

Automatic NLO predictions matched with parton showers for new physics

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Outline

1. A basic introduction to perturbative QCD @ colliders
2. Automating NLO calculations in QCD for new physics
3. NLO impact on dark matter searches at the LHC
4. Vector-like quark phenomenology
5. Summary - conclusions

New physics @ the LHC

◆ Path towards the characterization of (potentially observed) new physics

- ✿ Getting **information** on the nature of an observation (fits, etc.)
 - ★ Leading order Monte Carlo techniques are sufficient
- ✿ **Final words** on the nature of any potential new physics
 - ★ Accurate measurements and **precise predictions** (at least NLO QCD)

◆ Challenges with respect to new physics simulations

- ✿ Theoretically, we are still in the dark
 - ★ No sign of new physics, measurements are Standard-Model-like
- ✿ **No leading new physics candidate theory**
 - ★ Plethora of models to implement in the tools

◆ New physics is standard in many tools today

- ✿ Result of 20 years of development
- ✿ Precision: **processes can be simulated (easily) at the NLO-QCD accuracy**
- ✿ Used framework: **MG5_aMC@NLO** & showcases involving top quarks

QCD 101: predictions at the LHC

◆ Distribution of an observable ω : the QCD factorization theorem

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

- ❖ 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 \triangleright theoretical uncertainties

◆ Short distance physics: the partonic cross section

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

Fixed-order predictions

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

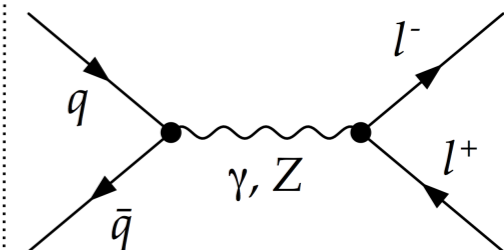
❖ Easily calculable

- ★ 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)

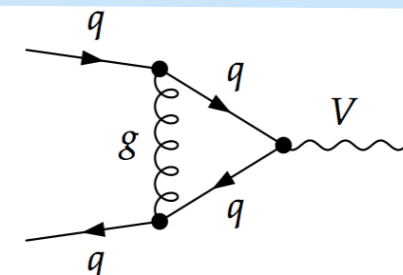
❖ Reduction of the theoretical uncertainties

- ★ First order where loops compensate trees

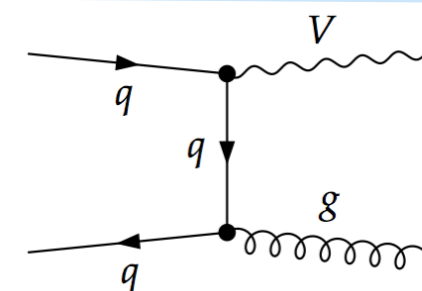
❖ Better description of the process

- ★ Impact of extra radiation
- ★ More initial states included
- ★ Sometimes not precise enough

The Drell-Yan example:
Representative virtual



Representative real

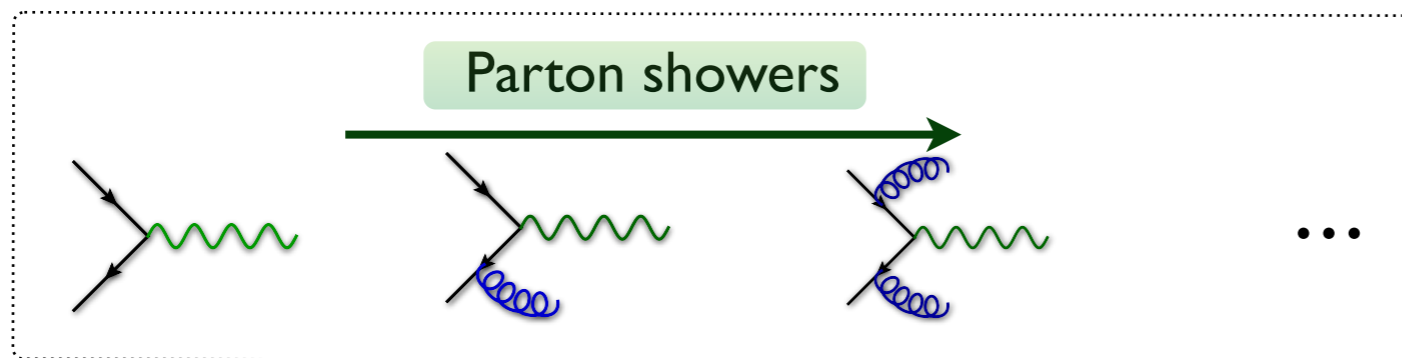


Matrix-element / parton shower matching

◆ Problems with NLO (fixed-order) calculations

- ❖ Soft and collinear radiation ➤ large logarithms
- ❖ **Spoiling 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)

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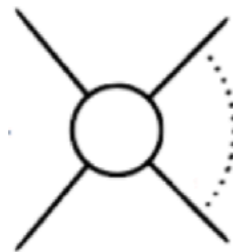
NLO calculations in a nutshell

◆ Contributions to an NLO result in QCD

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

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

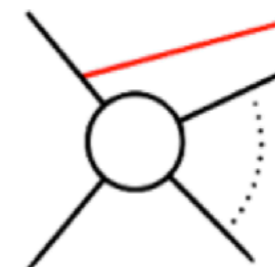
Born



Virtuals: one extra power of α_s and divergent



Reals: one extra power of α_s and divergent



♣ Challenge: automatically computing predictions for any process in any model

The virtuals

Virtual contributions

◆ Loop diagram calculations

❖ Calculations to be done in $d=4-2\epsilon$ dimensions

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

★ Numerical challenge

❖ Reducing loop integrals to scalar integrals

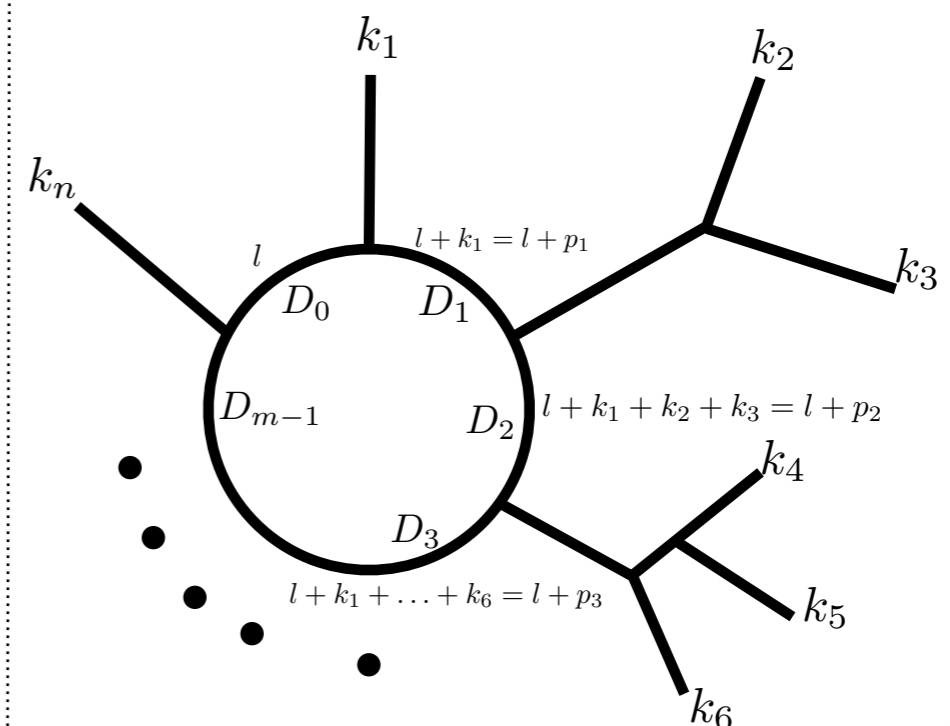
$$\int d^d \ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int d^d \ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

★ 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



From tensor to scalar loop integrals (I)

◆ In the past: the reduction is done at the integral level

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

- ❖ For instance: **Passarino-Veltman reduction** [Passarino & Veltman (NPB'79)]
- ❖ Contracting the tensorial structure of the numerator
- ❖ Extracting the a_i coefficients from the equalities

◆ More recent technique: the reduction can also be done at the integrand level

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

❖ **An integral equality does not however mean an integrand equality**

$$\int d^d \ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int d^d \ell \frac{1}{D_{i_0} D_{i_1} \cdots} \quad \not\Rightarrow \quad \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \frac{1}{D_{i_0} D_{i_1} \cdots}$$

❖ Spurious terms must be included

Example: the OPP method

[Ossala, Papadopoulos & Pittau (NPB'07; JHEP'08)]

◆ Apparition of spurious terms in the reduction

♣ We restore the equality at the integrand level by introducing **spurious terms**

$$\frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum \left[a_i + \tilde{a}_i(\ell) \right] \frac{1}{D_{i_0} D_{i_1} \cdots}$$

★ Their integral vanishes

★ Their functional form is known [del Aguila & Pittau (JHEP'04)]

♣ The integrand numerator can be decomposed

$$\begin{aligned}
 N(\ell) = & \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} \boxed{\left[d_{i_0 i_1 i_2 i_3} + \tilde{d}_{i_0 i_1 i_2 i_3}(\ell) \right]} \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i + \sum_{i_0 < i_1 < i_2}^{m-1} \boxed{\left[c_{i_0 i_1 i_2} + \tilde{c}_{i_0 i_1 i_2}(\ell) \right]} \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\
 & + \sum_{i_0 < i_1}^{m-1} \boxed{\left[b_{i_0 i_1} + \tilde{b}_{i_0 i_1}(\ell) \right]} \prod_{i \neq i_0, i_1}^{m-1} D_i + \sum_{i_0}^{m-1} \boxed{\left[a_{i_0} + \tilde{a}_{i_0}(\ell) \right]} \prod_{i \neq i_0}^{m-1} D_i + \underbrace{\tilde{P}(\ell) \prod_i^{m-1} D_i}_{\text{Remainder}} +)(\varepsilon)
 \end{aligned}$$

box coefficients
triangle coefficients
bubble coefficients
tadpole coefficients
Remainder

★ The coefficients are evaluated numerically

★ One chooses ℓ so that several denominators vanish ➤ simplifications

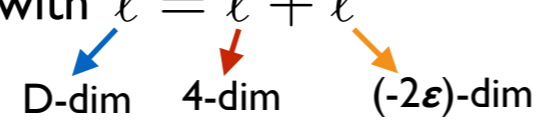
★ One gets a system of equations to (numerically) solve

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

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



- ♣ Numerical methods work in four dimensions ➤ to be accounted for

◆ The R_1 terms originate from the denominators

- ♣ Connected to the internal propagators

◆ The R_2 terms originate from the numerator

- ♣ Can be seen as extra diagrams with special Feynman rules

R_I terms

◆ The R_I terms originate 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)

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

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

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

♣ The denominator structure is already known at the reduction time

♣ The R_I coefficients are extracted during the reduction

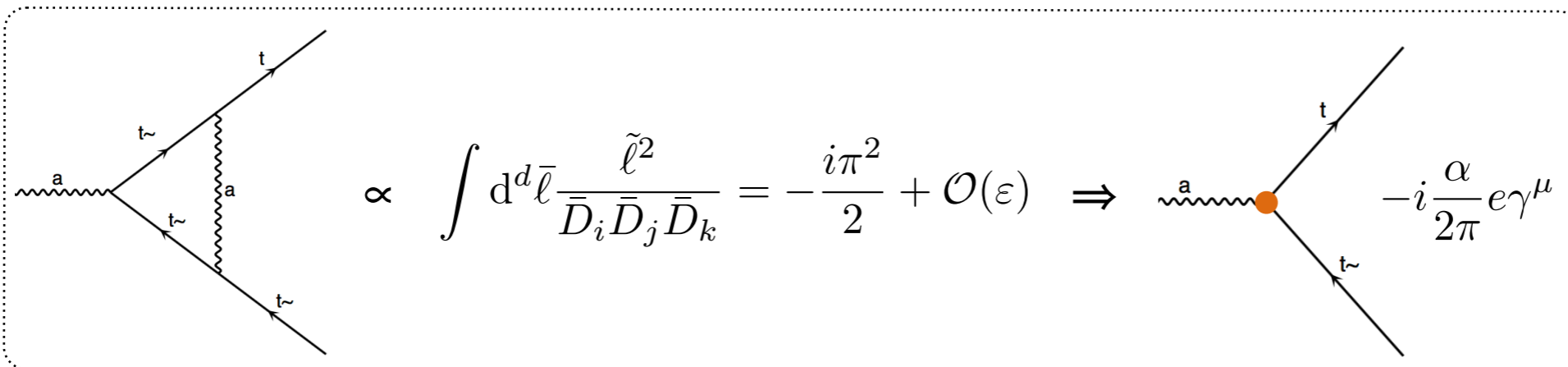
R₂ terms

◆ The R₂ terms originate from the numerator

$$\underbrace{\bar{N}(\bar{\ell})}_{\text{D-dim}} = \underbrace{N(\ell)}_{\text{4-dim}} + \underbrace{\tilde{N}(\tilde{\ell}, \ell, \varepsilon)}_{(-2\varepsilon)\text{-dim}} \quad \Rightarrow \quad R_2 \equiv \lim_{\varepsilon \rightarrow 0} \frac{1}{(2\pi)^4} \int d^d \bar{\ell} \frac{\tilde{N}(\tilde{\ell}, \ell, \varepsilon)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

- ❖ Practically, we isolate the epsilon part
- ❖ There is only a finite set of loops for which it does not vanish

◆ They can be re-expressed in terms of R₂ Feynman rules



$$\propto \int d^d \bar{\ell} \frac{\tilde{\ell}^2}{\bar{D}_i \bar{D}_j \bar{D}_k} = -\frac{i\pi^2}{2} + \mathcal{O}(\varepsilon) \Rightarrow \text{Feynman rule: } -i \frac{\alpha}{2\pi} e \gamma^\mu$$

◆ Properties of the R₂

- ❖ Process-dependent and model-dependent
- ❖ In a renormalizable theory, there is a finite number of them
 - ★ They can be calculated once and for all for a specific model
 - R₂ counterterm Feynman rules



Reals

Infrared divergences

◆ Properties of the NLO cross section

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

Including UV counterterms

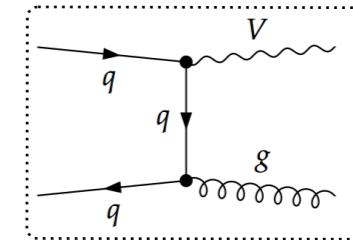
- ❖ All the individual pieces are **(infrared-)divergent**
 - ★ Issues for a numerical code
- ❖ The sum is **finite** (KLN theorem)
 - ★ **The divergences have the same origin and cancel**
 - ★ Numerically, their cancellation must be dealt with explicitly
 - ★ **Introduction of a subtraction method**

Origins of the infrared divergences

◆ Divergences are related to soft and collinear radiation

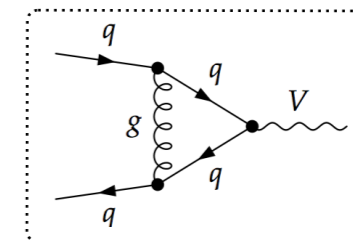
♣ Real emission (in the soft limit)

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



♣ Virtual corrections (in the soft limit)

$$iM \approx (ig_s)^2 \int d\ell \frac{k_1 \cdot k_2}{\ell^2 \left[k_2^0 \ell^0 (1 + \cos \theta) \right] \left[k_1^0 \ell^0 (1 - \cos \theta) \right]} iM^{\text{Born}}$$



♣ If we cannot distinguish “no branching” from “soft-collinear emission”

★ Cancellation occurs

★ Infrared safety: observables are not sensitive to soft-collinear emissions

◆ Structure of the poles

♣ Virtuals: in dimensional regularization, poles in the regularization parameter

♣ Real emission: poles appear after integration over the d -dimensional phase space

Subtraction methods

◆ Subtracting the poles

- ✿ The structure of the poles is known ➤ subtraction methods

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

- ✿ 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 computed 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 be added to the virtuals
- ✿ Should be integrable numerically conveniently

The Frixione-Kunszt-Signer subtraction (I)

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

◆ Division of the phase space

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

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

- ❖ The behavior of \mathcal{S}_{ij} is such that:

- ★ $\mathcal{S}_{ij} \rightarrow 1$ if the partons i and j are collinear
- ★ $\mathcal{S}_{ij} \rightarrow 1$ if the parton i is soft
- ★ $\mathcal{S}_{ij} \rightarrow 0$ 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

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

❖ The divergent behaviour of σ_{ij} reads

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

Controls the
soft pieces

Controls the
collinear pieces

❖ We define a divergence-free quantity

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

Regulators:
“plus-distribution”

No more IR
divergencies

Factorized
phase space

❖ The regulators introduce two parameters

$$\int_0^{\xi_{\max}} d\xi_i f(\xi_i) \left[\frac{1}{\xi_i} \right]_c = \int_0^{\xi_{\max}} d\xi_i \frac{f(\xi_i) - f(0)\Theta(\xi_{\text{cut}} - \xi_i)}{\xi_i}$$

$$\int_{-1}^{+1} dy_{ij} g(y_{ij}) \left[\frac{1}{1 - y_{ij}} \right]_\delta = \int_{-1}^{+1} dy_{ij} \frac{g(y_{ij}) - g(1)\Theta(y_{ij} - 1 + \delta)}{1 - y_{ij}}$$

Events and counter-events

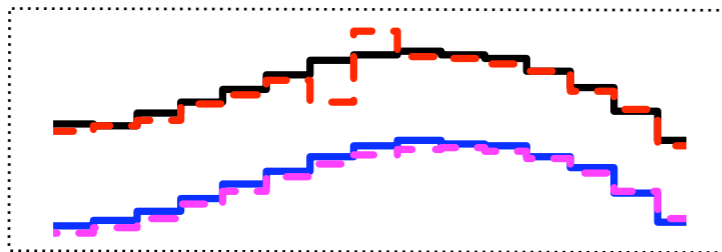
◆ The regulators define events and counter-events

♣ Integrating over the regulators gives

$$\begin{aligned}
 d\sigma_{ij}^{(n+1)} &= \left[\frac{1}{\xi_i} \right]_c \left[\frac{1}{1-y_{ij}} \right]_\delta \Sigma_{ij}(\xi_i, y_{ij}) d\xi_i dy_{ij} \\
 &= \int_0^{\xi_{\max}} d\xi_i \int_{-1}^{+1} dy_{ij} \frac{1}{\xi_i(1-y_{ij})} \left[\underbrace{\Sigma_{ij}(\xi_i, y_{ij})}_{\text{Event}} - \underbrace{\Sigma_{ij}(\xi_i, 1)\Theta(y_{ij} - 1 + \delta)}_{\text{Counter-event}} \right. \\
 &\quad \left. - \underbrace{\Sigma_{ij}(0, y_{ij})\Theta(\xi_{\text{cut}} - \xi_i) + \Sigma_{ij}(0, 1)\Theta(y_{ij} - 1 + \delta)\Theta(\xi_{\text{cut}} - \xi_i)}_{\text{Counter-event}} \right]
 \end{aligned}$$

◆ Properties of the events and counter-events

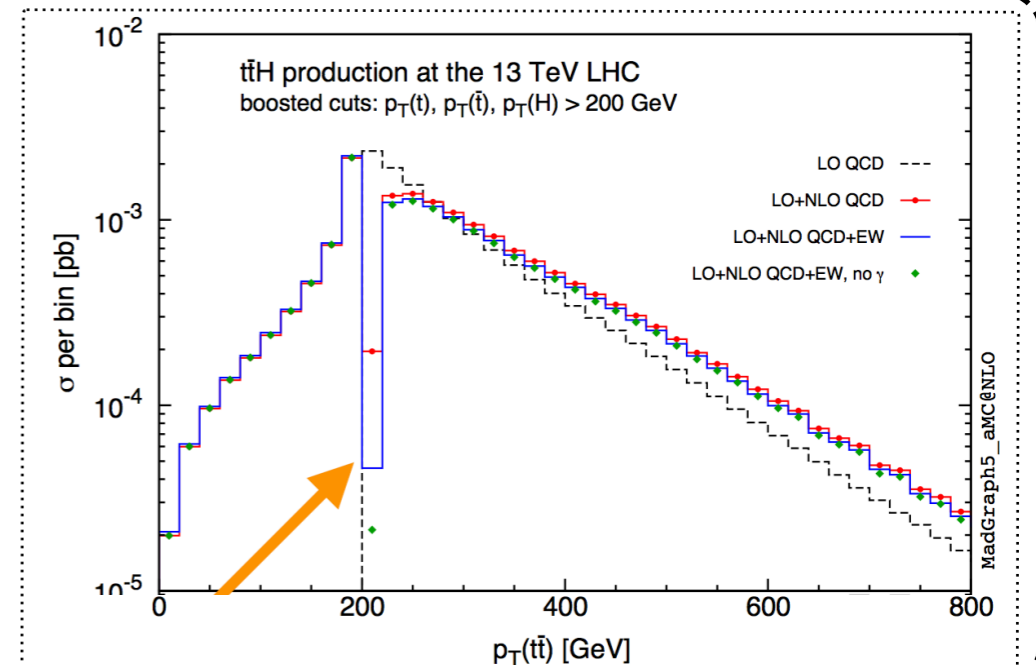
- ♣ If i and j are on-shell (event), the combined ij parton is on-shell (counter-event)
 - ★ This leads to a reshuffling of all particle momenta
- ♣ An event and the associated counter-event can fill different histogram bins
 - ★ **Peak-dip structure for the fixed-order distributions**
(even for IR safe observables and for any binning resolution)



Fixed order event generation

- ◆ Unweighting is not possible at the fixed order
 - ♣ Kinematic mismatch of events and counter-events
 - ★ The (n) -body and $(n+1)$ -body contributions are not bounded from above
 - ★ Only weighted events can be used

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



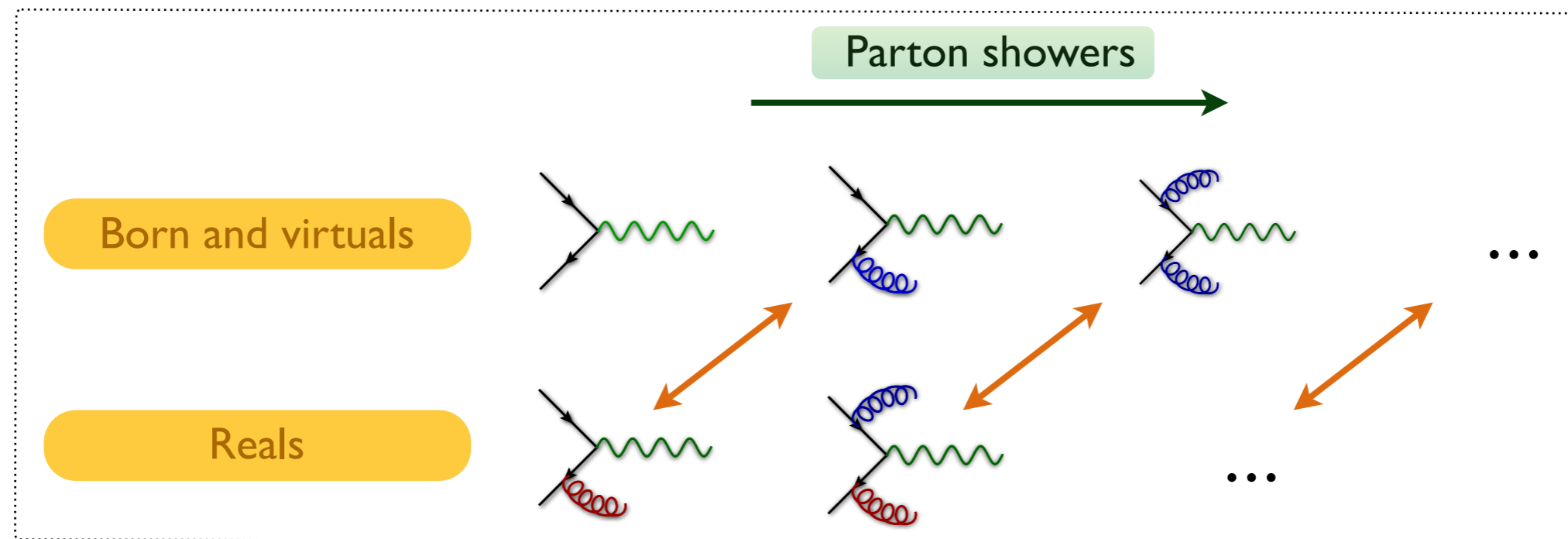
**Matching with
parton showers**

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

◆ Double counting when matching with parton showers



✿ 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)]

♦ One solution to the double counting issue: the MC@NLO method

♣ The shower is **unitary**

★ What is double counted in the virtuals is (minus) what is double counted in the reals

♣ We introduce MC counterterms: **adding and subtracting identical contributions**

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

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 (n) -body to $(n+1)$ -body final states

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

The MC@NLO prescription (2)

[Frixione, Webber (JHEP'02)]

◆ Properties of the Monte Carlo counterterms

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

- ❖ Maintain 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: $\mathcal{MC} \approx 0$, $\mathcal{I}_{\text{MC}}^{(n)} \approx 0$, $\mathcal{I}_{\text{MC}}^{(n+1)} \approx 1$ 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

★ Simultaneous usage of the NLO and MC counterterms

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

S-events

H-events

♣ In practice, S-events and H-events are generated separately

★ The related contribution can carry a negative weight

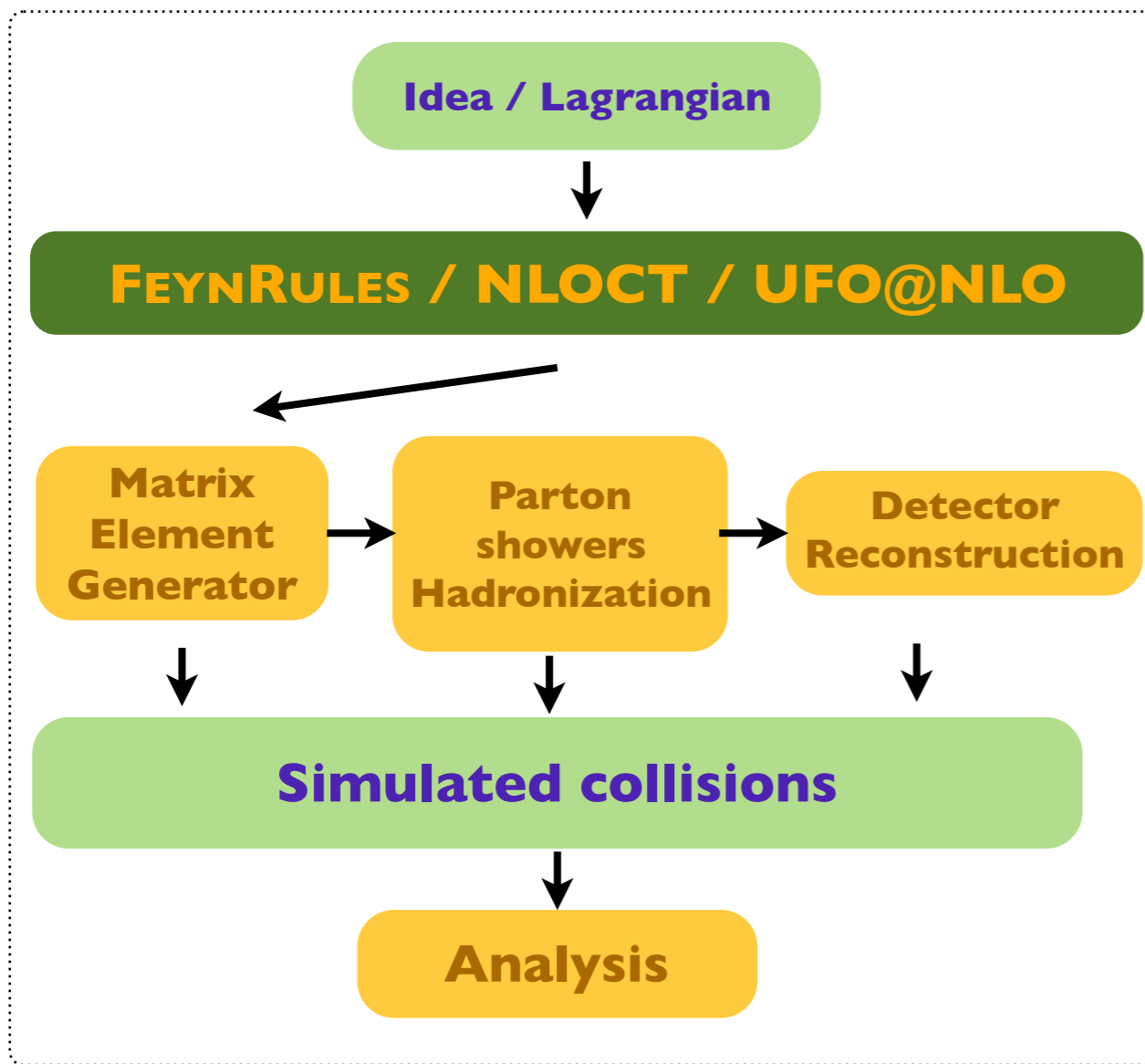
★ The sign of the weight has to be included in the unweighting procedure

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

**Summary: the NLO+PS
simulation chain**

Automatic NLO simulations with MG5_AMC

◆ From Lagrangians to analyzed NLO simulated collisions



- ❖ FEYNRULES is linked to NLOCT
 - ★ 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 (*in prep.*)]

- ❖ Parton shower matching: MC@NLO
 - ★ Automatic (MG5_aMC)
 - ★ Restrictions on the renormalization scheme

Model library

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

✦ Via a joint use of FEYNRULES and MADGRAPH5_aMC@NLO

✦ Many models are publicly available

★ MSSM and supersymmetry-inspired simplified models

★ BSM Higgs models

★ Extra gauge bosons

★ Dark matter simplified models

★ Higgs effective field theories

★ Top effective field theories

★ Vector-like quark models

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

Outline

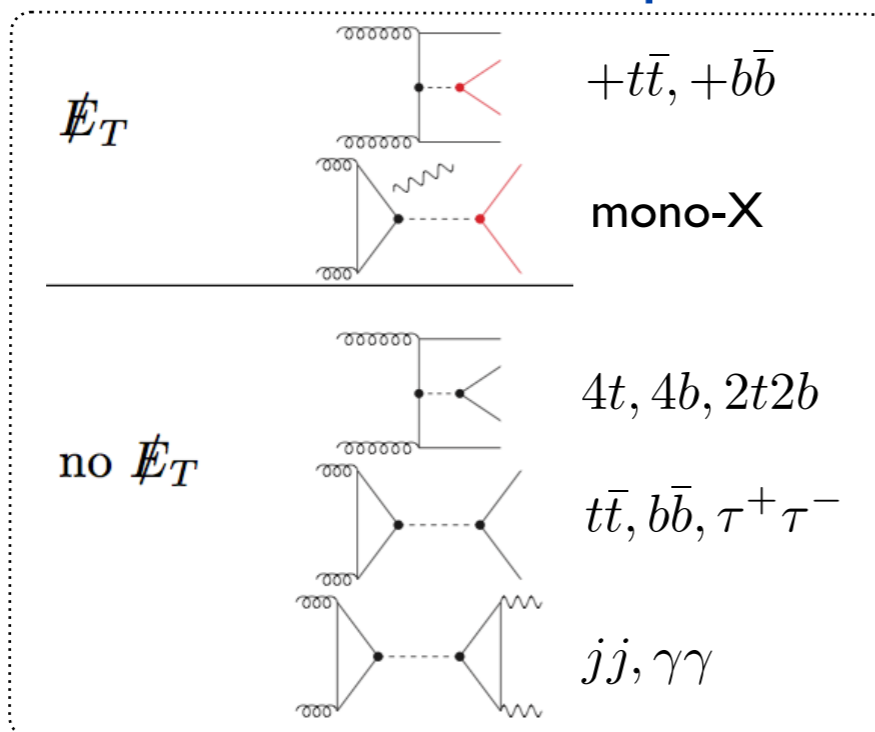
1. A basic introduction to perturbative QCD @ colliders
2. Automating NLO calculations in QCD for new physics
- 3. NLO impact on dark matter searches at the LHC**
4. Vector-like quark phenomenology
5. Summary - conclusions

Top-philic dark matter @ LHC

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

- ◆ A simplified model for dark matter with a mediator and a DM candidate
 - ❖ MFV motivation: **enhanced couplings to the third generation**

- ◆ This scenario can be probed in many ways at colliders



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

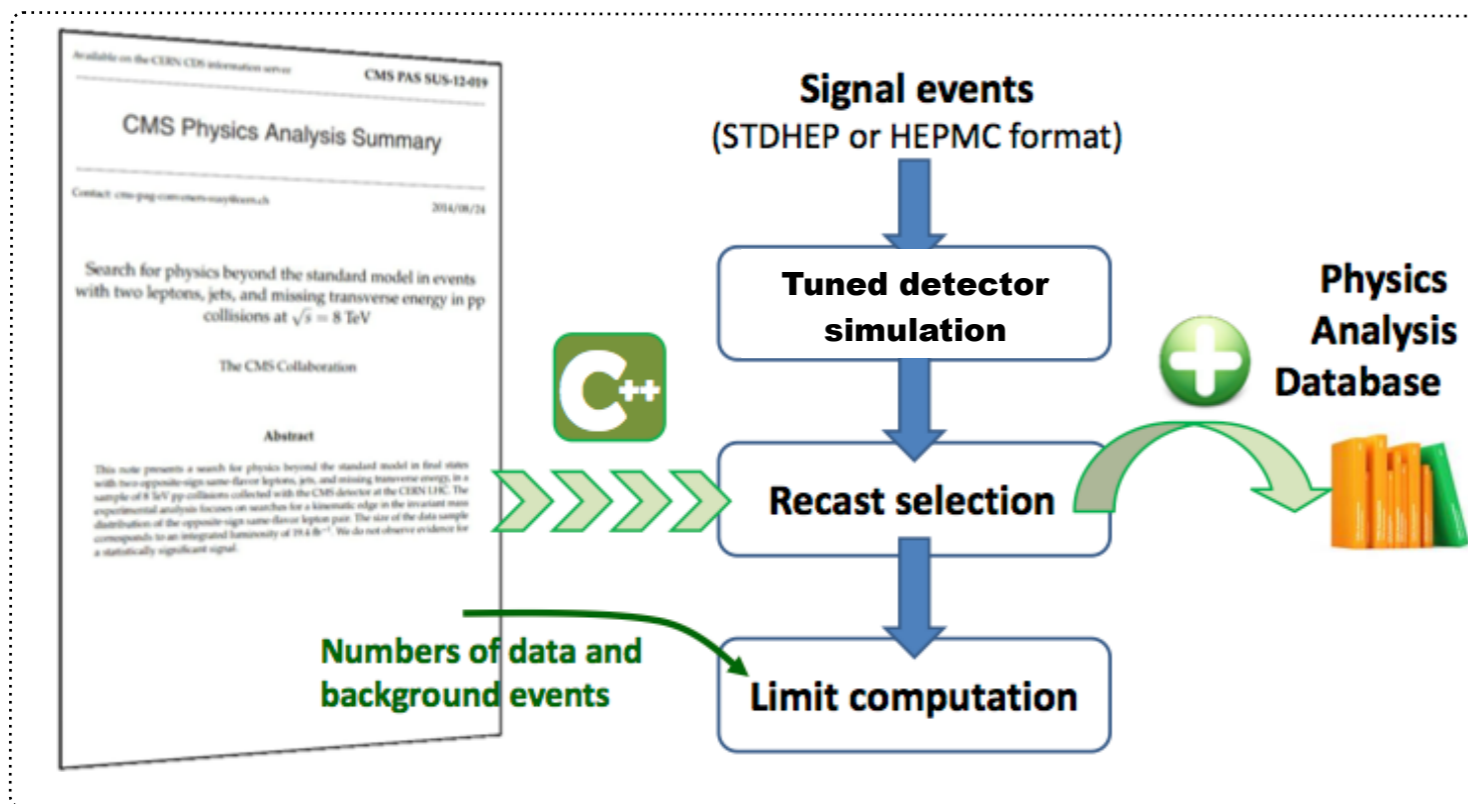
Recasting with MADANALYSIS 5

[Conte, BF, Serret (CPC '13); Conte, Dumont, BF, Wymant (EPJC '14); Dumont, BF, Kraml et al. (EPJC '15); Conte & BF (IJMPA '18)]

◆ 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

[Conte, BF, Serret (CPC '13); Conte, Dumont, BF, Wymant (EPJC '14); Dumont, BF, Kraml et al. (EPJC '15); Conte & BF (IJMPA '18)]

◆ 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	ϵ_i^{CMS}	MA5	ϵ_i^{MA5}	δ_i^{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%
	$\cancel{E}_T > 250$ GeV	8687.22	0.274	7563.04	0.219	20.00%
	$\cancel{E}_T > 300$ GeV	5400.51	0.621	4477.67	0.592	4.66%
	$\cancel{E}_T > 350$ GeV	3394.09	0.628	2813.70	0.628	0.00%
	$\cancel{E}_T > 400$ GeV	2224.15	0.6553	1753.71	0.623	4.93%
	$\cancel{E}_T > 450$ GeV	1456.02	0.654	1110.92	0.633	3.21%
	$\cancel{E}_T > 500$ GeV	989.806	0.679	722.83	0.650	4.27%
	$\cancel{E}_T > 550$ GeV	671.442	0.678	487.54	0.674	0.59%



Validated at
the 20% level

Issue with the low-
MET modelling in
DELPHES

MADANALYSIS 5 analyses on INSPIRE

[BF, Martini (2016)]

◆ 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](https://doi.org/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

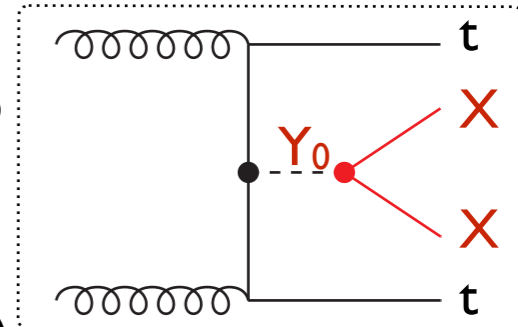
$t\bar{t}$ +MET constraints on top-philic dark matter

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

◆ A simplified model for top-philic dark matter

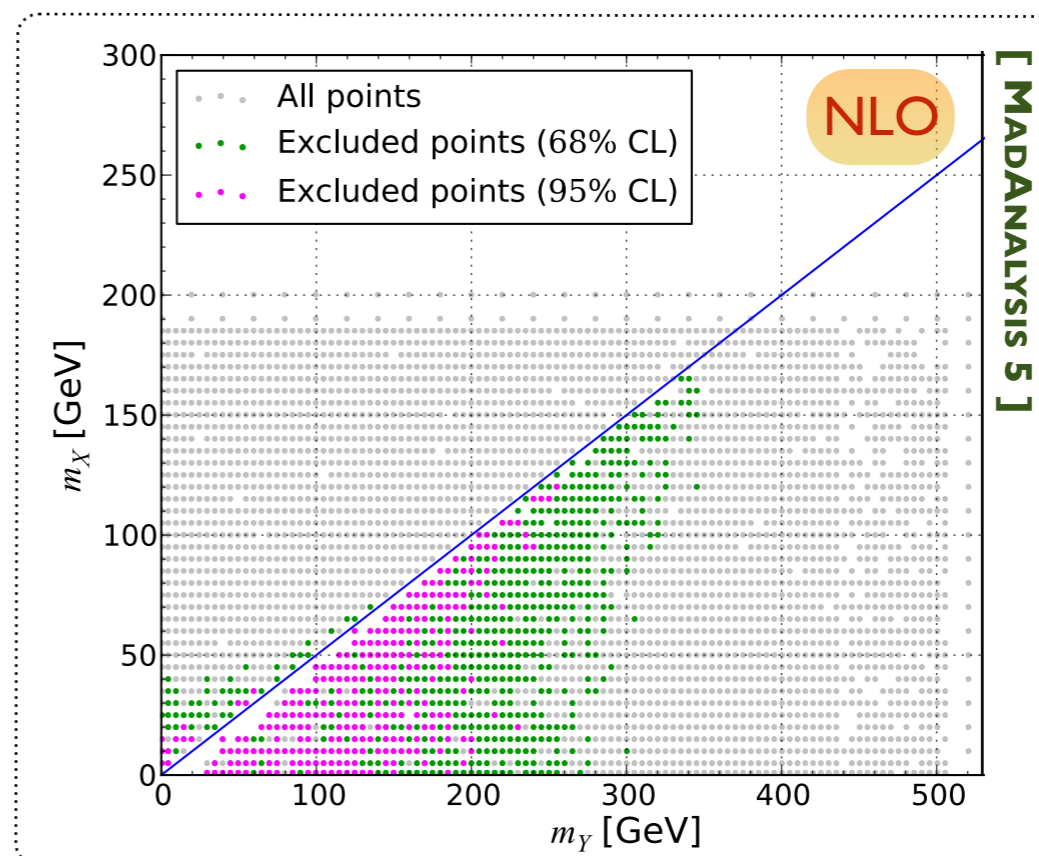
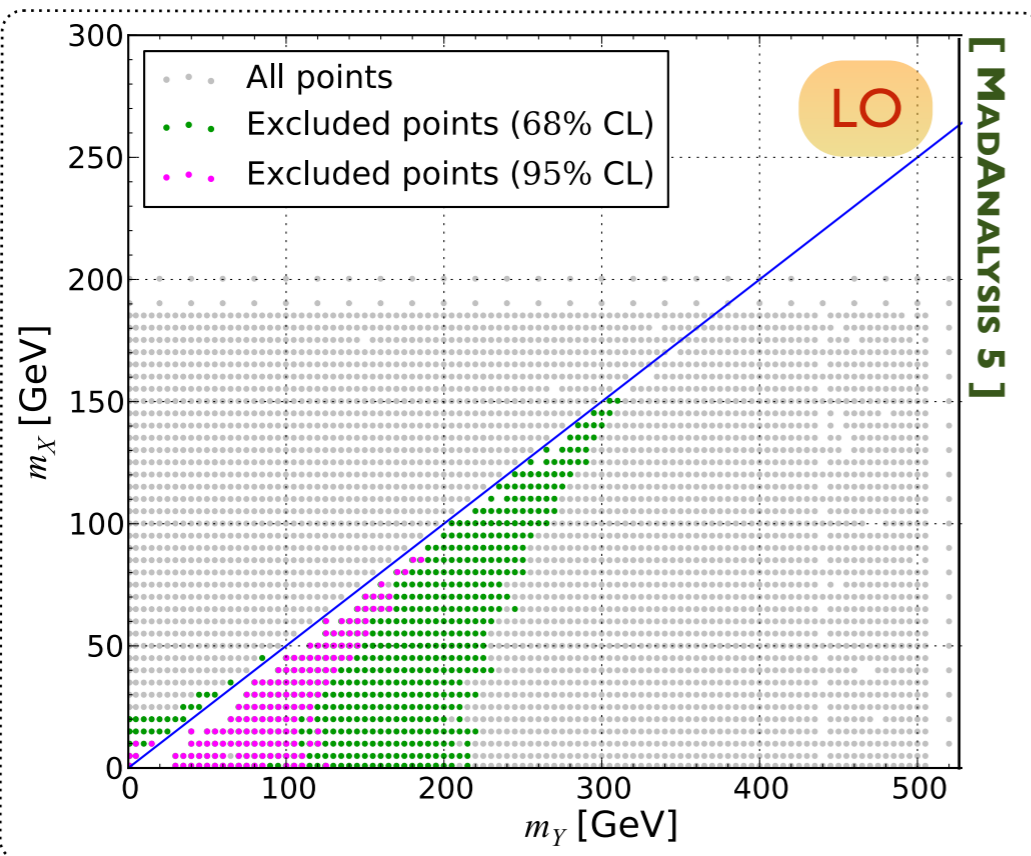
- ♣ A dark sector with a fermionic **dark matter candidate** X
- ♣ A (scalar) **mediator** Y_0 linking the dark sector and the top

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



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

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



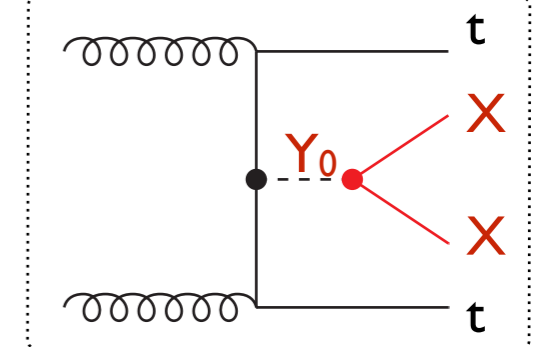
- ♣ How is the picture changing when including scale variations?

NLO effects on a CLs

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

◆ There are theoretical uncertainties on a CLs number

	(m_Y, m_X)	σ_{LO} [pb]	CL _{LO} [%]	σ_{NLO} [pb]	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**

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A general vector-like quark model

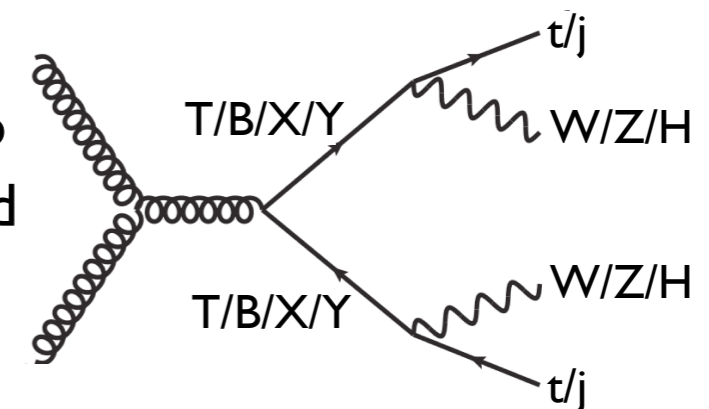
[BF & Shao (EPJC'17)]

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

$$\begin{aligned}
 \mathcal{L}_{\text{VLQ}} = & i\bar{Y}\not{D}Y - m_Y\bar{Y}Y + i\bar{B}\not{D}B - m_B\bar{B}B + i\bar{T}\not{D}T - m_T\bar{T}T + i\bar{X}\not{D}X - m_X\bar{X}X \\
 & - h \left[\bar{B} \left(\hat{\kappa}_L^B P_L + \hat{\kappa}_R^B P_R \right) q_d + \bar{T} \left(\hat{\kappa}_L^T P_L + \hat{\kappa}_R^T P_R \right) q_u + \text{h.c.} \right] \\
 & + \frac{g}{2c_W} \left[\bar{B} \not{Z} \left(\tilde{\kappa}_L^B P_L + \tilde{\kappa}_R^B P_R \right) q_d + \bar{T} \not{Z} \left(\tilde{\kappa}_L^T P_L + \tilde{\kappa}_R^T P_R \right) q_u + \text{h.c.} \right] \\
 & + \frac{\sqrt{2}g}{2} \left[\bar{Y} \not{W} \left(\kappa_L^Y P_L + \kappa_R^Y P_R \right) q_d + \bar{B} \not{W} \left(\kappa_L^B P_L + \kappa_R^B P_R \right) q_u + \text{h.c.} \right] \\
 & + \frac{\sqrt{2}g}{2} \left[\bar{T} \not{W} \left(\kappa_L^T P_L + \kappa_R^T P_R \right) q_d + \bar{X} \not{W} \left(\kappa_L^X P_L + \kappa_R^X P_R \right) q_u + \text{h.c.} \right]
 \end{aligned}$$

◆ Illustrative process

- ★ Quark partners decay into an electroweak boson and a jet/top
- ★ Pair, single and QV/QH associated production can be simulated



Total cross sections for pair production

[BF & Shao (EPJC'17)]

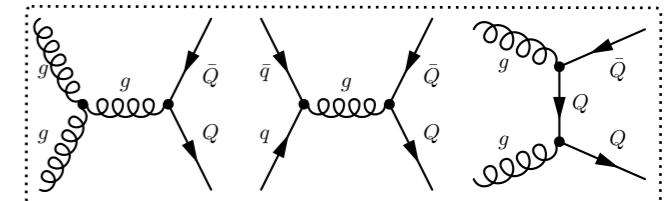
◆ Total rates for pair production at 13 TeV

m_T [GeV]	Scenario	σ_{LO} [pb]	σ_{NLO} [pb]
400	QCD	$(7.069 \cdot 10^0)^{+32.0\%+2.7\%}_{-22.6\%-2.7\%}$	$(1.004 \cdot 10^1)^{+9.4\%+2.5\%}_{-11.3\%-2.5\%}$
	TH1	$(7.022 \cdot 10^0)^{+30.2\%+1.2\%}_{-23.8\%-4.1\%}$	$(9.980 \cdot 10^0)^{+8.0\%+1.2\%}_{-12.5\%-3.8\%}$
800	QCD	$(1.261 \cdot 10^{-1})^{+33.2\%+3.8\%}_{-23.2\%-3.8\%}$	$(1.733 \cdot 10^{-1})^{+8.5\%+4.4\%}_{-11.1\%-4.4\%}$
	TH1	$(1.244 \cdot 10^{-1})^{+18.8\%+7.3\%}_{-31.2\%-14.0\%}$	$(1.702 \cdot 10^{-1})^{+2.3\%+6.0\%}_{-20.0\%-13.9\%}$
1200	QCD	$(7.685 \cdot 10^{-3})^{+34.0\%+5.8\%}_{-23.7\%-5.8\%}$	$(1.061 \cdot 10^{-2})^{+8.8\%+5.8\%}_{-11.4\%-5.8\%}$
	TH1	$(1.053 \cdot 10^{-2})^{+1.7\%+18.4\%}_{-36.7\%-25.8\%}$	$(1.372 \cdot 10^{-2})^{+16.6\%+18.2\%}_{-29.0\%-25.8\%}$
1600	QCD	$(7.477 \cdot 10^{-4})^{+34.9\%+8.5\%}_{-24.2\%-8.5\%}$	$(1.030 \cdot 10^{-3})^{+9.0\%+8.6\%}_{-11.6\%-8.6\%}$
	TH1	$(3.395 \cdot 10^{-3})^{+3.3\%+13.3\%}_{-27.0\%-19.9\%}$	$(4.117 \cdot 10^{-3})^{+14.6\%+14.4\%}_{-21.8\%-20.9\%}$
2000	QCD	$(8.980 \cdot 10^{-5})^{+35.5\%+18.3\%}_{-24.5\%-18.3\%}$	$(1.260 \cdot 10^{-4})^{+8.7\%+17.8\%}_{-11.7\%-17.8\%}$
	TH1	$(1.563 \cdot 10^{-3})^{+4.2\%+5.4\%}_{-20.0\%-13.0\%}$	$(1.960 \cdot 10^{-3})^{+6.3\%+6.0\%}_{-14.0\%-13.6\%}$

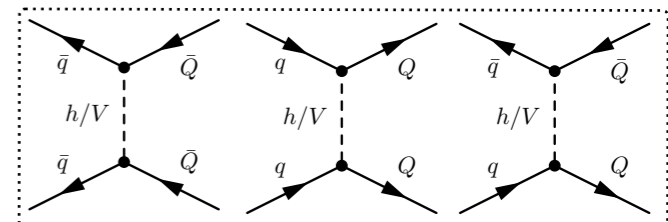
★ NNPDF 3.0 densities

★ Central scale: average M_T

★ ‘QCD’ QCD only



★ ‘TH1’: all diagrams (with Higgs exchanges)



♣ NLO effects

- ★ 50% increase of the rate
- ★ Reduction of the scale uncertainties

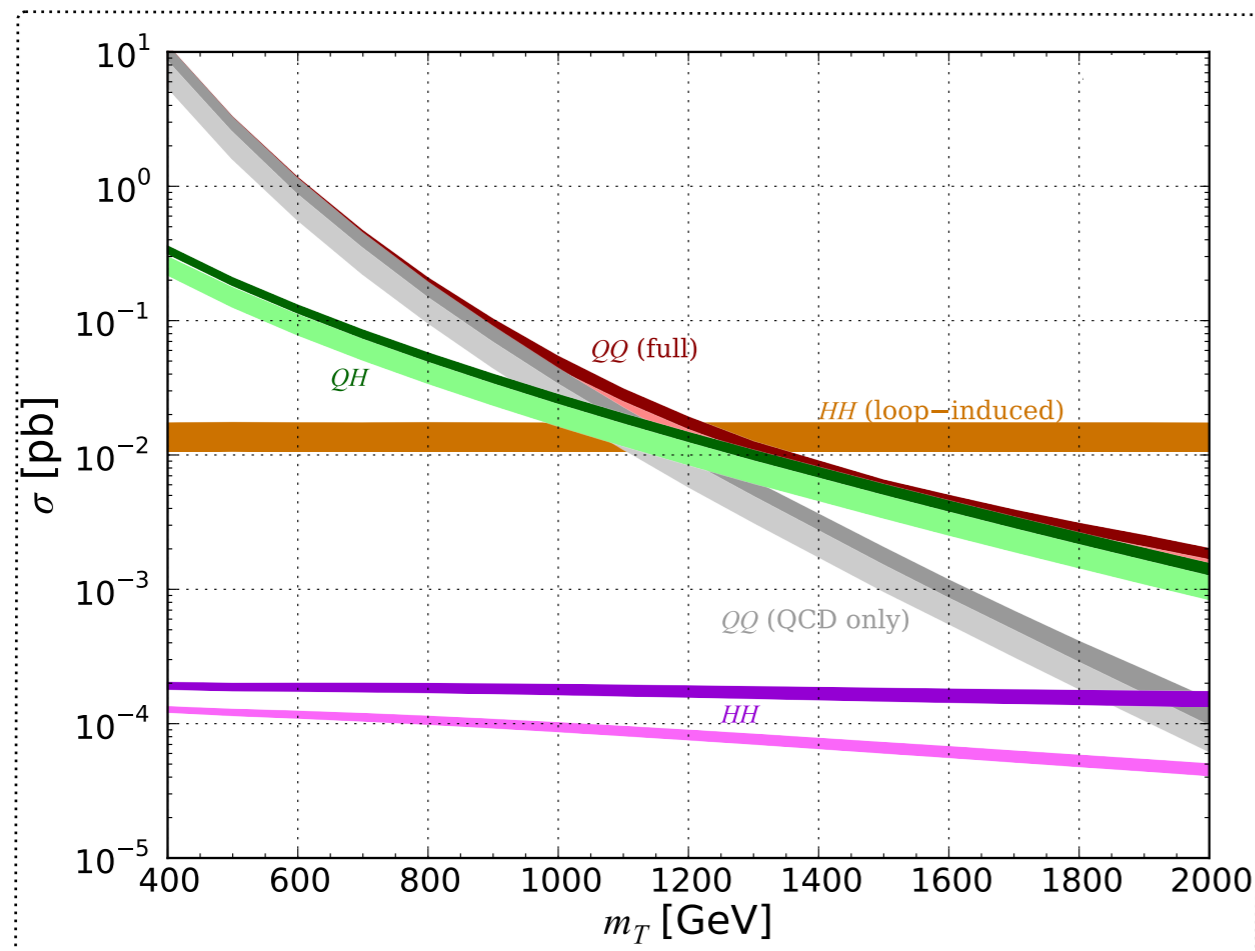
♣ Higgs-exchange diagrams

- ★ Dominate for large masses
- ★ Impact on the uncertainties

NLO total rates for diHiggs production

[Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (JHEP'17)]

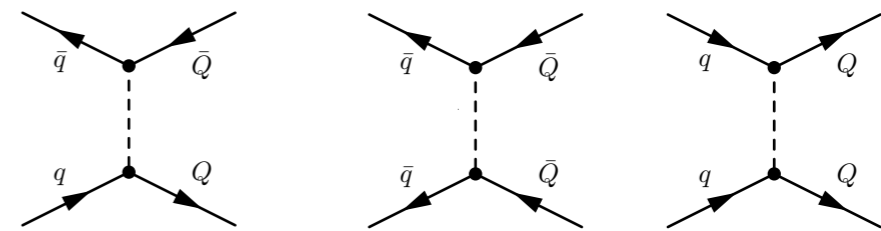
◆ Total rates (first NLO-QCD calculations in many cases)



❖ NLO: large K -factors, smaller errors

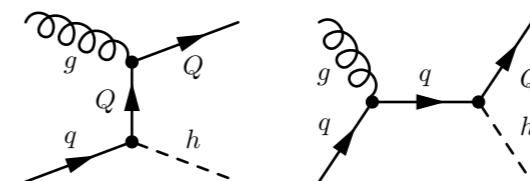
❖ EW diagrams for QQ production

★ Surpass QCD prod. at large mass



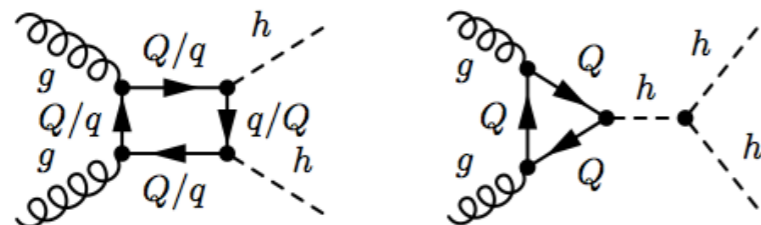
❖ QH production

★ Competes with QQ prod. at large mass



❖ H-boson pair production

★ Loop-induced diagrams dominate

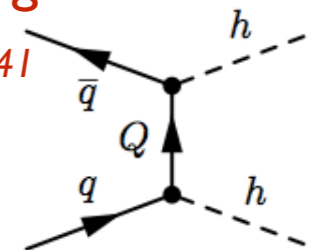


★ t -channel VLQ exchange diagrams: huge K -factor

➢ Coupling proportional to $m_Q/v_{SM} U_{41}$

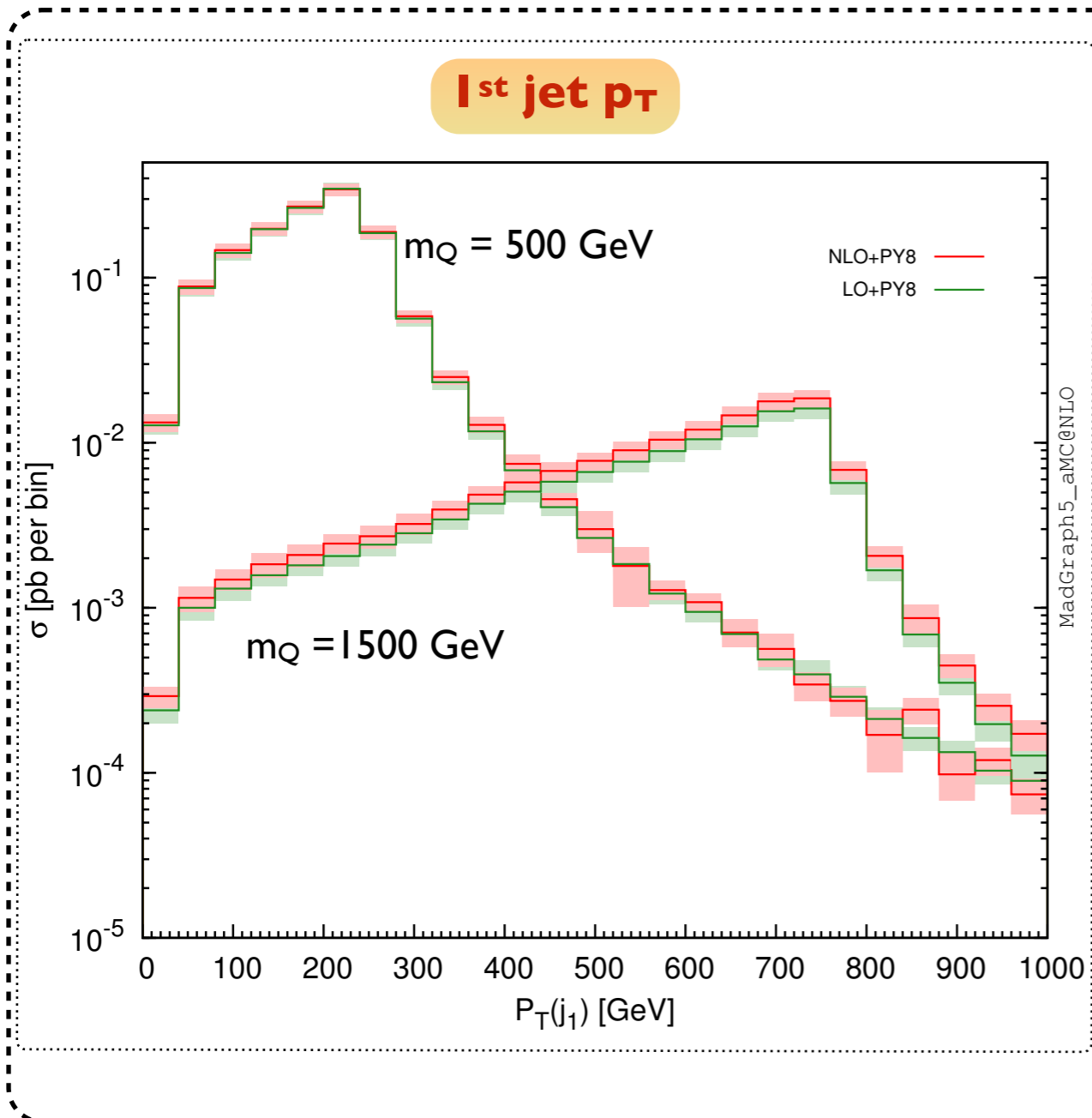
➢ Driven by the u-VLQ mixing U

➢ VLQ mass enhancement

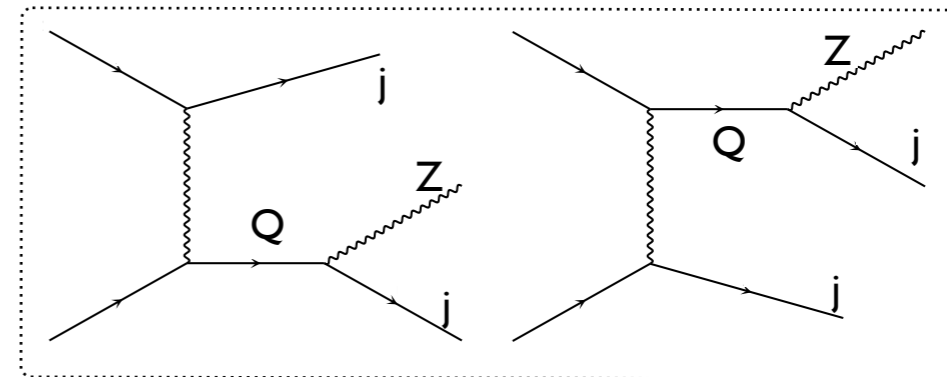


Single VLQ production: leading jet

[BF & Shao (EPJ)C'17]



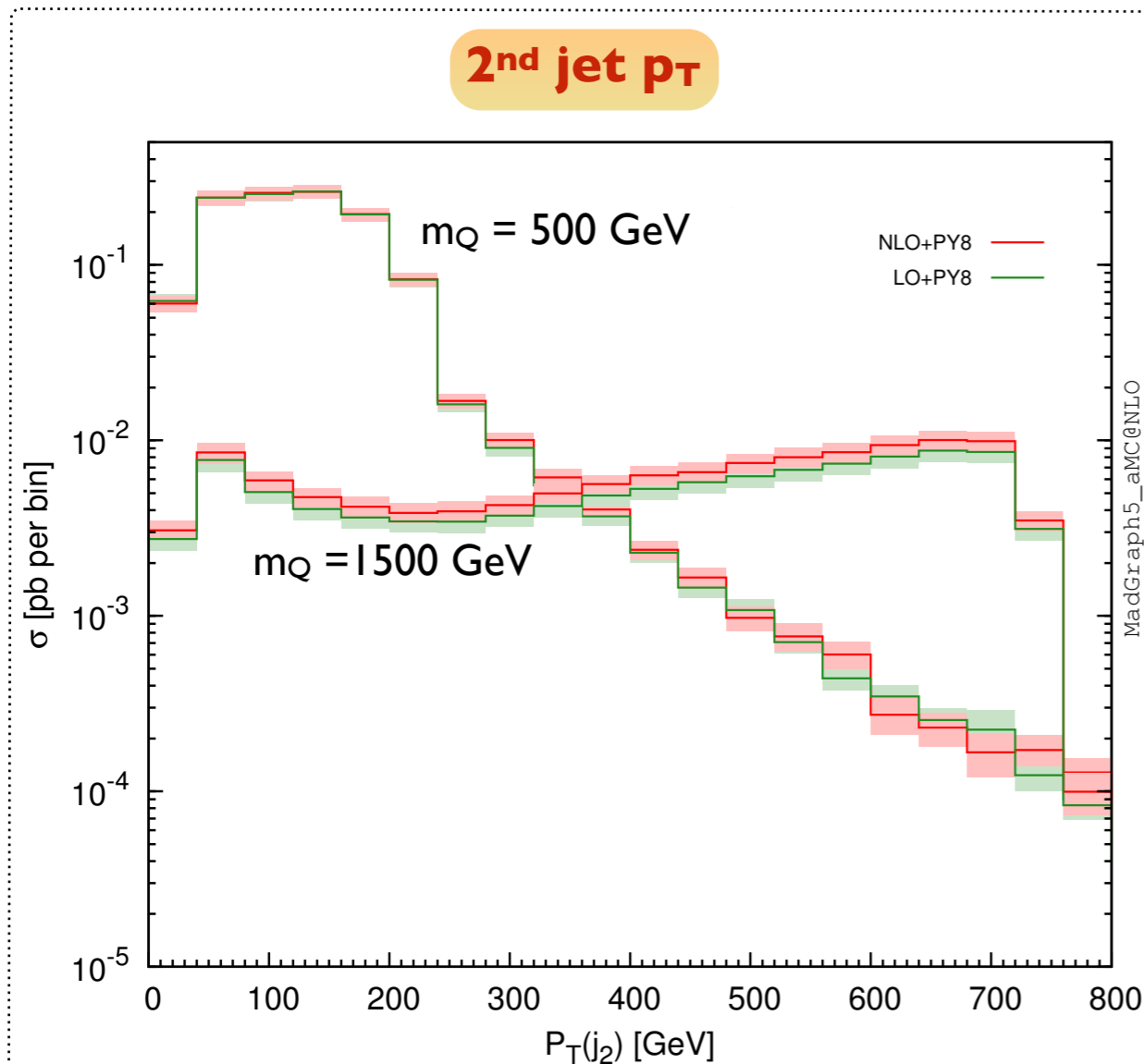
- ❖ Benchmark: the VLQ is an up partner
 - ★ Couples to the Z only



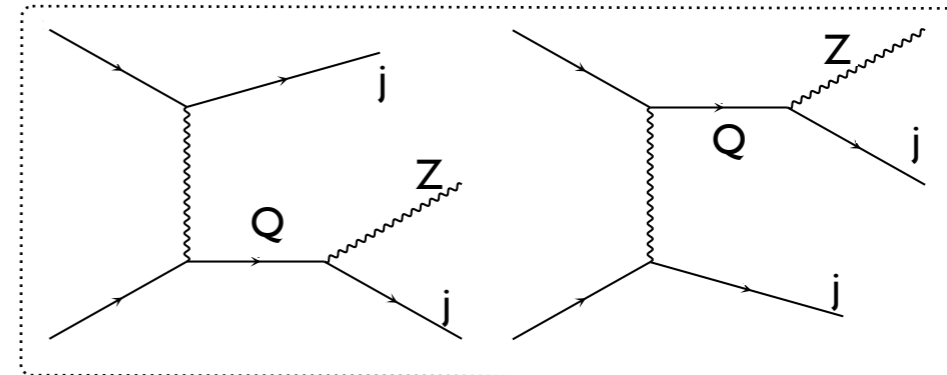
- ❖ The 1st jet mostly arises from Q decays
 - ★ Peak at about half the Q mass
- ❖ Constant K-factors (normalization effects)
 - ★ $K=1$ and 1.20 for $m_Q=500 \text{ GeV}$ and 1.5 TeV
- ❖ NLO effects
 - ★ Slight distortion of the shapes for large m_Q
 - ★ Reduction of the theoretical uncertainties

Single VLQ production: 2nd jet

[BF & Shao (EPJ)C'17]



- ❖ Benchmark: the VLQ is an up partner
 - ★ Couples to the Z only



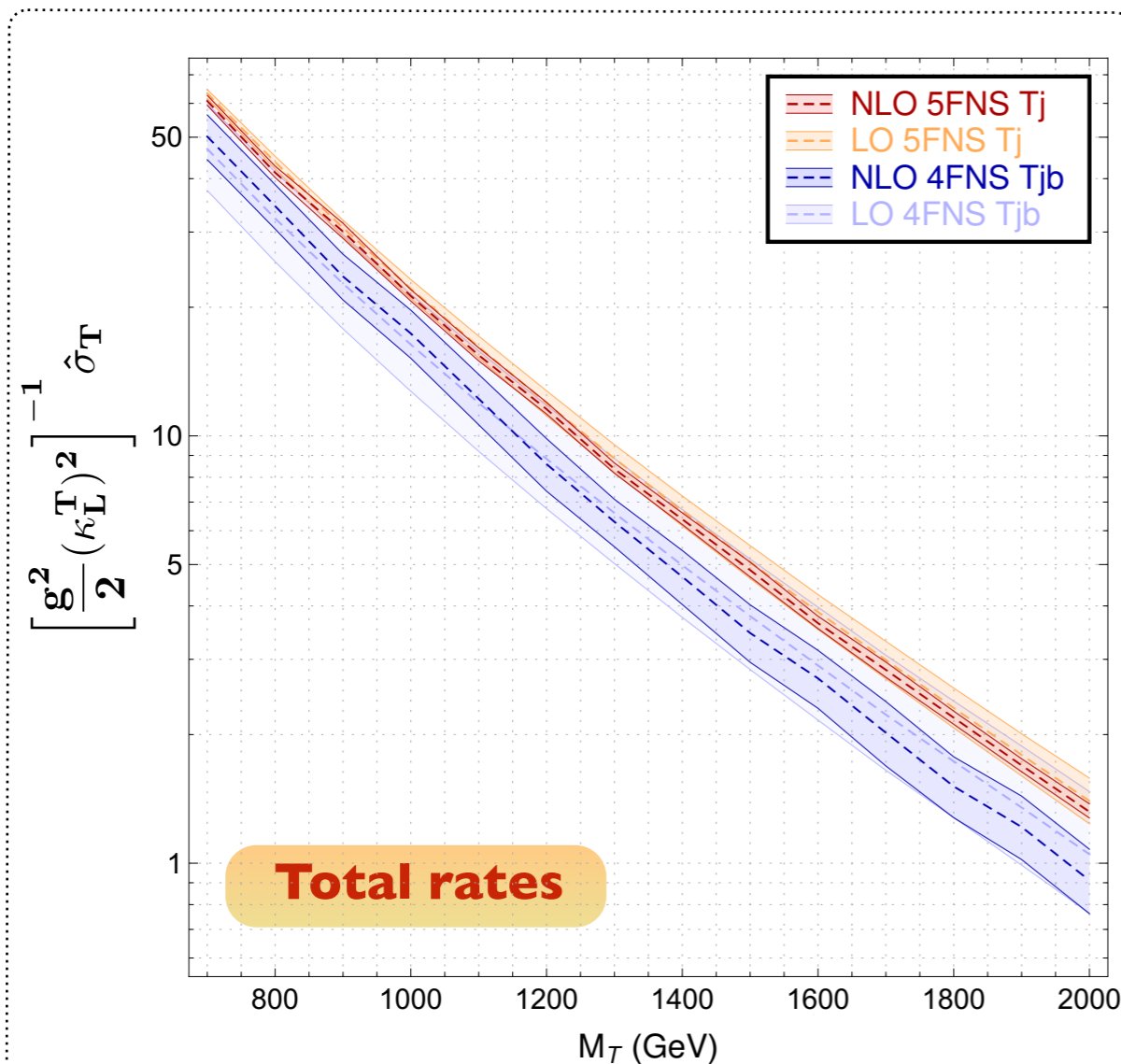
- ❖ The 2nd jet spectrum
 - ★ The low p_T region is depleted (Q is heavy)
 - ★ Plateau extending up to half the Q mass
 - jet issued either from the Q or from the Z
 - remainder: $Q \rightarrow Z j \rightarrow 3j$
- ❖ Constant K -factors (normalization effects)
 - ★ $K=1$ and 1.20 for $m_Q=500 \text{ GeV}$ and 1.5 TeV
- ❖ NLO effects
 - ★ Normalization enhancement (for large m_Q)
 - ★ Slight distortion of the shapes (for large m_Q)
 - ★ Reduction of the theoretical uncertainties

Single VLQ production: third generation

[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB'19)]

◆ Single top-partner production

- ❖ Benchmark: the VLQ is a top partner

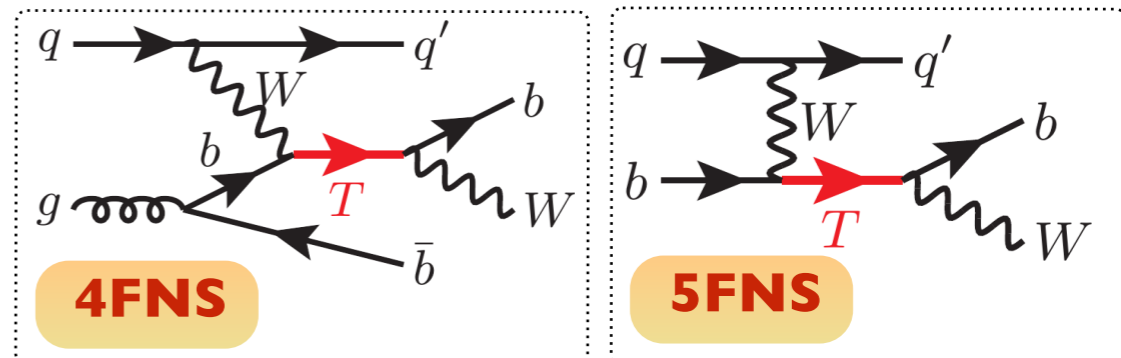


◆ Lagrangian and diagrams

- ❖ Production through W-couplings

$$\mathcal{L}_{\text{VLQ}} = i\bar{T}\not{D}T - m_T\bar{T}T + \frac{\sqrt{2}g}{2} \kappa_L^T \left[\bar{T}W P_L q_d + \text{h.c.} \right]$$

- ❖ Diagrams

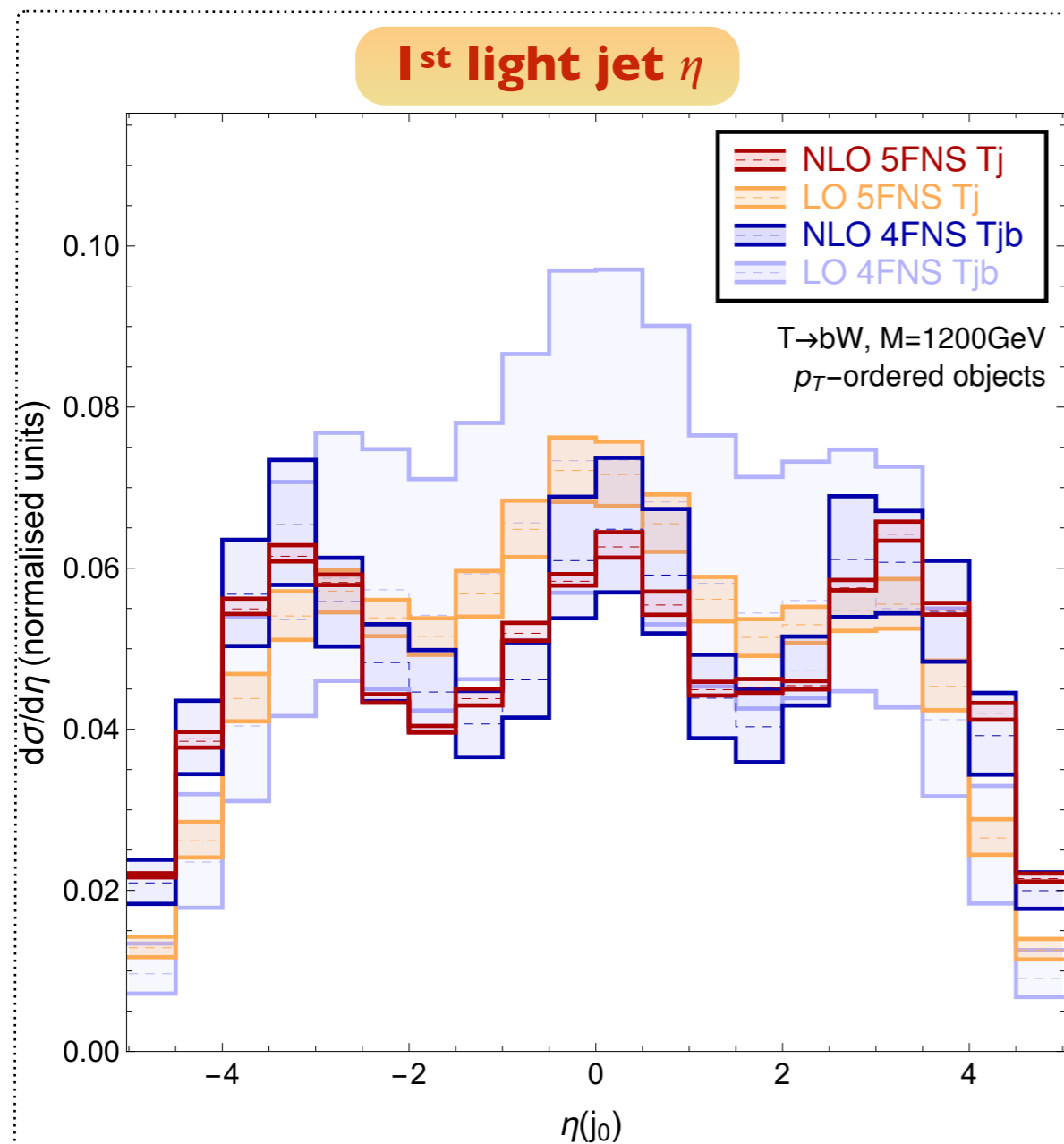


◆ Total rates at NLO

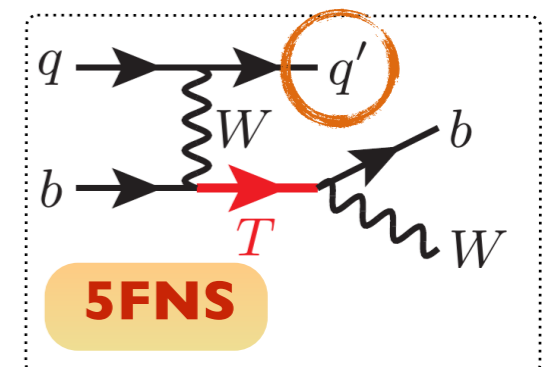
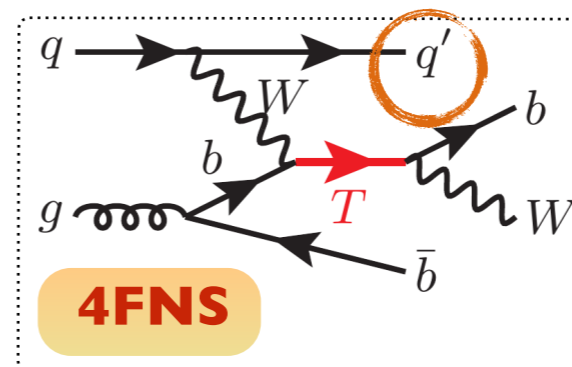
- ❖ 4 and 5FNS: b-mass treatment
- ❖ K-factors in the 5FNS: < 1 (virtuals)
- ❖ K-factors in the 4FNS: M_T dependent
- ❖ **NLO: reduction of the uncertainties**
- ❖ Log Q/m_b resummed in the 5FNS (differences at NLO for large masses)

Differential distributions

[Cacciapaglia, Carvalho, Deandrea, Flacke, BF, Majumder, Panizzi & Shao (PLB'19)]



- ❖ Benchmark: the VLQ is a top partner
 - ★ Couples to the W-boson
 - ★ The leading light jet: a key handle on the signal



- ❖ Very good shape agreement @NLO
 - ★ Forward jets crucial for signal selection
 - ★ 4FNS and 5FNS agree in shape
- ❖ NLO effects
 - ★ Important distortion of the shapes
 - K factors are NOT constant
 - ★ Reduction of the uncertainties at NLO

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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
 - ★ Extended Higgs sectors, extra gauge bosons
 - ★ Dark matter 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)