New developments in Monte Carlo tools for new physics

Fuks Benjamin

LPTHE - CNRS - UPMC

Phenomenology 2017 Symposium

University of Pittsburgh, 08 May 2017

The quest for new physics at the LHC

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

✤ Getting information on the nature of an observation

★ Fitting (and interpreting) deviations by some new physics signals

★ Leading order Monte Carlo tools and techniques can do a proper job

✤ Final words on the nature of any potential new physics

★ Accurate measurements of the model parameters

★ More precise predictions are mandatory

✦ New physics is a standard in many tools today

✤ Result of 20 years of developments

✤ NLO and loop-induced processes can now be simulated automatically

✤ BSM precision simulations are standard in MG5_aMC@NLO

Outline

1. Automating NLO calculations in QCD for new physics

2. Selection of phenomenology examples: SUSY, VLQ, DM, EFT, W'

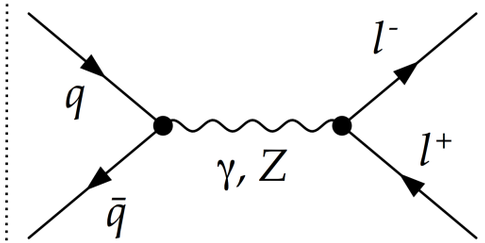
3. Summary - conclusions

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)

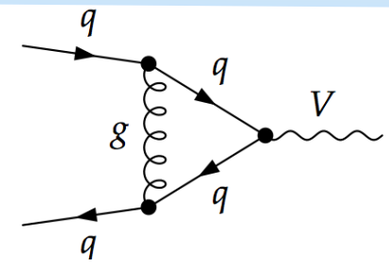
The Drell-Yan example



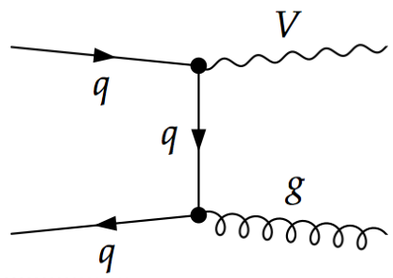
✦ Next-to-leading-order (NLO): $d\sigma \approx d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)}$

- ✤ 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



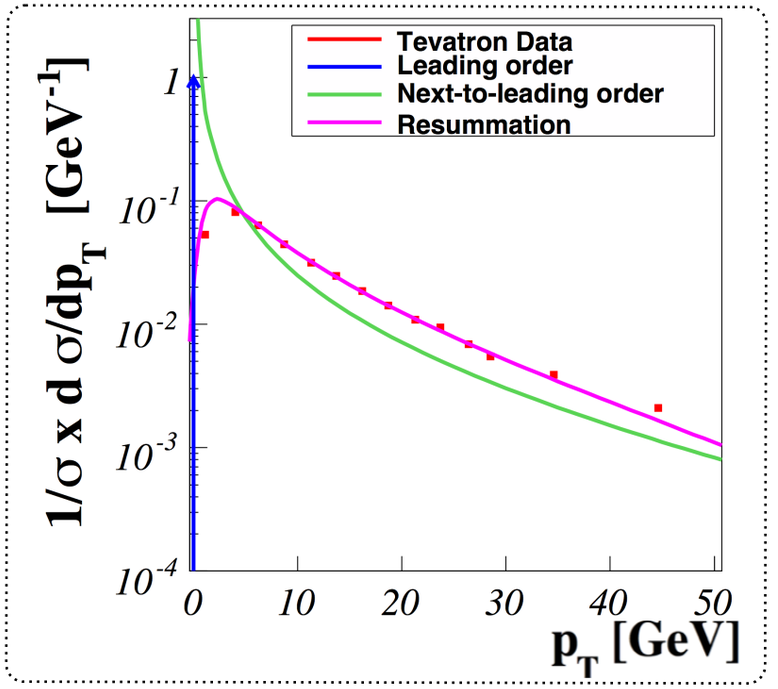
Representative real



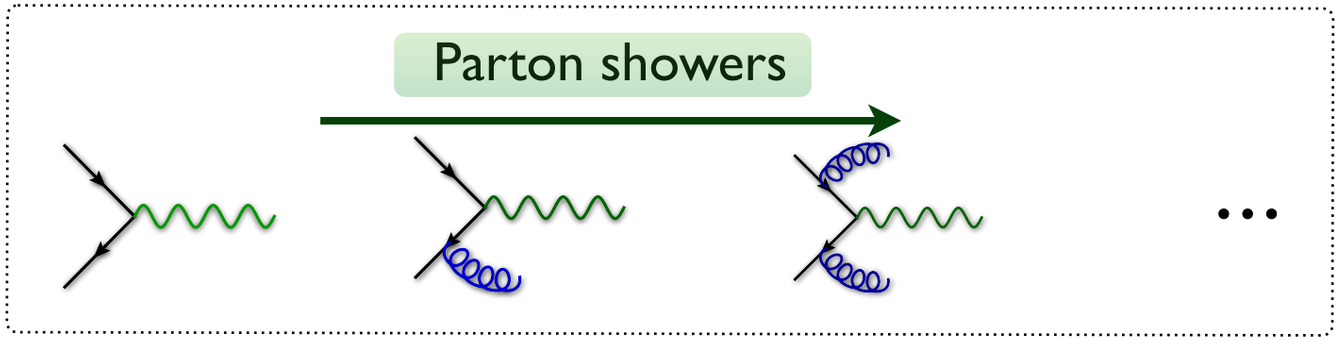
Matrix-element / parton shower matching

✦ 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)

Virtual contributions

✦ Loop diagram calculations

✤ Calculations to be done in $d=4-2\varepsilon$ dimensions

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

★ Numerical challenge

✤ Rewriting loop integrals with scalar integrals

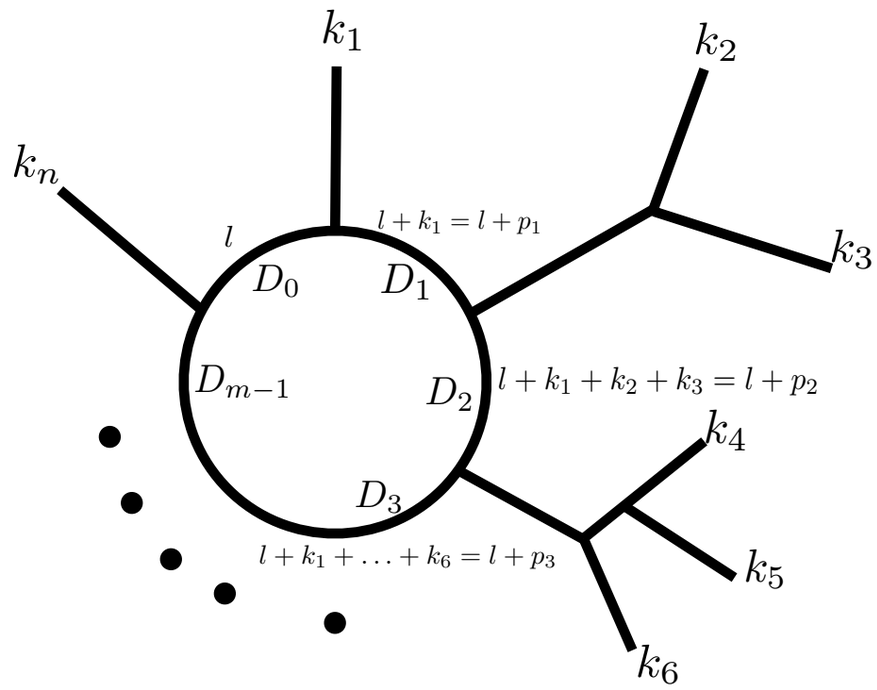
$$\int \mathrm{d}^d\ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int \mathrm{d}^d\ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

★ 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

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

D-dim 4-dim (-2ε)-dim

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

✦ The R_1 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)

✦ The R_2 terms originate 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

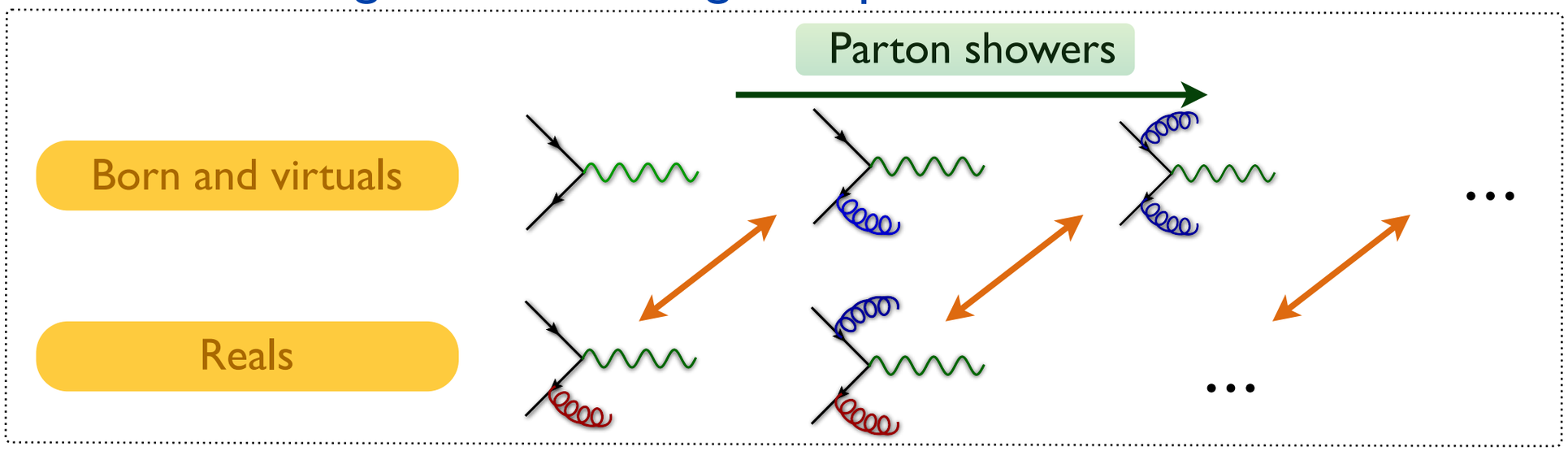
★ $\mathscr{C}$ subtracted from the reals ➢ makes them finite

★ $\mathscr{C}$ integrated and added back to the virtuals ➢ makes them finite

★ Integrals can be made numerically (in four dimensions)

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

✦ Double counting when matching with parton showers: another subtraction



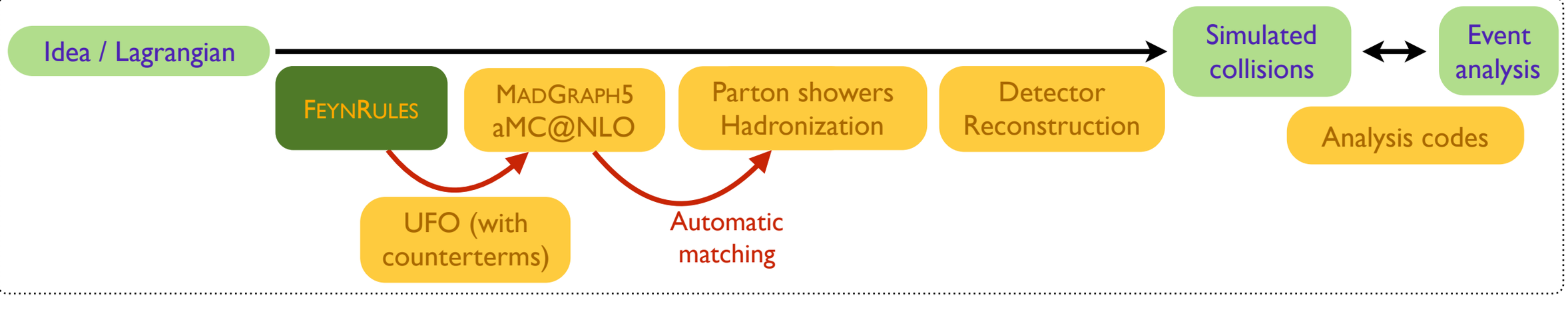
✤ Two sources of double counting that compensate each other (shower unitarity)

★ Radiation: both at the level of the reals and of the shower

★ No radiation: both in the virtuals and in the no-emission probability

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)]

Supersymmetry

In this talk: focus on the MSSM

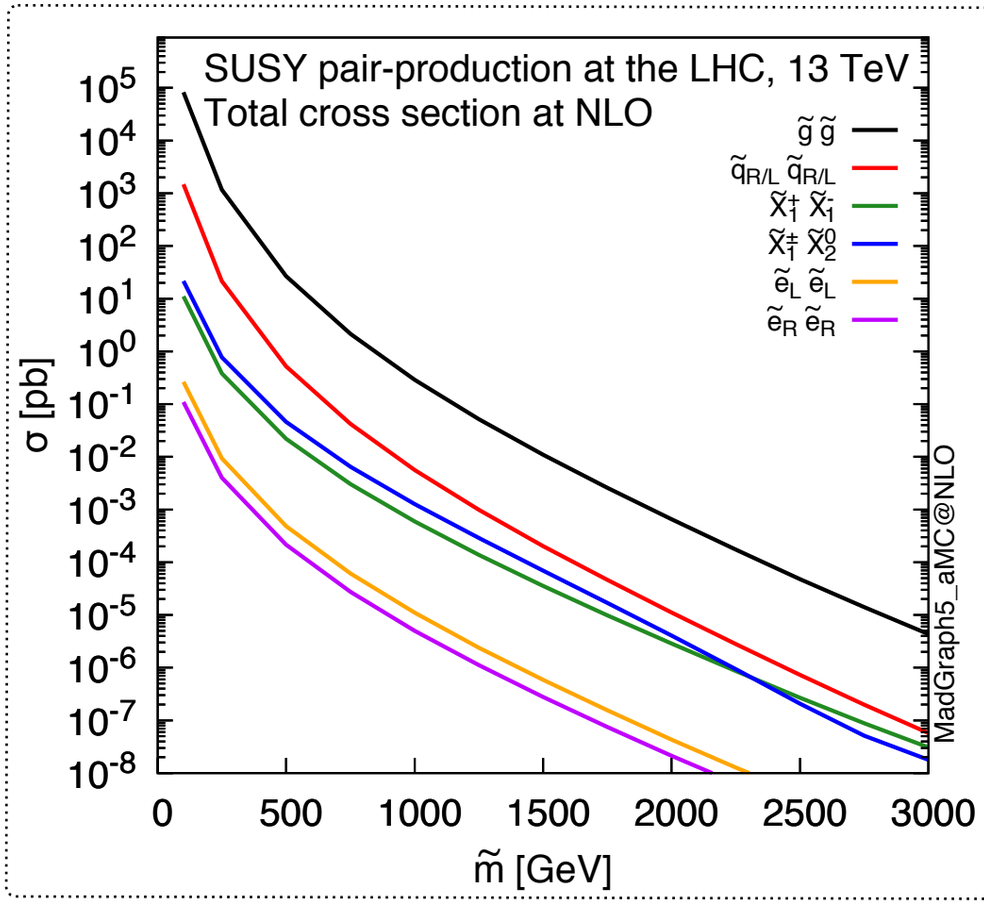
[Degrande, BF, Hirschi, Proudom & Shao (PRD'15; PLB'16)]

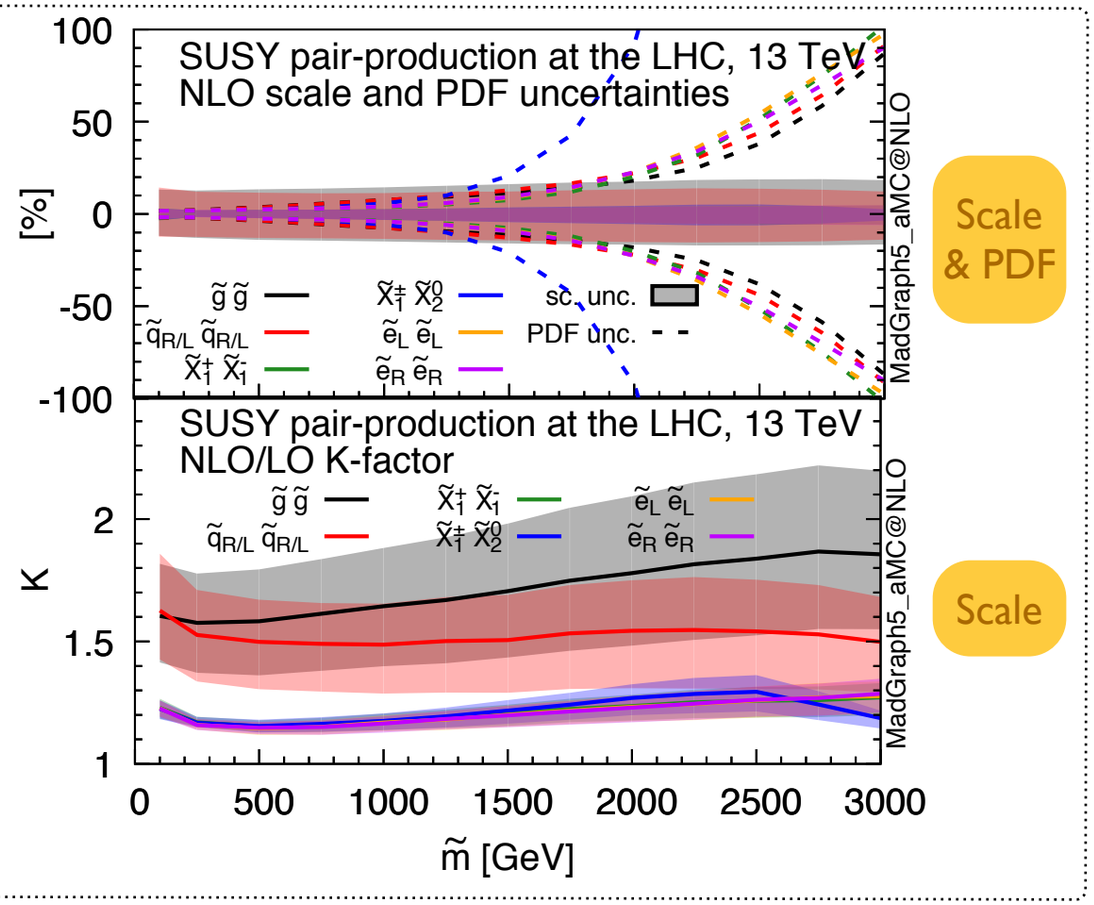
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (to appear)]

Total supersymmetric cross sections

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (to appear)]

✦ Total rates at 13 TeV for SUSY particle pair production





★ Central scales: average SUSY mass

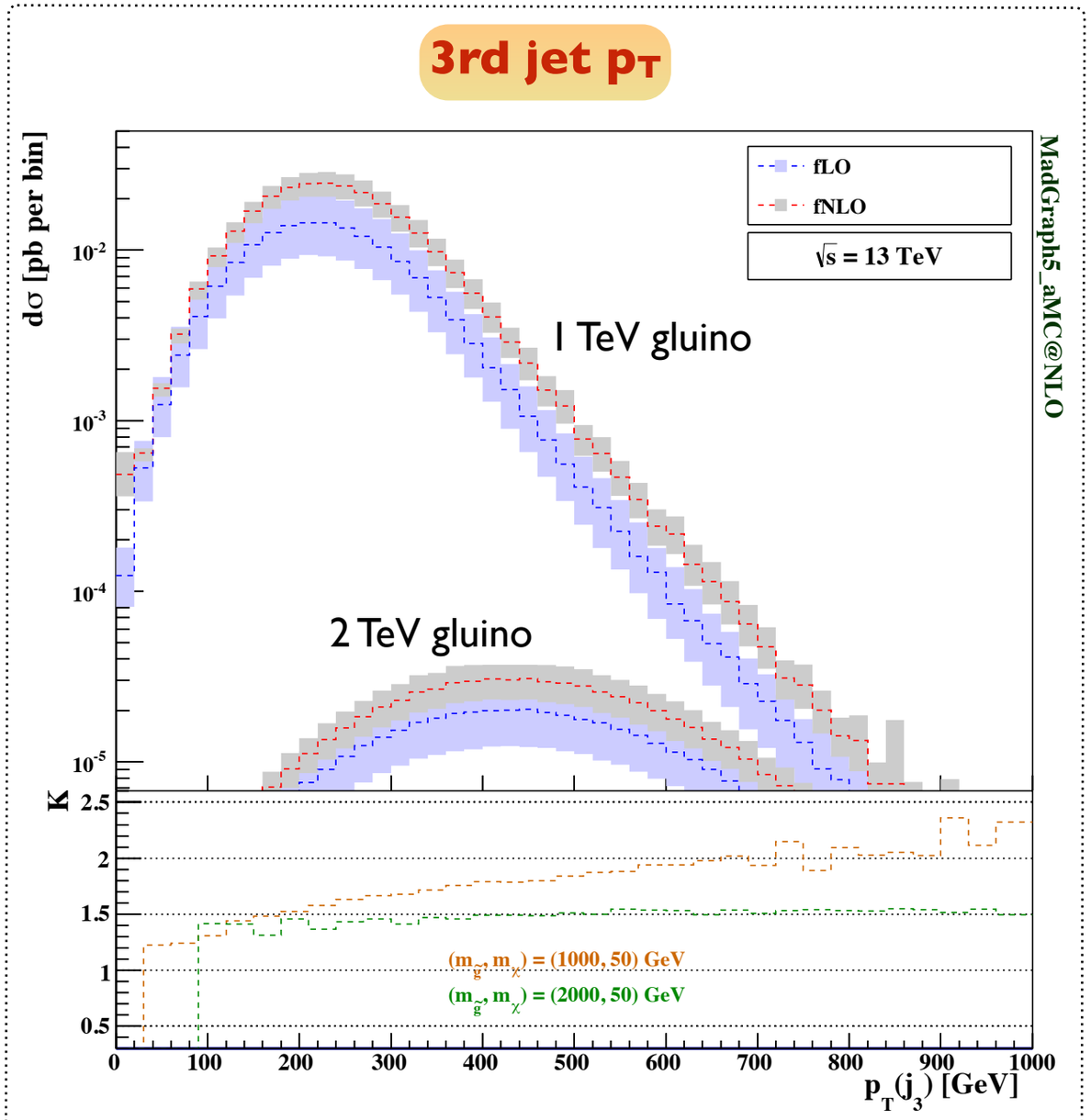
★ Parton densities: NNPDF 3.0

✦ Impact of the NLO corrections

- ✤ Strong processes: cross section enhancement of 50%-100% (genuine NLO effects)
- ✤ Scale uncertainties of 10-15% (strong) or a few % (electroweak)
- ✤ Huge PDF uncertainties in the high mass region (expected to be self cured)

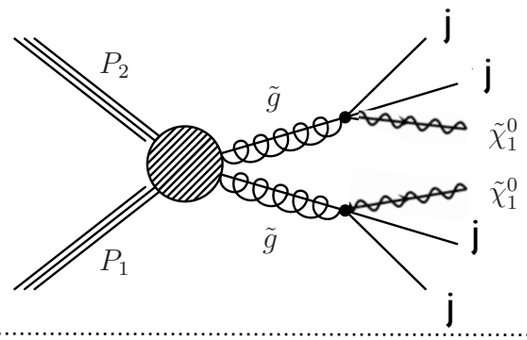
Fixed-order distributions: jet properties

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



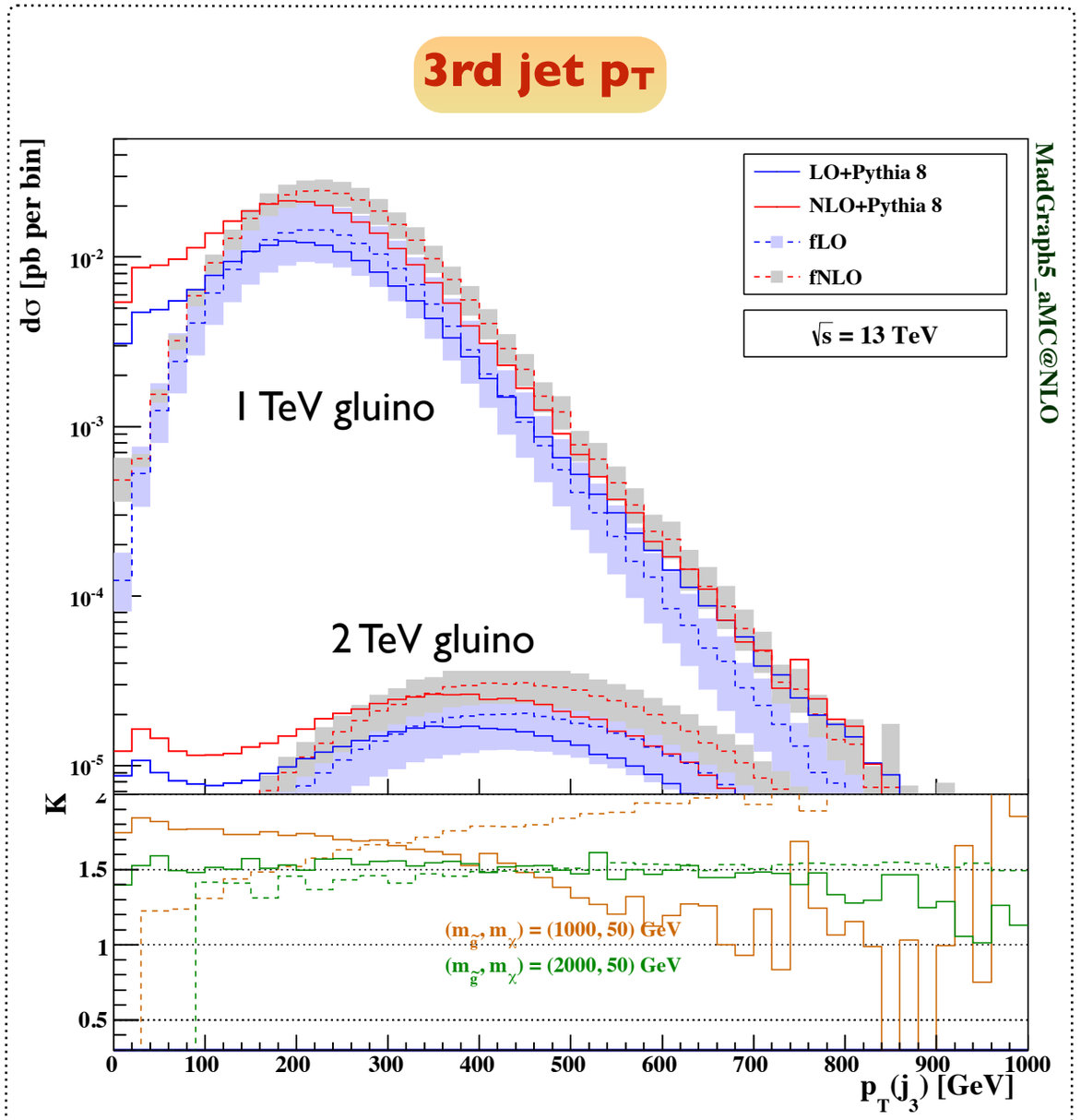
- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet (hard)
  - ★ Sometimes a radiation jet (soft)
    - ➢ not for the 1st and 2nd jets
- Constant *K*-factors not accurate
- NLO effects
  - ★ Crucial for a precise signal description
  - ★ Normalization modification
  - ★ Distortion of the shapes
  - ★ Reduction of the theoretical uncertainties

Gluino - multijet + MET



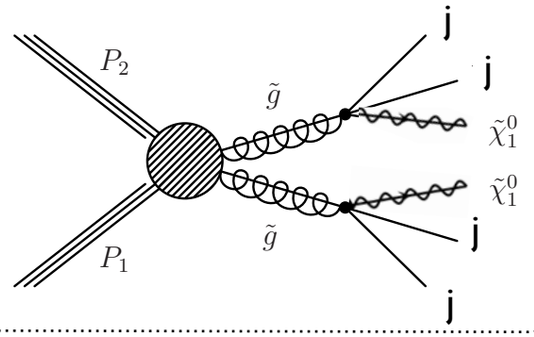
NLO+PS distributions: jet properties

[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)
- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes a radiation jet
  - ★ Entanglement of the two effects: two peaks

Gluino - multijet + MET



Vector-like quarks

In this talk: single VLQ production.
Other VLQ processes are available. See talk by D. Majumder for HH production.

[BF & Shao (EPJC'17)]
[Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (1703.10614)]

A general vector-like quark model

[BF & Shao (EPJC'17); Cacciapaglia, Cai, Carvalho, Deandrea, Flacke, BF, Majumder & Shao (1703.10614)]

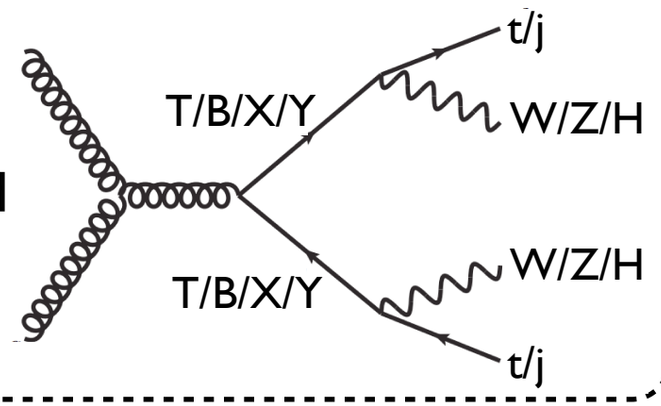
✦ An effective Lagrangian (with four partners: T, B, X and Y)

$$\begin{aligned}\mathcal{L}_{\rm VLQ} &= i\bar{Y}\not{D}Y - m_{_Y}\bar{Y}Y + i\bar{B}\not{D}B - m_{_B}\bar{B}B + i\bar{T}\not{D}T - m_{_T}\bar{T}T + i\bar{X}\not{D}X - m_{_X}\bar{X}X \\ &- h\left[\bar{B}\left(\hat{\kappa}_L^B P_L + \hat{\kappa}_R^B P_R\right) q_d + \bar{T}\left(\hat{\kappa}_L^T P_L + \hat{\kappa}_R^T P_R\right) q_u + \text{h.c.}\right] \\ &+ \frac{g}{2c_{_W}}\left[\bar{B}\not{Z}\left(\tilde{\kappa}_L^B P_L + \tilde{\kappa}_R^B P_R\right) q_d + \bar{T}\not{Z}\left(\tilde{\kappa}_L^T P_L + \tilde{\kappa}_R^T P_R\right) q_u + \text{h.c.}\right] \\ &+ \frac{\sqrt{2}g}{2}\left[\bar{Y}\not{W}\left(\kappa_L^Y P_L + \kappa_R^Y P_R\right) q_d + \bar{B}\not{W}\left(\kappa_L^B P_L + \kappa_R^B P_R\right) q_u + \text{h.c.}\right] \\ &+ \frac{\sqrt{2}g}{2}\left[\bar{T}\not{W}\left(\kappa_L^T P_L + \kappa_R^T P_R\right) q_d + \bar{X}\not{W}\left(\kappa_L^X P_L + \kappa_R^X P_R\right) q_u + \text{h.c.}\right]\end{aligned}$$

✦ Illustrative process

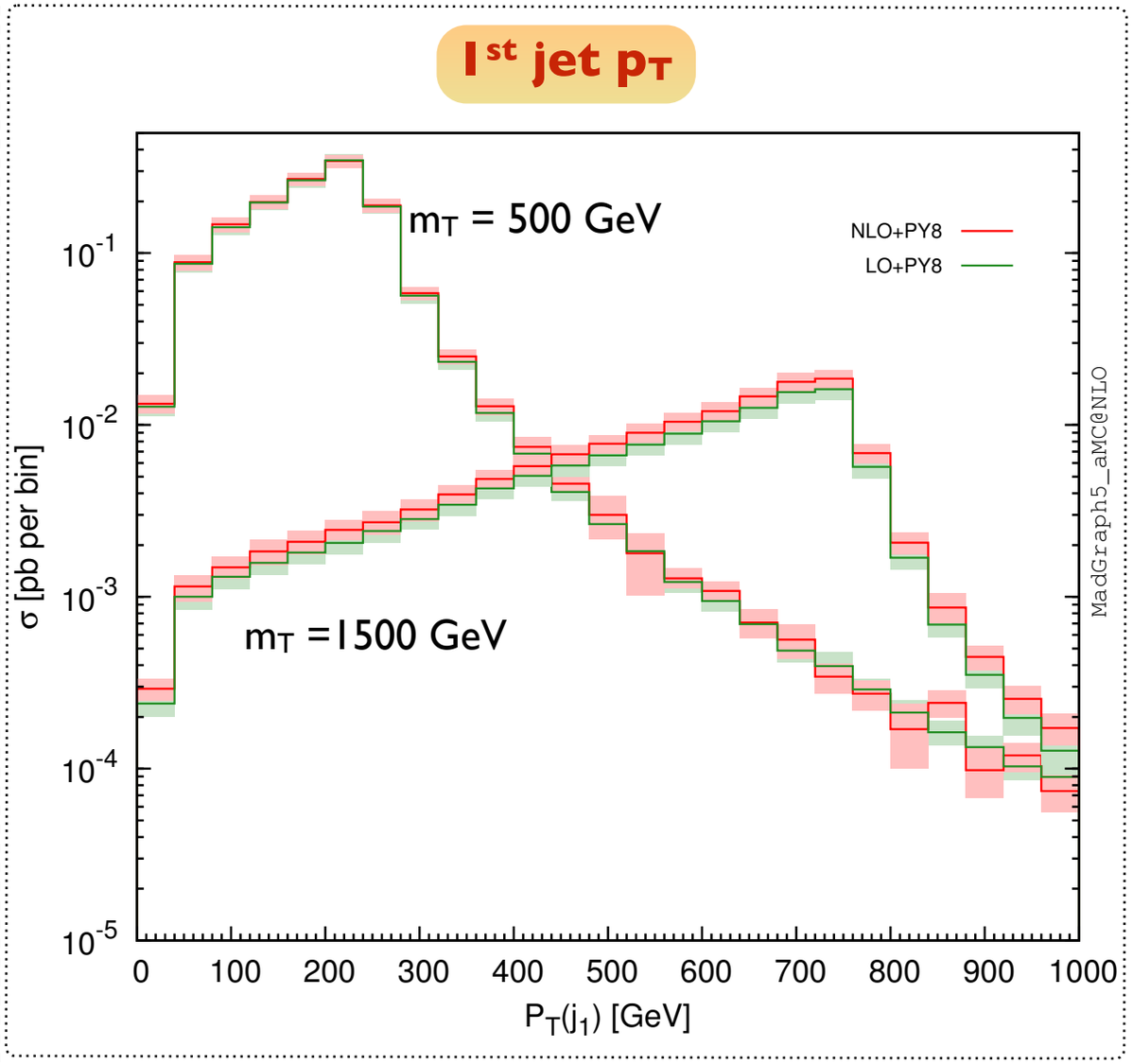
★ Quark partners decay into an electroweak boson and a jet/top

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

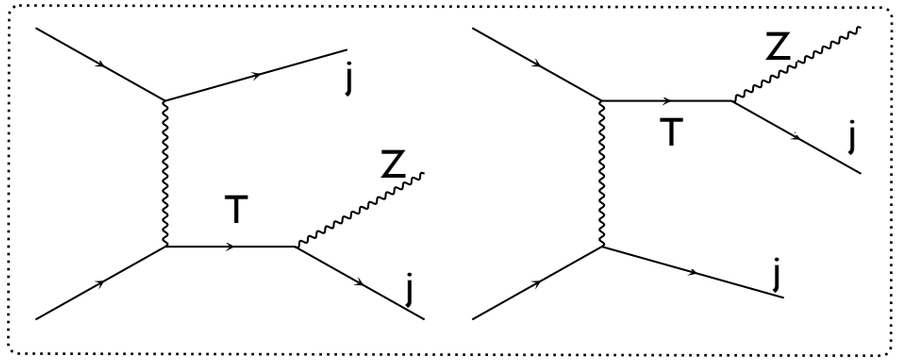


NLO+PS distributions: jets (1)

[BF & Shao (EPJC'17)]



✤ Benchmark: the VLQ is an up partner
- ★ Couples to the Z only
- ★ Single production study:



✤ The 1st jet mostly arises from T decays
- ★ Peak at about half the T mass

✤ Constant *K*-factors (normalization effects)
- ★ *K*=1 and 1.20 for m_T=500 GeV and 1.5 TeV)

✤ NLO effects
- ★ Slight distortion of the shapes (for large m_T)
- ★ Reduction of the theoretical uncertainties

Loop-induced processes

In this talk: DM analysis
See talk by J.H. Kim for HHH production at the FCC

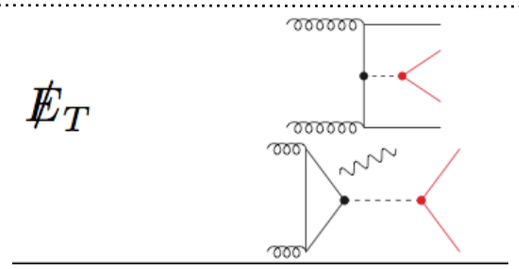
[BF, Kim & Lee (PRD'16, 1704.04298)]
[Arina, Backovic, Conte, BF, Guo *et al.* (JHEP'16)]
[Banerjee, Barducci, Bélanger, BF, Goudelis & Zaldivar (1705.02327)]

Collider probes for dark matter

✦ 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

Third-generation-philic dark matter

[Banerjee, Barducci, Bélanger, BF, Goudelis & Zaldivar (1705.02327)]

✦ A simplified model for 3rd generation-philic dark matter

✤ A gauge singlet dark sector with a fermionic dark matter candidate χ

✤ A gauge singlet pseudoscalar mediator A linking the dark and SM sectors

$$\mathcal{L} = \mathcal{L}_{\rm kin} - i\frac{y_\chi}{2} A\bar{\chi}\gamma_5\chi - i\sum_{f_u} c_u \frac{m_{f_u}}{v} A\bar{f}_u\gamma_5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} A\bar{f}_d\gamma_5 f_d$$

★ Loop-induced couplings to gluons (mediator production)

✦ Cosmologically attractive

✤ Evasion of direct detection bounds

✦ Benchmark

✤ 2HDM-inspired with enhanced Yukawas and tanβ = 1:

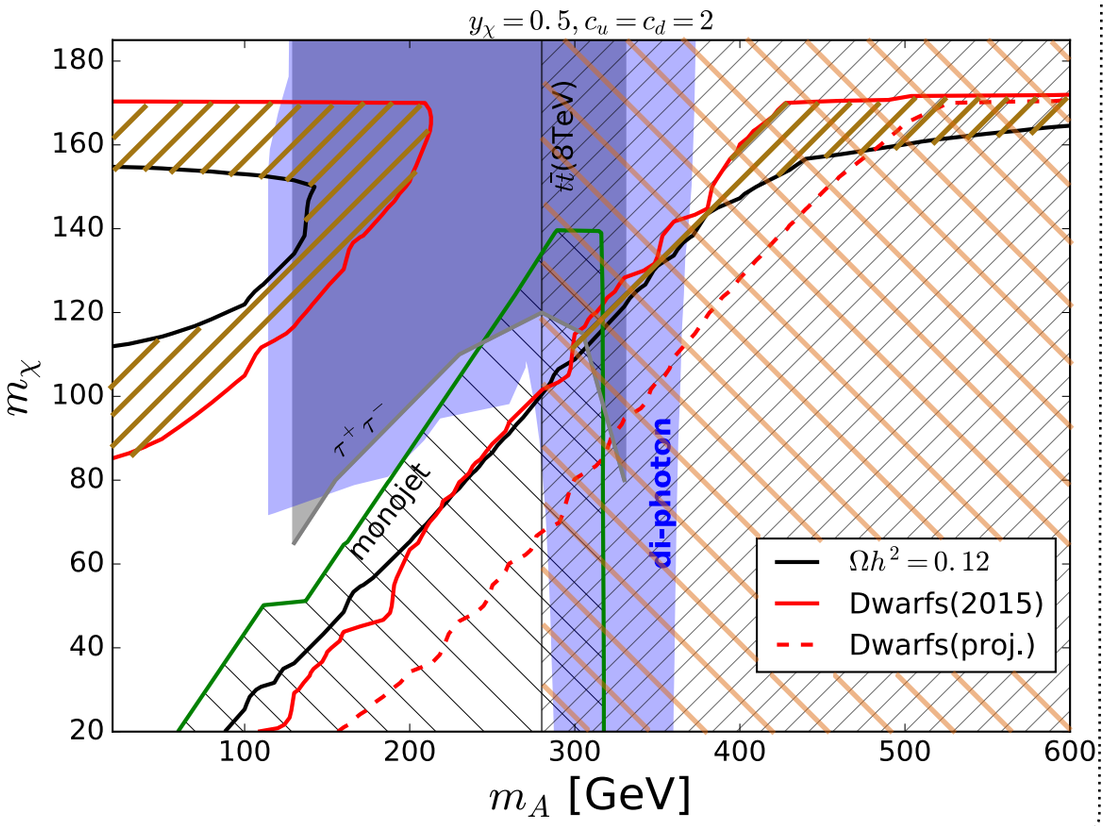
$$c_u = c_d = 2; y_\chi = 0.5$$

✤ Couplings that can reproduce cosmological data for weak scale masses

Collider-cosmology complementarity at work

[Banerjee, Barducci, Bélanger, BF, Goudelis & Zaldivar (1705.02327)]

✦ Current collider and cosmology data puts the model into trouble



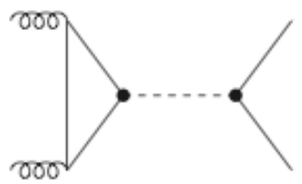
✤ Two regions favored by cosmology

★ Light mediator (between red and black)
- Too light χ ➢ underabundant
- Too heavy χ ➢ underabundant ($t\bar{t}$ threshold)
- Same behavior for Fermi-LAT results, but shifted (present *vs* early universe time)

★ Heavier mediator (m_A > 200 GeV)
- Always some good combination of masses

✤ Top-antitop exclusions (DM independent)

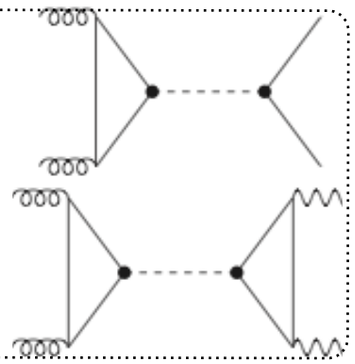
★ $t\bar{t}$ cross section (lighter A)
★ Resonance searches (heavy A)
★ 8 TeV still stronger than 13 TeV
★ $t\bar{t}A$ (with A invisible, NLO) subleading



✤ Diphoton and ditau

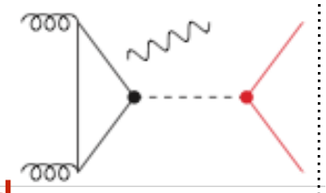
★ Driven by the BR behavior
- Invisible A decay
- $t\bar{t}$ effects (Γ_t and $\Gamma\gamma$, Γ_g)

★ Sensitive to light mediators



✤ Monojet and multijet + MET

★ Efficient if $m_A > 2\, m_X$
★ Efficient below the top threshold
★ The heavy mediator region is killed



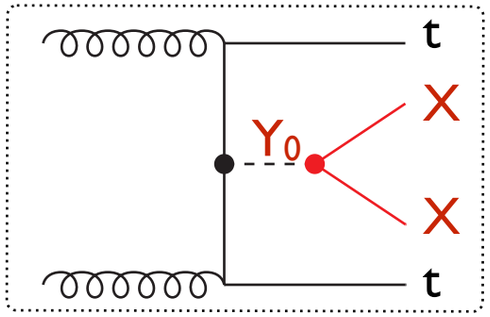
NLO effects on a CLs

[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

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



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

✦ There are theoretical uncertainties on a CLs number

	(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]	$\mathrm{CL}_{\rm LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\mathrm{CL}_{\rm NLO}$ [%]
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	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$

[MadAnalysis 5]

- ✤ An excluded point may not be excluded when accounting for uncertainties
- ✤ The CLs can increase / decrease at NLO (is a point really excluded at LO?)
- ✤ The error band is reduced

EFT @ NLO

In this talk: VH production; EFT validity issues

[Degrande, BF, Mawatari, Mimasu & Sanz (EPJC'17)]

(Higgs) Effective Field Theory at NLO in QCD

[Degrande, BF, Mawatari, Mimasu & Sanz (EPJC'17)]

✦ Illustrative Lagrangian (more operators can be included)

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

✦ Blue benchmark (allowed by LEP/LHC)

- ✤ $\bar{c}_B = \bar{c}_W = 0$; $\bar{c}_{HW} = 0.03$
- ✤ Two HVV structures arise

$$-g^{(1)}_{hvv}\left[V_{\mu\nu}V^{\mu\nu}h\right] - g^{(2)}_{hvv}\left[V_\nu \partial_\mu V^{\mu\nu} h\right]$$

✦ Orange benchmark (allowed by LEP/LHC ➢ cancellations)

- ✤ $\bar{c}_B = 0.015$; $\bar{c}_{HW} = -\bar{c}_W = 0.03$
- ✤ One HVV structure arises

$$-g^{(1)}_{hvv}\left[V_{\mu\nu}V^{\mu\nu}h\right]$$

✦ Effective field theories at NLO

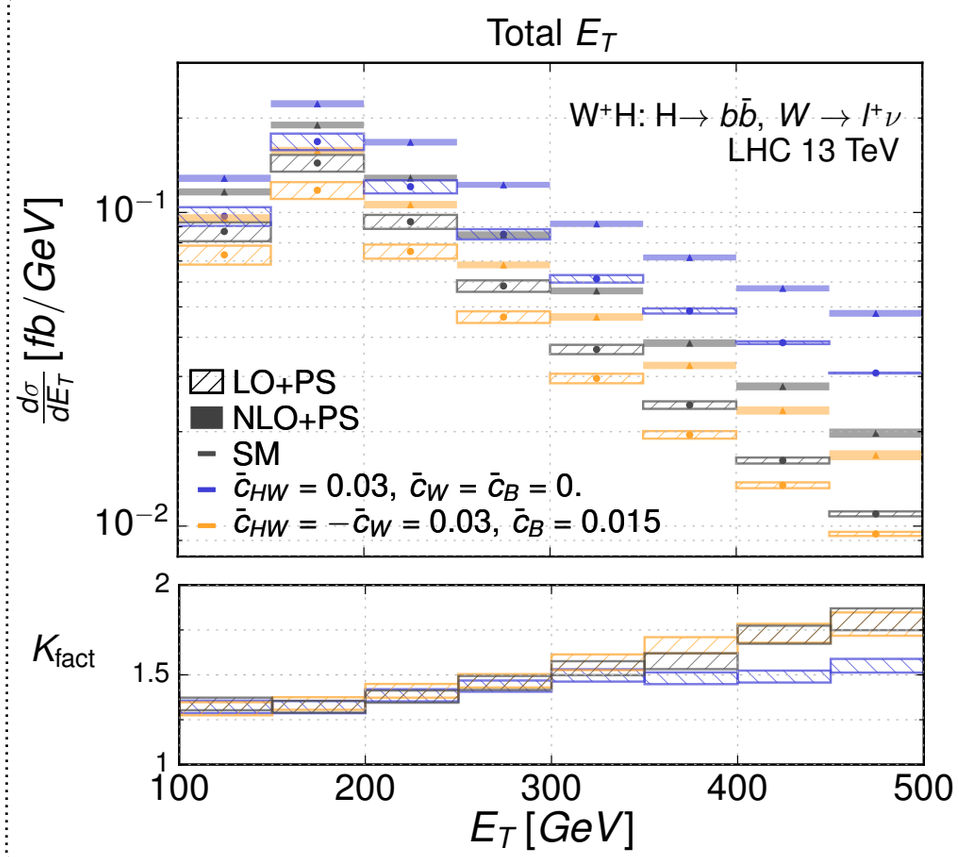
- ✤ Renormalizability: order by order in $1/\Lambda^2$ (double perturbative series)
- ✤ Precision of the QCD corrections can be included

$$\sigma \approx \underset{\text{SM@LO}}{1} + \underset{\text{SM@NLO}}{O(\alpha_s)} + \underset{\text{EFT@LO}}{O(1/\Lambda^2)} + \underset{\text{EFT@NLO}}{O(\alpha_s/\Lambda^2)}$$

WH production at the LHC - QCD corrections

[Degrande, BF, Mawatari, Mimasu & Sanz (EPJC'17)]

✦ QCD effects on VH production with BSM effects

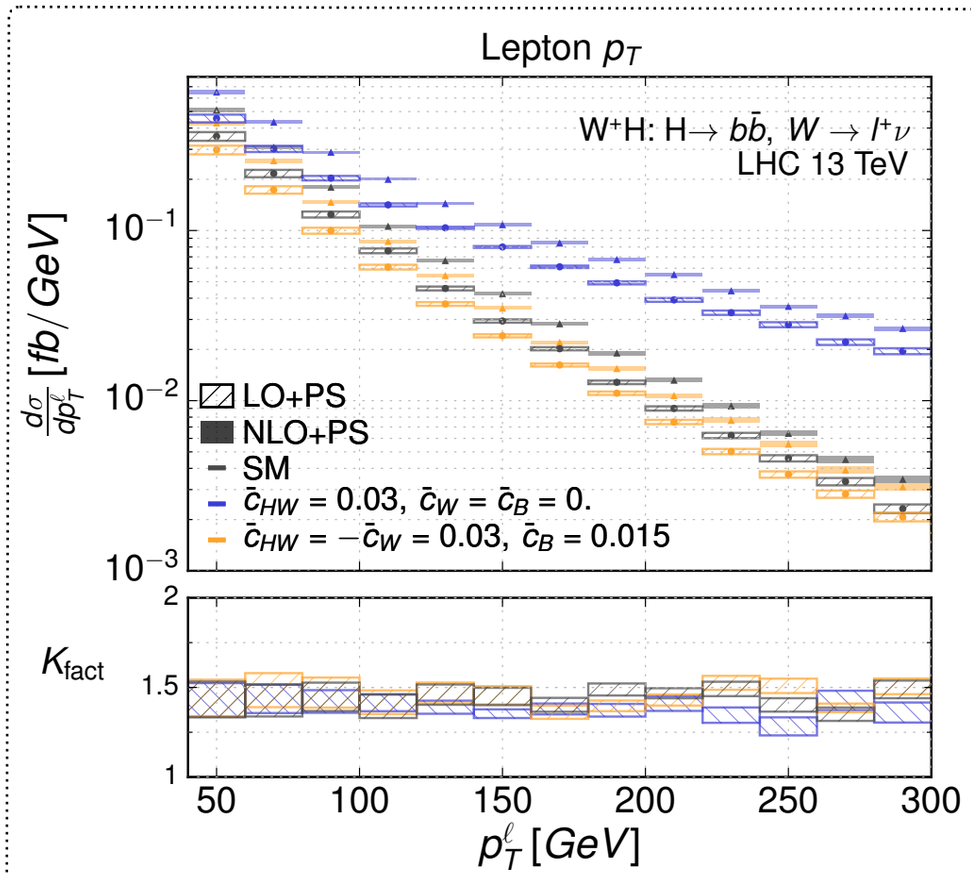


✤ Differential K-factors are scenario-dependent

★ Orange is very close to the SM case

★ Blue is in contrast flat

★ LO predictions are in both cases inaccurate



✤ Some observables show very flat K-factors

★ Typical for a Drell-Yan like topology

★ Not true when the leading jet is involved

✤ LO and NLO predictions do not overlap

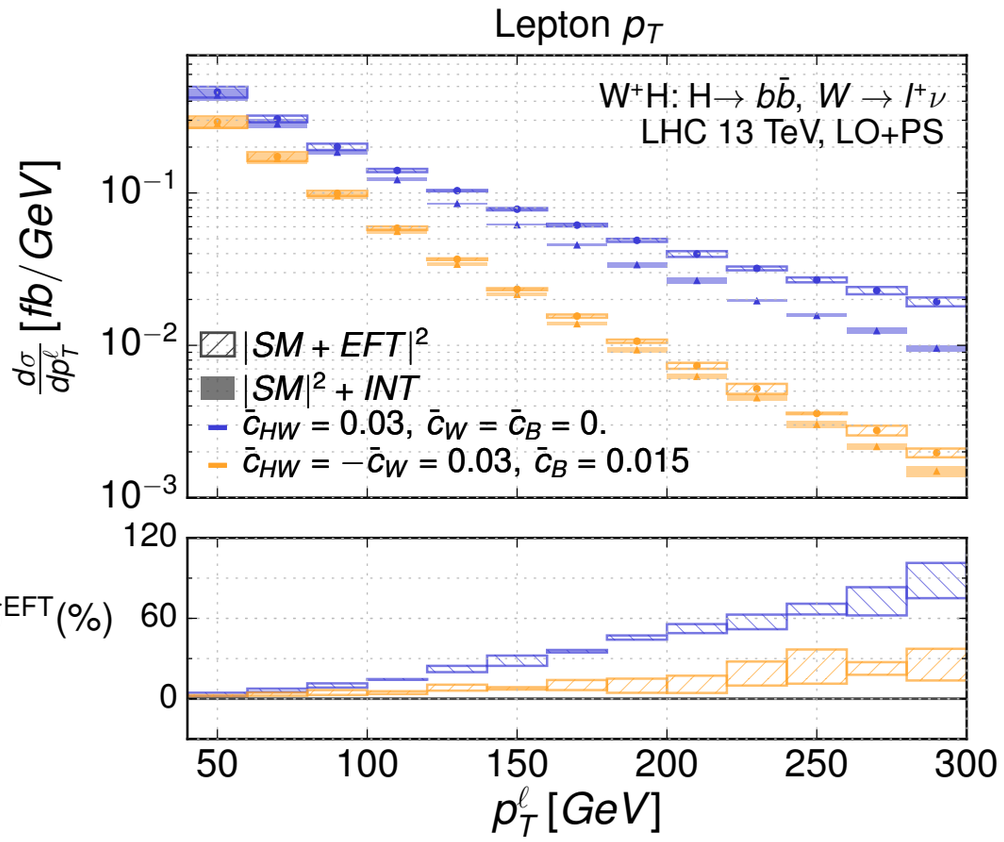
★ LO uncertainties could be underestimated

✤ Significant deviations from the Standard Model (the 2 structures of the *blue* setup)

EFT validity

[Degrande, BF, Mawatari, Mimasu & Sanz (EPJC'17)]

✦Unitarity and perturbativity checks



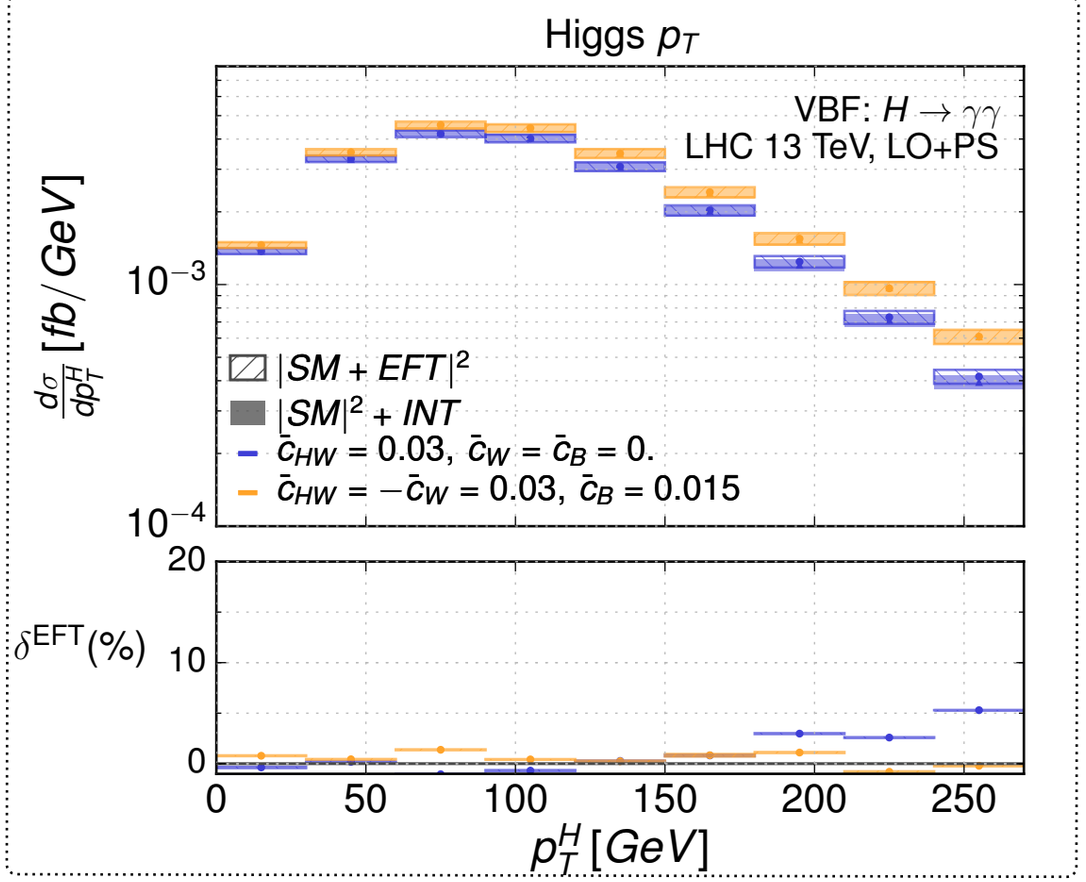
★ $1/\Lambda^4$ effects possibly large in the tails

★ Benchmark- and process-dependent

★ Care must be taken with the EFT interpretation

➢ WH: *orange* is OK, *blue* is not

➢ WBF: *orange* and *blue* OK



✤ VBF/VH complementarity for extracting constraints

Jet veto resummation

In this talk: impact on W'/Z' searches

[BF & Ruiz (JHEP'17)]

Jet veto resummation

✦ Importance of jet vetoes

- ✤ Jet veto involves large logarithms of the hard scale over the veto scale
- ✤ Reliable predictions necessitate their resummation
- ✤ Potential impact on the sensitivity to colorless new physics

✦ Matched resummed calculations can be derived in the MG5_aMC framework

- ✤ Jet veto resummation in the SCET framework, matched to the NLO results
- ✤ The process-dependent pieces are returned by MG5_aMC
- ✤ The NLO+NNLL matching is performed automatically

Evolution from the hard to the veto scale

Finite loop corrections

$$\frac{\mathrm{d}\sigma^{\mathrm{NLO+NNLL}}(p_T^{\mathrm{Veto}})}{\mathrm{dPS}_n} = \sum_{a,b=g,q,\overline{q}} E_I(Q^2, p_T^{\mathrm{Veto}}, \mu_h, \mu, R) \times \left(1 + \frac{\alpha_s(\mu_h)}{4\pi}\mathcal{H}_{ab}^{(1)}(Q^2, \mu_h)\right)$$

$$\times \left[\left.\frac{\mathrm{d}\sigma_{ab}^{\mathrm{NLO}}}{\mathrm{dPS}_{(n+1)}}\right|_{p_T<p_T^{\mathrm{Veto}}} - \frac{\alpha_s(\mu)}{4\pi}\left(\mathcal{H}_{ab}^{(1)}(Q^2,\mu) + E_I^{(1)}(Q^2, p_T^{\mathrm{Veto}}, \mu)\right)\frac{\mathrm{d}\sigma_{ab}^{\mathrm{LO}}}{\mathrm{dPS}_n}\right]$$

Beam functions contributions

Matching with the NLO

[Becher & Neubert (JHEP'12); Becher, Neubert & Rothen (JHEP'13); Becher, Frederix, Neubert & Rothen (EPJC'15)]

Jet veto impact on W' searches

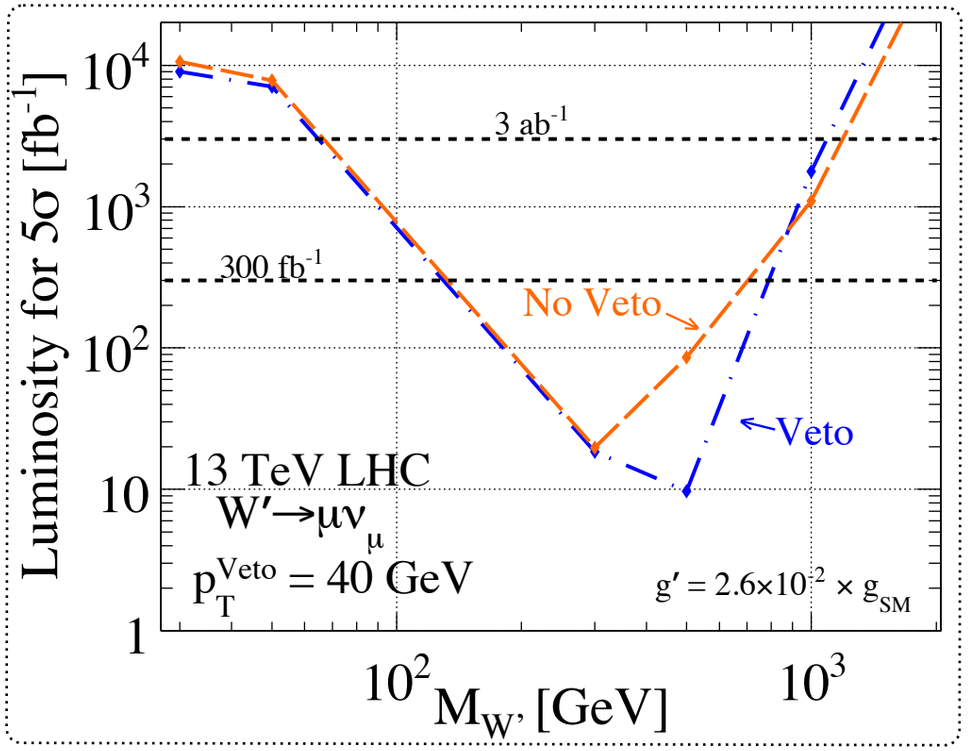
[BF & Ruiz (JHEP'17)]

✦ A comprehensive framework for W' searches

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\sum_{i,j}\left[\overline{u}_i V_{ij}^{\rm CKM}\, W'^{+}_{\mu}\,\gamma^{\mu}\left(\kappa_L^q P_L + \kappa_R^q P_R\right) d_j + \text{h.c.}\right]$$
$$-\frac{g}{\sqrt{2}}\sum_{i}\left[\overline{\nu}_{\ell_i} W'^{+}_{\mu}\,\gamma^{\mu}\kappa_L^{\ell} P_L \ell_i^- + \text{h.c.}\right]$$

★ No flavor violation on top of the SM one, and the coupling strengths are free

✦ Sensitivity of a typical W' search with and without a jet veto



✤ Considered typical W' search
- ★ Single isolated muon
- ★ MET properties constraints (significance, d$\Delta\varphi$)
- ★ W transverse mass (mass window selection)
- ★ Veto of jets with a p_T > 40 GeV

✤ Large variations in the utility of a veto
- ★ Related to the variation of S/B
  - ‣ The background depends on the W' mass
- ★ Very heavy case: S/B is unaffected by the veto
- ★ Lighter case: the background is DY-dominated
- ★ Intermediate: golden channel

Summary

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
- ✤ Loop-induced processes can be studied as well
- ✤ The same machinery can be used for resummation calculations (jet vetoes)

✦ Many models are already publicly available (on the FeynRules website)

- ✤ Supersymmetry (MSSM and simplified models)
- ✤ BSM Higgs models
- ✤ Dark matter simplified model
- ✤ Higgs and top effective field theories
- ✤ Vector-like quark models
- ✤ Z'/W' models (with a right neutrino) ⟶ See talk by R. Ruiz for a phenomenological example