Beyond the Standard Model phenomenology at the NLO in QCD

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Outline

The quest for new physics at the LHC

✦ The quest for physics beyond the Standard Model at the LHC is on-going

- ✤ 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
- ✤ Ingredient 1: predictions for the Standard Model background
- ✤ Ingredient 2: predictions for the new physics signals

Standard Model simulations: the status

✦ The need for better simulation tools has spurred a very intense activity

- Automated matrix element generation (MadGraph5, Sherpa, Whizard, *etc.*)
- Higher-order computations (Mc@Nlo, PowHeg, NNLO)
- Parton showering and hadronization (Pythia, Herwig, Sherpa)
- Matrix element - parton showering matching
- Merging techniques (MLM, CKKW, FxFx, UNLOPS, *etc.*)

✦ Standard Model simulations

- All processes relevant for the LHC can be simulated with a very good precision
- The precision will improve in the next few years (e.g. electroweak corrections)

Standard Model simulations under control
What about new physics?

New physics simulations: the challenges

- The challenges with respect to new physics simulations are different
  - Theoretically, we are still in the dark
    - No sign of new physics
    - All measurements are Standard-Model-like
  - There is not any leading new physics candidate theory
    - Plethora of models to implement in the tools

- New physics is a standard in many tools today
  - Result of 20 years of developments
  - Simulations mostly achieved at the leading-order accuracy in QCD
  - But this has started to change a couple of years ago

A Monte Carlo tool framework for new physics

✦ Streamlining the chain from the Lagrangian to analyzed simulated collisions

- ✤ Connect the physics to simulated LHC collisions: need for a framework
  - ★ … where any new physics model can be implemented
  - ★ … where any new physics model can be tested against data
  - ★ … easy to validate, to maintain
  - ★ … easily integrable in a software chain

✦ A framework for new physics simulations

- ✤ Inputs / Outputs
  - ★ A physics object: the Lagrangian (unique and non ambiguous, no MC dependence)
  - ★ Flexible (a change in the model = a change in the Lagrangian)
  - ★ Automatic derivation of the Feynman rules and generate MC model files
- ✤ Validation
  - ★ Automatic and systematical
- ✤ Distribution
  - ★ Public, transparent
  - ★ No private tools

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

Automating new physics simulations

✦ First steps towards a new physics simulation framework: LANHEP

- ✤ Restricted to the CALCHEP / COMPHEP environment
- ✤ Working environment: C

[Semenov (NIMA'97; CPC'98; CPC'09; CPC'16)]
[Boos *et al.* (IJMPC'94; NIMA'04)]
[Belyaev, Christensen & Pukhov (CPC'13)]

✦ FEYNRULES: a platform for new physics model implementations in MC tools

- ✤ Working environment: MATHEMATICA
  - ★ Flexibility, symbolic manipulations, easy implementation of new methods, *etc*.
- ✤ Interfaced to many Monte Carlo tools
  - ★ Dedicated translators to several tools (obsolete today thanks to the UFO)
- ✤ Automatic linking of Lagrangians to files in a given programming language

[Christensen & Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr & BF (CPC'14)]

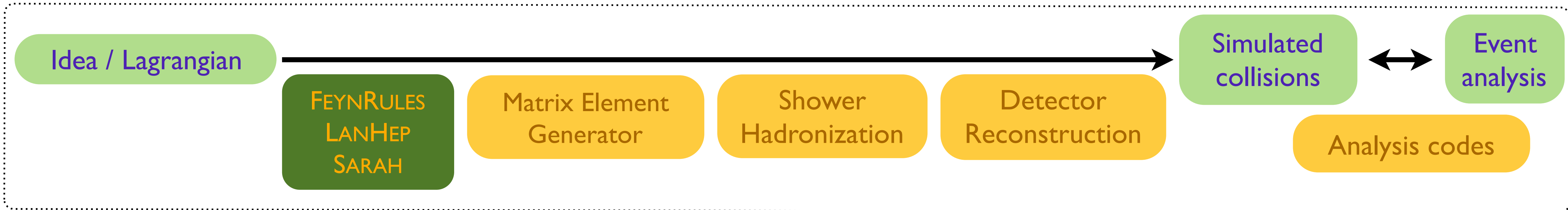
✦ The SARAH package

- ✤ Working environment: MATHEMATICA
- ✤ Interfaced to many Monte Carlo tools
- ✤ Spectrum generator features

[Staub (CPC'13; CPC'14)]

New physics simulations: other challenges

✦ A comprehensive approach to Monte Carlo simulations



✦ Implementation of any new physics theory in a MC tool is straightforward

Many interfaces dedicated to specific tools

★ Removal of non compliant vertices

★ Translation to a specific format/language

⚠ **Not efficient**

A step further: the Universal FEYNRULES Output

✦ Improving the maintenance: the UFO one format to rule them all

[Degrande, Duhr, BF, Grellscheid, Mattelaer, Reiter (CPC '12)]
[Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

✦ The UFO in a nutshell

- ✤ UFO ≡ Universal FEYNRULES output
  - ★ Universal as not tied to any specific Monte Carlo program
- ✤ Allows the models to contain generic color and Lorentz structures
  - ★ It is up to the different tools to discard what they cannot handle
- ✤ Consists of a PYTHON module to be linked to any code
- ✤ This module contains all the model information
- ✤ Can be employed for next-to-leading order calculations

✦ The UFO is now a standard and used by many other programs

ALOHA | GOSAM | HERWIG ++ | MADANALYSIS 5 | SHERPA

MADGRAPH5_aMC@NLO | WHIZARD | LANHEP | SARAH

Discoveries at the LHC (and simulations)

- ✦ Path towards the characterization of (potentially observed) new physics
  - ✤ Getting information on the nature of an observation
    - ★ Fitting deviations by some new physics signals
    - ★ Leading order Monte Carlo tools and techniques can do a proper job
    - ★ Reinterpretation of the signals in different theoretical frameworks
  - ✤ Final words on the nature of any potential new physics
    - ★ Accurate measurements of the model parameters
    - ★ More precise predictions are mandatory

Can precision predictions for new physics be automated?

Outline

1. Introduction: two decades of Monte Carlo developments for new physics
2. **Automating NLO calculations in QCD for new physics**
3. Phenomenology: supersymmetry, vector-like quarks, EFT and dark matter
4. Summary - conclusions

Predictions at the LHC (using QCD)

✦ Distribution of an observable ω: the QCD factorization theorem

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \sum_{ab}\int \mathrm{d}x_a\,\mathrm{d}x_b\,\mathbf{f}_{a/p_1}(x_a;\mu_F)\,\mathbf{f}_{b/p_2}(x_b;\mu_F)\,\frac{\mathrm{d}\sigma_{ab}}{\mathrm{d}\omega}(\ldots,\mu_F)$$

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

✦ Short distance physics: the partonic cross section

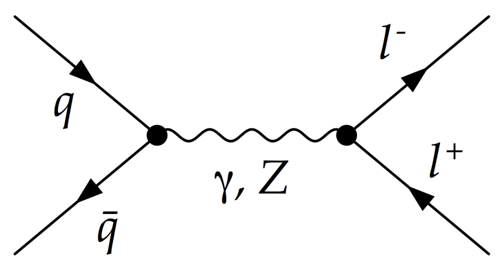
- Calculated order by order in perturbative QCD: $\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)} + \alpha_s\,\mathrm{d}\sigma^{(1)} + \ldots$
  - ★ The more orders included, the more precise the predictions
  - ★ Truncation of the series and α_s ➢ theoretical uncertainties

Fixed-order predictions

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

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

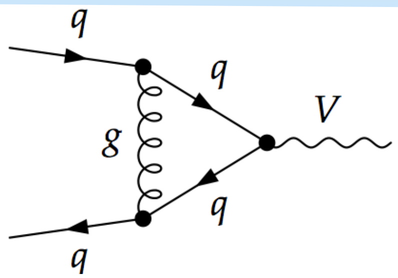
The Drell-Yan example



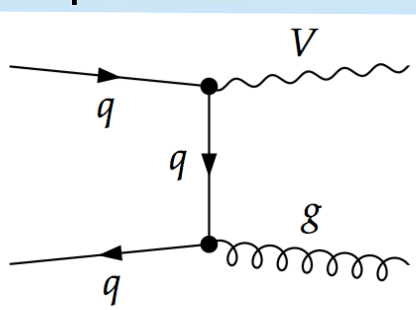
✦ Next-to-leading-order (NLO): $d\sigma \approx d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)}$

- ✤ 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 trees
- ✤ Better description of the process
  - ★ Impact of extra radiation
  - ★ More initial states included
  - ★ Sometimes not precise enough

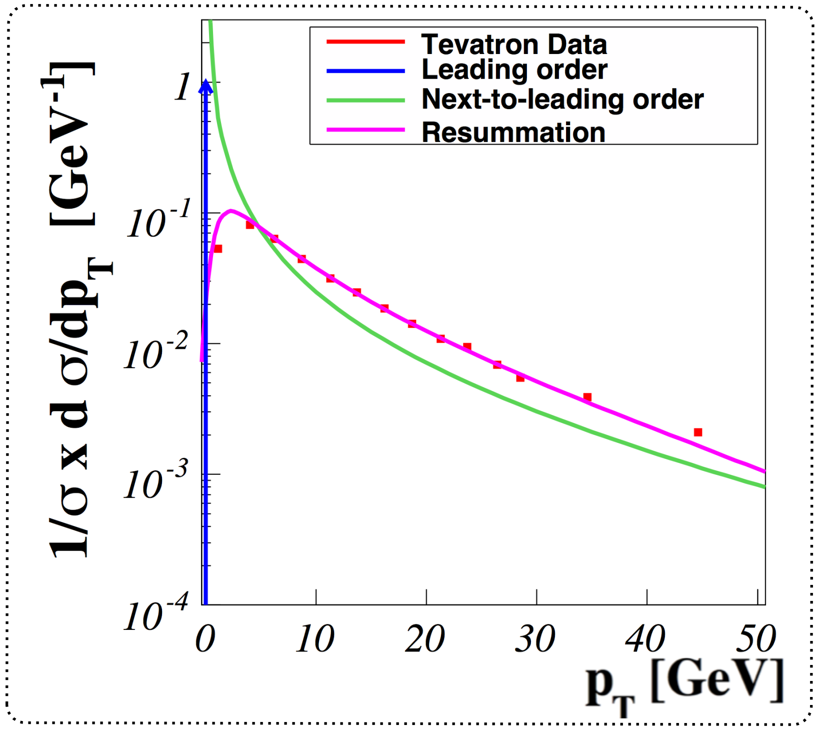
The Drell-Yan example: Representative virtual



Representative real

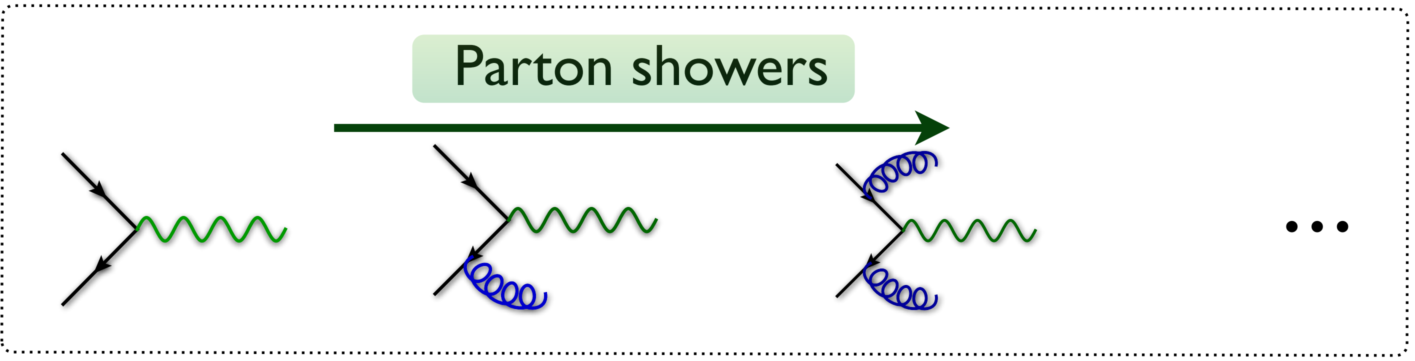


Matrix-element / parton shower matching



- ✦ Problems with NLO (fixed-order) calculations
  - ✤ Soft and collinear radiation ➢ large logarithms
  - ✤ Spoil the convergence of the perturbative series

- ✦ Matching with parton showers



  - ✤ Resummation of the soft and collinear radiation
  - ✤ Predictions for a fully exclusive description of the collisions
  - ✤ Suitable for going beyond the parton level (hadronization, detector simulation)

NLO calculations in a nutshell

✦ Contributions to an NLO result in QCD

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

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

Born | Virtuals: one extra power of α_s and divergent | Reals: one extra power of α_s and divergent

✤ Challenge: computing predictions numerically (and in four dimensions)

Virtual contributions

✦ Loop diagram calculations

- ✤ Calculations to be done in $d=4-2\varepsilon$ dimensions
  - ★ Divergences made explicit ($1/\varepsilon^2$, $1/\varepsilon$)

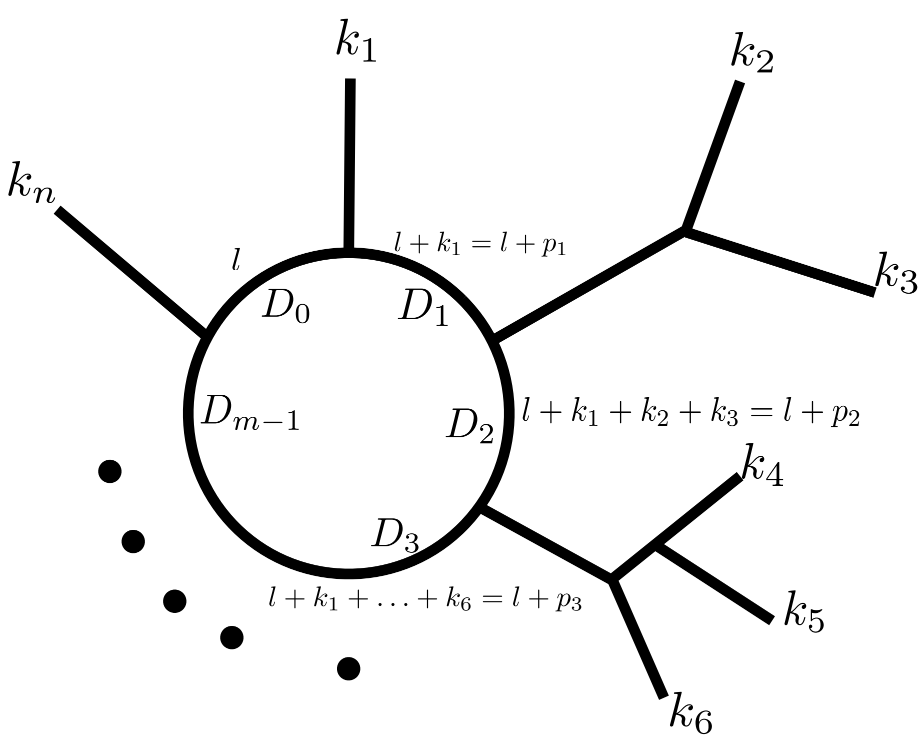
- ✤ Rewriting loop integrals with scalar integrals

$$\int \mathrm{d}^d\ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int \mathrm{d}^d\ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

  - ★ Involves integrals with up to four denominators
  - ★ The decomposition basis is finite

The basis integrals can be calculated once and for all

m-point diagram with *n* external momenta



The rational terms

✦ The loop momentum lives in a *d*-dimensional space

- ✤ The reduction should be done in *d* dimensions and not in 4 dimensions

$$\int \mathrm{d}^d\ell \frac{N(\ell,\tilde{\ell})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}} \quad \text{with } \bar{\ell} = \ell + \tilde{\ell}$$

($\bar{\ell}$: D-dim, ℓ: 4-dim, $\tilde{\ell}$: (-2ε)-dim)

- ✤ Numerical methods works in four dimensions: need to be compensated!

✦ The R_1 terms originates from the denominators

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

- ✤ These extra pieces can be calculated generically (3 integrals in total)

✦ The R_2 terms originates from the numerator

- ✤ Process-dependent contributions proportional to $\tilde{\ell}^2$
- ✤ 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 (➢ NLOCT) [Degrande (CPC'15)]
    - ➢ *R_2 counterterm Feynman rules*

Matching fixed order with parton showers

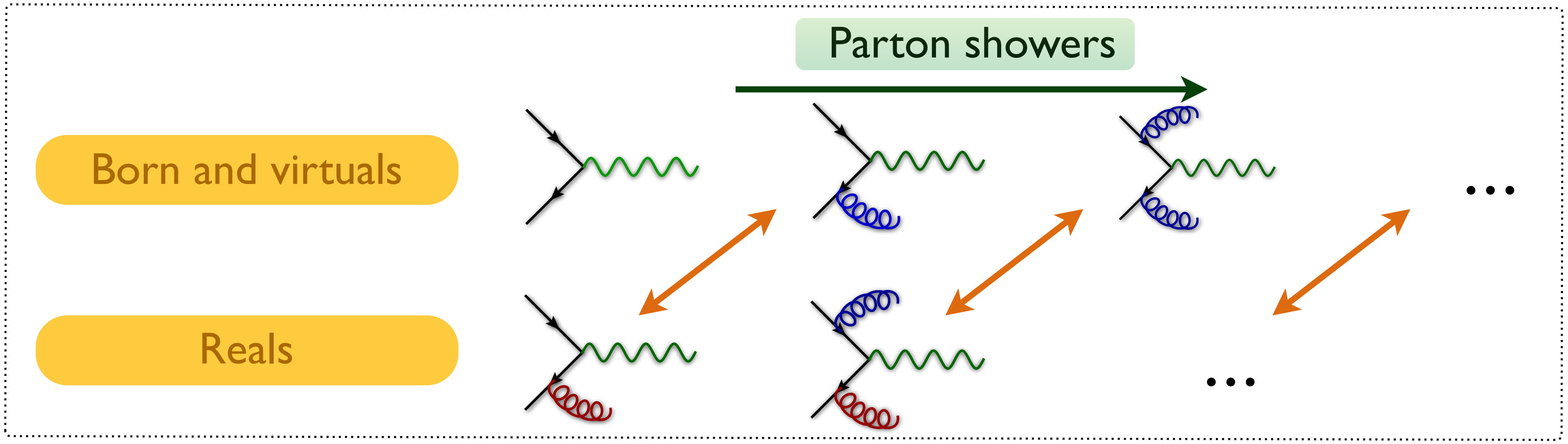
✦ Subtracting the poles

✤ The structure of the poles appearing at NLO is known ➢ subtraction methods

- ★ $\mathcal{C}$ subtracted from the reals ➢ makes them finite
- ★ $\mathcal{C}$ integrated and added back to the virtuals ➢ makes them finite
- ★ Integrals can be made numerically (in four dimensions)

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

✦ Double counting when matching with parton showers



✤ Two sources of double counting that compensate each other (shower unitarity)

- ★ Radiation: both at the level of the reals and of the shower
- ★ No radiation: both in the virtuals and in the no-emission probability

MG5_aMC@NLO: master formula

✦ Two series of counterterms: NLO and Monte Carlo

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

S-events H-events

★ $\mathcal{I}_{\rm MC}^{(n)}$ represents the shower operator for a (*n*)-body final state

✤ The MC counterterms match the real emission IR behavior (by definition)
- ★ They describe: how the shower gets from an (n)-body to a (n+1)-body final state
- ★ Same kinematics as the reals: pole cancelation
- ★ Extra component accounting for the soft divergences

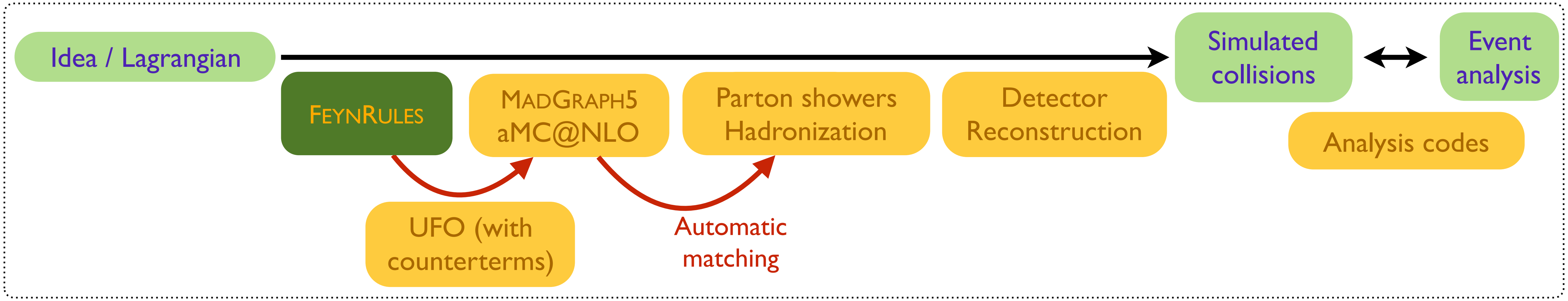
✤ The MC counterterms cannot be integrated numerically
- ★ Using simultaneously the NLO and MC counterterms in the virtuals

✤ 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

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

Automated NLO simulations with MG5_aMC

✦ A comprehensive approach to Monte Carlo simulations



✦ From Lagrangians to analyzed NLO simulated collisions

- ✤ FEYNRULES is linked to the NLOCT module
  - ★ Calculation of UV and R_2 counterterms
  - ★ Export of the information to the UFO

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14)]
[Degrande (CPC'15)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
[Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

✦ Matching with parton showers within MG5_aMC@NLO

- ✤ Monte Carlo subtraction terms automatically handled

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

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1. Introduction: two decades of Monte Carlo developments for new physics

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3. **Phenomenology: SUSY, vector-like quarks, EFT and dark matter**

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I - Supersymmetric QCD

✦ The supersymmetric QCD Lagrangian

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15; PLB'16)]

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

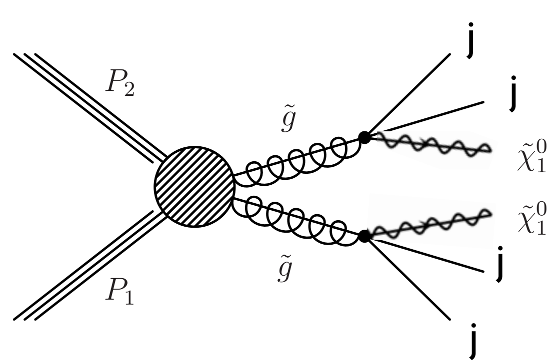
★ All (s)quarks, gluino and gluon supersymmetric-QCD interactions included

★ Missing: subtraction of the possible intermediate resonances in the reals [in progress]

★ We need to decouple either the squarks or the gluino

➢ Supersymmetry-inspired simplified models

Gluino - multijet + MET



Validation and total cross sections

✦ Total rates at 13 TeV

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15; PLB'16)]

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
500	$15.46^{+34.7\%+19.5\%}_{-24.1\%-19.5\%}$	$24.90^{+12.5\%+3.7\%}_{-13.4\%-3.7\%}$
750	$1.206^{+35.9\%+23.5\%}_{-24.6\%-23.5\%}$	$2.009^{+13.5\%+5.5\%}_{-14.1\%-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%+26.4\%}_{-24.8\%-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%+7.3\%}_{-14.8\%-7.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%+29.8\%}_{-24.5\%-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%+17.8\%}_{-16.6\%-17.8\%}$

★ Central scales: average gluino M_T

★ Parton densities: NNPDF 3.0

✦ Validation

✤ Analytical

★ Counterterms, UV / IR structure, *etc.*

✤ Numerical (with respect to PROSPINO) [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]

★ Generalization of the PROSPINO setup (different squark masses)

✦ NLO effects

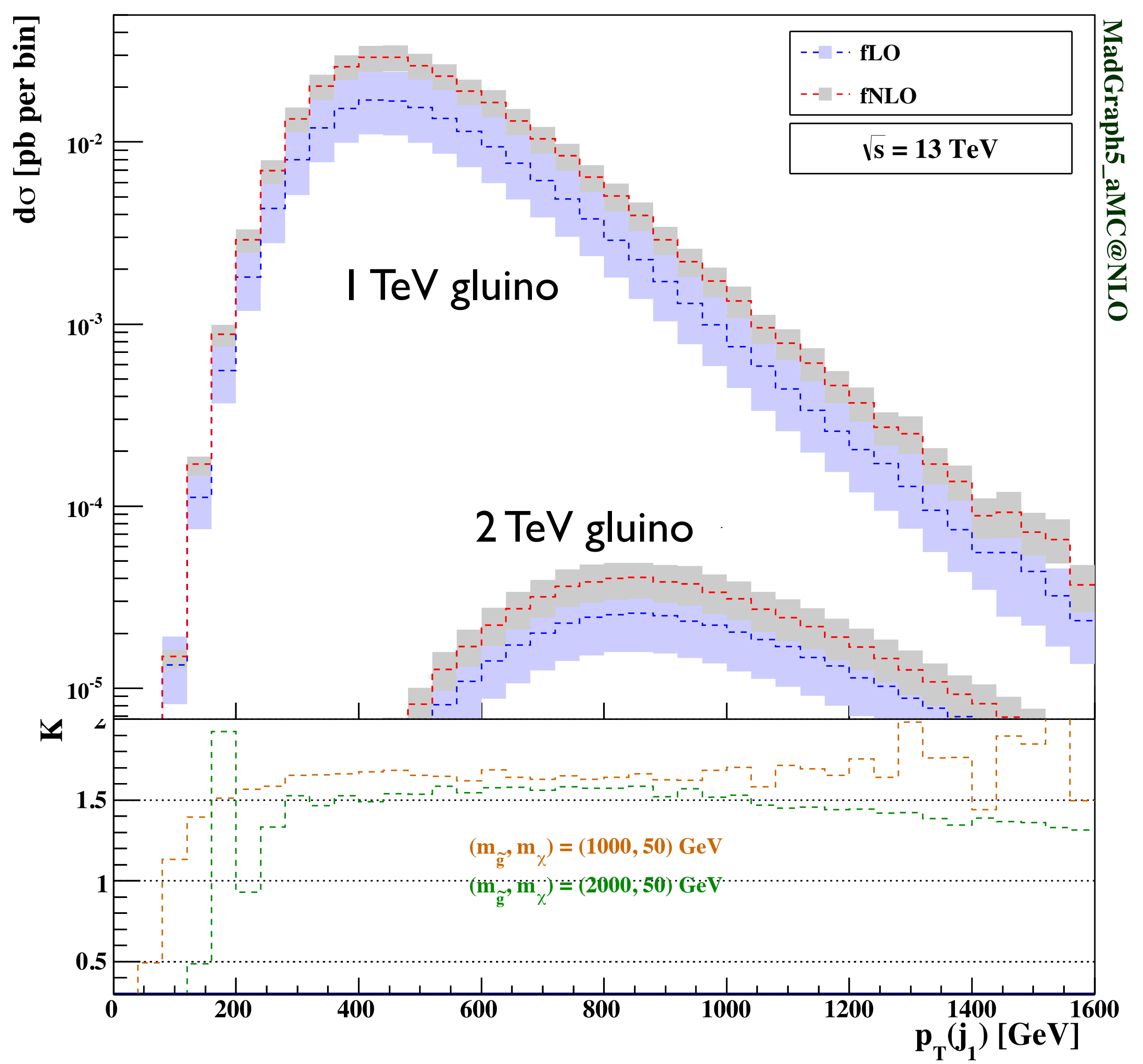
✤Enhancement of the cross section of 50% (genuine NLO contributions)

✤ Sizeable reduction of the scale / PDF uncertainties

★ Beware: poor quality of the NNPDF LO fit

Differential distributions: jet properties (I)

1st jet p_T



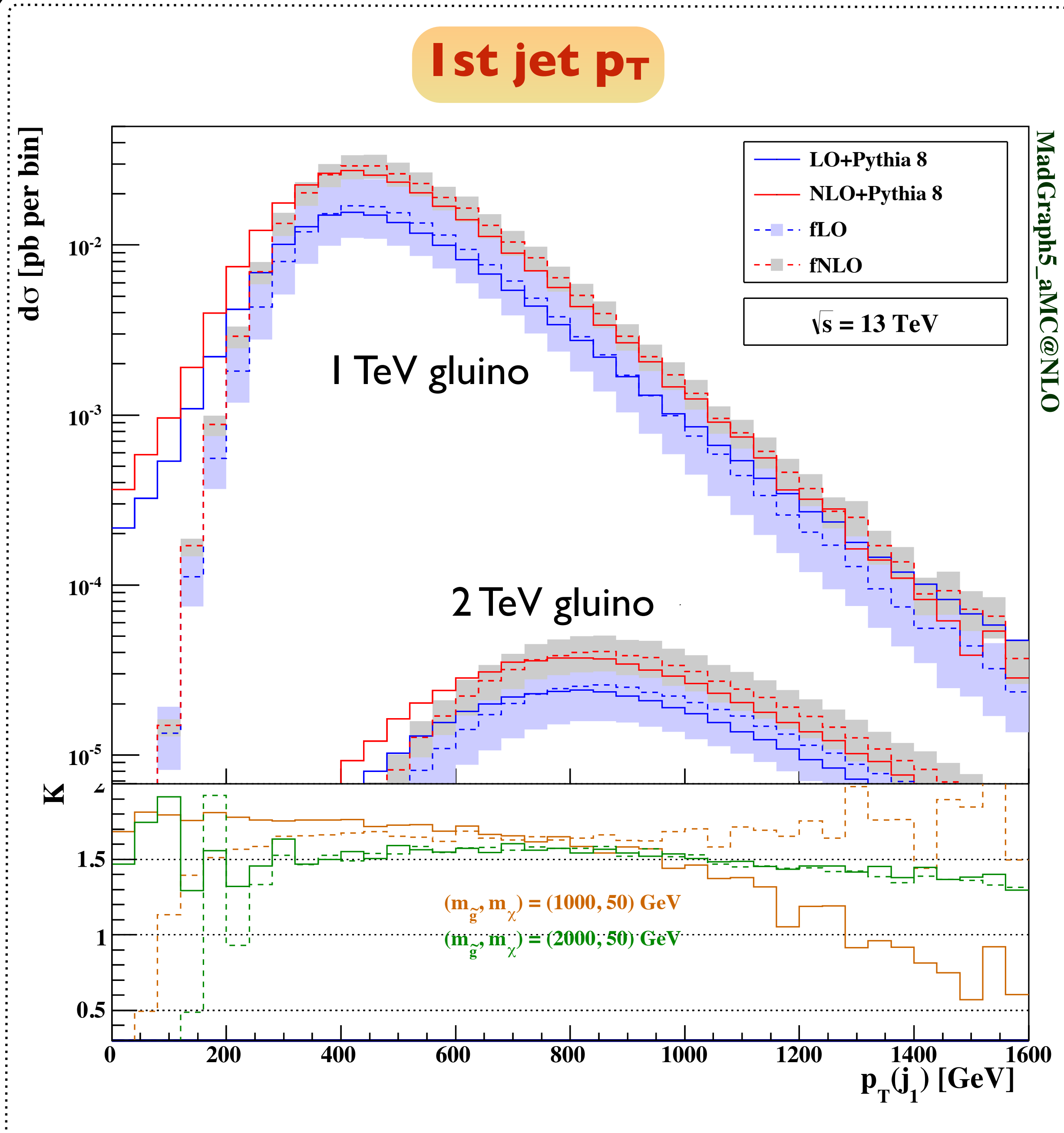
[Degrande, BF, Hirschi, Proudom & Shao (PLB'16)]

- ✤ The 1st jet mostly arises from gluino decays
  - ★ The low p_T region is depleted (heavy gluino)
- ✤ Constant *K*-factors not accurate
- ✤ NLO effects
  - ★ Normalization enhancement
  - ★ Distortion of the shapes
  - ★ Reduction of the theoretical uncertainties

LO description + constant *K*-factor:
➢ very inaccurate signal modelling
➢ in particular in the low-p_T region

Region better described by parton showers

Differential distributions: jet properties (2)



[Degrande, BF, Hirschi, Proudom & Shao (PLB'16)]

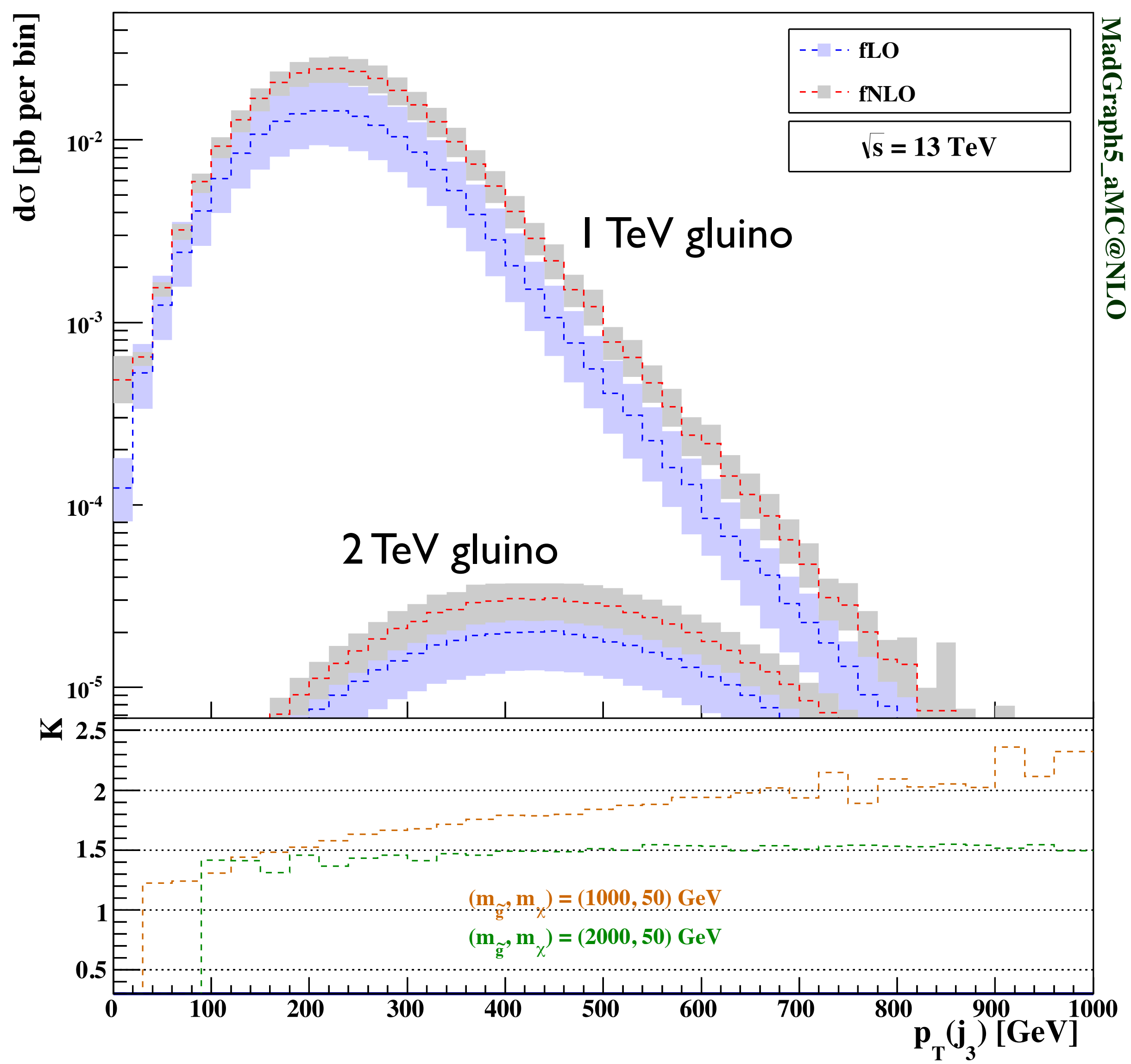
- ✤ Parton showers populate the low-p_T region
  - ★ Emitted partons often not reclustered back
  - ★ Extra softer jets
  - ★ Distortion of the spectrum
  - ★ Effects milder for hard p_T (the matrix element drives the shape)
- ✤ *K*-factor behavior (fixed-order *vs.* ME+PS)
  - ★ Changes more pronounced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

The 'decay' origin of the jet dominates
➢ single peak at large p_T value

Differential distributions: jet properties (3)

[Degrande, BF, Hirschi, Proudom & Shao (PLB'16)]

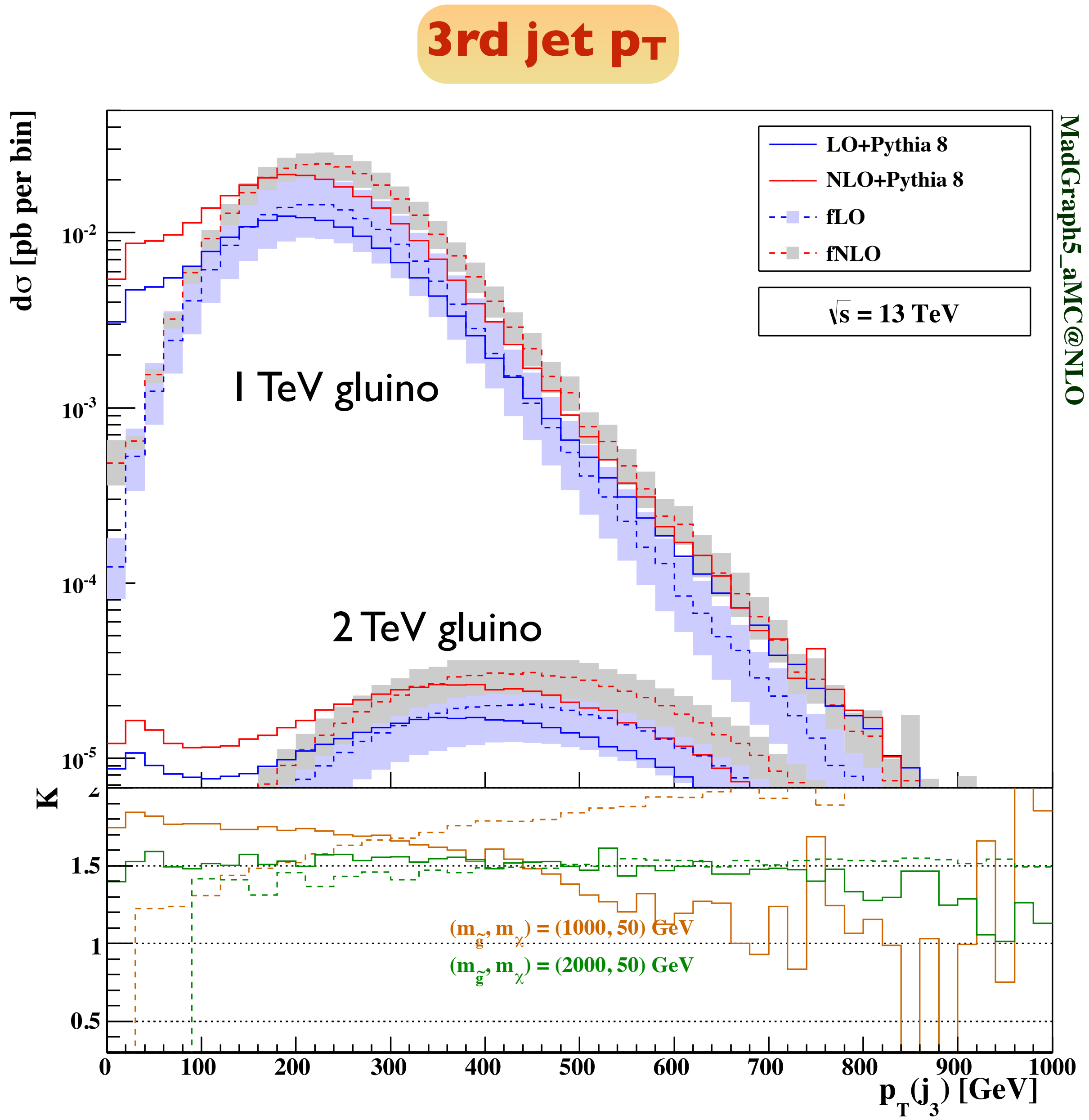
3rd jet p_T



- 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 signal description
  - ★ Reduction of the theoretical uncertainties

Differential distributions: jet properties (4)

[Degrande, BF, Hirschi, Proudom & Shao (PLB'16)]



- ✤ Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes a radiation jet
  - ★ Entanglement of the two effects: two peaks
- ✤ *K*-factor behavior (fixed-order *vs.* ME+PS)
  - ★ Changes more pronounced for 1 TeV gluinos
  - ★ Effect at larger p_T for 2 TeV gluinos

2 - Vector-like quark partners

[BF & Shao ('16); Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (*in prep.*)]

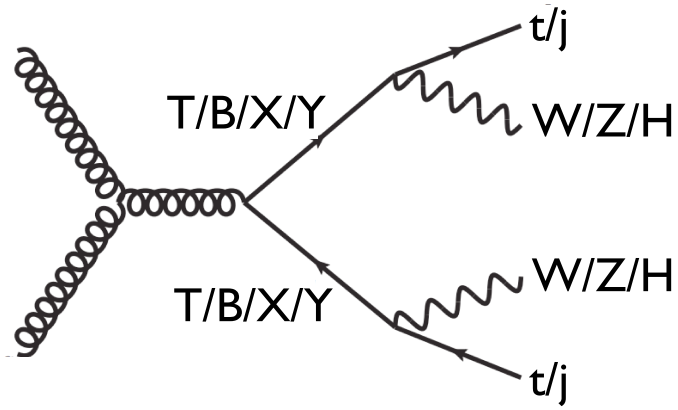
✦ An effective Lagrangian (with four partners: T, B, X and Y)

$$\begin{aligned}\mathcal{L}_{\rm VLQ} =\ & i\bar Y \not{D} Y - m_{\scriptscriptstyle Y} \bar Y Y + i\bar B \not{D} B - m_{\scriptscriptstyle B}\bar B B + i\bar T \not{D} T - m_{\scriptscriptstyle T} \bar T T + i\bar X \not{D} X - m_{\scriptscriptstyle X} \bar X X\\ & - h\ \Big[\bar B\Big(\hat\kappa^B_L P_L + \hat\kappa^B_R P_R\Big) q_d + \bar T\Big(\hat\kappa^T_L P_L + \hat\kappa^T_R P_R\Big) q_u + \text{h.c.}\Big]\\ & + \frac{g}{2c_W}\ \Big[\bar B \not{Z}\Big(\tilde\kappa^B_L P_L + \tilde\kappa^B_R P_R\Big) q_d + \bar T \not{Z}\Big(\tilde\kappa^T_L P_L + \tilde\kappa^T_R P_R\Big) q_u + \text{h.c.}\Big]\\ & + \frac{\sqrt{2}g}{2}\ \Big[\bar Y \not{W}\Big(\kappa^Y_L P_L + \kappa^Y_R P_R\Big) q_d + \bar B \not{W}\Big(\kappa^B_L P_L + \kappa^B_R P_R\Big) q_u + \text{h.c.}\Big]\\ & + \frac{\sqrt{2}g}{2}\ \Big[\bar T \not{W}\Big(\kappa^T_L P_L + \kappa^T_R P_R\Big) q_d + \bar X \not{W}\Big(\kappa^X_L P_L + \kappa^X_R P_R\Big) q_u + \text{h.c.}\Big]\end{aligned}$$

✦ Illustrative process

★ Quark partners decay into an electroweak boson and a jet/top

★ Pair, single and QV/QH associated production can be simulated



Illustrative example

[BF & Shao ('16); Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (*in prep.*)]

✦ Model description: T-Higgs interactions

$$\mathcal{L}_{\rm VLQ} = i\bar{T}\not{D}T - m_T\bar{T}T - h\left[\bar{T}\Big(\hat{\kappa}_L^T P_L + \hat{\kappa}_R^T P_R\Big)u + {\rm h.c.}\right]$$

★ Coupling proportional to $m_T/v_{SM}\ U_{41}$
- ➢ driven by the quark-VLQ mixing U
- ➢ VLQ mass enhancement

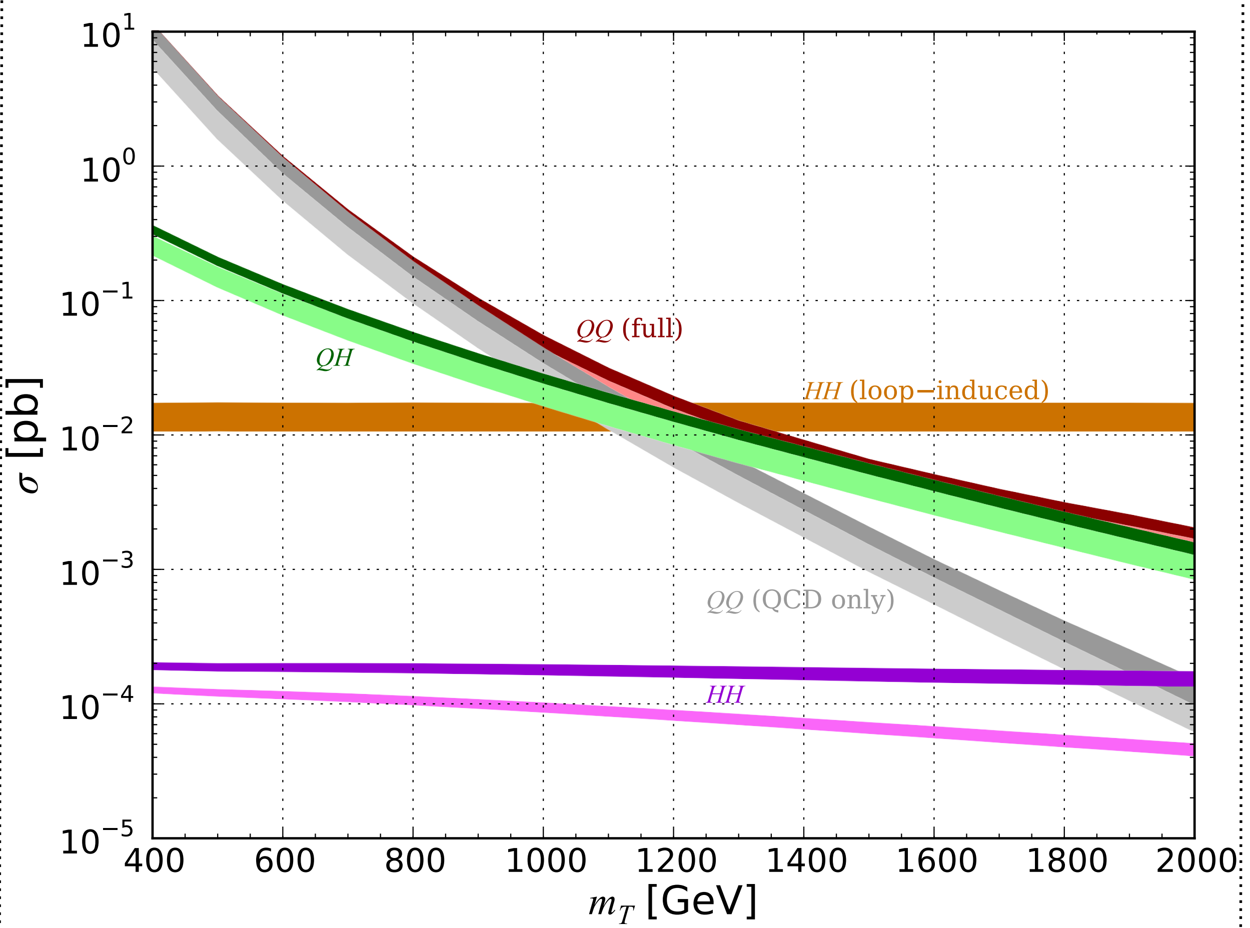
✦ Investigation of (inclusive) Higgs-pair production

- ✤ Production mode 1: TT pair-production followed by two T → uH decays
- ✤ Production mode 2: TH associated production followed by a T → uH decays
- ✤ Production mode 3: H-pair production (VLQ *t*-channel exchange or loop-diagrams)

NLO effects on total rates

[BF & Shao ('16); Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (*in prep.*)]

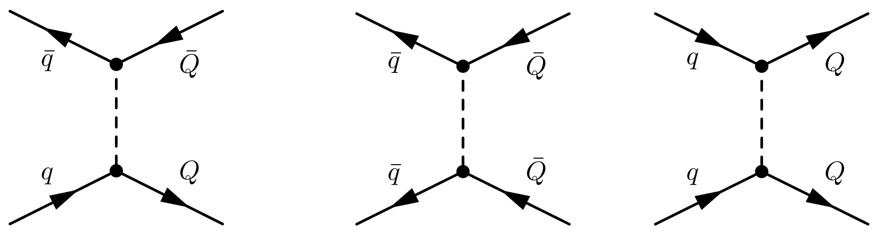
✦Total rates (first NLO-QCD calculations in many cases)



✤ NLO: large *K*-factors, smaller errors

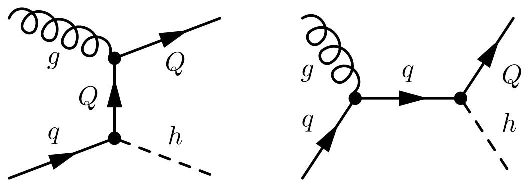
✤ EW diagrams for TT production

★ Dominates QCD prod. at large mass



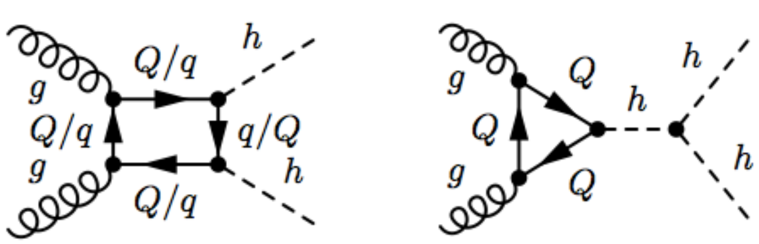
✤ TH production

★ Competes with TT prod. at large mass



✤ H-boson pair production

★ Loop-induced diagrams dominate

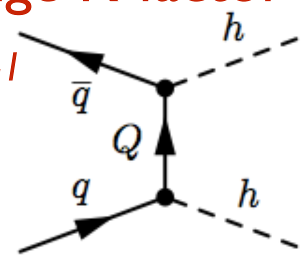


★ *t*-channel VLQ exchange diagrams: huge K-factor

➢ Coupling proportional to $m_T/v_{SM}\ U_{4l}$

➢ Driven by the u-VLQ mixing *U*

➢ VLQ mass enhancement

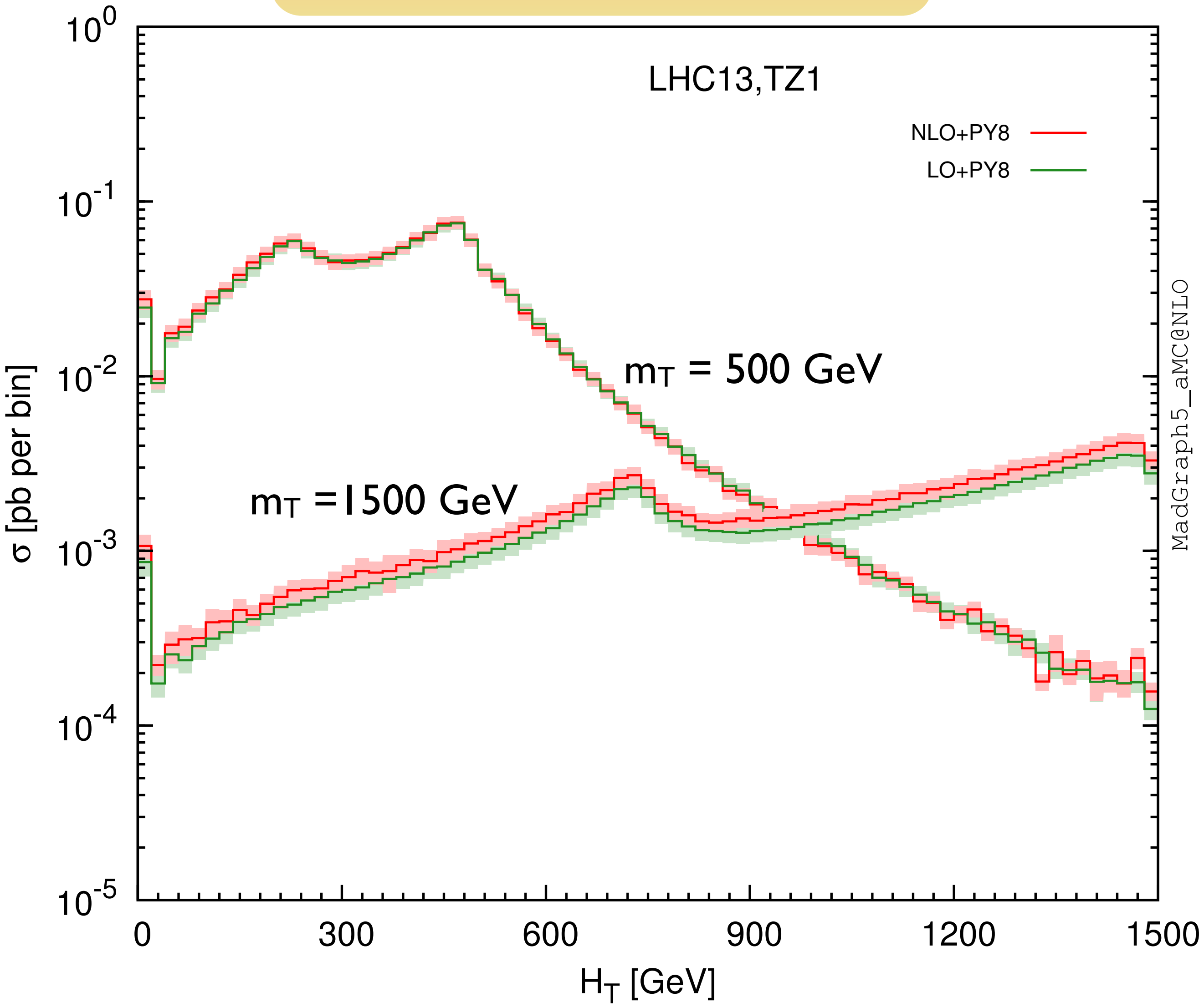


Differential distribution: jet activity

✦ Model description: T-Z interactions

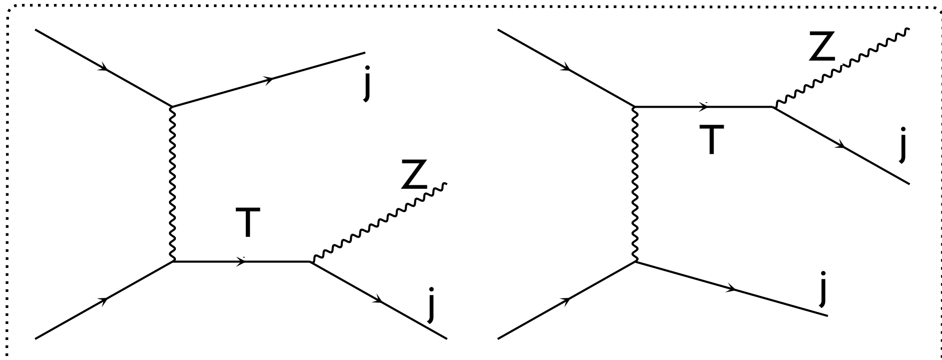
$$\mathcal{L}_{\rm VLQ} = i\bar{T}\not{D}T - m_T\bar{T}T + \frac{g}{2c_W}\Big[\bar{T}\not{Z}\Big(\tilde{\kappa}^T_L P_L + \tilde{\kappa}^T_R P_R\Big)u + {\rm h.c.}\Big]$$

Hadronic activity (H_T)



[BF & Shao ('16)]

✤ Diagrams



✤ Simulations: ME + PS

✤ H_T distribution
- ★ Scalar sum of the p_T of all reconstructed objects
- ★ Two-peaked structure (at M_T and $M_T/2$)
- ★ The 2nd peak: invisible Z decays

✤ Constant *K*-factor
- ★ *K*=1 (m_T=500 GeV)
- ★ *K*~1.20 (m_T=1500 GeV)

3 - (Higgs) Effective Field Theory

[Degrande, BF, Mawatari, Mimasu & Sanz ('16)]

✦ Standard Model EFT operators could impact electroweak Higgs production

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{g'^2}{4\Lambda^2}\bar{c}_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$
$$+\frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu} + \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu}$$
$$+\frac{ig'}{\Lambda^2}\bar{c}_{HB}\left[D_\mu\Phi^\dagger D_\nu\Phi\right]B^{\mu\nu}$$

★ Five operators as an illustrative example

✦ Effective field theories at NLO (in QCD)

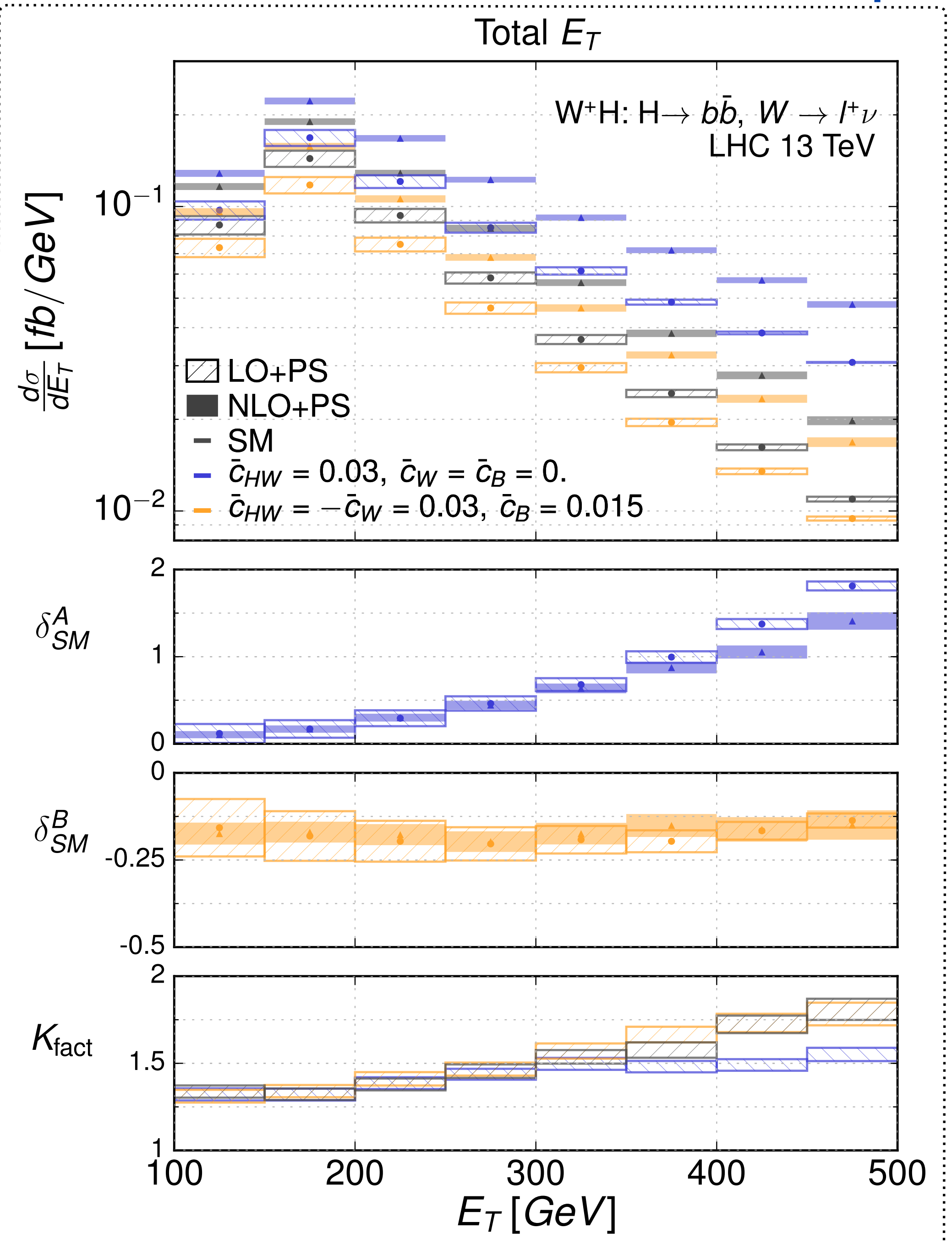
- ✤ Renormalizability: order by order in $1/\Lambda^2$
- ✤ Precision: including the QCD corrections
- ✤ Double perturbative series

$\sigma \approx 1$	+ $O(\alpha_s)$	+ $O(1/\Lambda^2)$	+ $O(\alpha_s/\Lambda^4)$
↓	↓	↓	↓
SM@LO	SM@NLO	EFT@LO	EFT@NLO

WH production at the LHC (I)

[Degrande, BF, Mawatari, Mimasu & Sanz ('16)]

✦ QCD and EFT effects on VH production



- ✤ Differential K-factors scenario-dependent
- ✤ Significant deviations from the Standard Model
  - ★ The *blue* scenario features specific hVV couplings
  - ★ Huge deviations in the tails

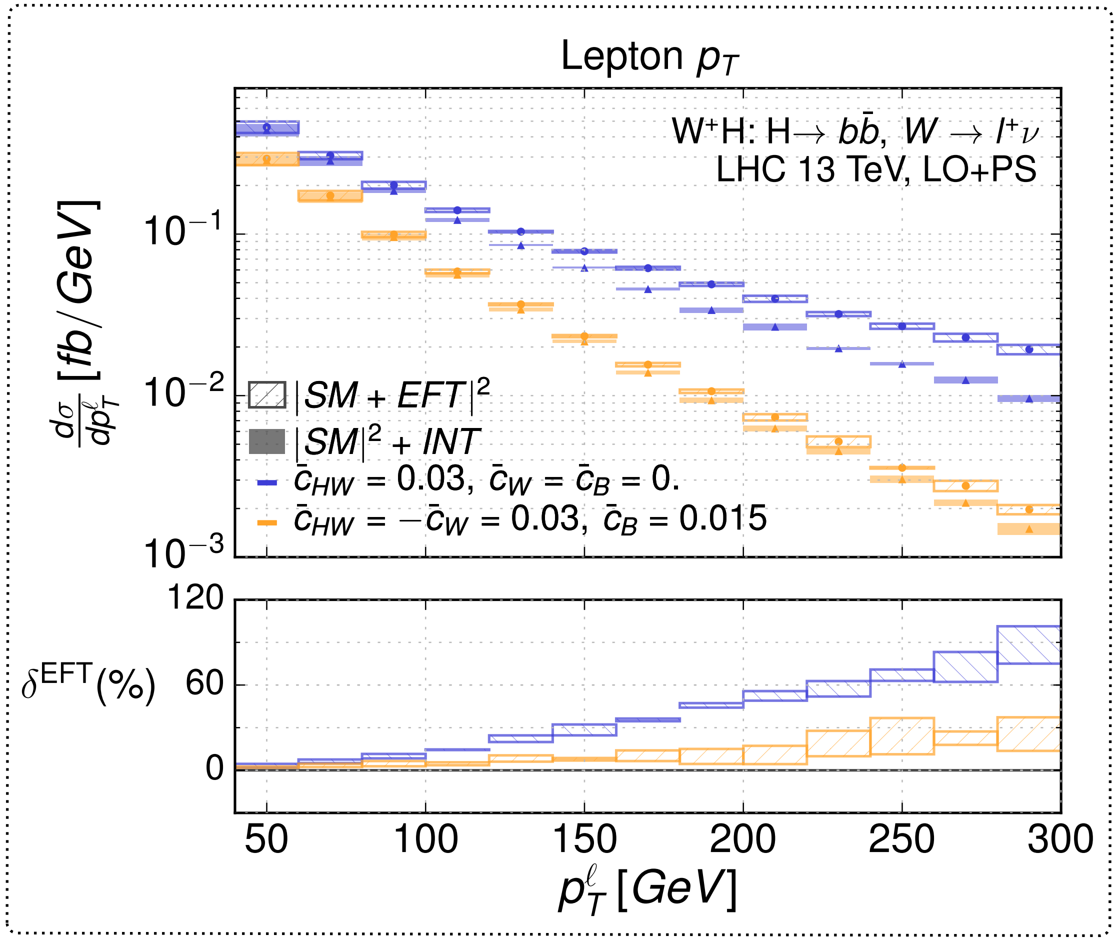
$$-g^{(2)}_{hww}\left[W^+_\nu\partial_\mu W^{-\mu\nu}h + \text{h.c.}\right]$$

  - ★ Could be exploited to further constrain SM EFT
- ✤ LO and NLO predictions do not overlap
  - ★ LO uncertainties could be underestimated

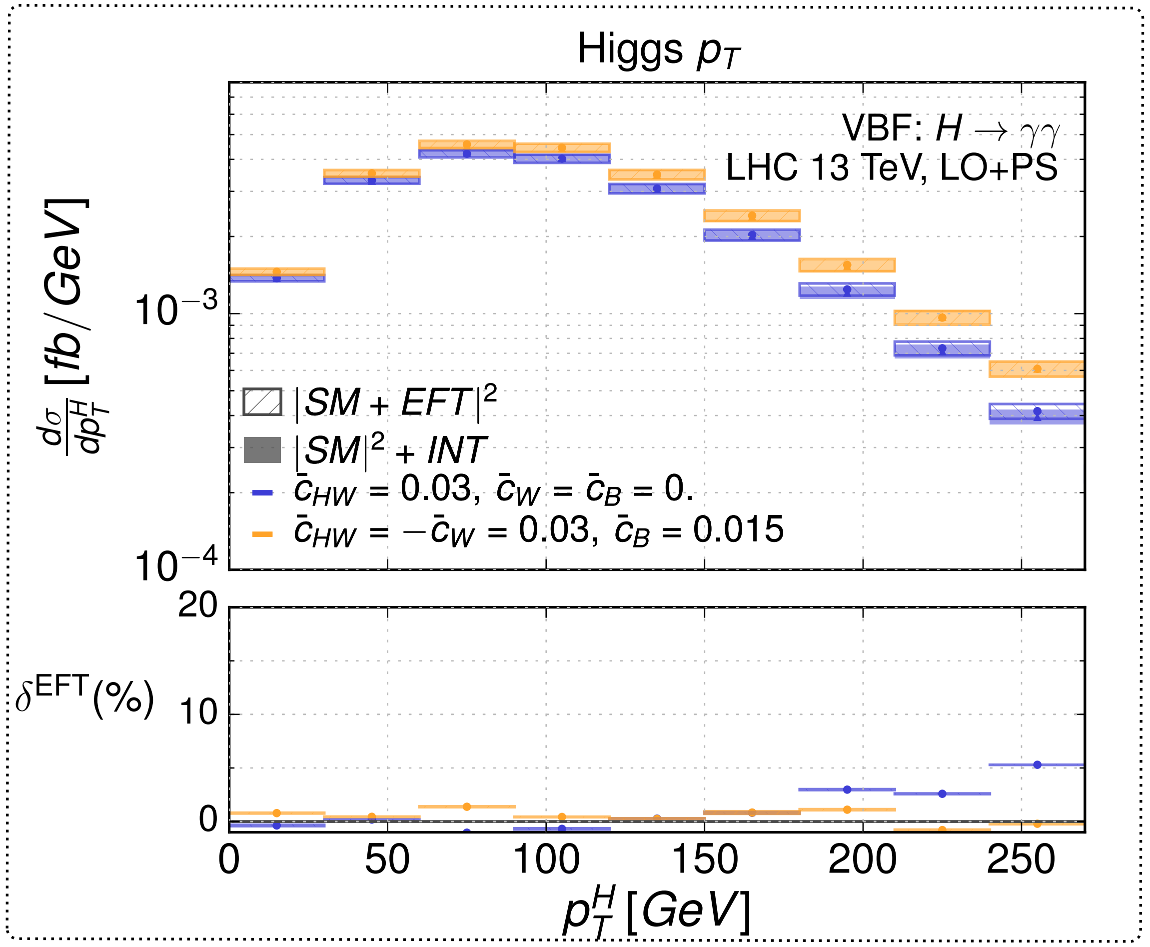
WH production at the LHC (2)

[Degrande, BF, Mawatari, Mimasu & Sanz ('16)]

✦Unitarity and perturbativity checks



- ★ $1/\Lambda^4$ effects possibly large (40-100%) in the tails
- ★ Benchmark- and process-dependent
- ★ Care must be taken with the EFT interpretation
  - ➢ WH: *orange* is OK, *blue* is not
  - ➢ VBF: *orange* and *blue* OK



4 - Top-philic dark matter

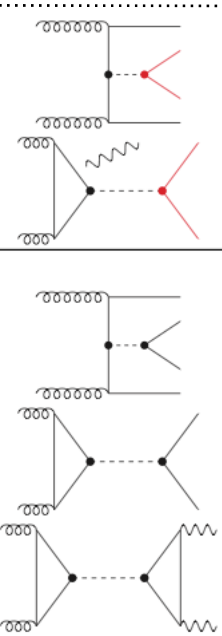
[Arina, Backovic, Conte, BF, Guo *et al.* (JHEP'16)]

✦ A simplified model for top-philic dark matter

- ✤ A dark sector with a fermionic dark matter candidate X
- ✤ A (scalar) mediator Y_0 linking the dark sector and the top

$$\mathcal{L}_{t,X}^{Y_0} = -\Big(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\Big) Y_0$$

- ✤ This scenario can be probed in many ways



$\not{E}_T$	$m_Y > 2m_X$	$+t\bar{t}$
	$m_Y > 2m_X$	$+j, +Z, +h$
no $\not{E}_T$	$m_Y > 2m_t$	$4t$
	$m_Y > 2m_t$	$t\bar{t}$
	$m_Y < 2m_X, 2m_t$	$jj, \gamma\gamma$

★ With or without missing energy
★ Via tree or loop-induced processes
★ Via top-enriched final states or not

- ✤ Examples: $t\bar{t}$+MET (CMS-B2G-14-004) and monojet (CMS-EXO-12-048)

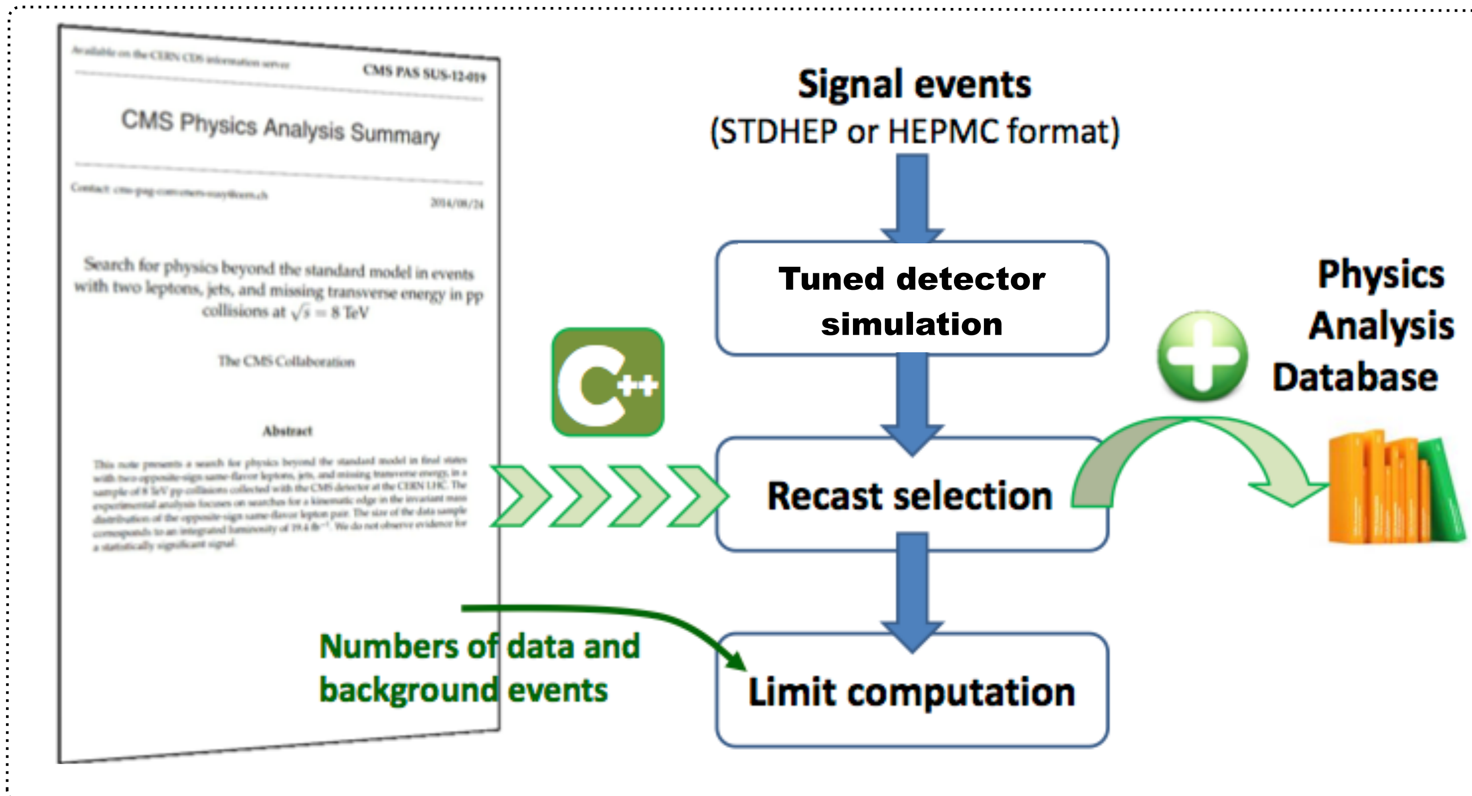
Recasting with MADANALYSIS 5

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

✦ The MADANALYSIS 5 strategy for the reinterpretation of an LHC analysis

- Relies on a (public) detector simulation mimicking ATLAS-CMS simulations
- Relies on a (public) framework where LHC analyses can be easily implemented

✦ Scheme



- 2 options for detector effects
  - ★ DELPHES/PGS-like (resolutions, efficiencies, *etc.*)
  - ★ RIVET-like (transfer functions)

Picked approach in MADANALYSIS 5

Implementing a new analysis in MadAnalysis 5

- Picking up an experimental publication
  - Reading
  - Understanding

✅ Relatively easy

- Writing the analysis code in the tool internal language

✅ Relatively easy

- Getting the information missing from the publication for a proper validation
  - Efficiencies (trigger, electrons, muons, b-tagging, JES, *etc.*)
    - ★ Including p_T and/or η dependence
    - ★ Accurate information
  - Detailed cutflows for some well-defined benchmark scenarios
    - ★ Exact definition of the benchmarks (SLHA spectra)
    - ★ Event generation information (cards, tunes, LHE files if possible)
  - Expected number of events in each region and cross sections
  - Digitized histograms (e.g., on HepData)

⚠️ Essential
❌ Often difficult!

- Comparing theory tools and real life
  (and beware of the genuine differences between both approaches)

Recasting CMS-EXO-12-048

[Conte, BF, Guo ('16)]

- Missing information for the validation
  - Discussion with CMS to get validation benchmarks
  - Cutflows and Monte Carlo information for given benchmarks

✅ Discussions with CMS needed

- Validation:

	Selection step	CMS	$\epsilon_i^{\rm CMS}$	MA5	$\epsilon_i^{\rm MA5}$	$\delta_i^{\rm rel}$
0	Nominal	84653.7		84653.7		
1	One hard jet	50817.2	0.6	53431.28	0.631	5.2%
2	At most two jets	36061	0.7096	38547.75	0.721	1.61%
3	Requirements if two jets	31878.1	0.884	34436.35	0.893	1.02%
4	Muon veto	31878.1	1	34436.35	1.000	0
5	Electron veto	31865.1	1	34436.35	1.000	0
6	Tau veto	31695.1	0.995	34397.54	0.998	0.3%
	$\not{E}_T > 250$ GeV	8687.22	0.274	7563.04	0.219	20.00%
	$\not{E}_T > 300$ GeV	5400.51	0.621	4477.67	0.592	4.66%
	$\not{E}_T > 350$ GeV	3394.09	0.628	2813.70	0.628	0.00%
	$\not{E}_T > 400$ GeV	2224.15	0.6553	1753.71	0.623	4.93%
	$\not{E}_T > 450$ GeV	1456.02	0.654	1110.92	0.633	3.21%
	$\not{E}_T > 500$ GeV	989.806	0.679	722.83	0.650	4.27%
	$\not{E}_T > 550$ GeV	671.442	0.678	487.54	0.674	0.59%

✅ Validated at the 20% level

Issue with the low-MET modelling in DELPHES

- The $t\bar{t}$+MET analysis (CMS-B2G-14-004) was validated to the 2-3% level

MADANALYSIS 5 analyses on INSPIRE

[BF, Martini ('16)]

- Implementation of LHC analyses can be uploaded on INSPIRE
  - DOI are assigned: can be cited, searched for, *etc.*

Information | Citations (1) | Files

Files are versioned, can be downloaded

MadAnalysis5 implementation of the CMS search for dark matter production with top quark pairs in the single lepton channel (CMS-B2G-14-004)

DOI and citations

Fuks, Benjamin; Martini, Antony

Description: This is the MadAnalysis5 implementation of the CMS search for dark matter in a channel where a pair of dark matter particles is produced in association with a top-antitop system. This search targets events featuring a single lepton originating from the top decays and a large amount of missing transverse energy.

Information how to use this code and a detailed validation summary are available at http://madanalysis.irmp.ucl.ac.be/wiki/PhysicsAnalysisDatabase. The CMS analysis is documented at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G14004.

Cite as: Fuks, B., Martiny, A. (2016). MadAnalysis5 implementation of the CMS search for dark matter production with top quark pairs in the single lepton channel (CMS-B2G-14-004). doi: 10.7484/INSPIREHEP.DATA.MIHA.JR4G

Automatic installation of all implemented analyses from MADANALYSIS 5

Record added 2016-05-09, last modified 2016-05-09

$t\bar{t}$+MET constraints on top-philic dark matter

[Arina, Backovic, Conte, BF, Guo *et al.* (JHEP'16)]

✦ A simplified model for top-philic dark matter

- ✤ A dark sector with a fermionic dark matter candidate X
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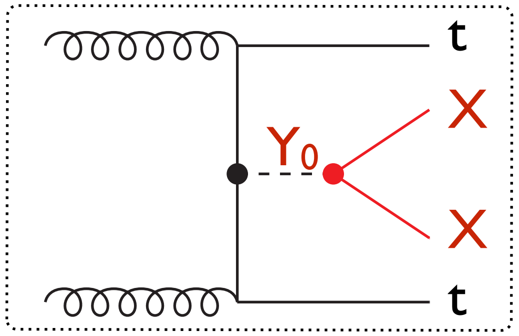
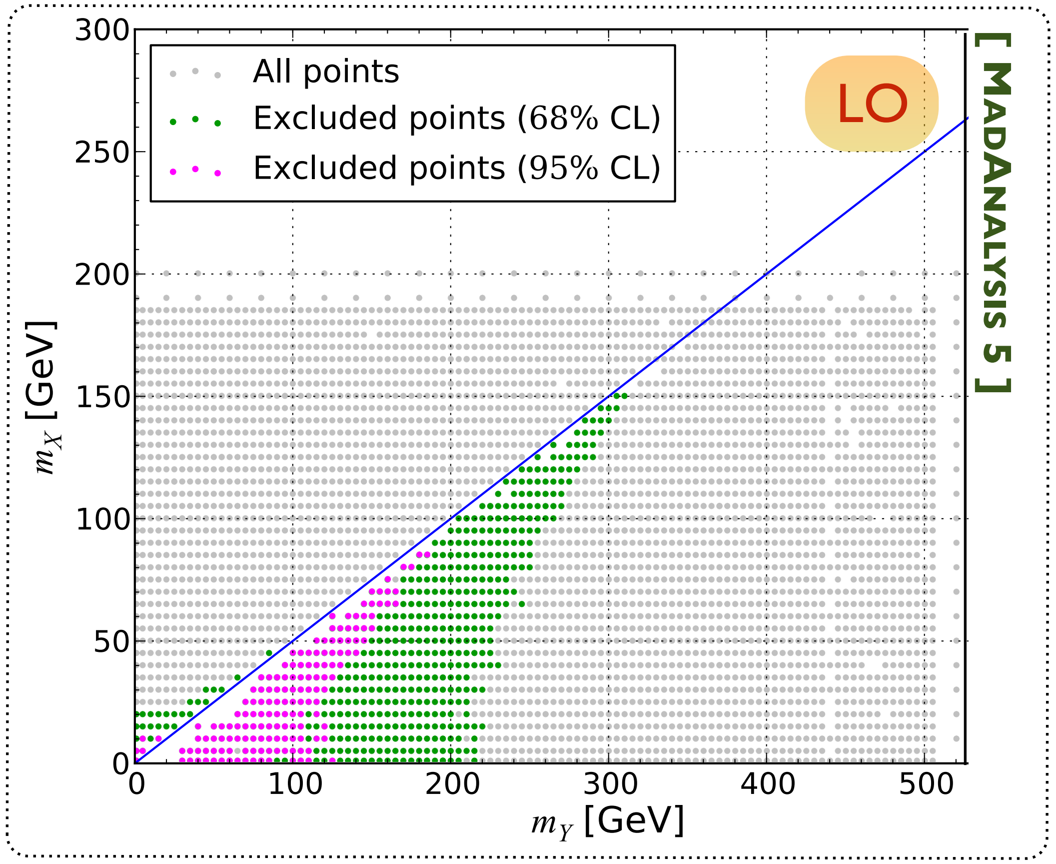
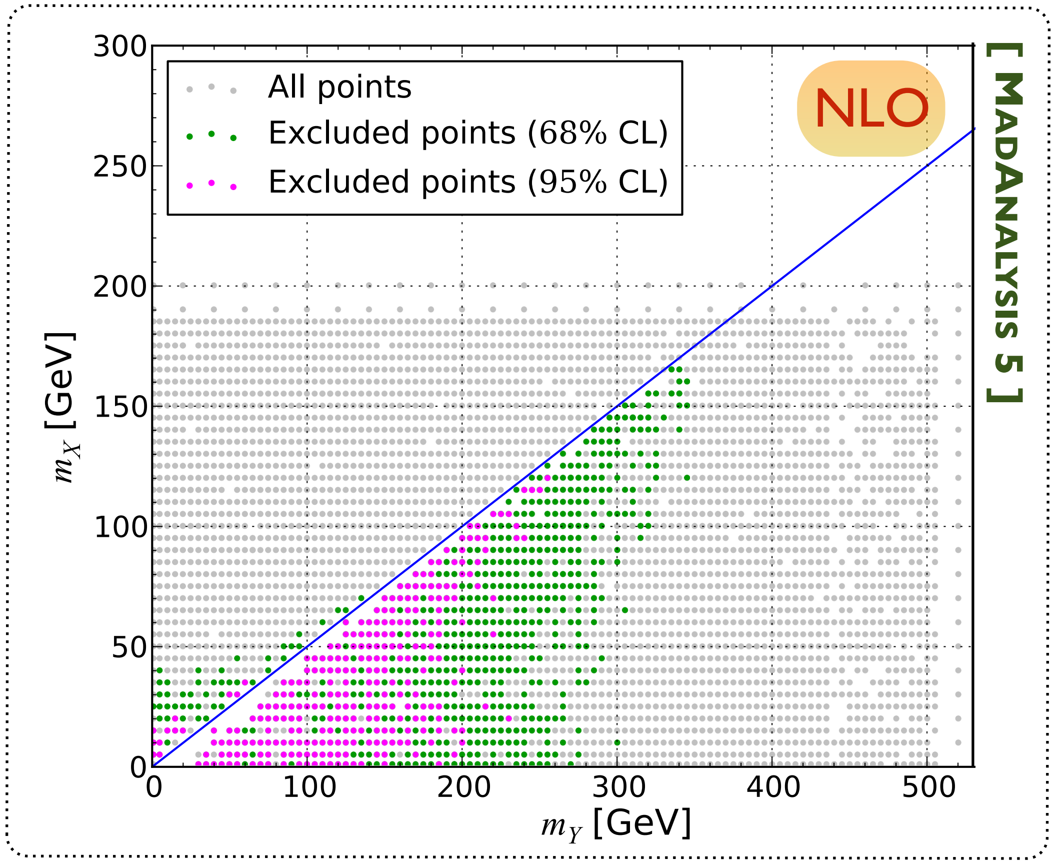


- ✤ Could be probed with $t\bar{t}$+MET events (CMS-B2G-14-004)

✦ For central scales: mild (but visible) NLO effects on the exclusions





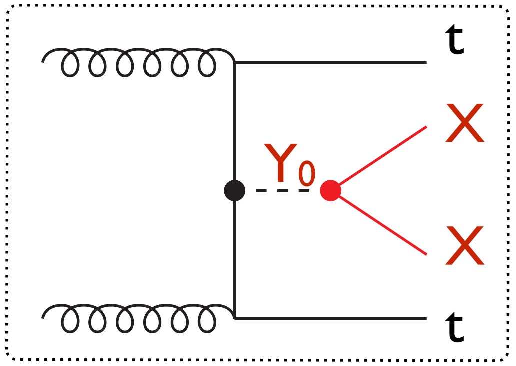
- ✤ How is the picture changing when including scale variations?

NLO effects on a CLs

[Arina, Backovic, Conte, BF, Guo *et al.* (JHEP'16)]

✦ There are theoretical uncertainties on a CLs number

	$(m_Y,\, m_X)$	$\sigma_{\rm LO}$ [pb]	$\rm CL_{LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\rm CL_{NLO}$ [%]
I	(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$98.7^{+0.8\%}_{-13.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$	$95.0^{+2.7\%}_{-0.4\%}$
II	(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$74.7^{+19.7\%}_{-17.7\%}$	$0.926^{+5.7\%}_{-10.4\%}$	$84.2^{+0.4\%}_{-14.4\%}$
III	(240, 100) GeV	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$



- ✤ An excluded point may not be excluded when accounting for uncertainties
- ✤ The CLs number can increase / decrease at NLO
- ✤ The error band is reduced

Outline

1. Introduction: two decades of Monte Carlo developments for new physics
2. Automating NLO calculations in QCD for new physics
3. Phenomenology: supersymmetry, vector-like quarks, EFT and dark matter
4. **Summary - conclusions**

Summary

✦ NLO-QCD simulations for new physics are now the state of the art

- Via a joint use of FEYNRULES and MADGRAPH5_aMC@NLO
- Divergences (UV, R_2, IR) and MC subtraction terms are automatically handled
- Many models are already publicly available (more to come)
  - Supersymmetry-inspired simplified models
  - BSM Higgs models
  - Dark matter simplified model
  - Higgs and top effective field theories
  - Vector-like quark models

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

✦ NLO effects are important

- Better control of the normalization
- Distortion of the shapes
- Reduction of the theoretical uncertainties
  - Effects on a CLs number (even if the central value shift is mild)