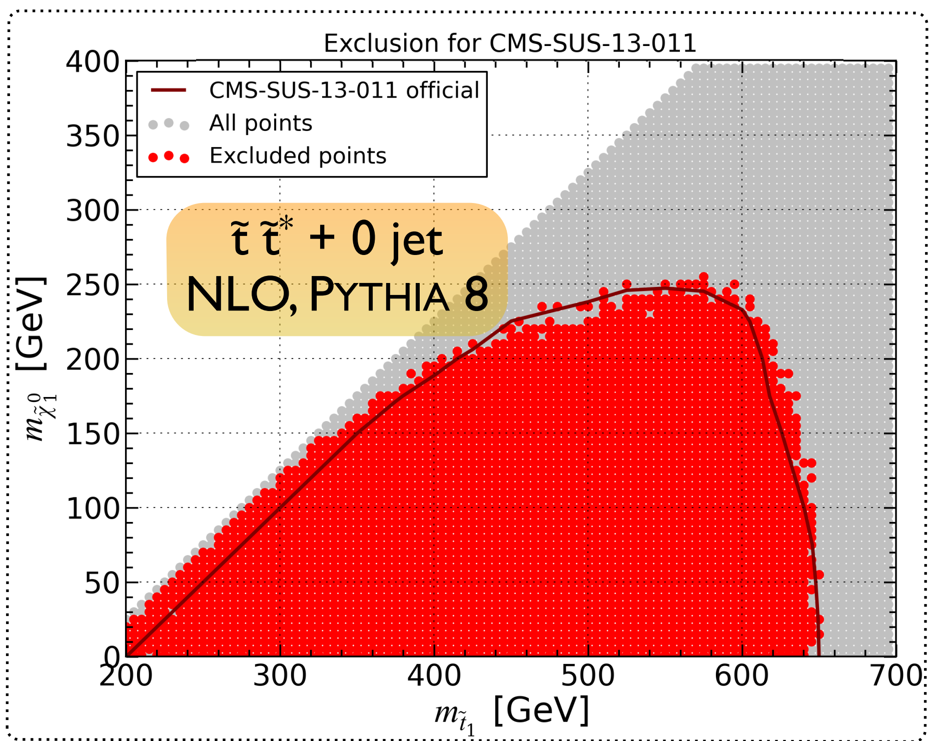
[Ambrogi, Conte, BF, Kulkarni & Molter (in preparation)]

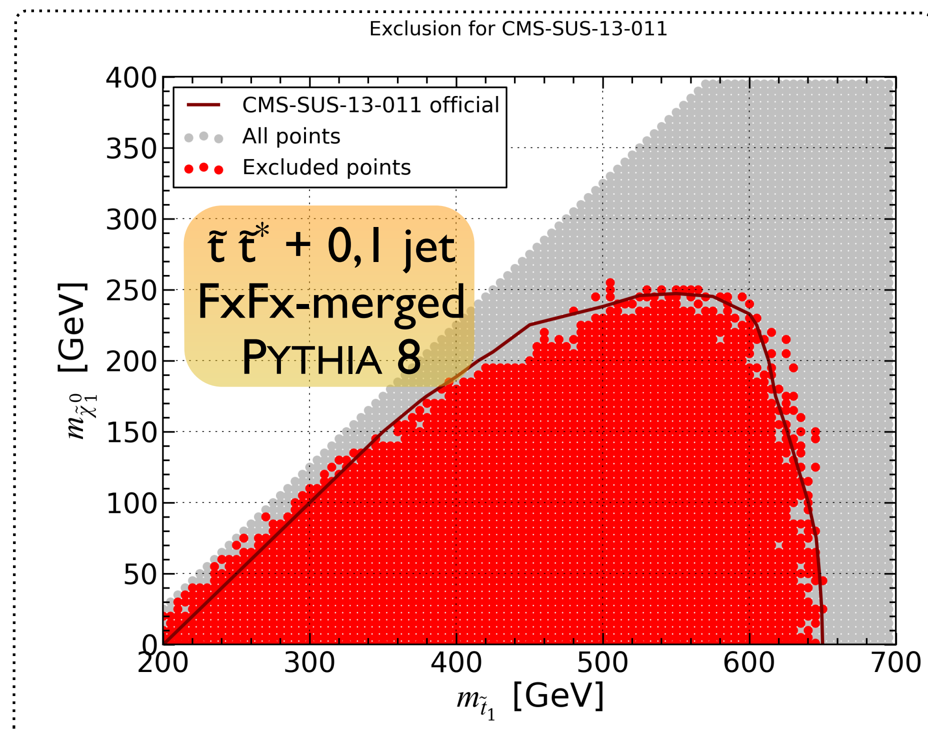
✦ NLO merging effects?

1. p p → $\tilde{t}\,\tilde{t}^*$ + 0 jet @NLO ; PYTHIA 8 with the MONASH tune
2. p p → $\tilde{t}\,\tilde{t}^*$ + 0,1 jet @NLO ; FxFx-merged ; PYTHIA 8 with the MONASH tune

✦ How are the limits changing?

✤ Stable constraints (due to the many jets already there at the LO)





Outline

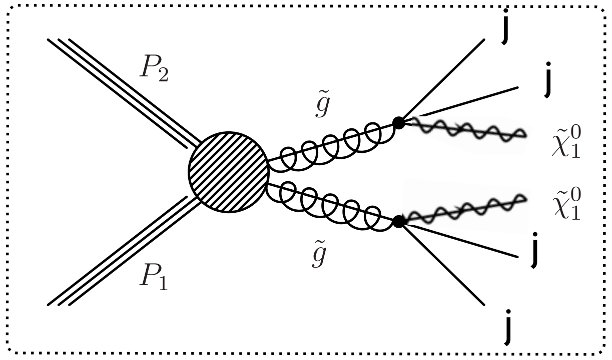
1. Need for precision Monte Carlo event generators
2. Automating NLO calculations in QCD with MADGRAPH5_aMC@NLO
3. Stop pair-production at the LHC
4. **Supersymmetric QCD @ NLO**
5. Summary - conclusions

Supersymmetric QCD

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

✦ Motivations

- ✤ First steps towards a complete non trivial model
- ✤ Missing: OS subtraction of intermediate resonances in the reals [in progress]
  - ★ Physics example: decoupled squarks (≡ gluino simplified models)
- ✤ Physics case: gluino searches in the multijet pair+MET channel



Supersymmetric QCD

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

✦ The supersymmetric QCD model

$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g} - m^2_{\tilde{q}_L} \tilde{q}_L^\dagger \tilde{q}_L - m^2_{\tilde{q}_R} \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}} \tilde{g}$$
$$+ \sqrt{2} g_s \Big[- \tilde{q}_L^\dagger T (\bar{\tilde{g}} P_L q) + (\bar{q} P_L \tilde{g}) T \tilde{q}_R + \text{h.c.} \Big] - \frac{g_s^2}{2} \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big]$$

★ All (s)quarks, gluino and gluon supersymmetric-QCD interactions included (the SM ones being omitted)

✦ Checks of the implementation

✤ Analytical checks of the UV structure of the model

✤ Numerical checks of the IR behavior

Gluino pair production: total rates

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

✦ Total rates at 13 TeV

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%}_{-21.9\%}{}^{+14.0\%}_{-14.0\%}$	$3183^{+10.8\%}_{-11.6\%}{}^{+1.8\%}_{-1.8\%}$
500	$15.46^{+34.7\%}_{-24.1\%}{}^{+19.5\%}_{-19.5\%}$	$24.90^{+12.5\%}_{-13.4\%}{}^{+3.7\%}_{-3.7\%}$
750	$1.206^{+35.9\%}_{-24.6\%}{}^{+23.5\%}_{-23.5\%}$	$2.009^{+13.5\%}_{-14.1\%}{}^{+5.5\%}_{-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%}_{-24.8\%}{}^{+26.4\%}_{-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%}_{-14.8\%}{}^{+7.3\%}_{-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%}_{-24.7\%}{}^{+29.4\%}_{-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%}_{-15.8\%}{}^{+11.3\%}_{-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%}_{-24.5\%}{}^{+29.8\%}_{-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%}_{-16.6\%}{}^{+17.8\%}_{-17.8\%}$

★ NNPDF 3.0
★ Scales set to the gluino mass
★ Scale uncertainties: factor of 2 up and down
★ PDF uncertainties: 100 NNPDF replica

✤ Agreement with PROSPINO [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]
- ★ Generalization of the PROSPINO setup (different squark masses)

✤ Enhancement of the cross section of 50%
- ★ Genuine NLO contributions

✤ Sizeable reduction of the scale uncertainties

✤ Drastic reduction of the PDF uncertainties
- ★ Due to the poor quality of the NNPDF LO fit

Differential distributions

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

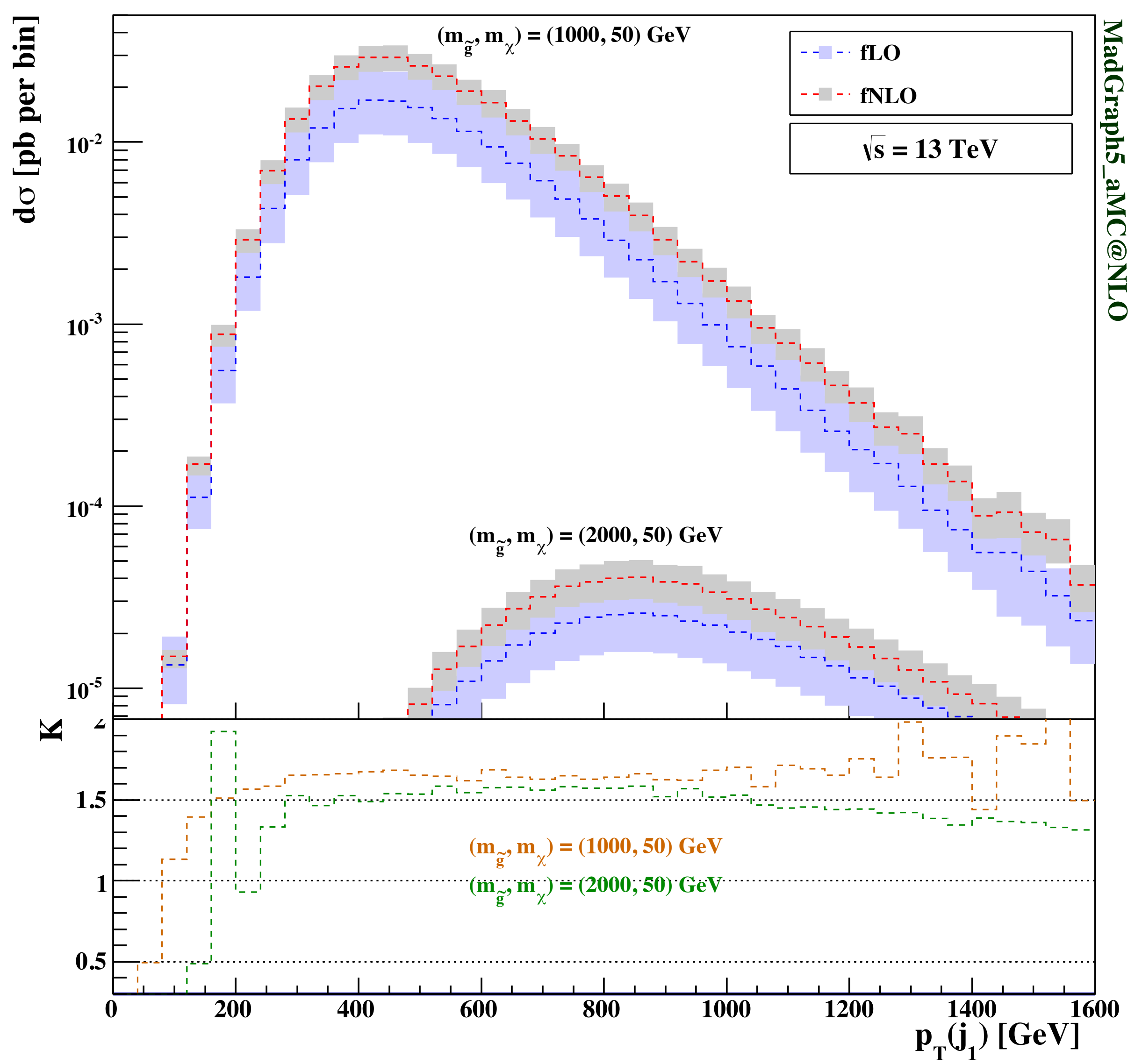
✦ Strategy for getting differential distributions at NLO and event generation

- Benchmarks: 1 or 2 TeV gluino; decoupled squarks; 50 GeV neutralino
- Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands (CPC'08)]
- Jet reconstruction: anti-k_T & FASTJET [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
- Analysis: MADANALYSIS 5 [Conte, BF, Serret (CPC'13)]
- Recap: four jets are issued from the gluino decays

Differential distributions: fixed order results (1)

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

1st jet p_T



- The first jet mostly arises from decays
  - The low pT region is depleted (heavy gluino)
- Constant *K*-factors not accurate for small p_T
- NLO effects
  - Normalization increase
  - Distortion of the shapes
  - Reduction of the theoretical uncertainties

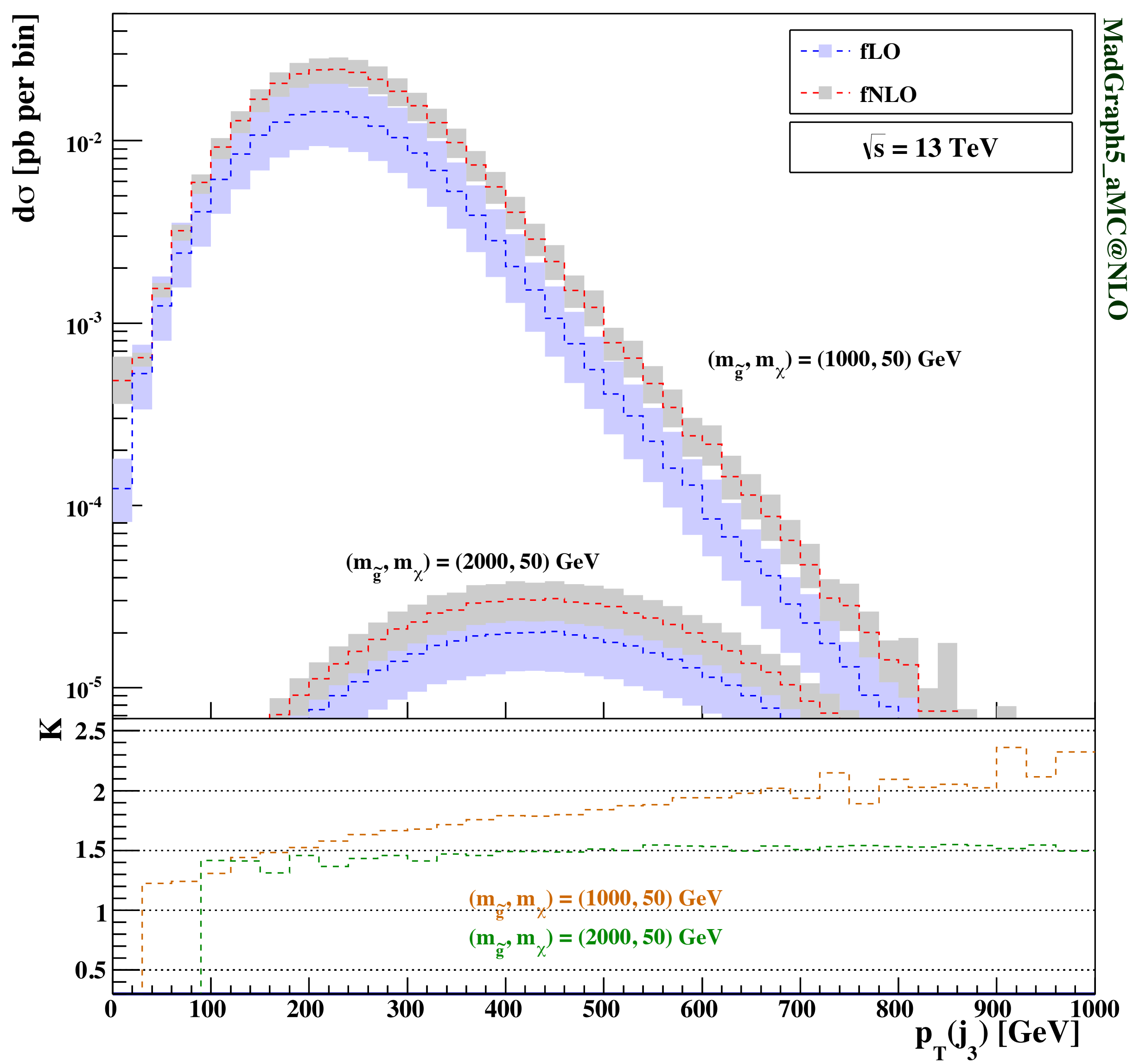
A LO description with a constant *K*-factor could yield a very inaccurate signal modelling in the low-p_T region

Region better described by parton showers

Differential distributions: fixed order results (2)

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

3rd jet p_T

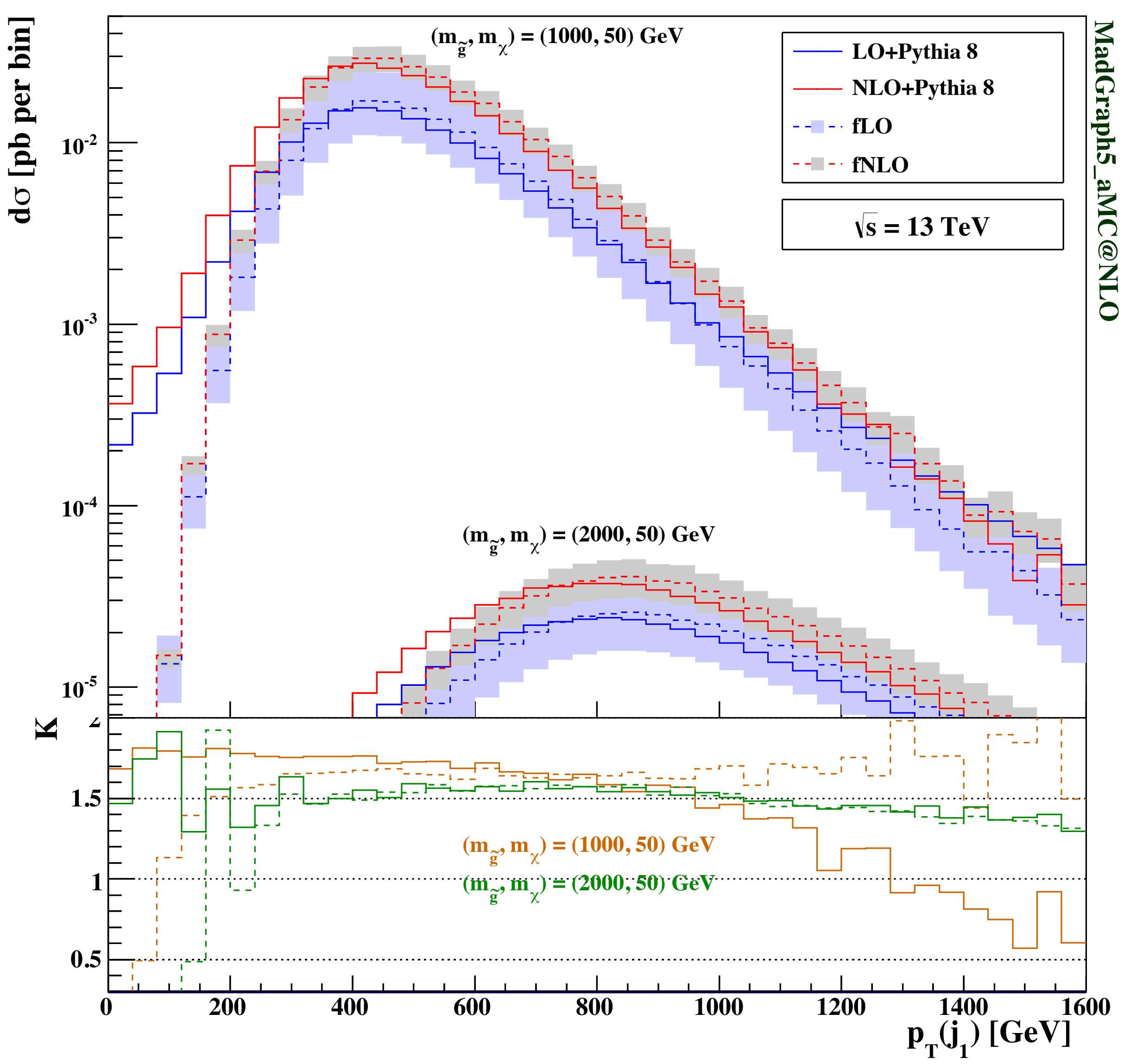


- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes a radiation jet
  - ★ More activity in the low-p_T region
- Constant *K*-factors not accurate
  - ★ At all for 1 TeV gluinos
  - ★ In the small p_T region for 2 TeV gluinos
- NLO effects
  - ★ Crucial for a precise description of the signal
  - ★ Reduction of the theoretical uncertainties
- Shower effects ➢ low p_T region

Differential distributions: matching to parton showers

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

1st jet p_T

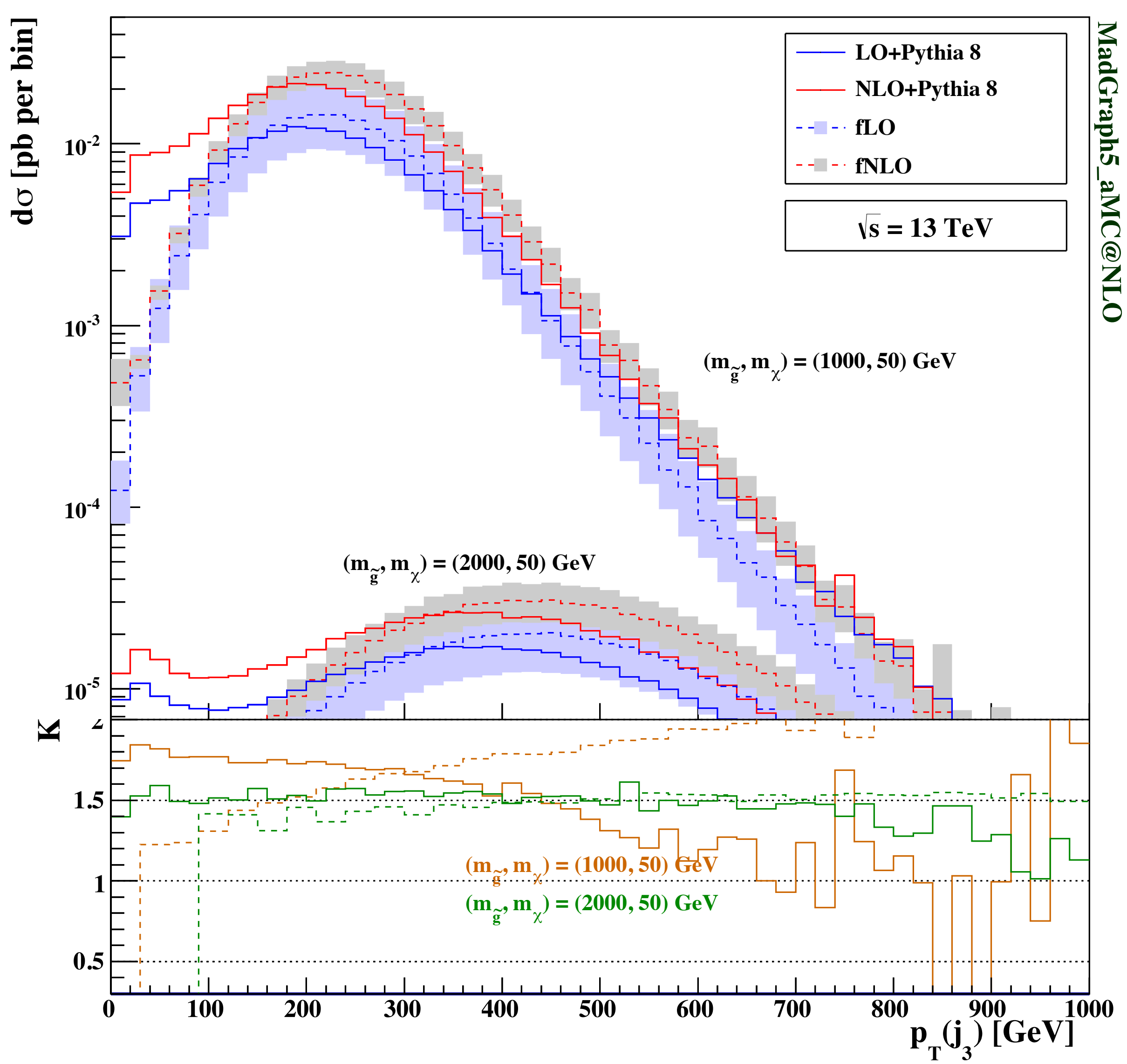


- Parton showers populate the low-p_T region
  - ★ Emitted partons often not reclustered back
  - ★ Extra softer jets
  - ★ Distortion of the spectrum
  - ★ Effects milder for hard p_T (the matrix element drives the shape)
- *K*-factor behavior (fixed-order *vs.* ME+PS)
  - ★ Changes more pronounced for 1 TeV gluinos
    - ➢ Drastic change of the behavior
  - ★ Effects appear at larger p_T for 2 TeV gluinos
- The "decay" origin of the jets dominates
  - ★ Single peak at a large p_T value

Differential distributions: matching to parton showers

[Degrande, BF, Hirschi, Proudom & Shao (1510.00391)]

3rd jet p_T



- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes a radiation jet
  - ★ Entanglement of the two effects: two peaks
- Parton showers populate the low-p_T region
  - ★ Emitted partons often not reclustered back
  - ★ Extra softer jets
  - ★ Distortion of the spectrum
  - ★ Effects milder for hard p_T (the matrix element drives the shape)
- *K*-factor behavior (fixed-order *vs.* ME+PS)
  - ★ Changes more pronounced for 1 TeV gluinos
  - ★ Effect at larger p_T for 2 TeV gluinos

Outline

New physics simulations at NLO in QCD

✦ The automation of NLO simulations (in QCD) for new physics is now feasible

- ✤ Via a joint use of FEYNRULES and MADGRAPH5_aMC@NLO
- ✤ Divergence cancellation (UV, R_2 and MC counterterms) are automatically handled
- ✤ A few models are now publicly available (more to come)

✦ Model database

- ✤ Stop/sgluon/gluino simplified models [Degrande, BF, Hirschi, Proudom & Shao]
- ✤ SUSY-QCD (subtraction of intermediate resonances in development)
- ✤ Electroweakinos and sleptons soon available [BF, Klasen, Lamprea & Zaro]
- ✤ The Two-Higgs-Doublet Model [Degrande]
- ✤ The Georgi-Machacek model [Peterson]
- ✤ Dark matter simplified model [Martini & Mawatari]
- ✤ Higgs effective field theory [Degrande, BF, Mawatari, Mimasu & Sanz]
- ✤ Top effective field theory [Zhang]

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