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Status of MadGraph5_aMC@NLO

ATLAS-CMS MC meeting
CERN, 2/5/2017

Thanks to:

Johan Alwall, Rikkert Frederix, Valentin Hirschi, Fabio Maltoni, Olivier Mattelaer, Roberto Pittau, Hua-Sheng Shao, Tim Stelzer, Paolo Torrielli, Marco Zaro, Andreas Papaefstathiou, Stefan Prestel, Valerio Bertone, Marius Wiesemann, Davide Pagani, Eleni Vryonidou, Andrew Papanastasiou, Kentarou Mawatari, Celine Degrande, Benjamin Fuks

and to our experimental and theoretical colleagues for their feedback

About a month ago, the final meeting of Michelangelo's ERC grant (LHCTheory) has been largely devoted to discussing physics and technical issues in MG5_aMC@NLO

ATLAS and CMS members were present, and I'll limit myself here to reviewing some of the highlights of that meeting

Types of computations available:

- fLO Fixed order, tree level
- fNLO Fixed order, NLO
- LO+PS Hard tree-level events, showered
- NLO+PS Hard NLO events, showered (MC@NLO)
- MLM/CKKW-merged Multijet tree-level merging
- FxFx- or UNLOPS-merged Multijet NLO merging

The Lagrangian-to-events chain is automated through:

FeynRules(+NLOCT) - MG5_aMC@NLO - PSMC

Most of the recent work went into extending the physics scope of the code

- Compatibility with increasingly complicated models
- Improved numerics at the NLO
- User “hooks”

And: efforts to improve steering capabilities of external codes from within MG5_aMC

The latter is particularly useful for standalone tests

Highlights of recent activity

- Interface to Pythia8 and MadAnalysis5
- Extended one-loop reduction options (through linking Collier)
- More work on loop-induced processes (towards NLO)
- Mixed QCD-QED NLO corrections
- SUSY with NLO QCD corrections, and on-shell subtraction
- Plugins

The current public version is:

MG5_aMC@NLO v2.5.4

released on 28/3/2017

W.r.t. v2.4 series:

- Several major functionalities added
- A number of bug fixes, none major

2.5.0:

- interface to Collier (expand one-loop reduction capabilities)
- `install` command for PY8 (solves e.g. dependence issues)
- PY8 interface at the LO (important for merging)
- MadAnalysis5 interface
- NLO and LO reweights work in multicore
- add plugin support
- bias LO event generation
- support CKKW-L

2.5.1:

- interface to H7
- parallelisation of PY8 LO runs
- `install` command for MadDM

2.5.3:

- new default shower reference scale ($\sqrt{\hat{s}} \longrightarrow H_T/2$)
- madspin “set spinmode onshell” allows MS to handle decays with more than two decay products. Doesn’t work for loop induced
- LHE-like output for fNLO (BE CAREFUL)

For a complete list of the changes, see the Update notes

Pythia8 interface

Pending publication (if ever :/): V.H., O. Mattelaer, S. Prestel

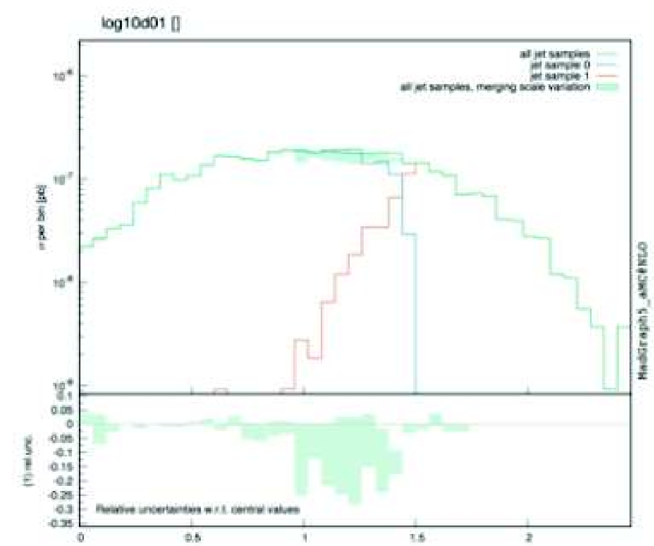
Pythia8 installation and use:

```
MG5_aMC > install pythia8
MG5_aMC > install mg5amc_py8_interface
ProcOuput > shower pythia8 run_01
[...]/ProcOuput/Cards/pythia8
```

- Supports CKKW-L for LO merging
- Merging systematics computed on-the-fly
- Parallelization of Pythia8 runs
- Merging systematics weights propagated through HEPMC event files
- Ability easily output HEPMC events to a FIFO file
- Do-it-all Pythia8 driver.

MLM p p > Z + {0,1}j

```
Cross-section :   1535 +- 4.319 pb
Nb of events :  10000
Pythia8 merged cross-sections are:
 > Merging scale = 10     : 653.9      +/- 1.7     [pb]
 > Merging scale = 20     : 698.42     +/- 1.7     [pb]
 > Merging scale = 30     : 712.55     +/- 1.7     [pb]
 > Merging scale = 40     : 709.02     +/- 1.7     [pb]
 > Merging scale = 50     : 706.56     +/- 1.7     [pb]
```



- **No excuse** anymore for sticking to Pythia6!

- We've had a number of reports, from both ATLAS and CMS, of unexpected behaviour with LO PY8 mergings
  (e.g. rejection rates too large)

- The use of this interface helps avoid trivial mistakes

- HW++/H7 does not have yet the same level of integration in the MC phase as PY8 (it does for partonic cross sections)

- HW++/H7 `Contrib/` stuff is being upgraded $\longrightarrow$

technical aspects

- LO and FxFx merging contained in a single library add-on to Herwig 7: “ExternMerge”.
  - currently available at:

    https://bitbucket.org/andreasp/externmerge

- straightforward to compile,
- use via standard-type Heriwg 7 input files.

Shower reference scale

This is essentially the median value μ_0 of a range in which shower scales (EMSCA) are picked on a event-by-event basis

$$D(\mu) = \begin{cases} 1 & \mu \leq \mu_1 \,, \\ \text{monotonic} & \mu_1 < \mu \leq \mu_2 \,, \\ 0 & \mu > \mu_2 \,, \end{cases}$$
$$\mu_{\rm sh} = D^{-1}(r) \,,$$

- What has been changed is the functional form of μ_0 – the code (`montecarlocounter.f`) is also more flexible, so other forms can be implemented easily
- μ_1 and μ_2 are related to μ_0 by parameters found in `run_card.dat` and `madfks_mcatnlo.inc`

Shower reference scale

- The new default shower scale seems to induce a smoother behaviour (w.r.t. fNLO) than the previous one
- It is important to have data that support this statement (incidentally: this is *not* the case for $t\bar{t}b\bar{b}$)
- The differences induced by the two scales *may* be large only in MC-dominated regions. If that's not the case, re-consider the situation carefully (more tomorrow)

Integral reduction

MG5_aMC@NLO features an internal OLP (MadLoop), which is responsible for the computation of the virtual matrix elements. GoSam can be used as well

Collier is yet another tool in the array of available integral-reduction codes called by ML (the other being CutTools, IREGI, Golem95, Samurai, Ninja), with dynamical switching among them (in user-defined order)

A valuable addition, especially for low-multiplicity, high-rank cases. Most of the stuff still done with Ninja; interesting to see what happens close to the IR limits (for loop-induced processes)

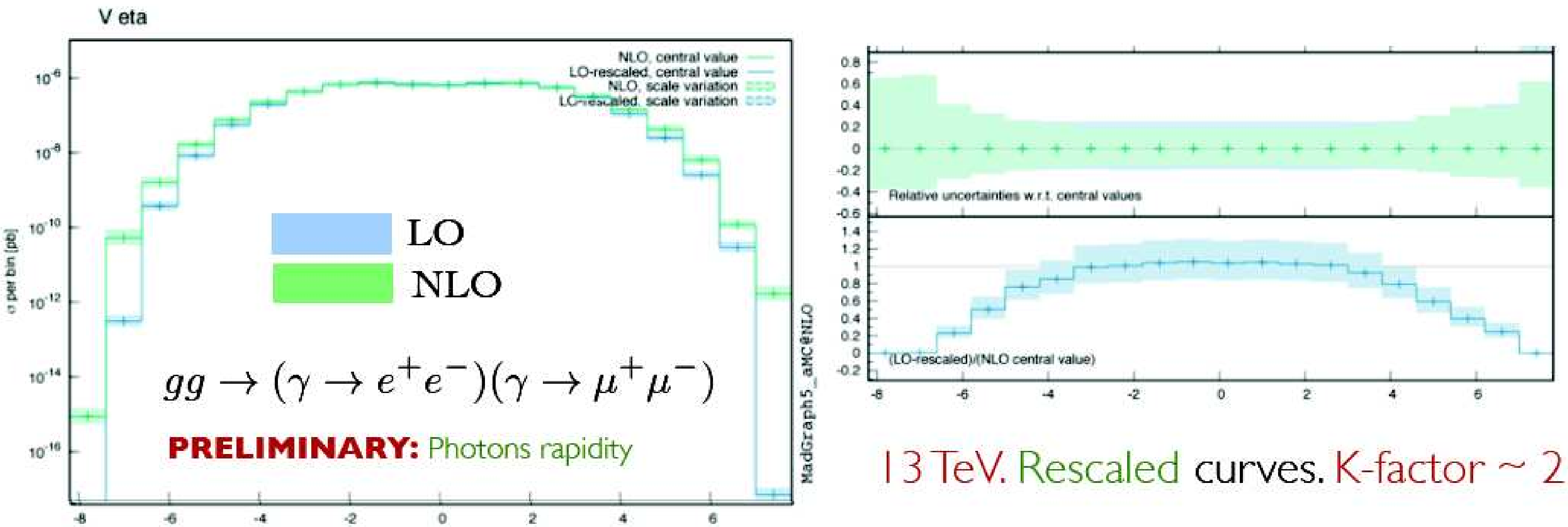
Loop-induced processes

- Automation achieved from v2.3.0 onwards
- Incremental improvements with versions
- Both reweighting (w.r.t. an underlying, possibly fake, EFT) and direct integration are possible, with pros and cons
- First attempts to push it to NLO (customised, not automated)

Loop-Induced at NLO

Feasibility study completed for diphoton decayed:

- 2-loop amplitudes from VVamp (A.Manteuffel, L.Tancredi [arXiv:1503.08835])
- Needed ad-hoc parallelization of MadFKS.
- Performed with ad-hoc linking/interface of 2-loop, Born and Reals MEs.
- Threshold for the distance to IR singularities where reals are replaced by local counterterms had to be increased by two 10-folds.



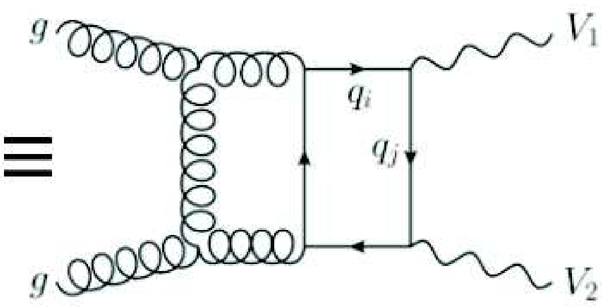
13 TeV. Rescaled curves. K-factor ~ 2

- Flexible implementation of the of 2-loop helicity amplitudes in their covariant form as a **UFO vertex**.

2-LOOP HEL. AMPLITUDE AS A UFO VERTEX

$$S^{\mu\nu\rho\sigma}(p_1,p_2,p_3) = a_1 g^{\mu\nu}g^{\rho\sigma} + a_2 g^{\mu\rho}g^{\nu\sigma} + a_3 g^{\mu\sigma}g^{\nu\rho}$$
$$+ \sum_{j_1,j_2=1}^{3}\Big(b^{(1)}_{j_1j_2}\, g^{\mu\nu}\, p^{\rho}_{j_1}\, p^{\sigma}_{j_2} + b^{(2)}_{j_1j_2}\, g^{\mu\rho}\, p^{\nu}_{j_1}\, p^{\sigma}_{j_2} + b^{(3)}_{j_1j_2}\, g^{\mu\sigma}\, p^{\nu}_{j_1}\, p^{\rho}_{j_2}$$
$$+ b^{(4)}_{j_1j_2}\, g^{\nu\rho}\, p^{\mu}_{j_1}\, p^{\sigma}_{j_2} + b^{(5)}_{j_1j_2}\, g^{\nu\sigma}\, p^{\mu}_{j_1}\, p^{\rho}_{j_2} + b^{(6)}_{j_1j_2}\, g^{\rho\sigma}\, p^{\mu}_{j_1}\, p^{\nu}_{j_2}\Big)$$
$$+ \sum_{j_1,j_2,j_3,j_4=1}^{3} c_{j_1j_2j_3j_4} p^{\mu}_{j_1}\, p^{\nu}_{j_2} p^{\rho}_{j_3}\, p^{\sigma}_{j_4},$$

$\equiv$




```
GGAA = Vertex(name = 'GGAA',
           particles = [ P.G, P.G, P.A, P.A ],
           color = [ 'Identity(1,2)' ],
           lorentz = [ L.A, L.B, L.C, L.D, L.E,
                       L.F, L.G, L.H, L.I, L.J,
                       L.K, L.L, L.M, L.N, L.O,
                       L.P, L.Q, L.R, L.S, L.T
                     ],
            couplings = {(0,0):C.GGAA_C1, (0,1):C.GGAA_C2, (0,2):C.GGAA_C3, (0,3):C.GGAA_C4, (0,4):C.GGAA_C5,
                         (0,5):C.GGAA_C6, (0,6):C.GGAA_C7, (0,7):C.GGAA_C8, (0,8):C.GGAA_C9, (0,9):C.GGAA_C10,
                         (0,10):C.GGAA_C11, (0,11):C.GGAA_C12, (0,12):C.GGAA_C13, (0,13):C.GGAA_C14, (0,14):C.GGAA_C15,
                         (0,15):C.GGAA_C16, (0,16):C.GGAA_C17, (0,17):C.GGAA_C18, (0,18):C.GGAA_C19, (0,19):C.GGAA_C20
                        })
```

- Allows a tool like MG5_aMC to generate arbitrary 2-loop amplitudes containing this loop (with any decay or vector quantum numbers.)
- The above should be viewed as template for distributing two-loop computations analytical results. UFO extension?

Increasing model complexity

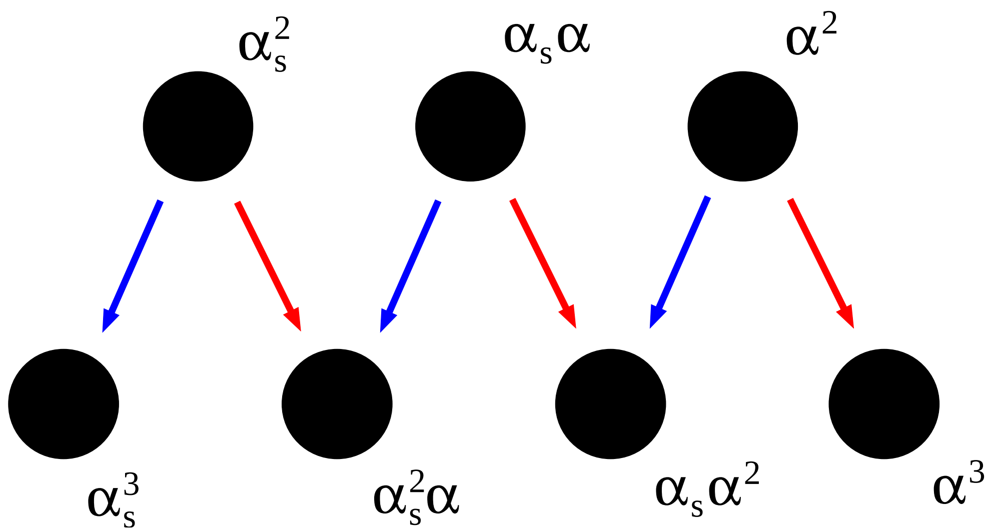
- The core MG5_aMC@NLO code can handle:
  a) mixed-coupling expansion (v2.6.X); *b)* $\simeq$ arbitrary BSM@NLO
- For mixed couplings, the primary example is QCD+EW (no shower yet)
- For BSM@NLO (eg SMEFT, SUSY), the present bottleneck is to set up and test the model
  (bar for OS subtraction, which is largely achieved but still being refined)

Mixed-coupling expansion

Consider dijet production; Σ is a generic observable

$$\Sigma_{jj}^{(\mathrm{LO})}(\alpha_S,\alpha) = \alpha_S^2\,\Sigma_{2,0} + \alpha_S\alpha\,\Sigma_{2,1} + \alpha^2\,\Sigma_{2,2}$$
$$\equiv \Sigma_{\mathrm{LO},1} + \Sigma_{\mathrm{LO},2} + \Sigma_{\mathrm{LO},3}$$
$$\Sigma_{jj}^{(\mathrm{NLO})}(\alpha_S,\alpha) = \alpha_S^3\,\Sigma_{3,0} + \alpha_S^2\alpha\,\Sigma_{3,1} + \alpha_S\alpha^2\,\Sigma_{3,2} + \alpha^3\,\Sigma_{3,3}$$
$$\equiv \Sigma_{\mathrm{NLO},1} + \Sigma_{\mathrm{NLO},2} + \Sigma_{\mathrm{NLO},3} + \Sigma_{\mathrm{NLO},4}$$

Usually, $\Sigma_{\mathrm{NLO},1}$=NLO QCD, $\Sigma_{\mathrm{NLO},2}$=NLO EW (weak+QED)



Current syntax (leading terms, i.e. LO/NLO QCD)

```
MG5_aMC> generate a b > c d e f [QCD]
```

Will become (or something similar):

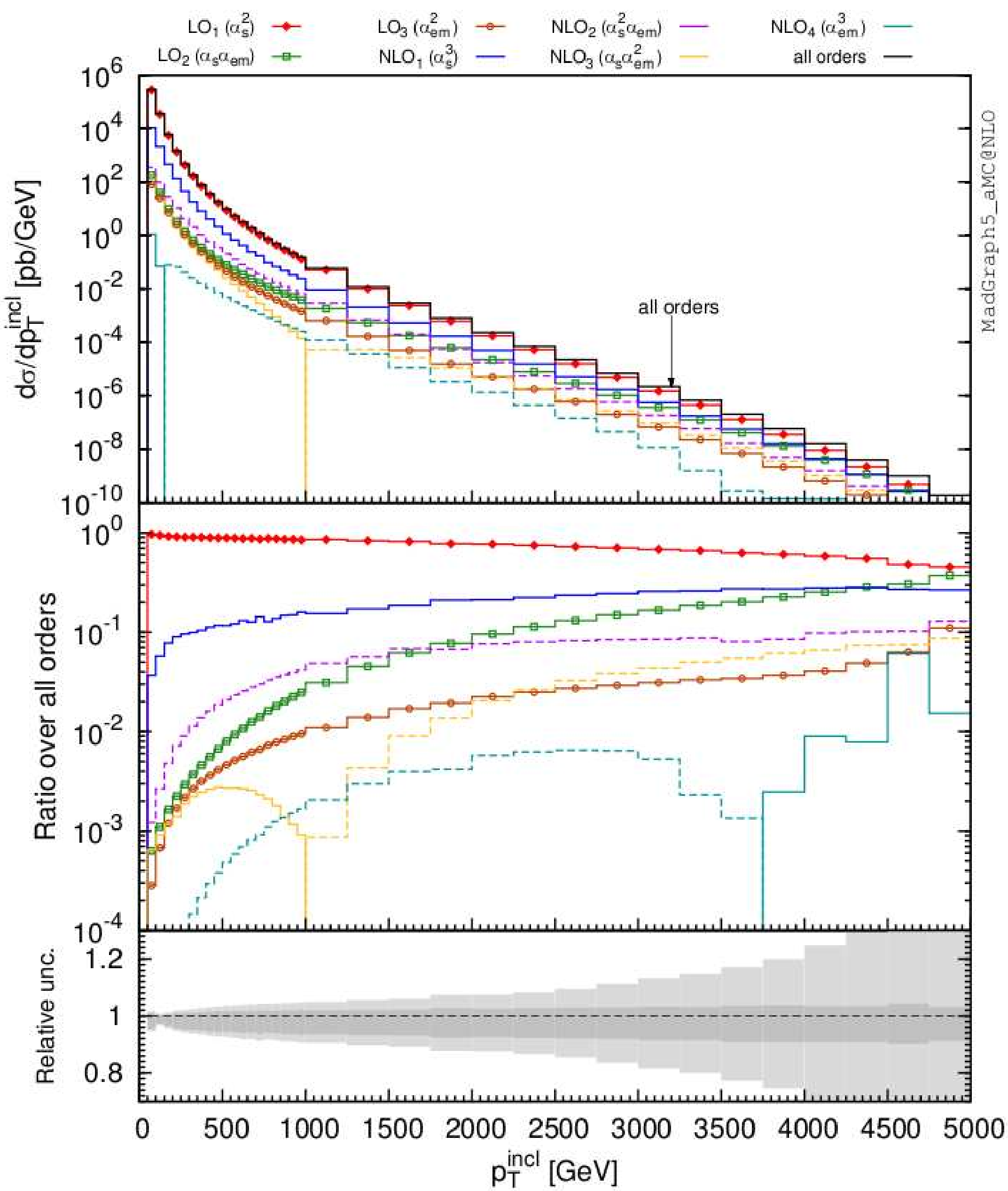
```
MG5_aMC> generate a b > c d e f QCD=n QED=m [QCD QED]
```

in order to include in the computation all the terms that factorise:

$$\text{LO} \qquad \alpha_S^k \alpha^p\,, \qquad k \le n\,, \qquad p \le m\,, \qquad k+p=b$$

$$\text{NLO} \qquad \alpha_S^k \alpha^p\,, \qquad k \le n+1\,, \qquad p \le m+1\,, \qquad k+p=b+1$$

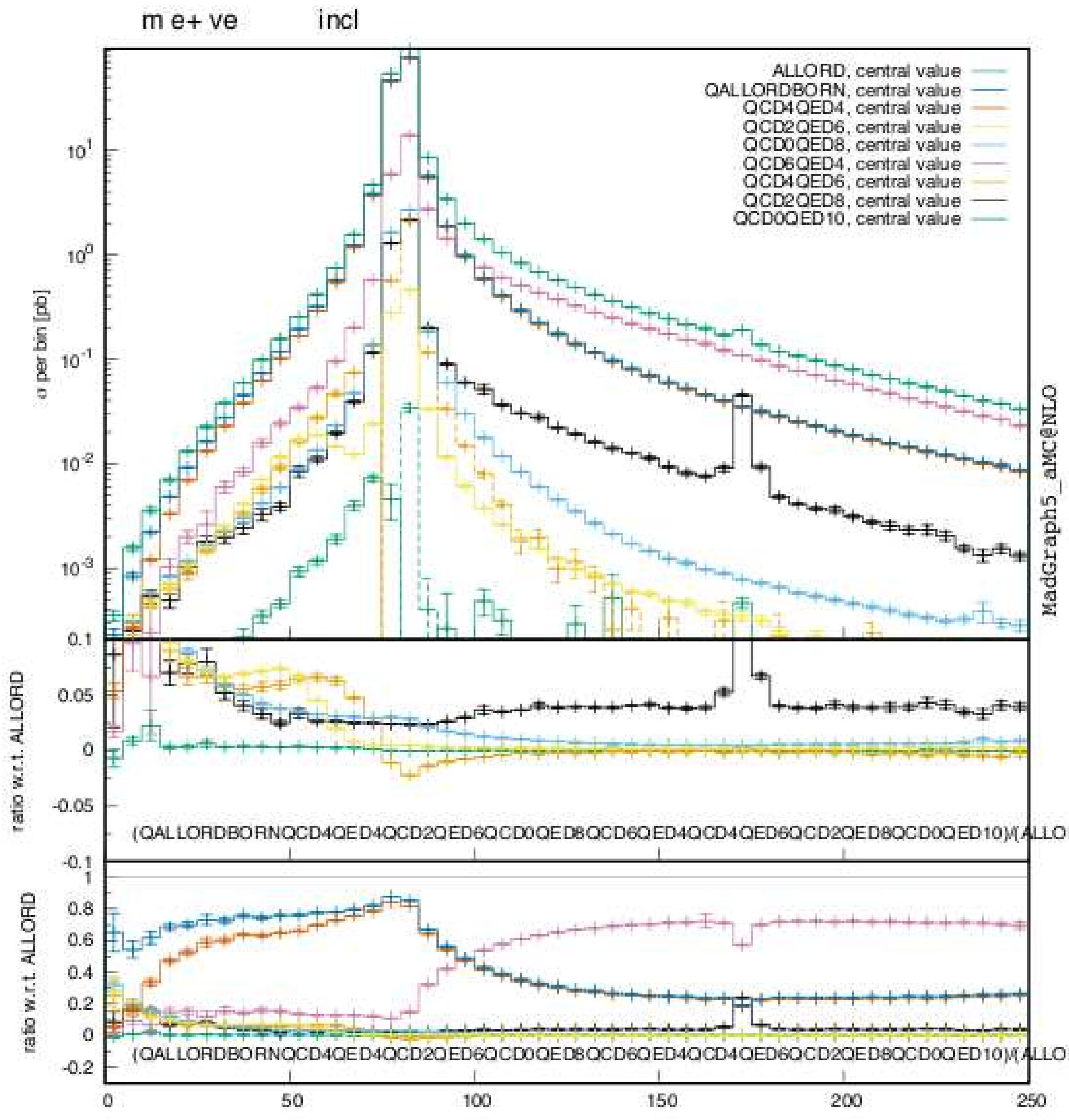
The capability of computing very suppressed terms seems an overkill, but there is a rule of thumb: if something can be computed, sooner or later it will turn out to be useful



Inclusive dijet p_T (1612.06548)

- Subleading LO and NLO have opposite signs. Eventually LO's grow faster than NLO's
- Owing to cancellations, both LO and NLO are necessary
- Significance of non-QCD effects increases with p_T
- So does PDF uncertainty – impact of photon is large but not dominant

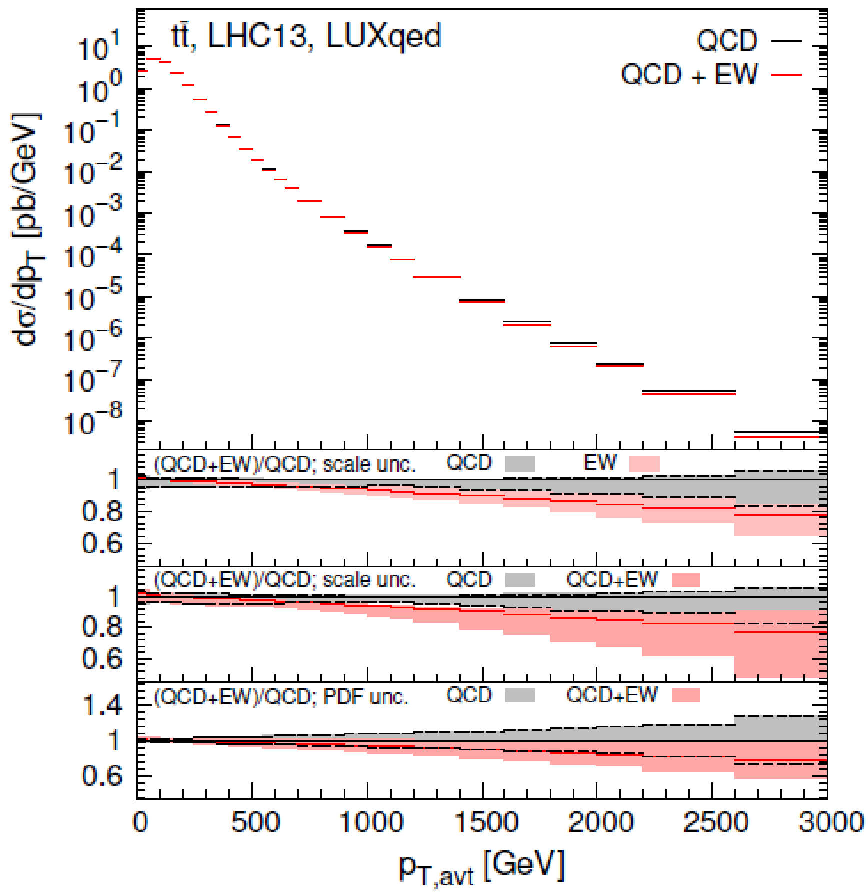
Preliminary: $W(\to e\nu_e)jj$ production



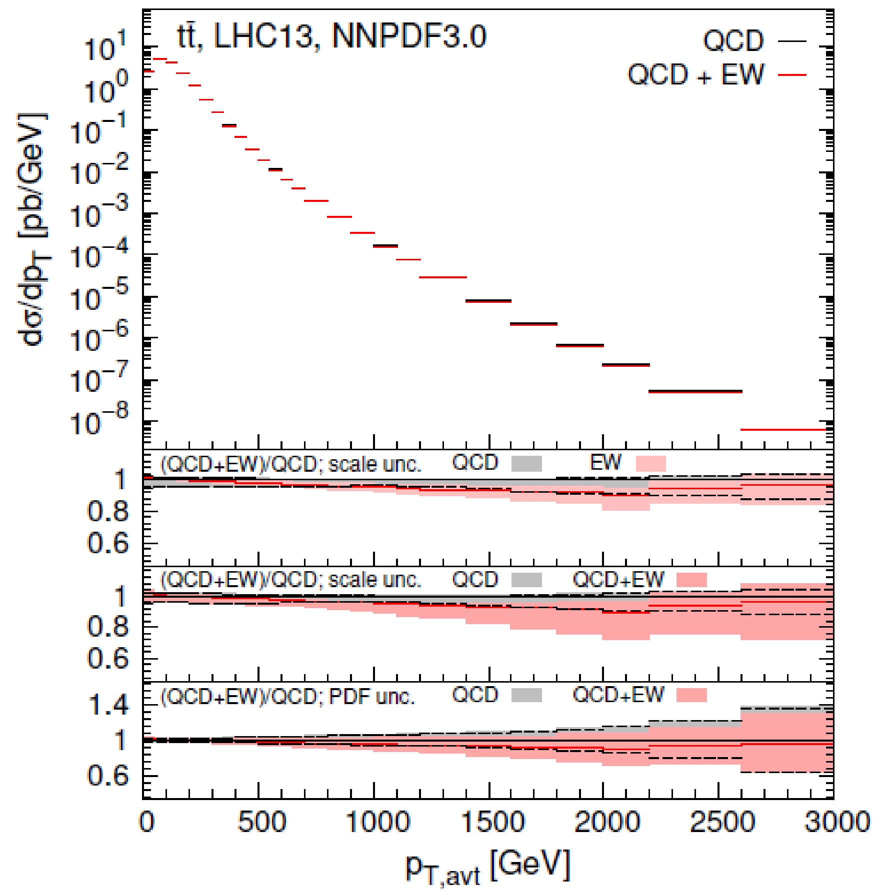
We are stress testing the code with many different processes, analogously to what was done for QCD corrections

13 TeV

$p_{T,\mathrm{avt}}$



LUXQED



NNPDF3.0QED

D. Pagani, at Louvain meeting

NNLO QCD + NLO EW

Underpinning all this: at fixed-order, we always work in $\overline{\mathrm{MS}}$-like schemes, with the assumption that:

> A photon is taggable (i.e. can be subject to physical cuts) only if it emerges from a fragmentation process

Thus:

- A fragmentation function (FF) $D_\gamma^{(a)}$ must be introduced for each possible $a \to \gamma$ "hadronisation", with a any "parton"
- Key: this includes $D_\gamma^{(\gamma)}$ for $\gamma \to \gamma$ (turns a short-distance photon into a taggable photon)

Similar ideas may be used for leptons (recycle stuff known in QCD)

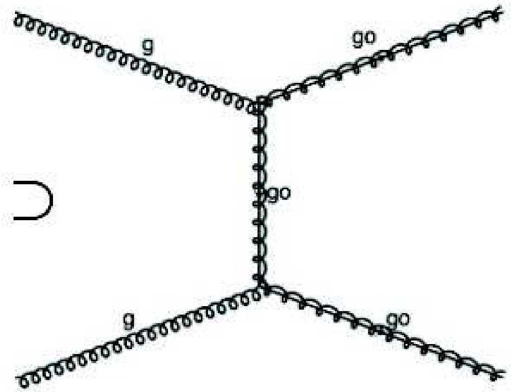
TOWARDS FULL MSSM@NLO

SUSY QCD for the QCD sector only is already available in
C. Degrande, B. Fuks, V. H., J. Proudom, H-S.Shao [arXiv:1510.00391]

- Gluinos pair production...

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

$\supset$

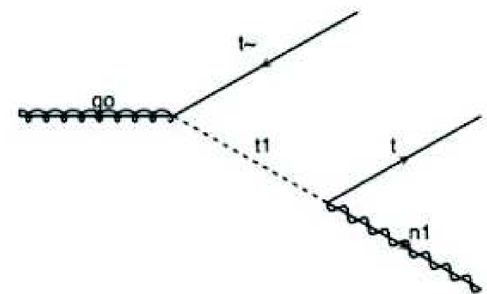


$\otimes$

- ... including the squark decay.

$$\mathcal{L}_{\rm decay} = \frac{i}{2} \bar{\chi} \not{\partial} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi$$
$$+ \sqrt{2} g' \Big[- \tilde{q}_L^\dagger Y_q (\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + \text{h.c.} \Big]$$

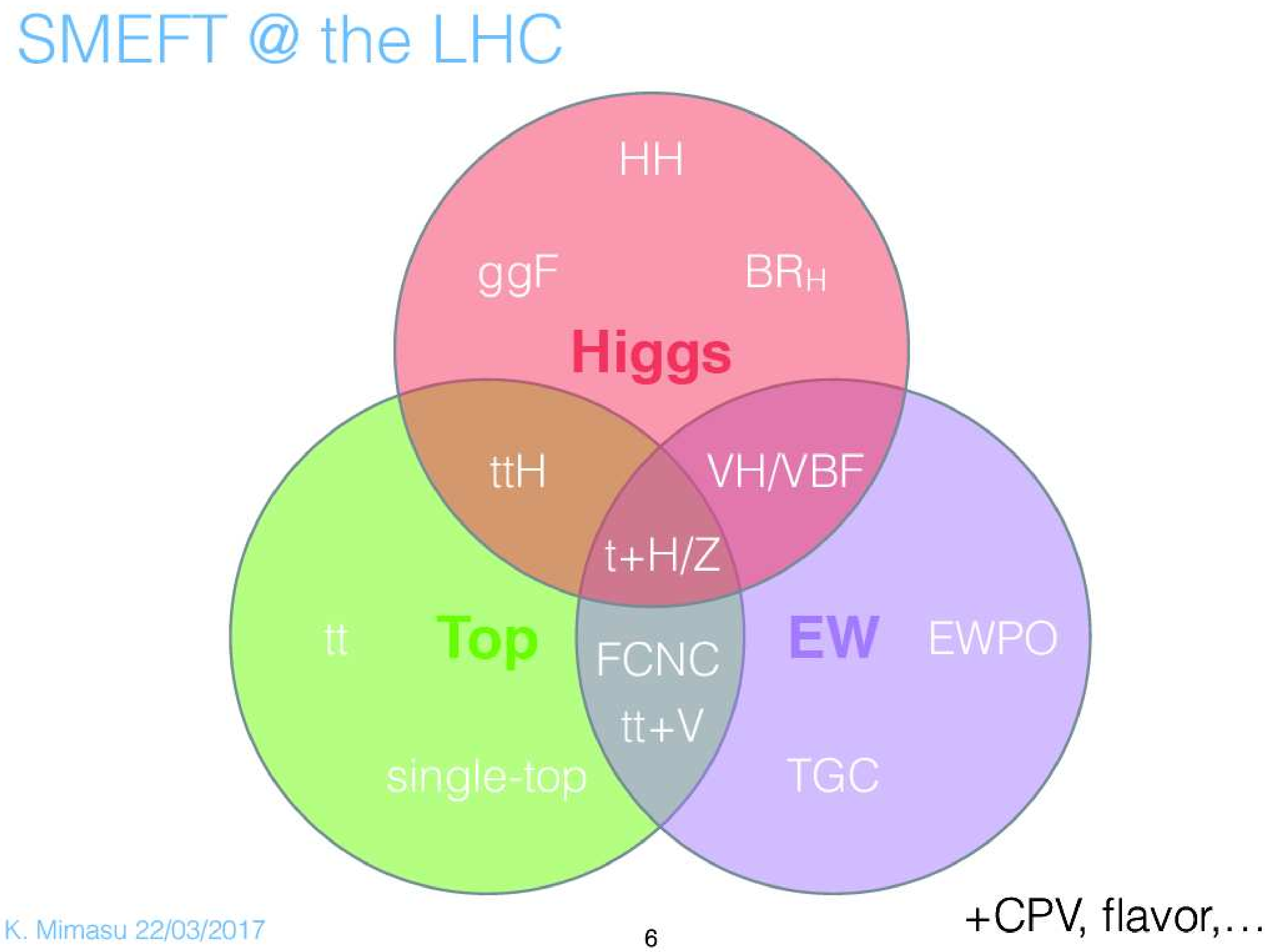
$\supset$



Majorana flow, top quark mixing matrix renorm, SUSY restoring CT: Solved.

EFTs

- Code-wise, just another BSM case: model construction is key
- Chief example: SMEFT, whose complete version is being prepared, but which has been extensively studied in several sub-sectors
- Final version most likely in Warsaw basis (bar 4-fermion operators)
- Largely irrelevant to the end user, who can translate inputs with the help of Rosetta



Steadily growing number of applications, especially in the top sector.
Usage does not require any particular expertise

[Degrande, Fuks, Mawatari, KM, Sanz; arXiv:1609.04833]

HELatNLO

http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

- SMEFT implementation in FeynRules + NLOCT framework
  - Generate NLO ready UFO file
  - Simulation performed with MadGraph5_aMC@NLO ~ any process!
  - First results for VBF in SMEFT @ NLO in QCD
- Includes 5 operators affecting Higgs couplings to W/Z/γ
  - First step for EW Higgs production
- Builds upon previous LO implementation of full SILH basis

  [Alloul, Fuks & Sanz; JHEP 1404 (2014) 110]
- Modification of EW parameters taken into account in the (m_Z, α_S, G_F) input scheme

In summary:

A lot of work is being done on NLO model construction.
Work in close contact with the authors (and bug them)

Plugins

`https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Plugin`

"...the plugin idea is to allow some modification of the code behaviour without the need to modify the core code"

So far:

- New output type (for LO processes)
- New cluster type
- Modification of the interface (new commands/modification of commands)

Development and maintainance are fully independent of MG5_aMC

Conclusions

- The code is too big for a single person to know it all: users are encouraged to submit questions through Launchpad

- Core features are still actively developed, but "beyond-NLO" stuff is receiving increasing attention

- Lots of interplay with model builders

- Non-LHC matters (e.g. MadDM, e^+e^-) are alive and kicking