Status of aMC@NLO

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NLOwPS

- Experimentalists love the general purpose parton shower programs: Pythia, Herwig and Sherpa
  - With MLM or CKKW matching, they give a very good description of (shapes of) distributions in large regions of phase-space
  - Hadronization models well-tuned to data
    - Completely exclusive description of final state that can serve as input to a detector simulation
- However, they are LO predictions, which means that they describe rates rather poorly; lack the possibility for a reliable PDF uncertainty estimate; etc

NLOwPS: INGREDIENTS

- The three ingredients to NLOwPS event generation are
  - Virtual amplitudes: compute the loops automatically in a reasonable amount of time
  - How to deal with infra-red divergences and phase-space integration in an efficient way: virtual corrections and real-emission corrections are separately divergent and only their sum is finite (for IR-safe observables) according to the KLN theorem
  - The matching of these processes to a parton shower without double counting
- All three implemented in the automatic `aMC@NLO` package

Virtual corrections

- MadLoop [Hirschi, RF, Frixione, Garzelli, Maltoni, Pittau (2011)] uses the OPP method [Ossola, Papadopoulos & Pittau (2006)] as implemented in CutTools [Ossola, Papadopoulos & Pittau (2007)] to compute virtual contributions from tree-level diagrams
- Based on setting up a system of linear equations to find the coefficients in front of the basis of scalar integrals by sampling the integrand
- Needs special treatment to get also the rational term
- Completely general (and numerical) method

Factoring IR poles

- The MadFKS [RF., Frixione, Maltoni & Stelzer (2009)] code uses the FKS subtraction scheme [Frixione, Kunszt, Signer (1995)] to factor the soft and collinear poles from the phase-space integrals and cancel them against the poles from the virtual corrections
- Based on splitting the phase-space integrals in regions in which there is (maximally) one collinear and one soft divergence
- Allows for optimized numerical phase-space integration
- Parallel in nature: can make use of many CPUs simultaneously to speed-up the calculation
- Process independent

Parton-level NLO results

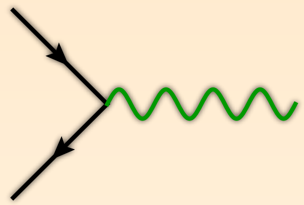
[RF., Frixione, Maltoni & Stelzer (2009)]

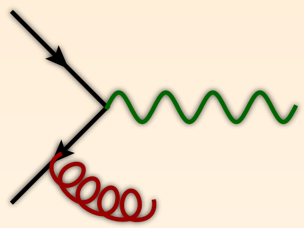
- Results with MadFKS +MadLoop
- Errors are the MC integration uncertainty only
- Cuts on jets, γ*/Z decay products and photons, but no cuts on b quarks (their mass regulates the IR singularities)
- Efficient handling of exceptional phase-space points
- Running time: two weeks on ~150 node cluster leading to rather small integration uncertainties
- MadFKS+MadLoop results are fully differential in the final states (but only parton-level)

	Process	μ	n_{lf}	Cross section (pb) LO	Cross section (pb) NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

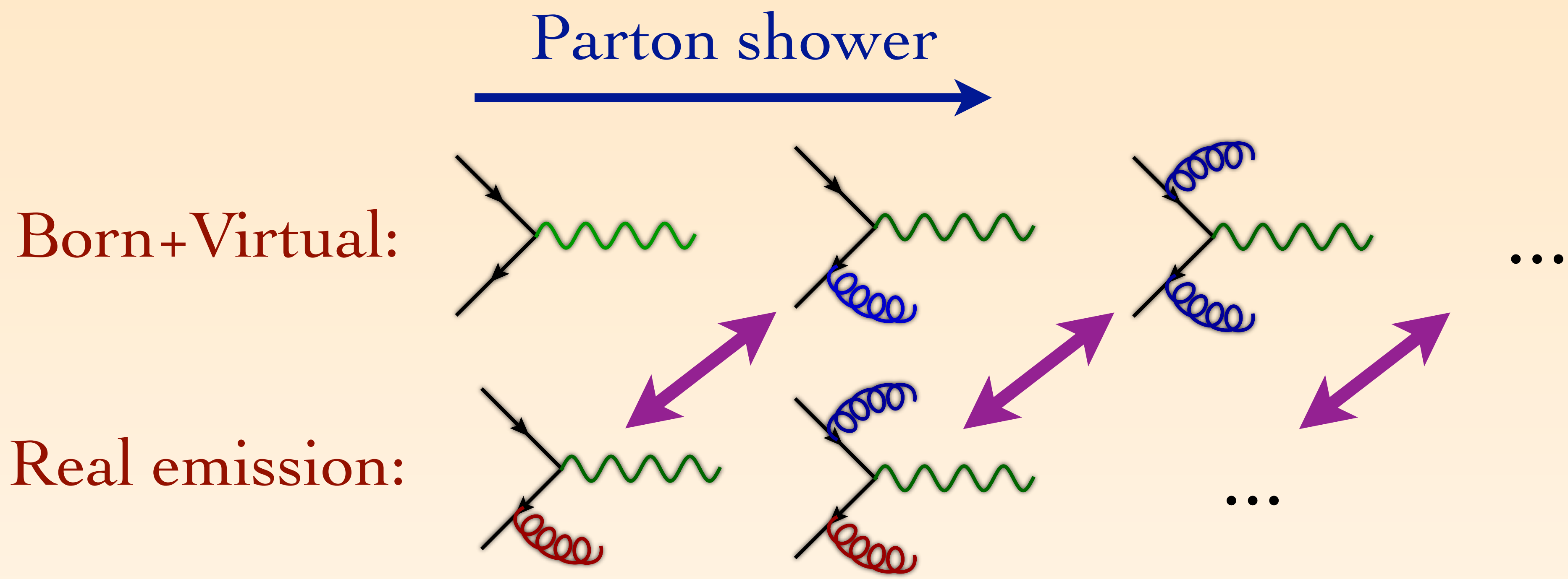
Matching to the Parton Shower

Parton shower

Born+Virtual: 

Real emission: 

Matching to the Parton Shower



- There is double counting between the real emission matrix elements and the parton shower: the extra radiation can come from the matrix elements or the parton shower
- There is also an overlap between the virtual corrections and the Sudakov suppression in the zero-emission probability

Double counting in virtual/Sudakov

- The Sudakov factor Δ (which is responsible for the resummation of all the radiation in the shower) is the no-emission probability
- It's defined to be $\Delta = 1 - P$, where P is the probability for a branching to occur
- By using the conservation of probability in this way, Δ contains contributions from the virtual corrections implicitly
- Because at NLO the virtual corrections are already included via explicit matrix elements, Δ is double counting with the virtual corrections
- In fact, because the shower is unitary, what we are double counting in the real emission corrections is exactly equal to what we are double counting in the virtual corrections (but with opposite sign)!

MC@NLO procedure

[Frixione & Webber (2002)]

- To remove the double counting, apply the MC@NLO procedure: add and subtract the same term to the m and m+1 body configurations

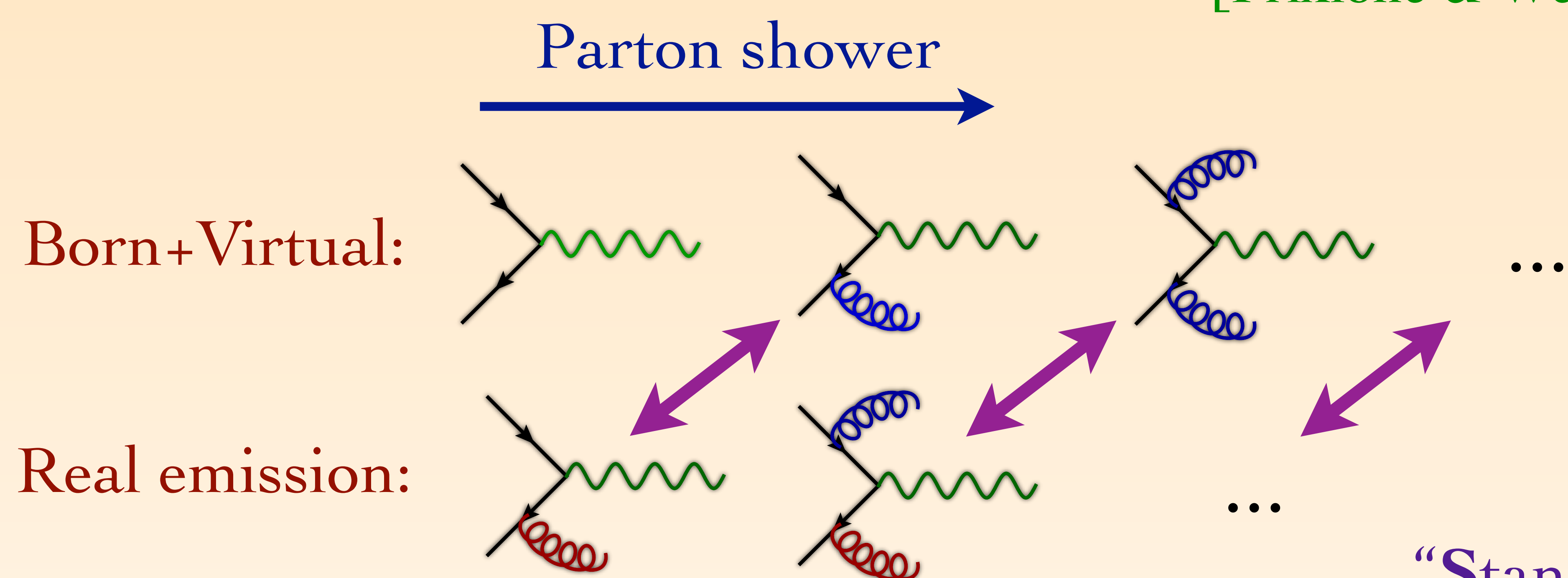
$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right)\right] \mathcal{F}_{\mathrm{MC}}^{(m)} + \left[d\Phi_{m+1}(R - MC)\right] \mathcal{F}_{\mathrm{MC}}^{(m+1)}$$

Where the *MC* are defined to be the contribution of the parton shower to get from the m body Born final state to the m+1 body real emission final state

- The POWHEG method [Nason (2004)] is another method to remove the double counting by applying an inclusive NLO correction to a given Born PS point, and adjusting the first MC emission to correspond to the (Sudakov suppressed) real-emission matrix elements

MC@NLO procedure

[Frixione & Webber (2002)]



$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right)\right] \mathcal{F}_{\mathrm{MC}}^{(m)}$$

"Standard event"

$$+ \left[d\Phi_{m+1} (R - MC) \right] \mathcal{F}_{\mathrm{MC}}^{(m+1)}$$

"Hard event"

- Double counting is explicitly removed by including the "Monte Carlo subtraction terms"

Current status of MC subtraction

- The MC subtraction terms are Shower Monte Carlo specific: each partons shower needs different subtraction terms
- Current status of `aMC@NLO` is
  - aMC@NLO/Herwig6: working and fully tested
  - aMC@NLO/Pythia6 (Q^2-ordered): working and well-tested
  - aMC@NLO/Pythia6 (p_T-ordered): initial state implemented, final state is work in progress. High priority
  - aMC@NLO/Pythia8: initial state implemented, final state is work in progress. High priority
  - aMC@NLO/Herwig++: all implemented but final state needs still validation. Lower priority

MC@NLO properties

- Good features of including the subtraction counter terms

  1. **Double counting avoided**: The rate expanded at NLO coincides with the **total NLO cross section**

  2. **Smooth matching**: MC@NLO coincides (in shape) with the parton shower in the soft/collinear region, while it agrees with the NLO (i.e. real-emission) in the hard region

  3. **Stability**: weights associated to different multiplicities are separately finite. The *MC* term has the same infrared behavior as the real emission, and allows for the generation of **unweighted events**

- Not so nice feature (not so much of the method, but of the parton shower one is matching to):

  1. **Parton shower is approximate even in the soft/collinear region**: In general the parton shower is only correct up to leading color and is averaged over the helicity of the parton branching. To correctly cancel all singularities, the *MC* terms need to be slightly generalized which might lead to some left-over double counting. **In practice no effects seen here**

We still need FKS subtraction

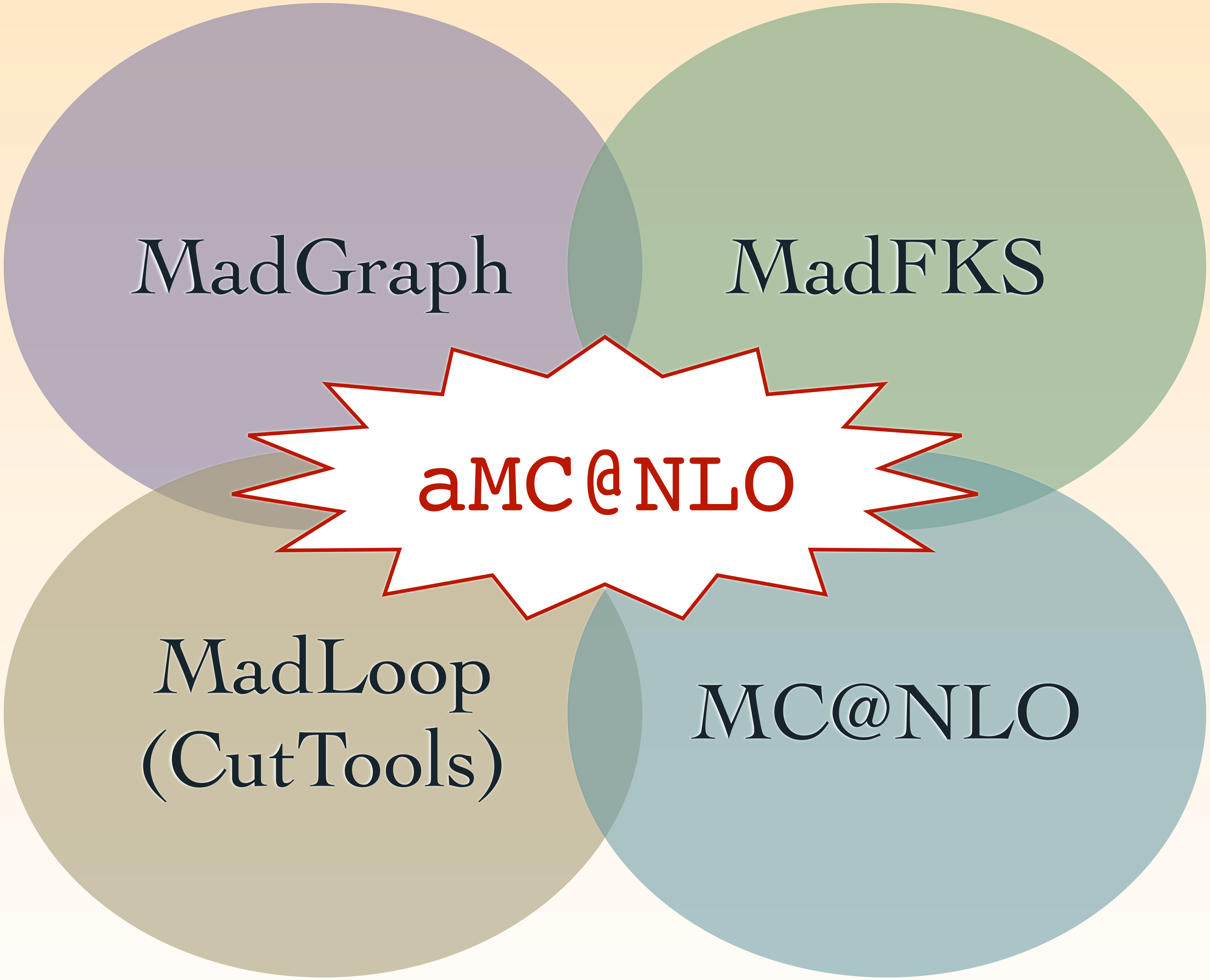
$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right)\right] I_{\mathrm{MC}}^{(m)}(O) \quad + \left[d\Phi_{m+1}(R - MC)\right] I_{\mathrm{MC}}^{(m+1)}(O)$$

- We cannot do the one-particle integral over the *MC* terms analytically. To factorize the poles and cancel them to the explicit poles in the virtual corrections, we use the FKS subtraction, A^{FKS}

$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \left[d\Phi_m \left(B + \left(\int_{\mathrm{loop}} V + \int d\Phi_1 A^{\mathrm{FKS}}\right) + \int d\Phi_1 \left(MC - A^{\mathrm{FKS}}\right)\right)\right] I_{\mathrm{MC}}^{(m)}(O)$$
$$+ \left[d\Phi_{m+1}(R - MC)\right] I_{\mathrm{MC}}^{(m+1)}(O)$$

- In general, the MC is approximate even in the soft/collinear region (due to leading color, average over helicities). Approximate the *MC* terms by the exact FKS subtraction terms A^{FKS} very close to the limit

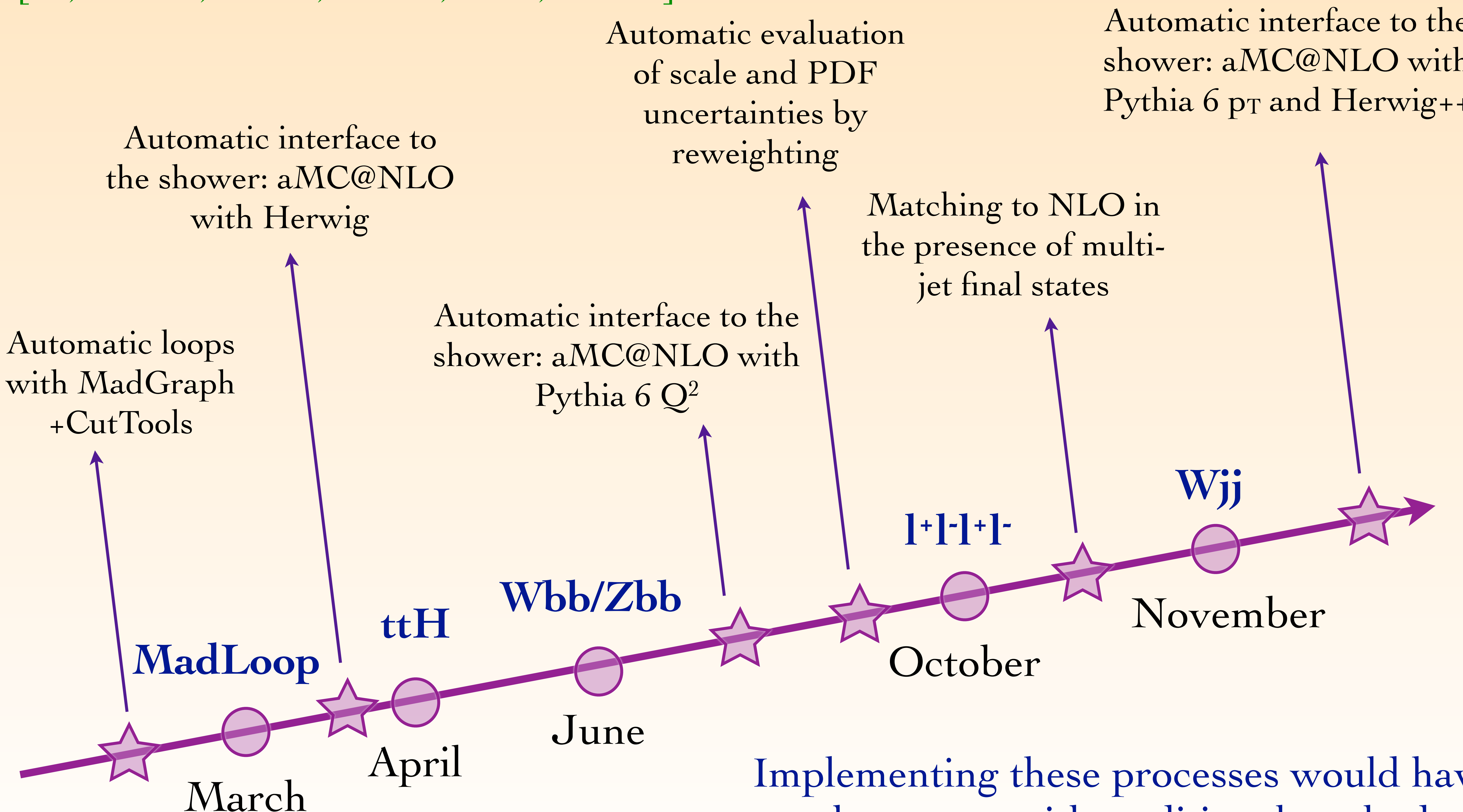
The aMC@NLO code



http://amcatnlo.cern.ch

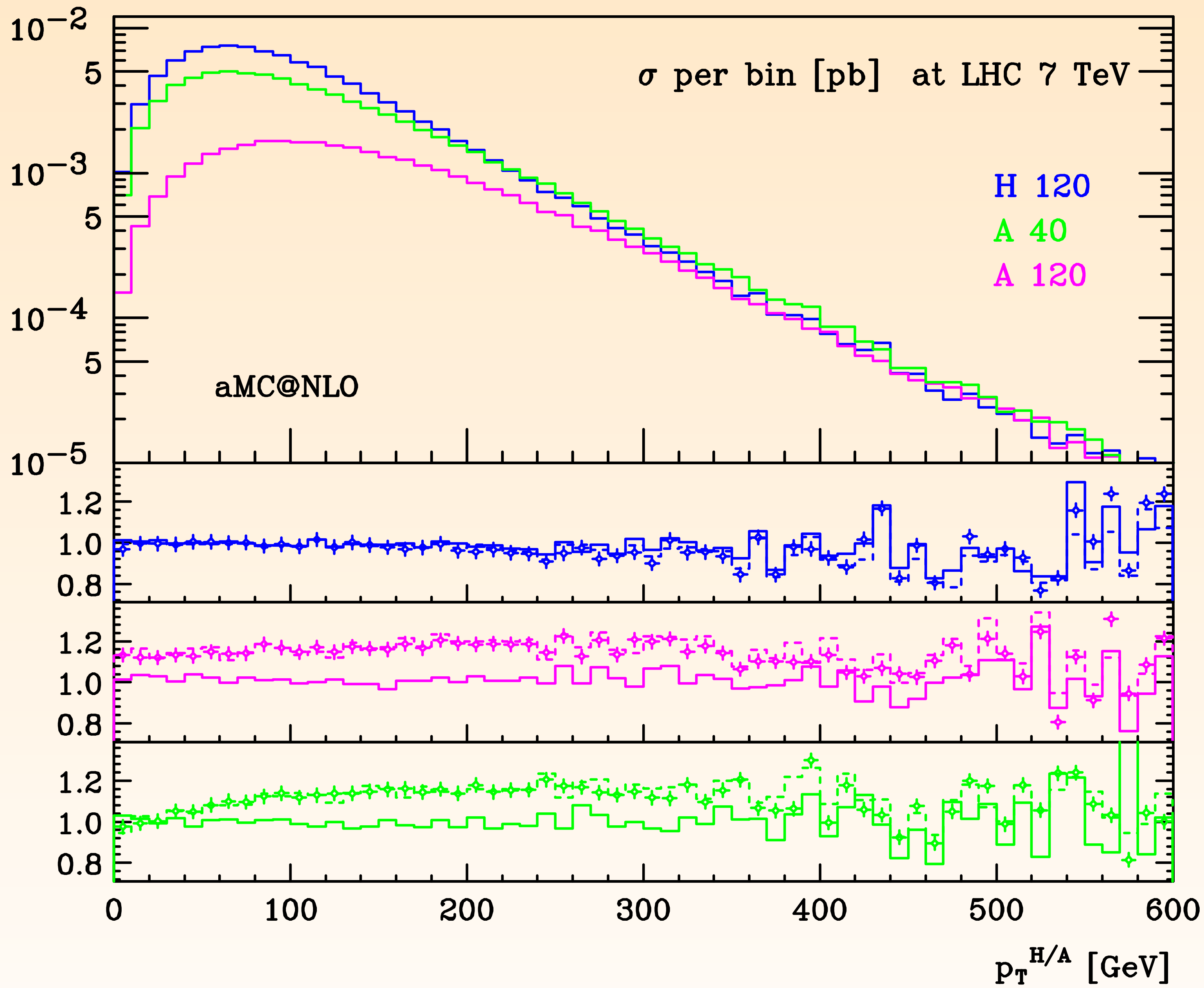
aMC@NLO: year 2011

[RF, Frixione, Hirschi, Maltoni, Pittau, Torrielli]



Implementing these processes would have taken years with traditional methods

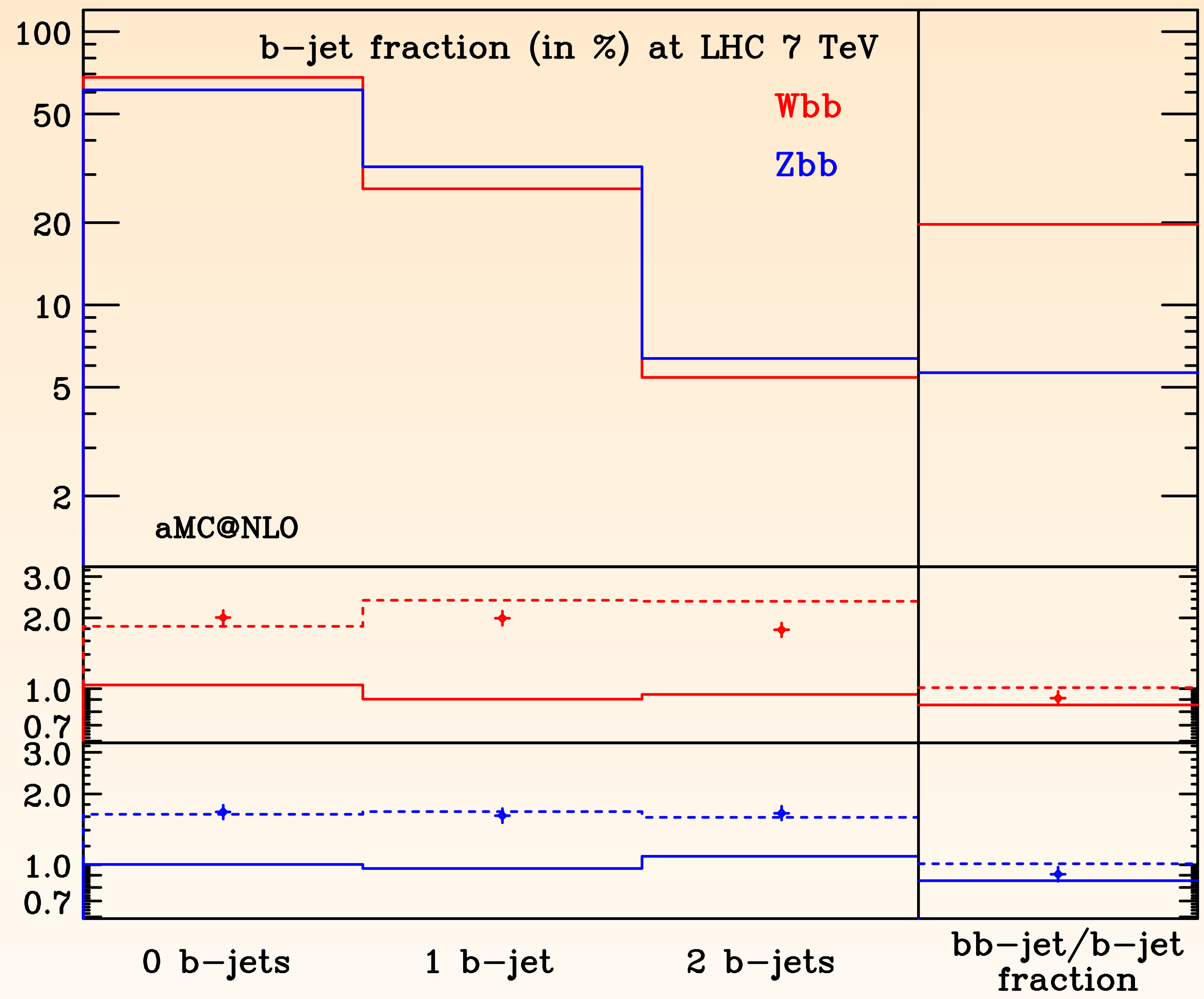
Higgs boson production in association with a top pair



- Boosted Higgs scenario works also for pseudo-scalar Higgs bosons

arXiv:1104.5613 [hep-ph]

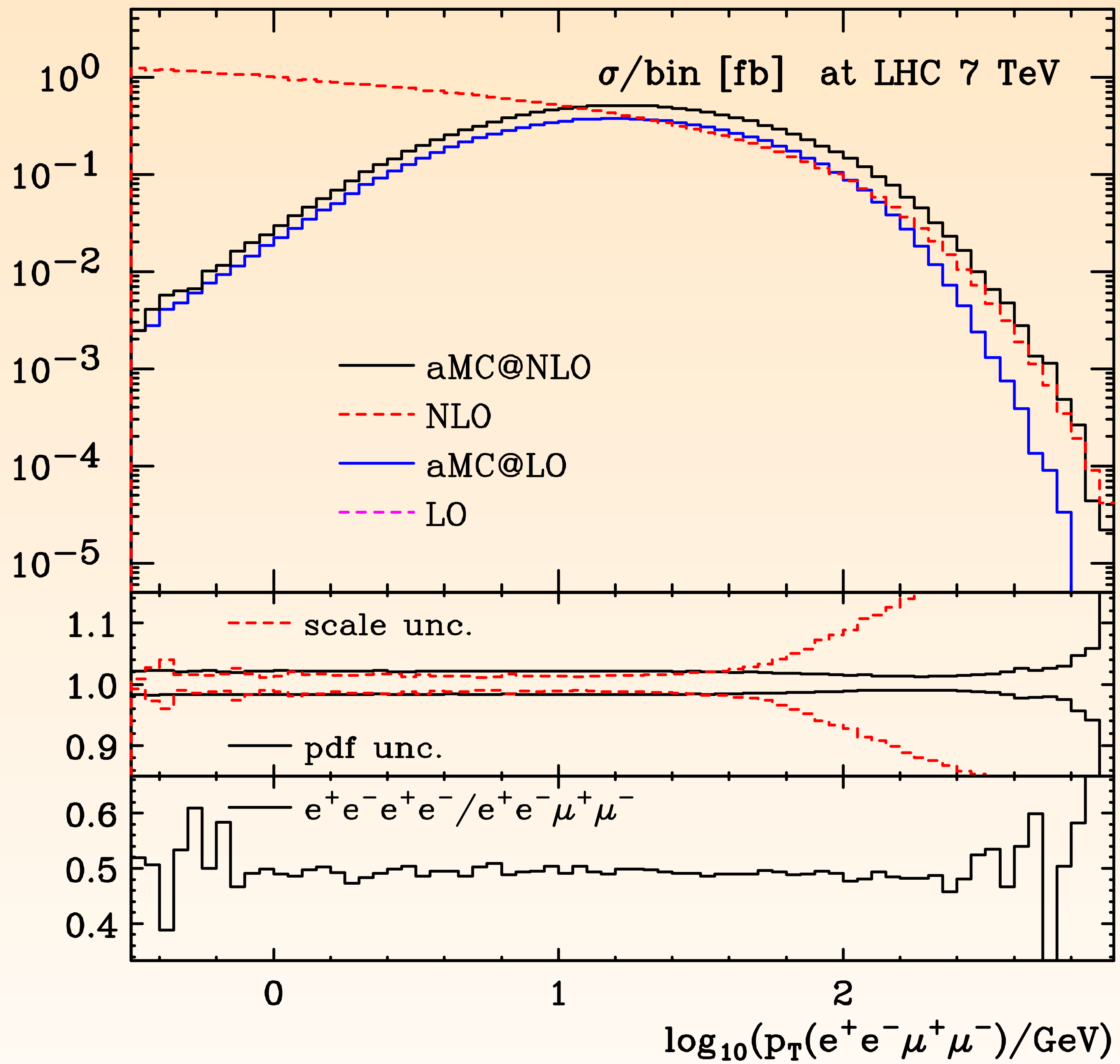
Wbb and Zbb production at the LHC



- Rates for Wbb and Zbb production

arXiv:1106.6019 [hep-ph]

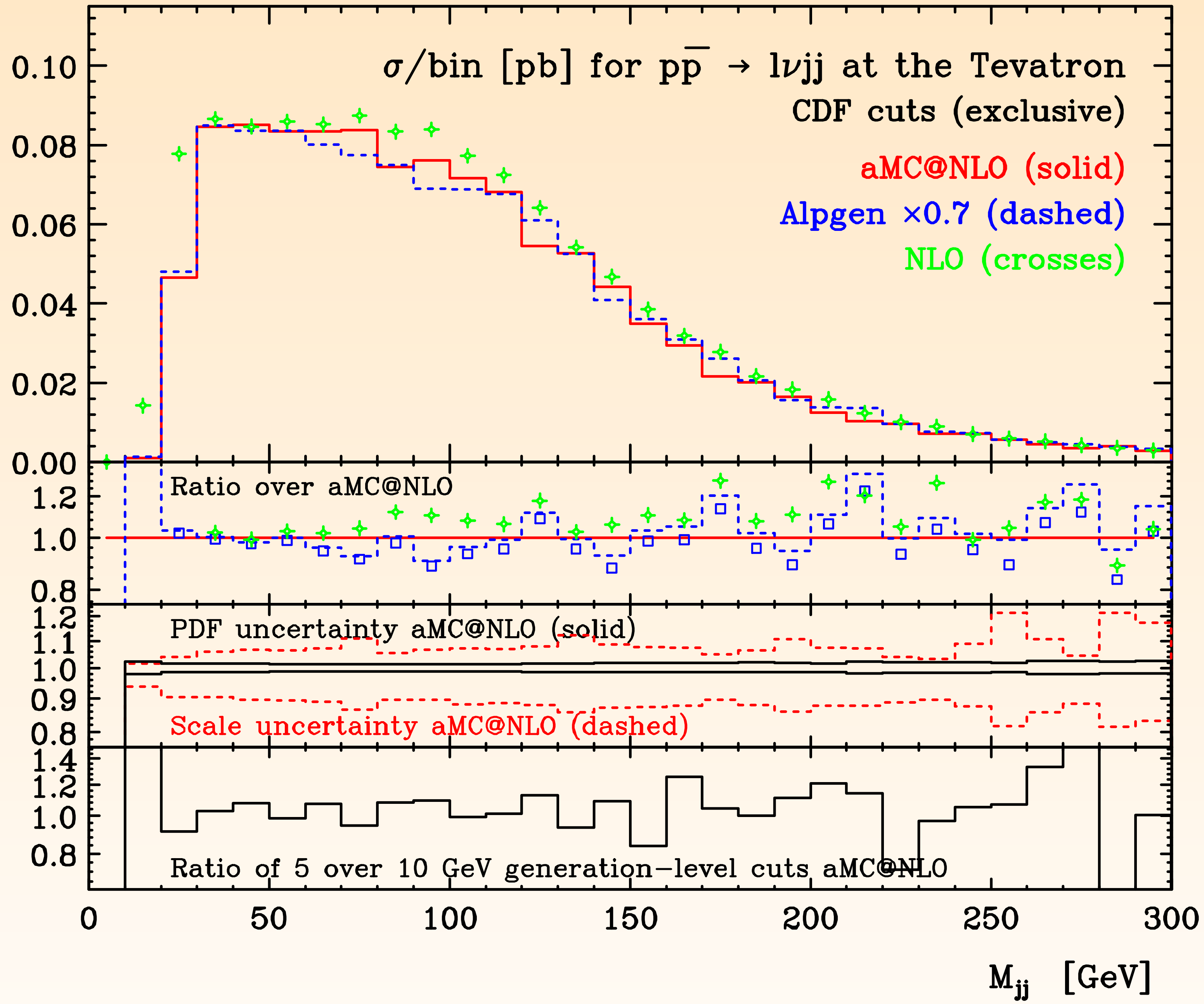
4-LEPTON PRODUCTION



- Determination of scale and PDF uncertainties without any extra CPU costs

arXiv:1110.4738 [hep-ph]

Wjj at the Tevatron



- NLOwPS effects are not responsible for the excess of events seen in the di-jet invariant mass by the CDF collaboration

arXiv:1110.5502 [hep-ph]

aMC@NLO this year

Year 2011: "proof of principle"
Completely Automatic generation of events at NLO accuracy is possible and such a code can be used for phenomenology

Year 2012: "going public"
Rewrite the code so that it can be used by anyone (without help from us!)

aMC@NLO in MG5

MadGraph5

J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer

- LO parton level event generator
- Complete rewrite of the MG4 diagram generation code in a python language
- Numerical phase-space integration and event generation is still in fortran
- Extremely user-friendly python shell including a tutorial to get familiar with the use of the code
- Available from, e.g., http://madgraph.hep.uiuc.edu/

```
************************************************************
*                                                          *
*          W E L C O M E  to  M A D G R A P H  5           *
*                                                          *
*                                                          *
*                 *                       *                *
*                   *        * *        *                  *
*                     * * * * 5 * * * *                    *
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         VERSION 1.3.16                2011-09-11         *
*                                                          *
*    The MadGraph Development Team - Please visit us at    *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                                                          *
*               Type 'help' for in-line help.              *
*           Type 'tutorial' to learn how MG5 works         *
*                                                          *
************************************************************
load MG5 configuration from /Users/omatt/.mg5_config
Loading default model: sm
models.import_ufo: Restrict model sm with file models/sm/rest
models.import_ufo: Run "set stdout_level DEBUG" before import
INFO: Change particles name to pass to MG5 convention
Defined multiparticle p = g u c d s u~ c~ d~ s~
Defined multiparticle j = g u c d s u~ c~ d~ s~
Defined multiparticle l+ = e+ mu+
Defined multiparticle l- = e- mu-
Defined multiparticle vl = ve vm vt
Defined multiparticle vl~ = ve~ vm~ vt~
mg5>help
```

MadFKS in MG5

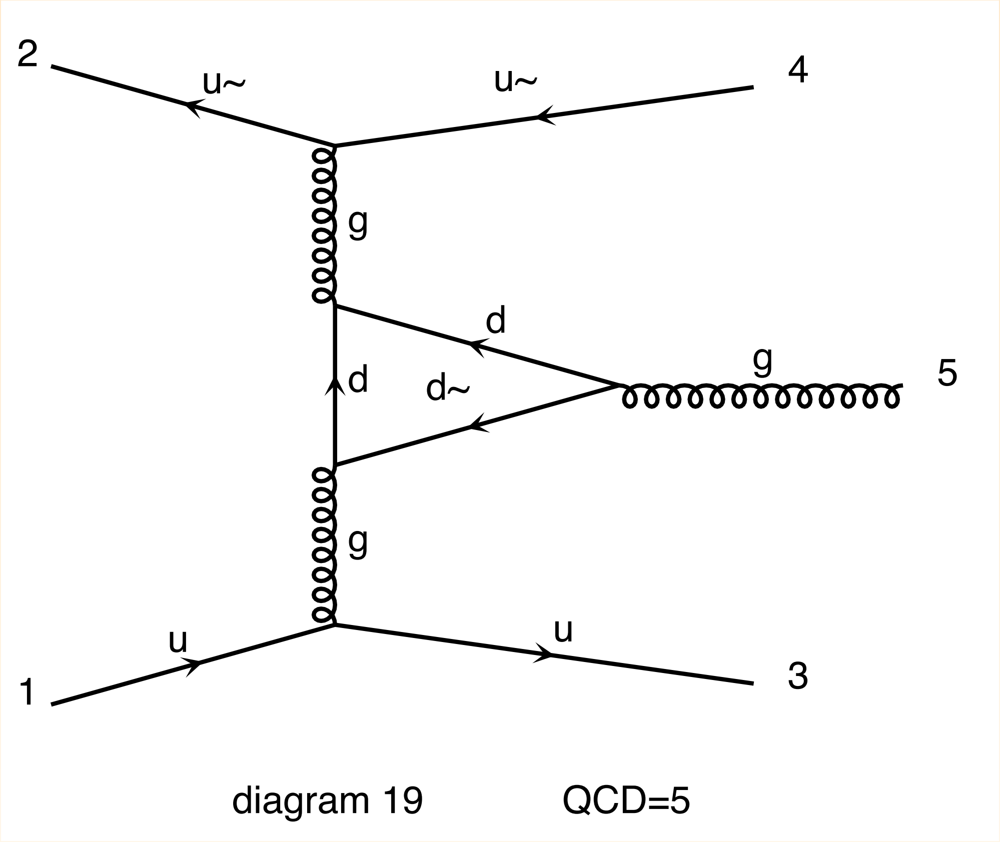
[mostly by RF and Marco Zaro]

- In the MG4 framework, the MadFKS code was set-up to start from a given real-emission process
- In MG5, it has been restructured to start from a Born process
  - There are several real-emission contributions to a given Born (from different types of splittings, but also due to the FKS phase-space partitioning)
  - The new structure allows for a Monte Carlo sum over real emission contributions (with importance sampling)
- Great reduction of the number of integration channels
- More optimization is still possible (that is already there in LO MG5) using 'mirroring' and 'subprocess combination'

MadLoop in MG5

[mostly by Valentin Hirschi]

- All limitations of the current MadLoop in the MG4 framework completely removed
- Drawing of the loop diagrams ☺
  [by Olivier Mattelaer]
- Much faster code (both generation and evaluation)
- Generation of the R_2 counter terms from any Lagrangian using FeynRules
  [By Celine Degrande]



- Complex mass scheme and SU(2) Feynman gauge are almost there
  [by Diogo Buarque Franzosi]
- Loop-induced processes are working, but need more efficient PS handling
  [under investigation by Antoine Laureys]

MadLoop V4 to V5

Great improvements

✓ = non-optimal | ✓ = done optimally | ✗ = not done | ✗ = not done YET

Task	MadLoop V4	MadLoop V5
Generation of L-Cut diagrams, loop-basis selection	✓-	✓++
Support NLO BSM models	✗	✓
Counter-term (UV/R2) diagrams generation	✓-	✓
Mixed order perturbation (generation level)	✗	✓
File output	✓--	✓
Drawing of Loop diagrams	✗	✓
Full SM implementation for QCD perturbations	✓	✓
4-gluon R2 computation	✗	✓
Automated parallel tests	✗	✓
Automatic sanity checks (Ward, ε^{-2})	✓	✓
EPS handling	✓ (no mp)	✓ (mp)
Virtual squared	✓-	✓
Decay Chains	✗	✗
Automatic loop-model creation	✗	✗
Complex mass scheme and massive bosons in the loop	✗	✗/✓

aMC@NLO in MG5

[mostly by RF, Stefano Frixione and Paolo Torrielli]

- Improvements:
  - Generation of S and H events in one go
    $\longrightarrow$ common contributions computed only once for each PS point
  - Work in progress: better structured integrands leading to fewer negatively weighted events
  - Under investigation: improved determination of the starting scale for the parton shower (in particular for the H events, even though this is formally a higher order effect)
  - Pythia p_T-ordered showers are work in progress

Conclusions

- By offering NLO accuracy, improved by resummation of soft/collinear radiation (by the parton shower), results for high-precision collider phenomenology can be obtained
- Flexible, completely automatic event generators at NLO accuracy will become publicly available for analyses very soon. (`aMC@NLO` is already available to a selected group of CMS & ATLAS experimentalists)
- The MadGraph 5 framework offers many improvements over MadGraph4. In particular,
  - faster and more general loop generation/evaluation
  - MadFKS starting from Born: improved phase-space generation
  - complex mass scheme
  - efficient loop-induced processes

aMC@NLO website

aMC@NLO

http://amcatnlo.cern.ch

- On the aMC@NLO website you can find
  - Latest news on aMC@NLO
  - NLO event samples ready for showering and analysis
  - Compare with MadLoop: a single phase-space point for the virtual for any user-defined process in the SM. Useful for comparison/checking private calculations. No need to install anything!*

* Temporarily off-line due to the CP3 cluster update