News from MadGraph5_aMC@NLO

Rikkert Frederix
CERN theory group

HP2.5, GGI Florence, Italy, Sep. 5-7, 2014

MadGraph5_aMC@NLO

J. Alwall, RF, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H-S. Shao, T. Stelzer, P. Torrielli, M. Zaro
arXiv:1405.0301 [hep-ph]

- MadGraph5_aMC@NLO is an event generator framework for any LO and NLO (in QCD) computations
- Any process in the SM or BSM can be computed
  (for NLO: model file including UV (and R_2) counter terms need to be provided)
- Complexity of the process is only limited by available CPU power
  most 2->4 processes can be run on a modern desktop machine
- Matching to Herwig6/++ and Pythia6/8 partons showers is supported
- High level of automation

Level of automation

- NLO predictions are really as simple as:

Level of automation

- NLO predictions are really as simple as:

```
$ ./bin/mg5_aMC
```

Level of automation

- NLO predictions are really as simple as:

```
$ ./bin/mg5_aMC

MG5_aMC> generate p p > h h t t~ [QCD]
```

Level of automation

- NLO predictions are really as simple as:

```
$ ./bin/mg5_aMC
MG5_aMC> generate p p > h h t t~ [QCD]
MG5_aMC> output my_NLO_hhtt_process
```

Level of automation

- NLO predictions are really as simple as:

```
$ ./bin/mg5_aMC
MG5_aMC> generate p p > h h t t~ [QCD]
MG5_aMC> output my_NLO_hhtt_process
MG5_aMC> launch
```

In this talk

- Focus only on NLO computations
- Focus only on the code itself, not on any pheno with the code (see Eleni's talk tomorrow for a pheno example)
- I'll discuss some recent development
    - Some phase-space optimisation currently in use in the code
    - MG5_aMC + aMCfast + APPLgrid
- and some on-going developments
    - FxFx and UNLOPS merging with pythia8 and Herwig++
    - Towards EW corrections:
        - Better control over coupling orders
        - Improved phase-space in the context of (charged) resonances

Phase-space integration

- In the MG5_aMC phase-space integration, virtual corrections are integrated together with the real-emission corrections: this gives stabler results, with less negatively weighted events
- However, virtual corrections are slow. Even with OpenLoops technique (see Philipp's talk) for which we have an independent implementation in MadGraph5_aMC@NLO
- Hence, you do not want to include them for all phase-space points
- In MG5_aMC we use two ways of reducing the time spend in (already highly-optimised) virtual corrections:
  - Improved Monte Carlo sum over helicities
  - Approximate virtual corrections
- Both methods are used internally, and hidden from the user point of view

Improved MC over helicities for the virtual corrections

- Naive Monte-Carlo over helicities (i.e. randomly picking a single helicity per PS point) does not improve the speed of the code:
  - Fluctuations between PS points are greatly enhanced
  - Even including grids to pick the helicity configuration that give large contributions does not help much, because correlations between phase-space regions and importance of certain helicity configurations
  - Computing helicity summed matrix elements is not as slow as computing each helicity independently
- Solution: pick helicity at random for each PS point with probability based on the Born helicity configurations!
  - Fluctuations between PS points not larger than when explicitly summing over helicities
  - It is impossible that $|B_i|^2$ is zero, while $2\mathrm{Re}[V_i\, B_i^*]$ is not

Approximate virtuals

- **(Finite parts of the) virtual corrections are often numerically small**
  - Dynamically determine the fraction of PS points for which to include the virtual corrections
    - when including them, their weight is multiplied by the inverse of this fraction
  - Make sure that the integration uncertainty from the virtuals alone is always smaller than the uncertainty from everything else. This determines the minimal fraction
- **Sometimes virtuals are not small**, which means that we cannot significantly reduce the fraction of PS points for which we include them
  - Examples are Wbb, Zbb, ttbb, WWbb (It seems very much related to the 4F scheme, although single-top 4F seems an exception...)
  - But we can make the virtual small!
    - Virtuals are almost equal to a constant times the Born
    - Determine this constant dynamically and include this approximation for every phase-space point (very fast). The actual time consuming bit is the computation of the difference between the approximate and the exact virtual corrections, which is now small and needs to be computed only for a fraction of phase-space points
    - In fact, we don't use a single constant, but we setup a (coarse) grid to have some phase-space dependence in the constant

In practice:

MadGraph5 2.0.0beta3

```
Summary:
Process p p > t t~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 1.770e+02 +- 1.7e+00 pb
Ren. and fac. scale uncertainty: +13.5% -13.0%
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.16
Total running time : 12m 12s

DEBUG:
Number of loop ME evaluations: 168120
```

MadGraph5_aMC@NLO

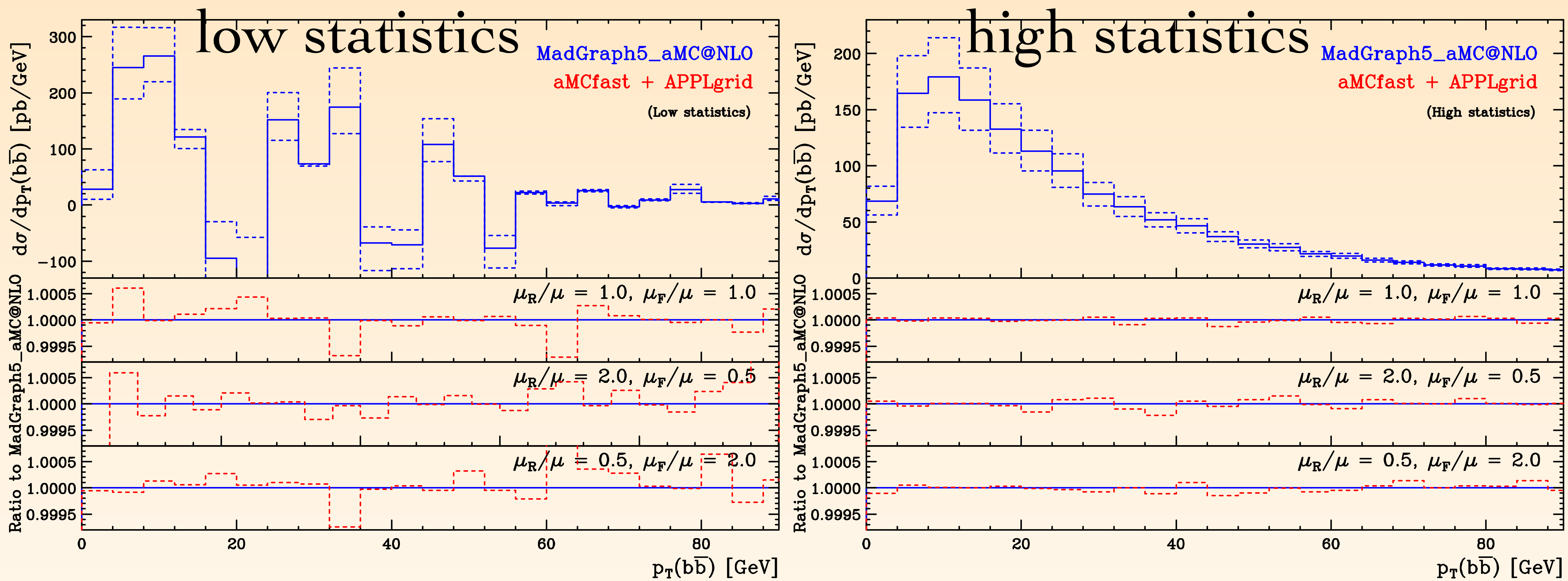
```
Summary:
Process p p > t t~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 1.765e+02 +- 9.2e-01 pb
Ren. and fac. scale uncertainty: +12.2% -12.3%
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.16
Total running time : 1m 35s

DEBUG:
Number of loop ME evaluations (by MadLoop): 6967
```

- This time includes the process generation, the grid setup, etc.
- Already for simple processes a big gain in computing time, gain is even more significant for more complicated processes

PDF fitting

- For PDF fitting the (N)NLO computation needs to be many orders of magnitude faster still: one needs to be able to compute a cross section for any PDF set (and ren/fac scale) thousands of times
- Solution: parametrise the cross section for each bin of each histogram —stripped from PDF and scale dependence— in the form of look-up tables
  - Available packages FastNLO and APPLgrid
- aMCfast is an interface between MG5_aMC and APPLgrid
  [V. Bertone, RF, S. Frixione, J. Rojo, M. Sutton, arXiv:1406.7693]
  - Works for any process, and can be directly steered from the usual run_card file
  - Available in the next release v2.2.0 (within a couple of weeks)

MadGraph5_aMCatNLO + aMCfast + APPLgrid

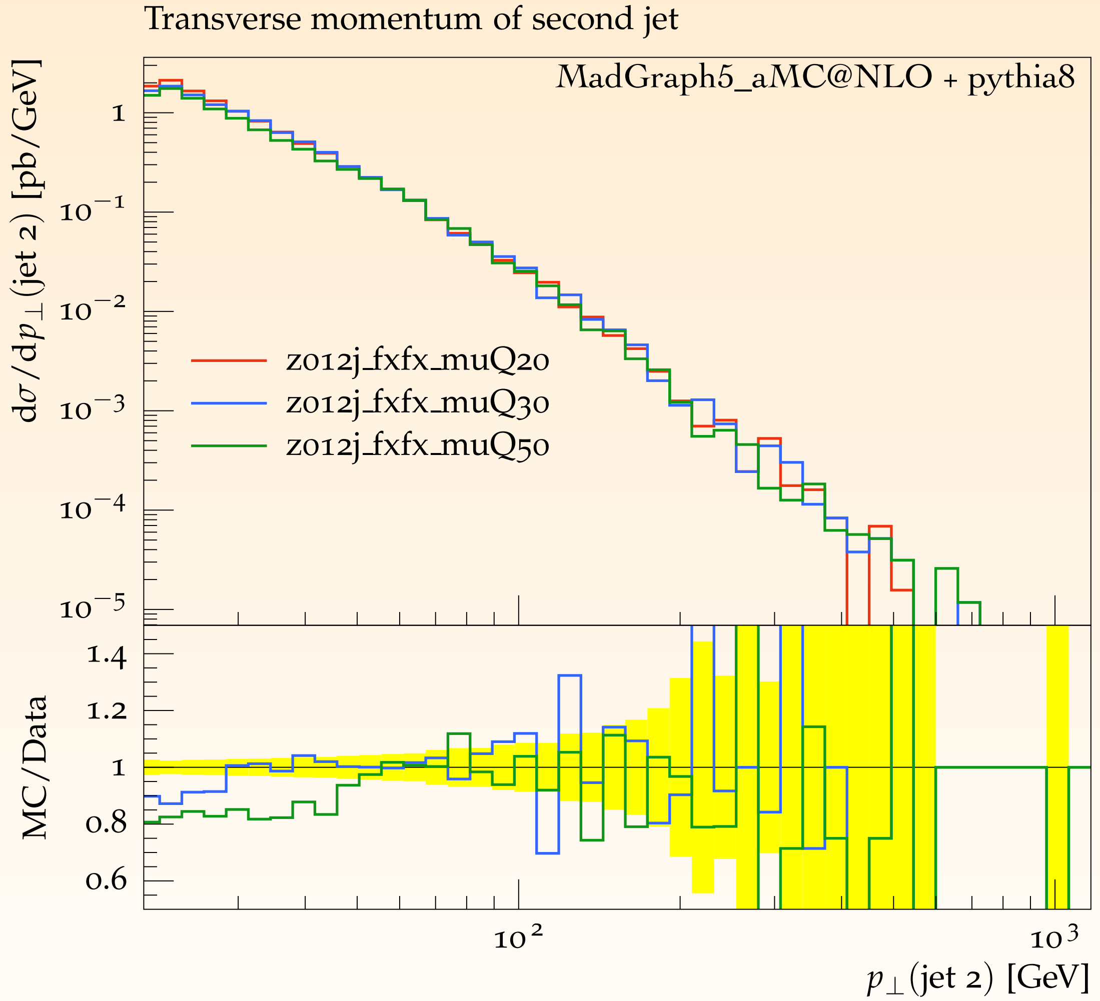


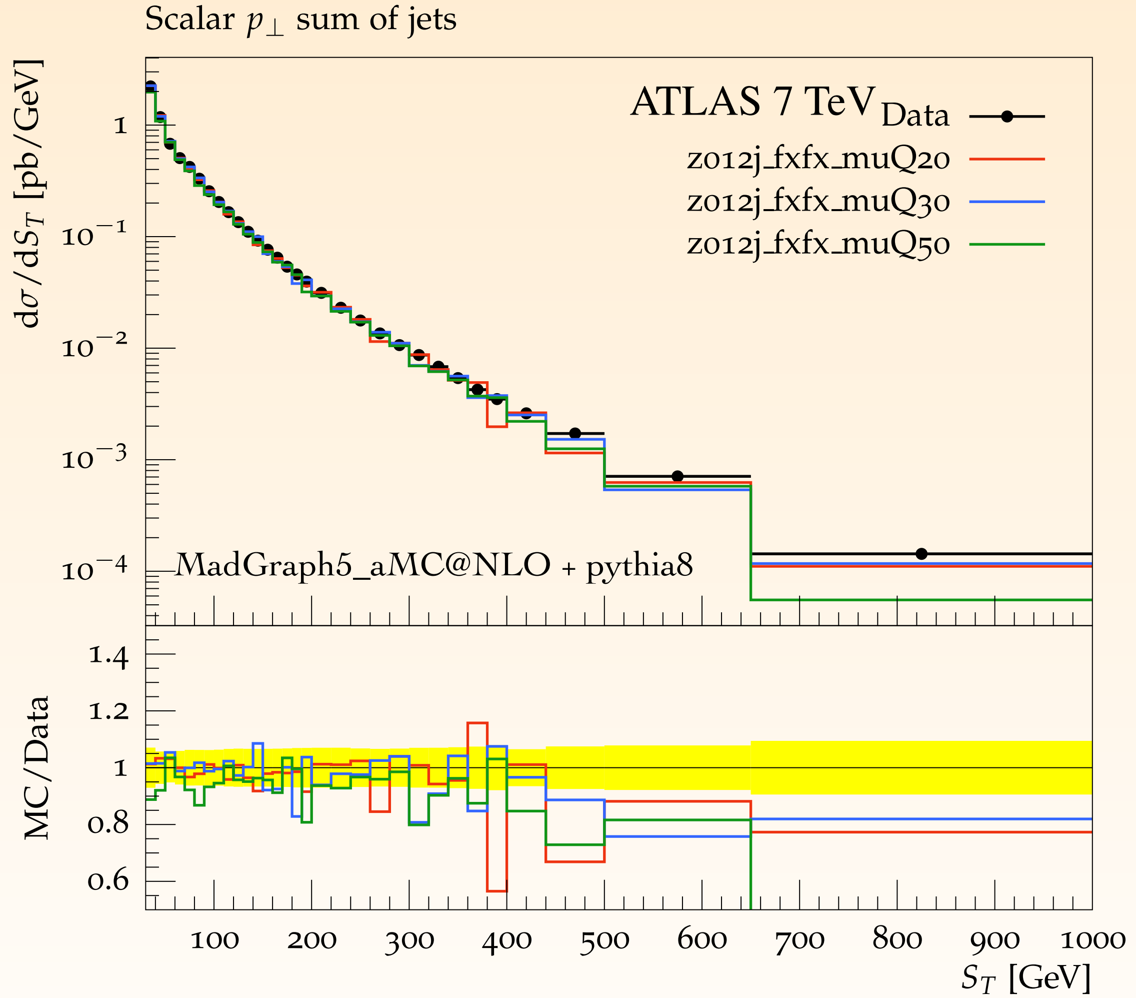
- Transverse momentum distributions of the bbbar pair in Zbb production
- Difference between reconstructed observables from the APPLgrid look-up tables and original run below the per mille level
- Next steps: can this also be done for NLO+PS? Do we need PDF sets fitted using NLO+PS predictions?

FxFx & UNLOPS merging

[In collaboration with S. Prestel and A. Papaefstathiou]

- FxFx and unlops merging: combining matrix elements of various multiplicities at NLO consistently with the parton shower
- Main difference with UNLOPS is that the total inclusive cross section does not change when including the higher multiplicity matrix elements



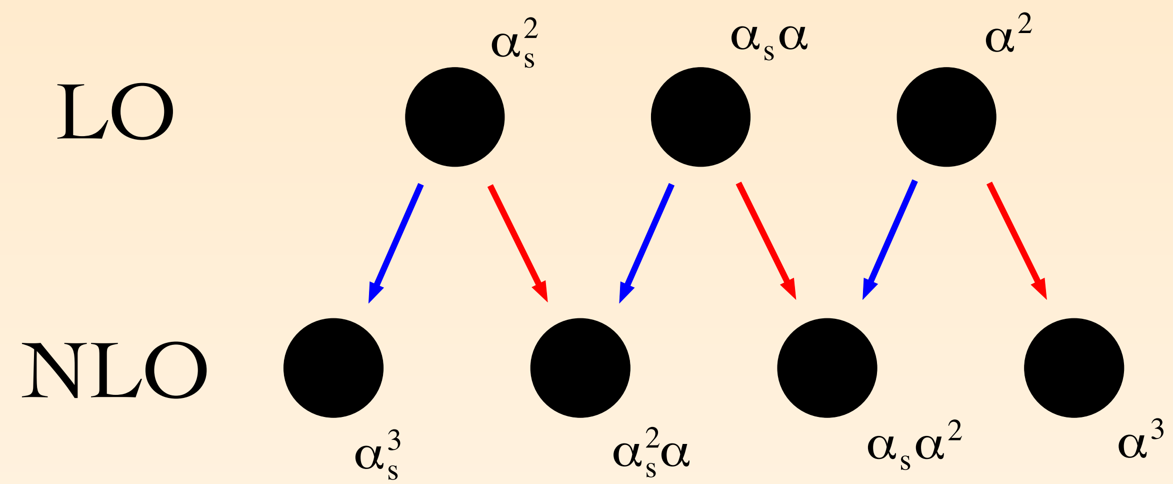


- Next release v2.2.0: support for FxFx merging with pythia8 and Herwig++, and unlops merging with pythia8

Towards automation of EW corrections

Which NLO corrections?

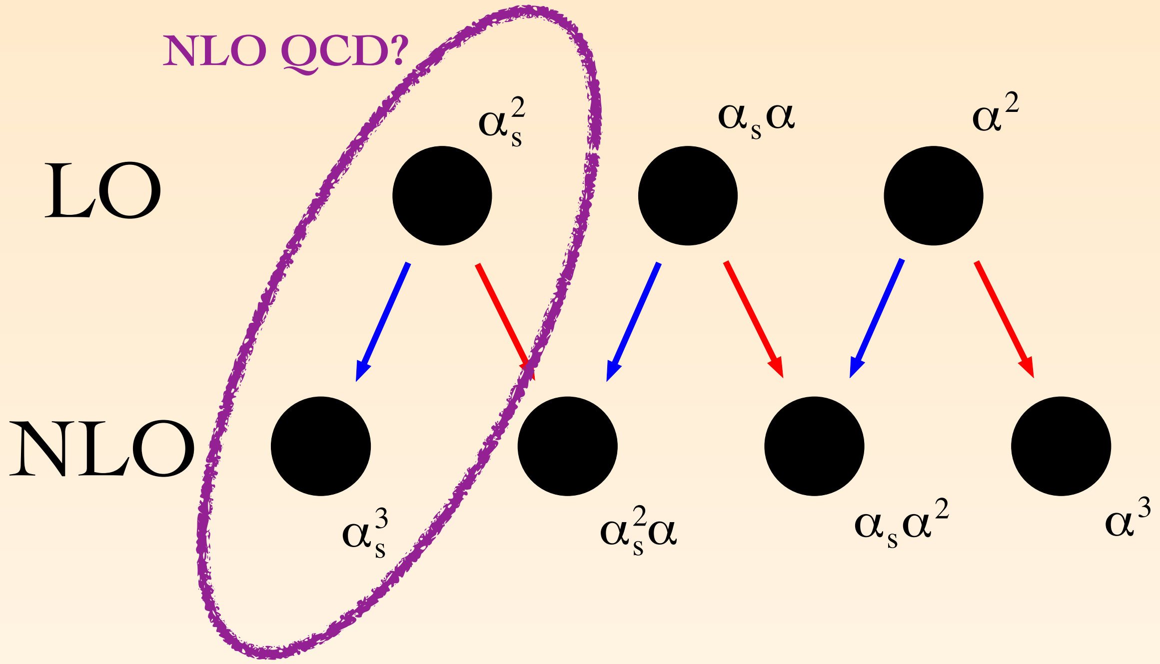
- Consider, for example, di-jet production



- Blue lines: QCD corrections; Red lines: EW corrections?
- QCD and EW NLO cannot be disentangled (**except for the two extremes**)
- In MadGraph5_aMC@NLO, work in process is to get separate matrix elements and cross sections for each of the black circles, including proper cancelation of IR singularities in intermediate results, recycling intermediate results as much as possible, etc.
  - Tricky bookkeeping…

Which NLO corrections?

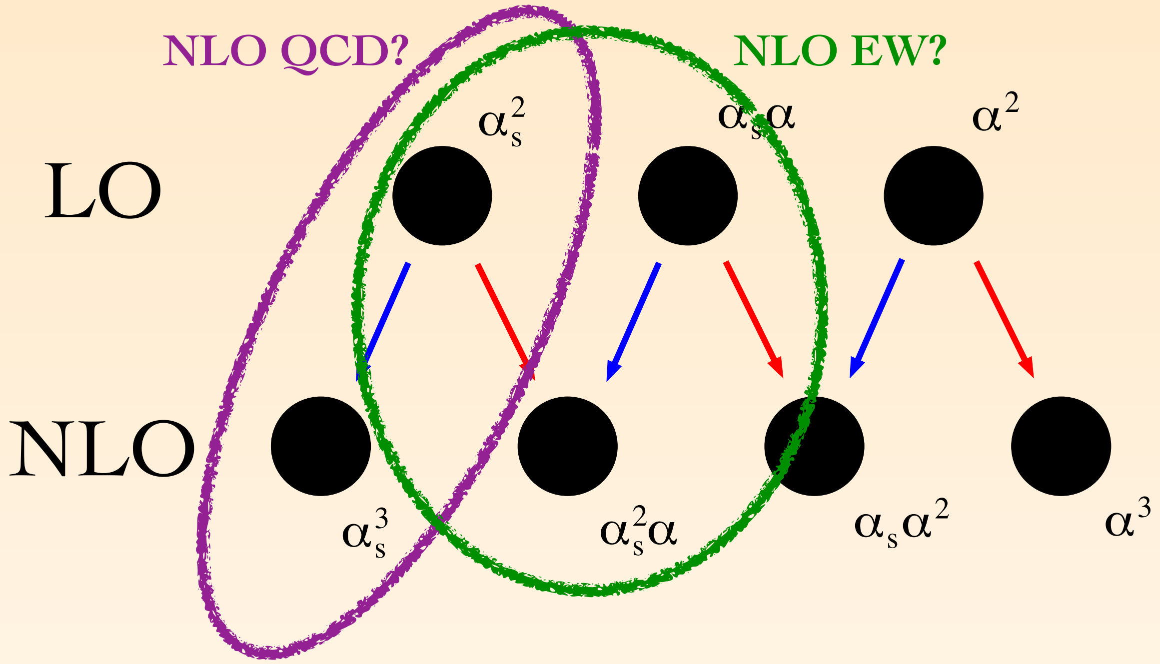
- Consider, for example, di-jet production



- Blue lines: QCD corrections; Red lines: EW corrections?
- QCD and EW NLO cannot be disentangled (**except for the two extremes**)
- In MadGraph5_aMC@NLO, work in process is to get separate matrix elements and cross sections for each of the black circles, including proper cancelation of IR singularities in intermediate results, recycling intermediate results as much as possible, etc.
  - Tricky bookkeeping…

Which NLO corrections?

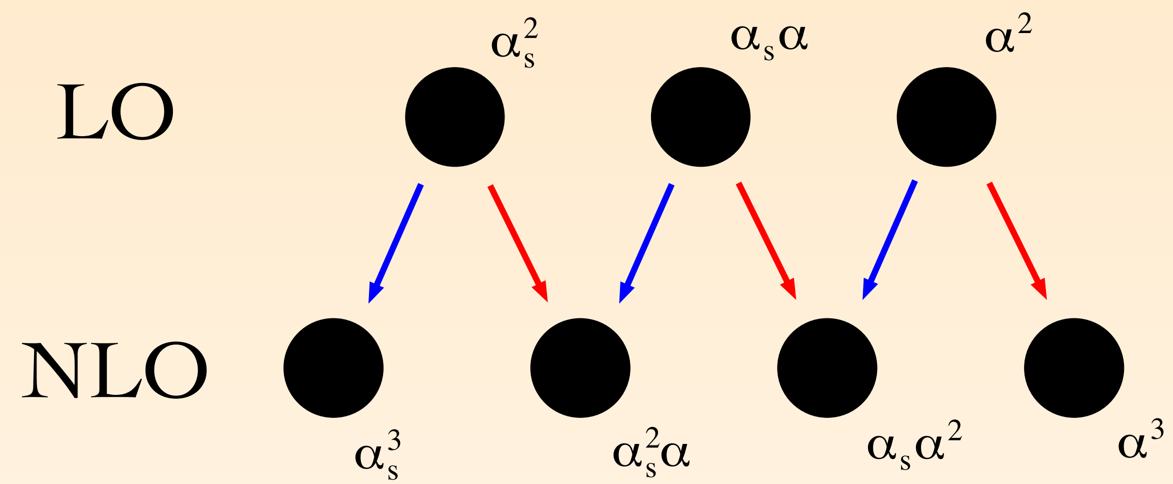
- Consider, for example, di-jet production



- Blue lines: QCD corrections; Red lines: EW corrections?
- QCD and EW NLO cannot be disentangled (**except for the two extremes**)
- In MadGraph5_aMC@NLO, work in process is to get separate matrix elements and cross sections for each of the black circles, including proper cancelation of IR singularities in intermediate results, recycling intermediate results as much as possible, etc.
  - Tricky bookkeeping…

Which NLO corrections?

- Consider, for example, di-jet production



- Blue lines: QCD corrections; Red lines: EW corrections?
- QCD and EW NLO cannot be disentangled (**except for the two extremes**)
- In MadGraph5_aMC@NLO, work in process is to get separate matrix elements and cross sections for each of the black circles, including proper cancelation of IR singularities in intermediate results, recycling intermediate results as much as possible, etc.
  - Tricky bookkeeping…

Phase-space mapping

- When including photon radiation, the default FKS phase-space mapping is not ideal in the case of resonances that are charged, or their decays products are charged
  - In this case, invariants are not fixed between events and counter-events, leading to large fluctuations when the width is small
  - CS dipoles have similar problem, although less severe: more invariants are kept fixed
- Similar problem also for QCD in the case top quarks and decays. So far dealt with using brute force: single top A. Papanastasiou et al. arXiv:1305.7088, top pairs RF arXiv:1311.4893
- Easy to fix in the narrow width approximation, because no talk between production and decay. Hence, for decays, one can use the usual FKS mapping, but in the rest-frame of the resonance (instead of the CM frame)
- Beyond the narrow width approx, there is no separation between production and decay
- Need an improved mapping that keeps more invariants fixed

Putting it together

- EW corrections are not more complicated than QCD corrections: all techniques developed for QCD can be directly applied to EW (OPP, OpenLoops, FKS, CS, MC@NLO method, etc.)
- However, a general implementation is non-trivial
  - mixed QCD/EW corrections
  - book keeping is very tricky
  - phase-space mapping is non-trivial
- Hence, a full implementation will still need some work…

Conclusions

- NLO QCD, including matching to the parton shower, well-established and fully implemented in MadGraph5_aMC@NLO for any process
- Methods for merging & matching matrix elements with various multiplicities consistently to the shower (e.g. FxFx and unlops merging) are established, but surprises might still show-up
  - Improvements still possible
  - Comparison study between FxFx and unlops with pythia8 and herwig++ is underway
- Next major step in the MadGraph5_aMC@NLO code is implementation of EW corrections (or better: NLO corrections in any coupling constant)
  - Work has started, but still a lot needs to be done