MadLoop in aMC@NLO

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Presentation
@ RADCOR

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Contents

- Motivations
- aMC@NLO in a nutshell
- MadLoop: from MG4 towards MG5
- Results
- Closing words

Why NLO?

NLO is important because

- NLO corrections are large in QCD
- NLO corrections significantly affect the shape of distributions
- It reduces the scale dependence inherent to tree-level cross-sections
- New production channels open at NLO
- Accurate theoretical prediction are necessary for the search of signals events in large background samples.

Automation would help!

WHY AUTOMATION?

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  Trade time spent on computing a process with time on studying the physics behind it.

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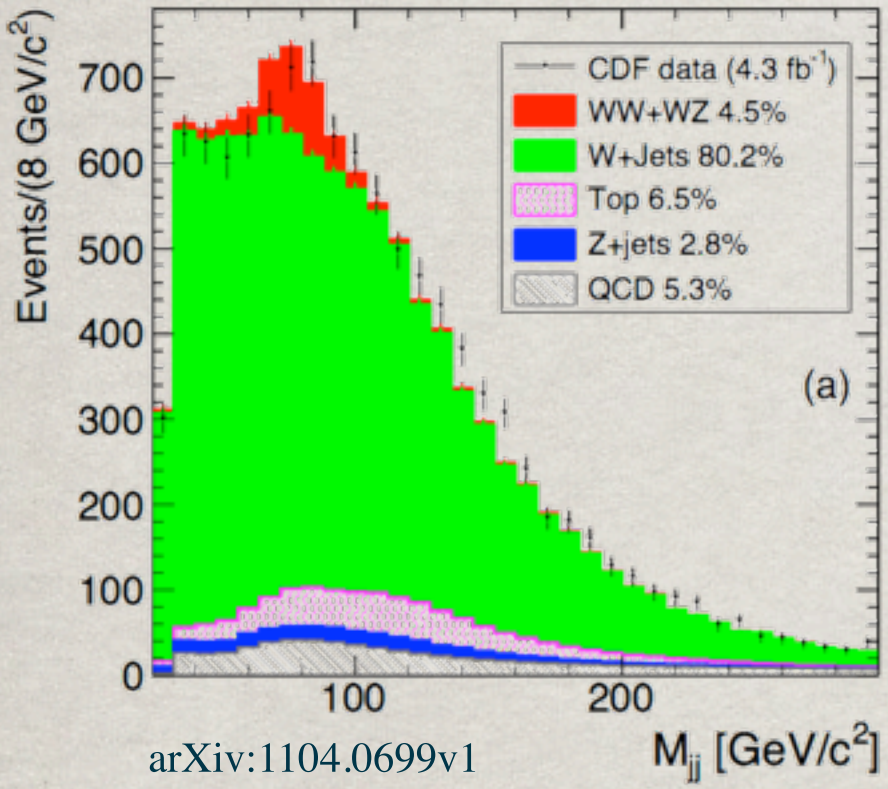
- Use of the same framework for all processes

  It only requires to know how to efficiently use one single program to do all NLO phenomenology.

Existing tools

- Flexible tools for NLO predictions do not exist:
  - MCFM [*Campbell & Ellis & ...*] has it available almost all relevant process for background studies at the Tevatron and LHC, but gives only fixed-order, parton-level results
  - MC@NLO [*Frixione & Webber & ...*] has matching to the parton shower to describe fully exclusive final states, but the list of available processes is relatively short
  - POWHEG BOX [*Nason et al.*] provides a framework to match any existing parton level NLO computation to a parton shower. However, the NLO computation is not automated and some work by the user is needed to implement a new process
- Idea: write an automatic tool that is flexible and allows for any process to be computed at NLO accuracy, including matching to the parton shower to deliver events ready for experimentalists ➔ **a**MC@NLO

Wjj AT TEVATRON

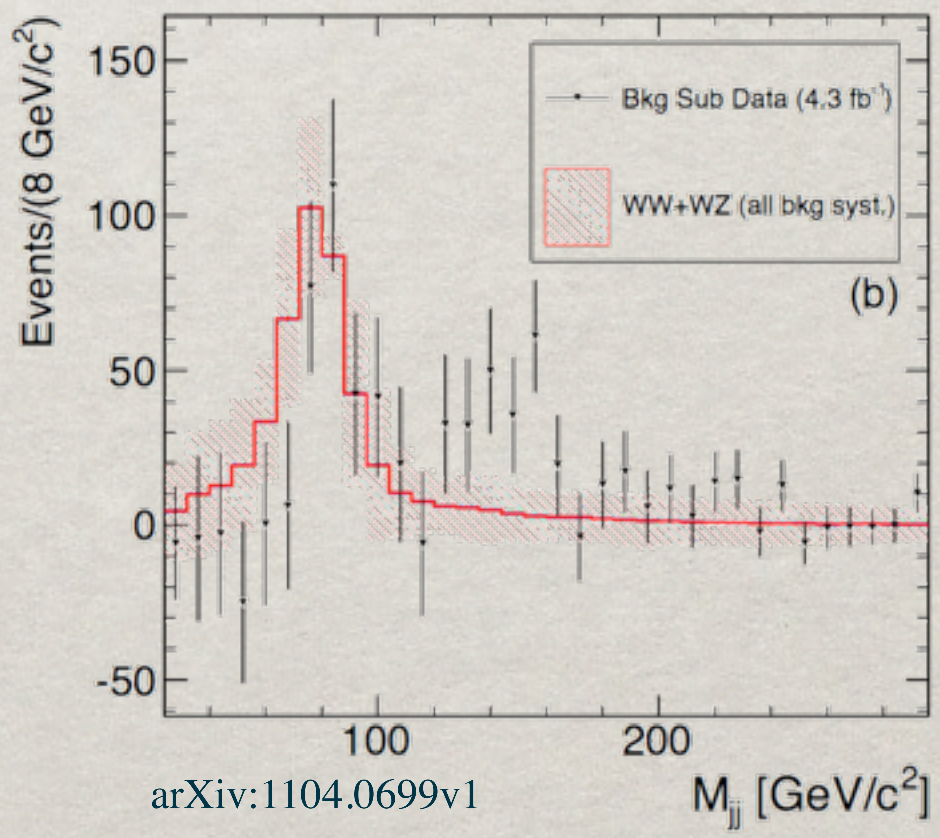


arXiv:1104.0699v1

CDF observes 3-σ deviation to the SM signal.

- New Physics, stat. fluctuations?
- Unreliable prediction?
  - ➡ W+jets treated at LO !
  - ➡ Mistreatment of background?

Having NLO computations by default lead to more conclusive observations.



arXiv:1104.0699v1

aMC@NLO in a nutshell

- MadFKS, build on MadGraph, computes all contributions to a NLO computation, except for the finite part of the virtual amplitude
- MadLoop computes the virtual corrections to any process in the SM using the OPP method as implemented in CutTools
- Combine MadFKS and MadLoop to get any distribution/cross section at (parton-level) NLO accuracy
- Add terms to remove double counting when matching to the parton shower: aMC@NLO
- Shower the generated events using Herwig or Pythia to get fully exclusive predictions at NLO accuracy (for IR-safe observables).

arXiv:1104.0699v1

NLO Basics

NLO contributions have two parts

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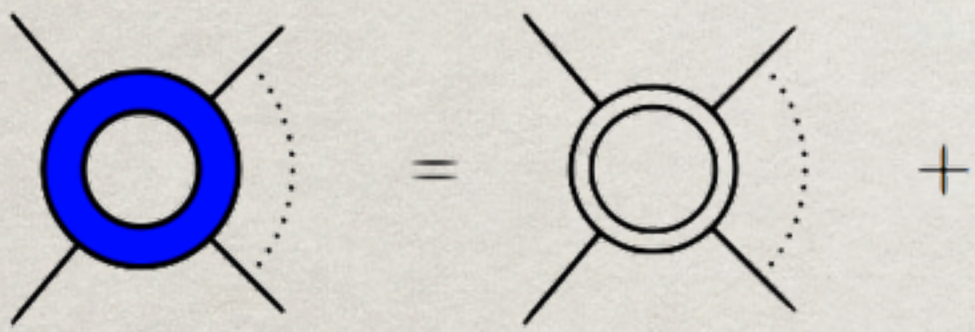

$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V +$$

Virtual part

- Used to be bottleneck of NLO computations
- Algorithms for automation known in principle but not yet efficiently implemented
- This work brings automation using MadGraph and CutTools interfaced through MadLoop.

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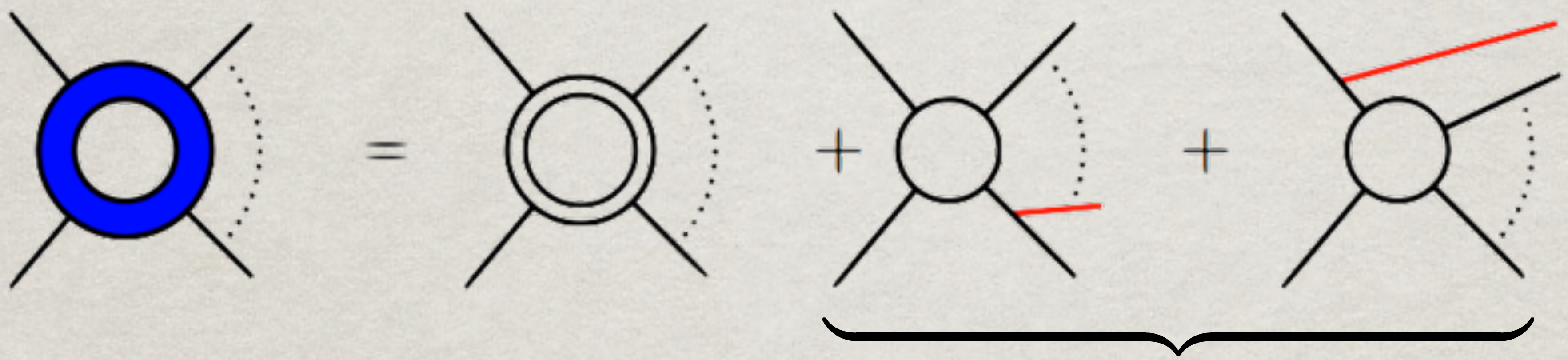

$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R +$$

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Real emission part

- Automated for different methods
- Challenge is the systematic extraction of singularities
- MadFKS using the FKS subtraction method successfully implemented on MGv4

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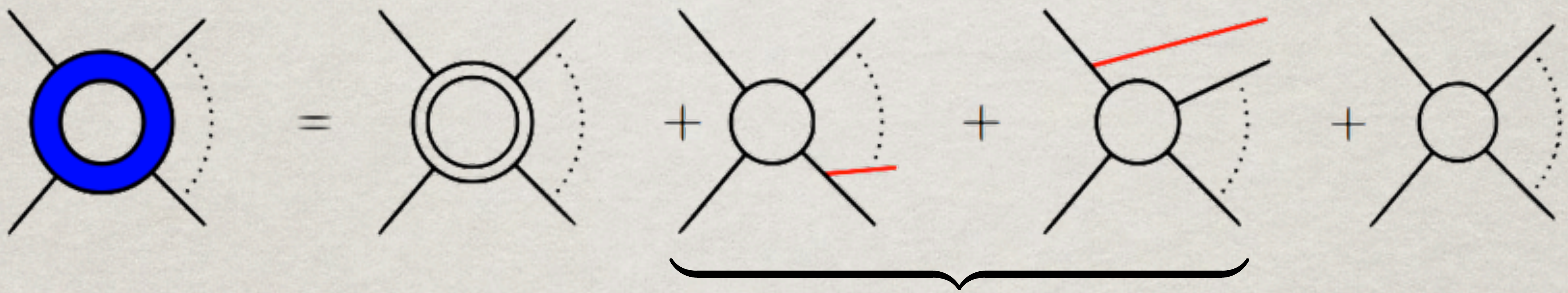

$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Virtual part

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Subtraction terms

IR divergences are dealt with using subtraction terms

$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

$$\Downarrow$$

$$\sigma^{\text{NLO}} = \int_m \left[d^{(4)}\sigma^B + \int_l d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A \right] + \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A \right]$$

- Each integral is finite.
- The only missing input required from MadFKS is the *finite part* of the virtual amplitude.
- This is the part MadLoop provides!

MadFKS

MadFKS

Phase-space: Divide and Conquer

- Real emission part : $d\sigma^R = |M^{n+1}|^2 d\phi_{n+1}$
- $|M^{n+1}|^2$ diverges as $\frac{1}{\chi_i^2}\frac{1}{1-y_{ij}}$ with $\begin{aligned}\chi_i &= \frac{E_i}{\sqrt{\hat{s}}}\\ y_{ij} &= \cos\theta_{ij}\end{aligned}$
- Divide phase-space so that each partition has at most one soft and one collinear singularity

$$d\sigma^R = \sum_{ij} S_{ij}|M^{n+1}|^2 d\phi_{n+1} \qquad \sum_{ij} S_{ij} = 1$$

- Use plus distribution to regulate the singularities $\int d\chi \left(\frac{1}{\chi}\right)_+ f(\chi) = \int d\chi \frac{f(\chi)-f(0)}{\chi}$

$$d\tilde{\sigma}^R = \sum_{ij}\left(\frac{1}{\chi_i}\right)_+ \left(\frac{1}{1-y_{ij}}\right)_+ \chi_i^2(1-y_{ij})S_{ij}|M^{n+1}|^2 d\phi_{n+1}$$

FKS vs CS dipoles

N^2 vs N^3

- CS uses soft singularities to organize the subtractions :
  - ➔ Three-body kernels, so naive n^3 scaling
  - ➔ Each subtraction term has a different kinematics
  - ➔ All subtraction terms must be subtracted to $\mathcal{M}^{(r)}$

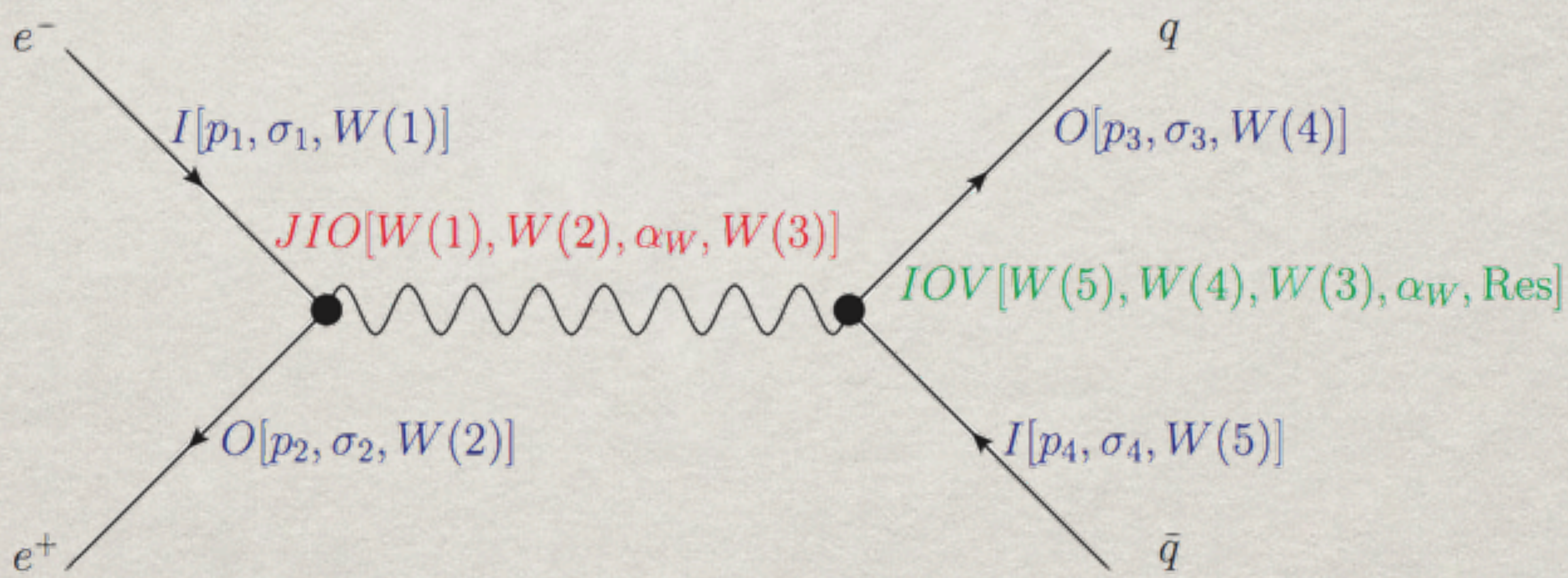
- MadFKS, based on the collinear structures :
  - ➔ The majority of the subtractions can be grouped together. *Ex:* The 2 → N gluons process as 3 subtractions ∀N
  - ➔ Soft and collinear counter-terms can be defined as to have the same kinematics so that the subtraction term is unique.
  - ➔ The collinear structure is better suited to existing formalisms for NLO parton shower matching.

MadLoop

MadGraph

The evolutive way of computing tree-diagrams

- First generates all tree-level Feynman Diagrams
- Compute the amplitude of each diagram using a chain of calls to HELAS subroutines



- Finally square all the related amplitude with their right color factors to construct the full LO amplitude

Cut-Loop diagrams

With a specific example

Consider $e^+e^- \to \gamma \to u\bar{u}$:

- Loop particles are denoted with a star. When MG is asked for $e^+e^- \to u^*\bar{u}^*u\bar{u}$ it gives back eight diagrams. Two of them are:

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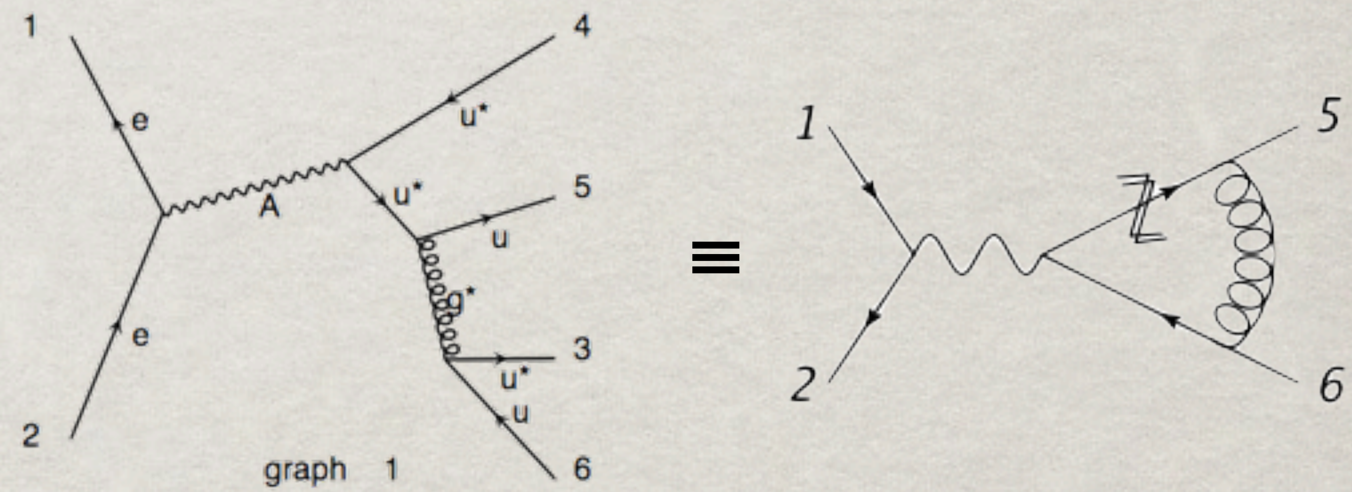

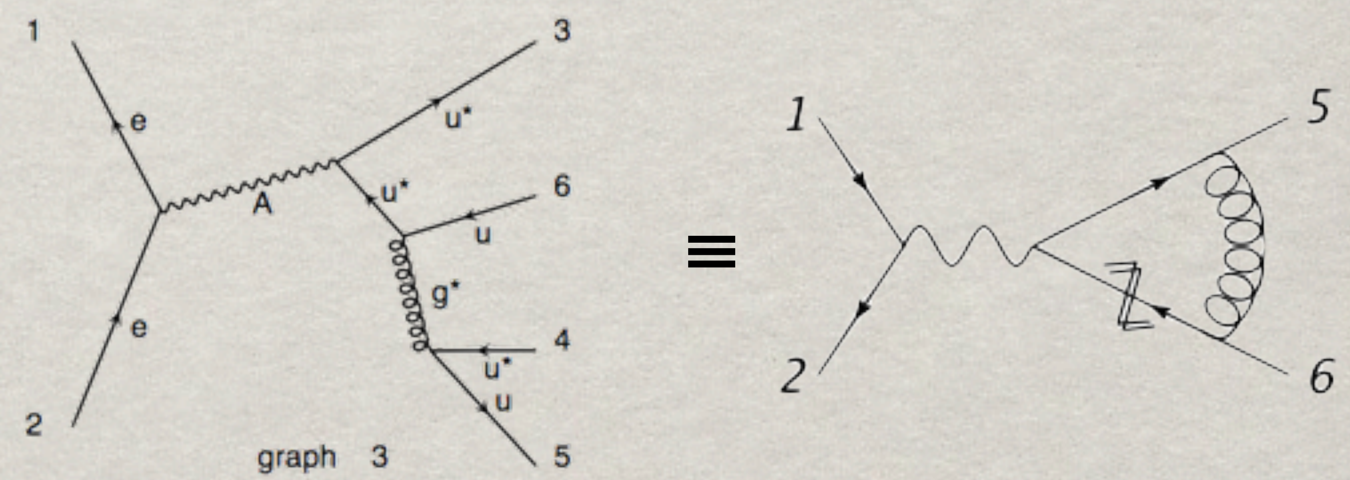

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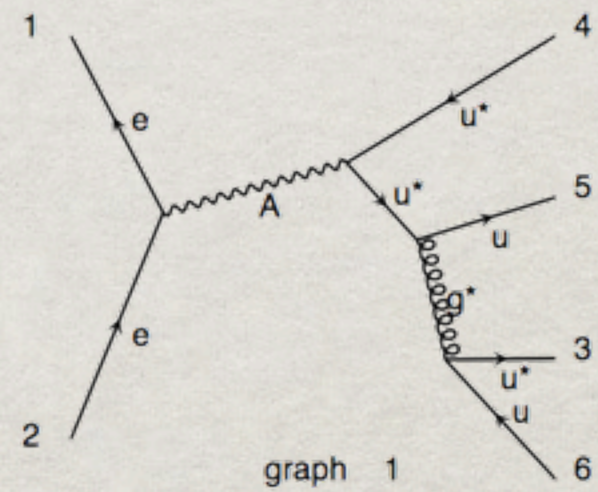
- Tags are associated to each cut-diagram. Those whose tags are **mirror and/or cyclic permutations** of tags of diagram already in the loop-basis are taken out.



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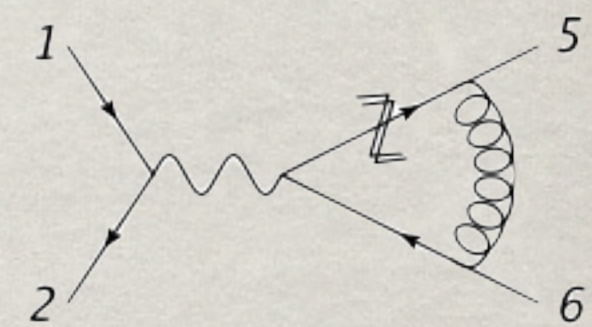
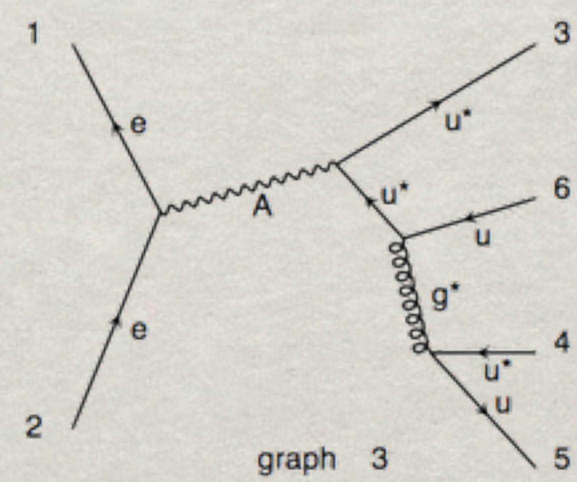


$\text{Diag}_{\,1} = [u^*(6)g^*(5)u^*(A)]$



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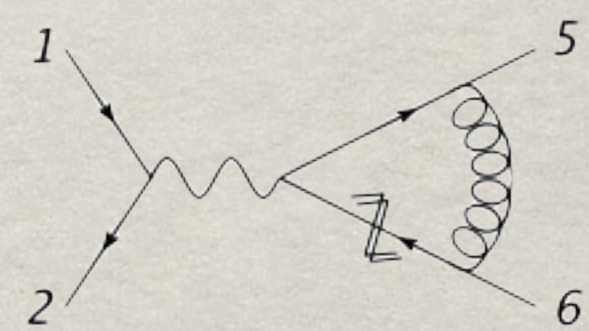

$\text{Diag}_{\,3} = [u^*(A)u^*(6)g^*(5)]$

Cut-Loop diagrams

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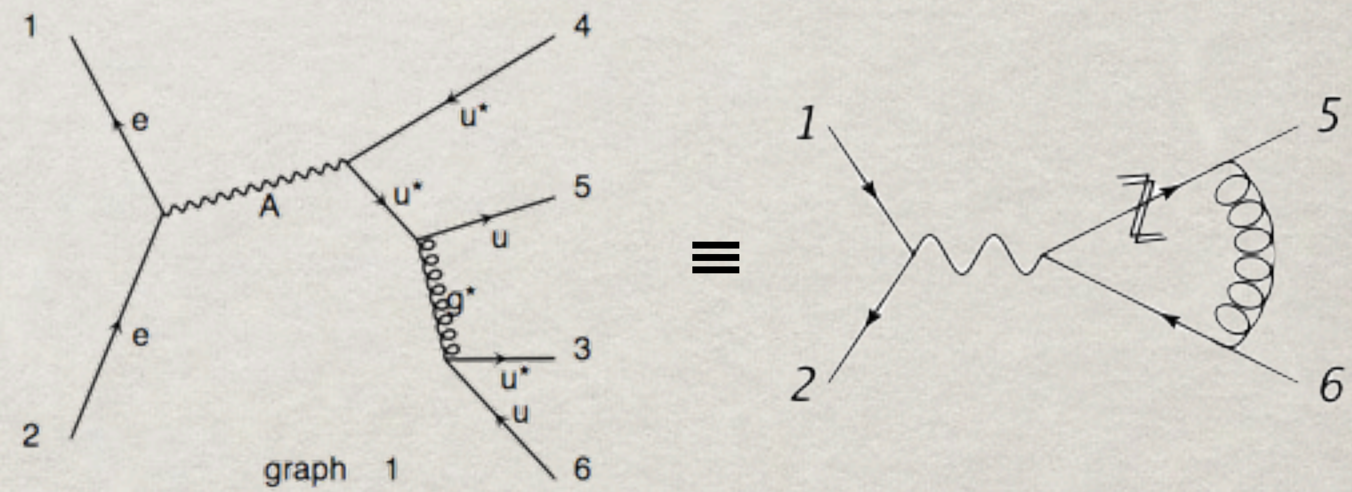
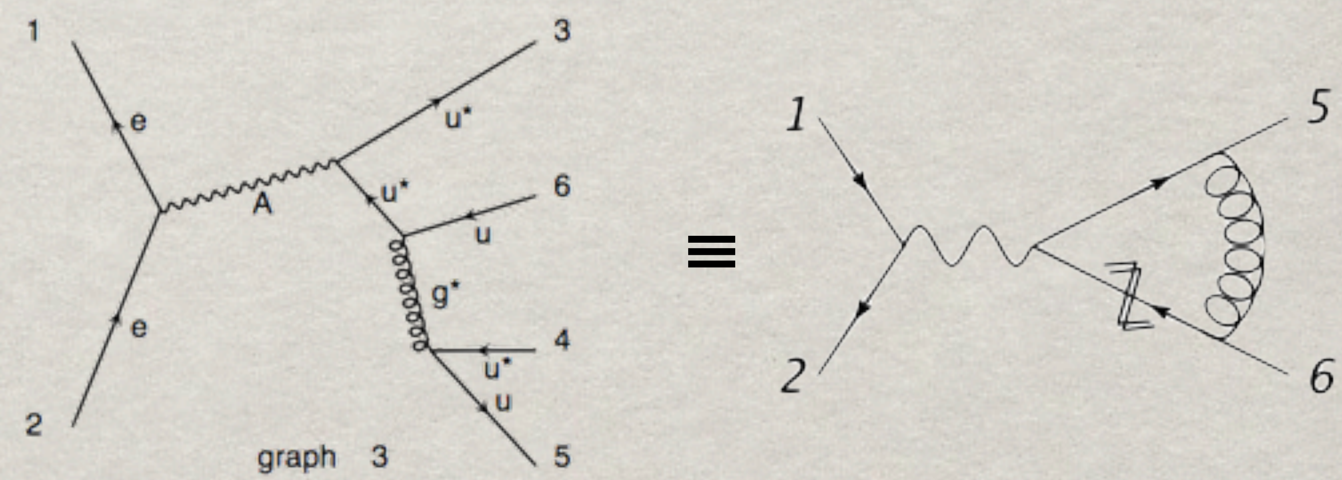
- Additional custom filter to eliminate tadpoles and bubbles attached to external legs.



Diag $_1 = [u^*(6)g^*(5)u^*(A)]$



Diag $_3 = [u^*(A)u^*(6)g^*(5)]$

CutTools

Or how to compute loops without doing so

- CutTools uses the OPP method for loop reduction at the integrand level

$$\bar{q}^2 = q^2 + \tilde{q}^2 \qquad (q \cdot \tilde{q}) = 0$$

$$\bar{D}_i = (\bar{q} + p_i)^2 - m_i^2 \,, \quad p_0 \neq 0 \,.$$

$$\int d^{(d)}\sigma^V = \int d^{(4+\epsilon)} \left(A(\bar{q}) + \tilde{A}(\bar{q}) \right)$$

$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}} \quad \left(\tilde{A}(\bar{q}) \to \text{R2} \right)$$

$$\begin{aligned} N(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3) \right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\ &+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2) \right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\ &+ \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1) \right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\ &+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0) \right] \prod_{i \neq i_0}^{m-1} D_i \\ &+ \tilde{P}(q) \prod_{i}^{m-1} D_i \end{aligned}$$

- R2 can be obtained with a tree-level-like computation with special Feynman-Rules.
- Evaluation of N(q) for different specific q's allows to algebraically obtain the coefficients a, b, c and d
- Reconstruction of the $\tilde{q}$ dependance of the numerator gives the cut-constructible part R1 of the finite part of the virtual amplitude

Finite part = R1 + R2

MadLoop

Fighting Exceptional Phase Space points

- CutTools can asses the numerical stability of the computation of a loop by
  - ➥ By sending $m_i^2 \to m_i^2 + M^2$, CT has an independent reconstruction of the numerator and can check if both match.
  - ➥ CT ask MadLoop to evaluate the integrand at a given loop momentum and check if the result is close enough to the one from the reconstructed integrand.

- When an EPS occurs, MadLoop tries to cure it:
  - ➥ Check if Ward Identities hold at a satisfactory level
  - ➥ Shift the PS point by rescaling momenta : $k_i^3 = (1 + \lambda_\pm) k_i^3$
  - ➥ Provide an estimate of the virtual for the original PS point with uncertainty:

$$v_{\lambda_\pm}^{FIN} = \frac{V_{\lambda_\pm}^{FIN}}{|\mathcal{A}_{\lambda=0}^{born}|^2} \quad c = \frac{1}{2}\left(v_{\lambda_+}^{FIN} + v_{\lambda_-}^{FIN}\right) \quad \Delta = \left|v_{\lambda_+}^{FIN} - v_{\lambda_-}^{FIN}\right| \quad V_{\lambda=0}^{FIN} = \left|\mathcal{A}_{\lambda=0}^{born}\right|^2 (c \pm \Delta)$$

  - ➥ If nothing works, then use the median of the results of the last 100 stable points

LOCAL CHECKS

YOU DON'T WANT THE EXHAUSTIVE LIST...

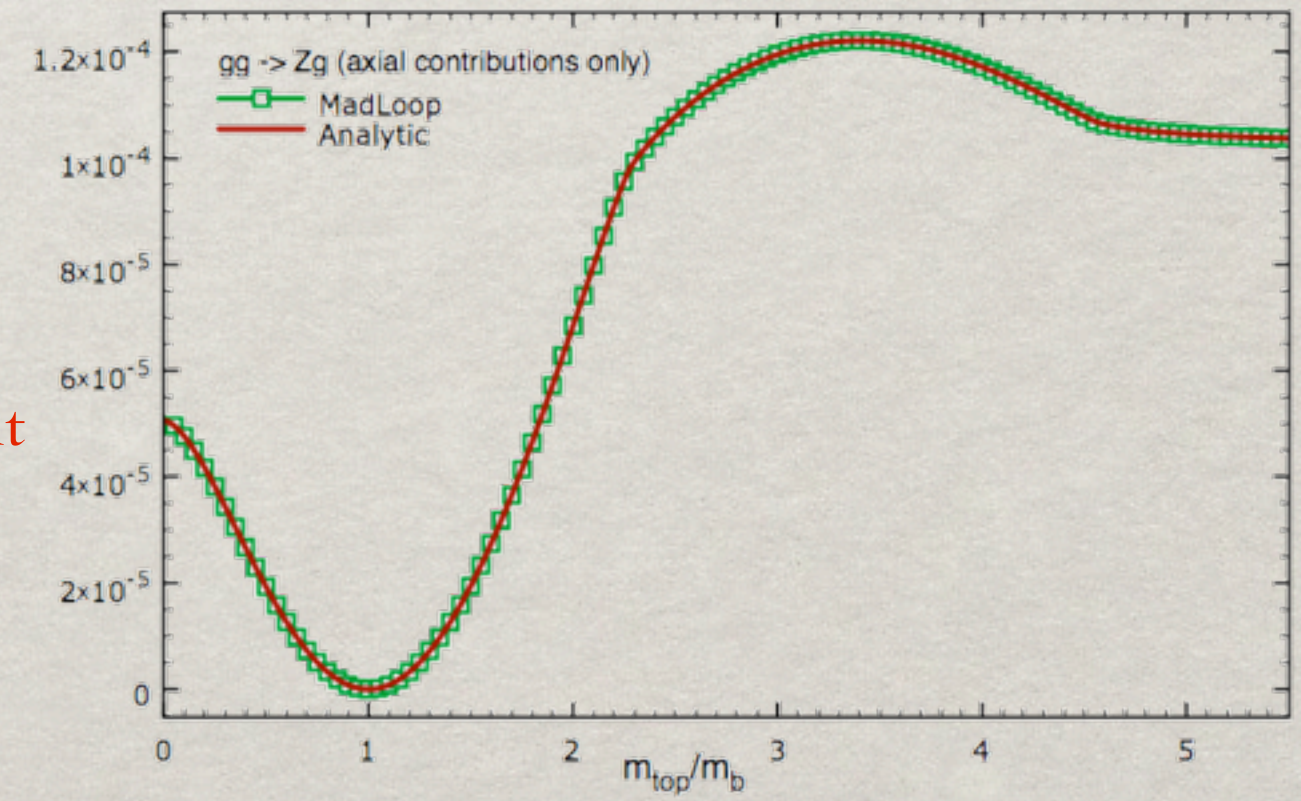
$u\bar{u} \to W^+W^-b\bar{b}$	MADLOOP	Ref. [33]
a_0	2.338047209268890E-008	2.338047130649064E-008
c_{-2}	-2.493920703542680E-007	-2.493916939359002E-007
c_{-1}	-4.885901939046758E-007	-4.885901774740355E-007
c_0	-2.775800623041098E-007	-2.775787767591390E-007
$gg \to W^+W^-b\bar{b}$		
a_0	1.549795815702494E-008	1.549794572435312E-008
c_{-2}	-2.686312747217639E-007	-2.686310592221201E-007
c_{-1}	-6.078687041491385E-007	-6.078682316434646E-007
c_0	-5.519004042667462E-007	-5.519004727276688E-007

Ref. [33] : A. van Hameren *et al.*

- We believe the code is very robust - e.g., MadLoop helped spot mistakes in published loop computations (Zjj , W^+W^+jj)

- The numerics are pin-point on analytical data, even with several mass scales.

- Analytic computations from an independent implementation of the helicity amplitudes by J.J van der Bij *et al.*



Integrated Results

- Running time: Two weeks on a 150+ node cluster
- Proof of efficient EPS handling with $Zt\bar{t}$
- Successful cross-check against known results
- Large K-factors sometimes
- No cuts on b, robust numerics with small P_T

	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

NLO PARTON SHOWER MATCHING

A LA MC@NLO

[*Torrielli, RF & Frixione*]

$$d\sigma^{(\mathbb{H})}_{\text{MC@NLO}} = d\phi_{n+1}\left(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

$$d\sigma^{(\mathbb{S})}_{\text{MC@NLO}} = \int_{+1} d\phi_{n+1}\left(\mathcal{M}^{(b+v+rem)}(\phi_n) - \mathcal{M}^{(c.t.)}(\phi_{n+1}) + \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

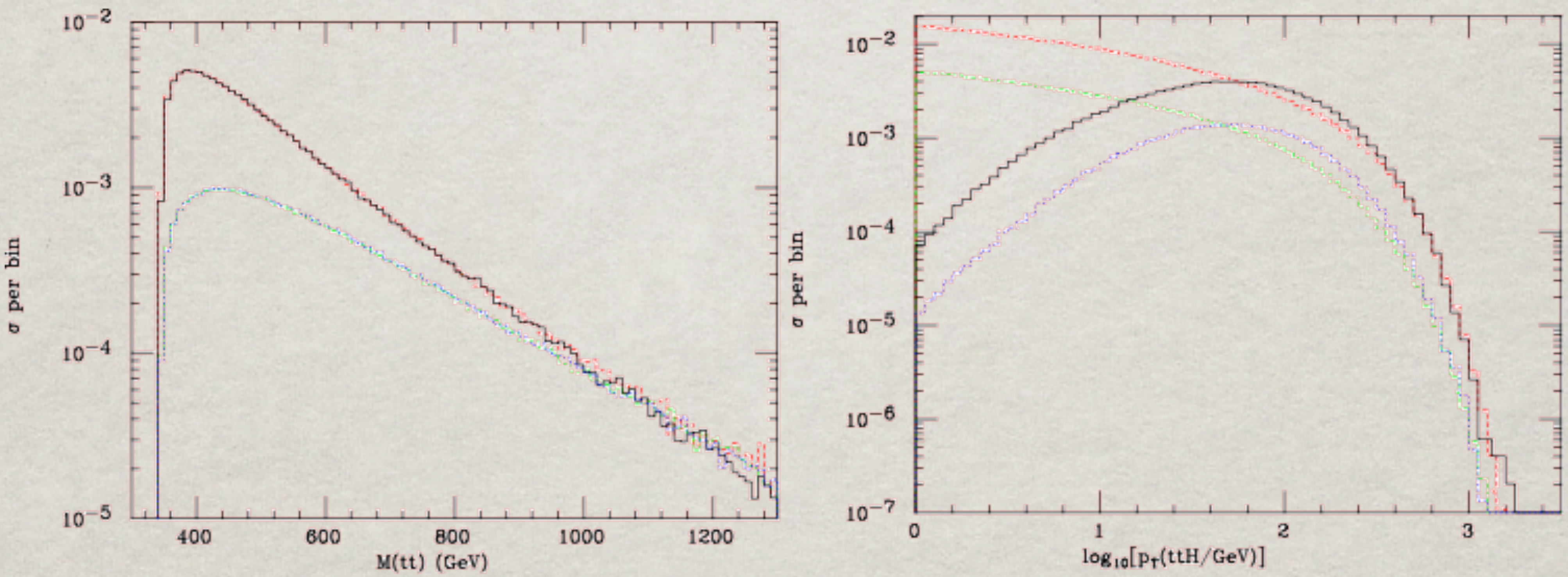
- In black: pure NLO, fully tested in MadFKS
- In red: MC counter terms have been implemented for Herwig6, Pythia and Herwig++ (but only fully tested for Herwig)
  - FKS subtraction is based on a collinear picture, so are the MC counter terms: branching structure is for free
  - Automatic determination of color partners
  - Works also when MC-ing over helicities

DISTRIBUTIONS

FULL MACHINERY AT WORK

- Case study of $[H/A]t\bar{t}$ with starring actors: (but also $[W/Z/\gamma]b\bar{b}$ and Wjj to come)

MGv4, CT, MadFKS, MadLoop and aMC@NLO interfaced to Herwig6 !



Solid: aMC@NLO scalar. Dashed: aMC@NLO pseudoscalar

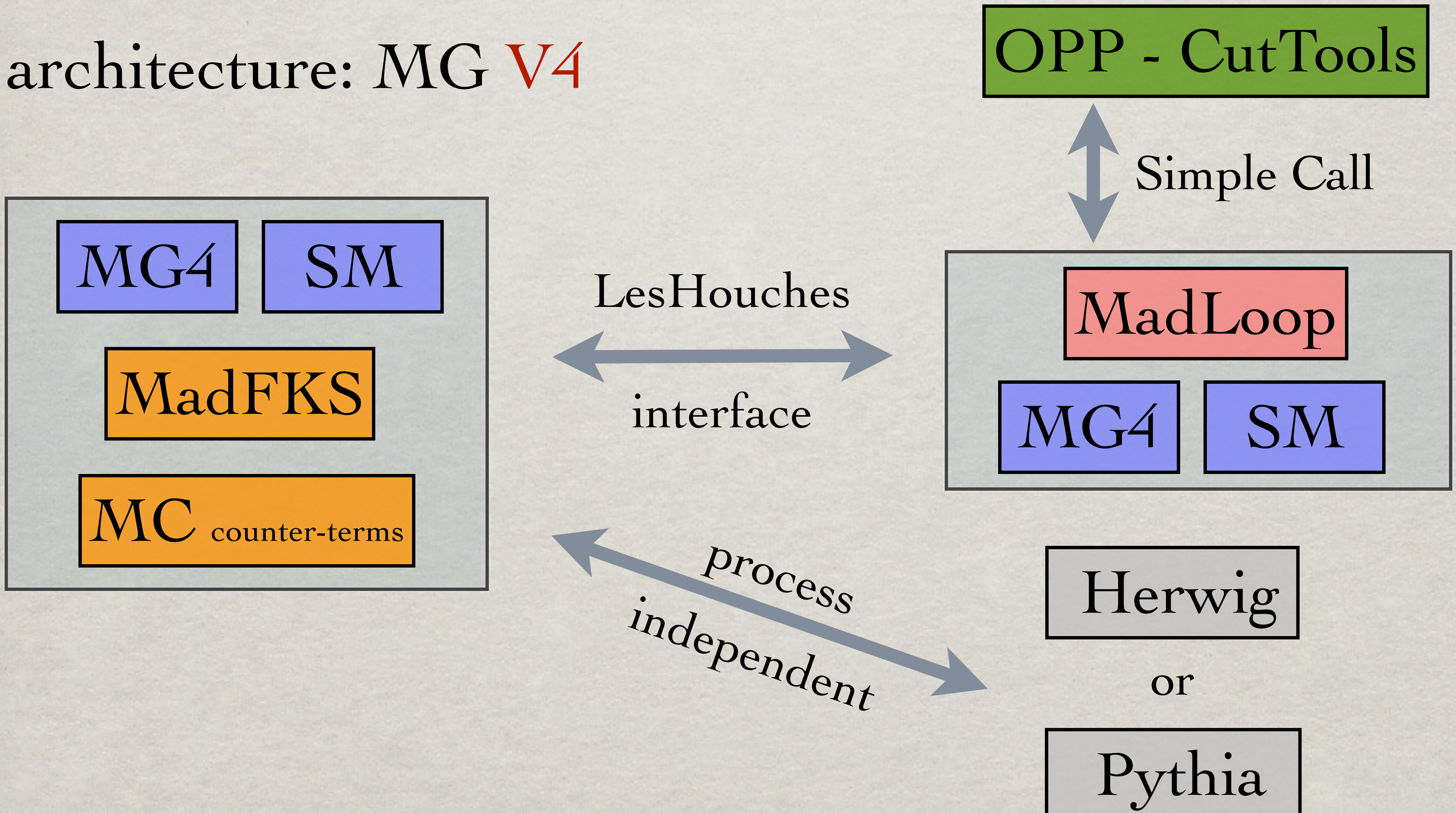
Dotted: NLO scalar. Dotdashed: NLO pseudoscalar

Left: $t\bar{t}$ invariant mass. Right: $t\bar{t}H$ p_T

aMC@NLO

Towards full automation

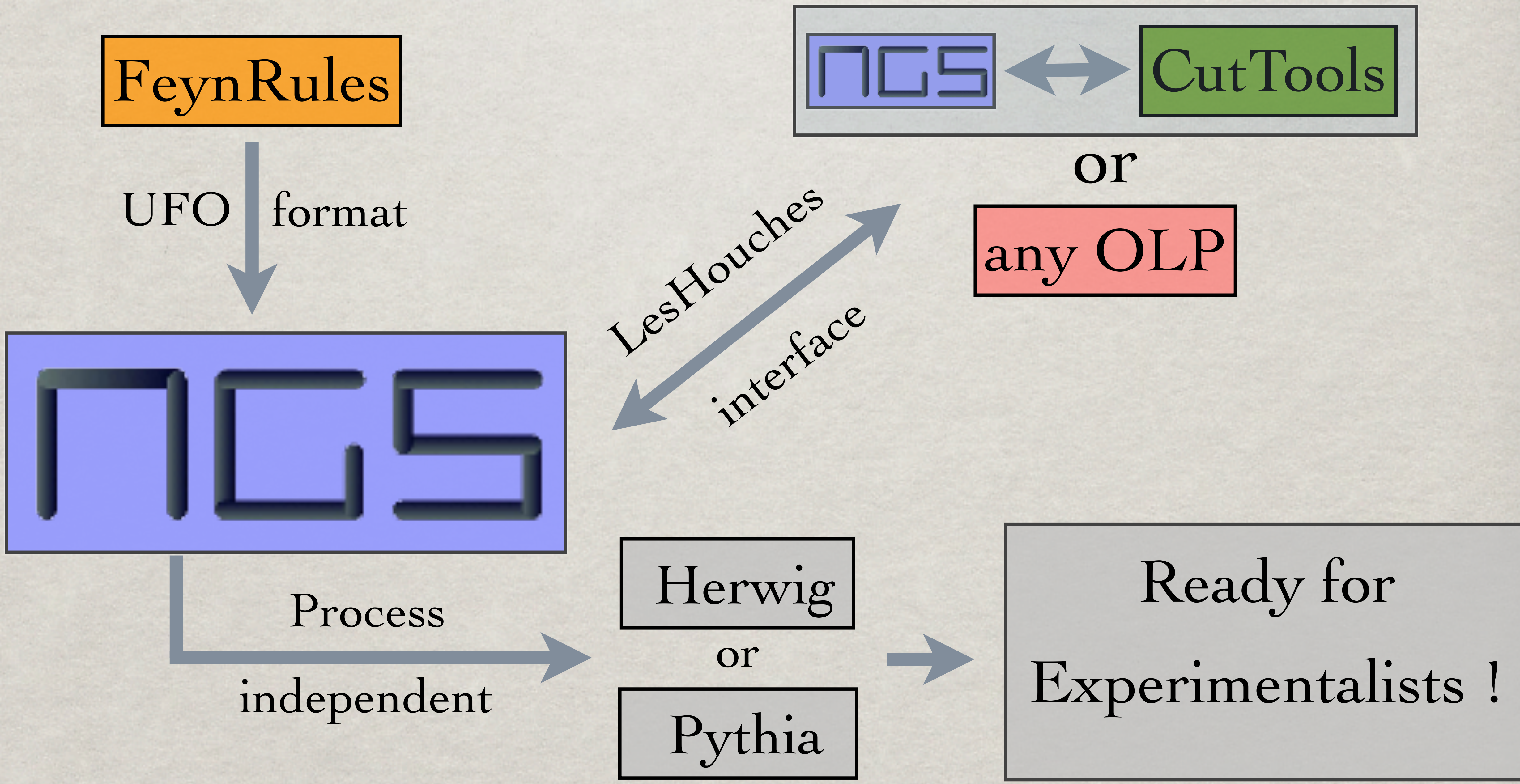
architecture: MG V4



aMC@NLO

FULL AUTOMATION

architecture: MG V5



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	✓-	✓++
Drawing of Loop diagrams	✕	✓
Full SM implementation	✓	✕
Counter-term (UV/R2) diagrams generation	✓-	✓
Complex mass scheme and massive bosons in the loop	✕	✕
Color Factor computation	✓-	✓
File output	✓--	✓
4-gluon R2 computation	✕	✓ (checks still needed)
Virtual squared	✓-	✕
Decay Chains	✕	✕
EPS handling	✓ (no mp)	✕
Sanity checks (Ward, ε^{-2})	✓	✕
Mixed order perturbation (generation level)	✕	✓
Automatic loop-model creation	✕	✕
Symmetry factor automatic computation	✕	✕

Loop-Cut diagrams

- How faster are they generated?

Loop-Cut diagrams

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Process	Generation time[1]		Output size[2]		Compilation time[3]		Running time[4]	
d d~ > u u~	**8.750 s**	**5.378 s**	200 Kb	268 Kb	0.931 s	2.996 s	0.0088 s	0.0094 s
d d~ > d d~ g	**17.04 s**	**104.8 s**	124 Kb	1.7 Mb	4.799 s	19.181 s	0.64 s	0.74 s
d d~ > d d~ u u~	**22.50 s**	**2094 s**	232 Kb	3.3 Mb	37.75 s	45.02 s	1.93 s	2.34 s
g g > g g g g	**2277 s**	×	25 Mb	×	NOT COMPILING YET	×	NOT COMPILING YET	×

[1] : Process generated in a massless n_f=2 QCD model with reduced particle content.
[2] : Of the equivalent `matrix.f` file. [4] : Per PS points, computed over 1000 PS points.
[3] : In MG5, no smart line-breaks for the `JAMP` definition. MG5@NLO = ♦, MadLoop = ♦

Loop-Cut diagrams

- How faster are they generated?

Process	Generation time[1]		Output size[2]		Compilation time[3]		Running time[4]	
`d d~ > u u~`	**8.750 s**	**5.378 s**	200 Kb	268 Kb	0.931 s	2.996 s	0.0088 s	0.0094 s
`d d~ > d d~ g`	**17.04 s**	**104.8 s**	124 Kb	1.7 Mb	4.799 s	19.181 s	0.64 s	0.74 s
`d d~ > d d~ u u~`	**22.50 s**	**2094 s**	232 Kb	3.3 Mb	37.75 s	45.02 s	1.93 s	2.34 s
`g g > g g g g`	**2277 s**	×	25 Mb	×	NOT COMPILING YET	×	NOT COMPILING YET	×

[1] : Process generated in a massless `nf=2` QCD model with reduced particle content.
[2] : Of the equivalent `matrix.f` file. [4] : Per PS points, computed over 1000 PS points.
[3] : In MG5, no smart line-breaks for the `JAMP` definition. MG5@NLO = ♦, MadLoop = ♦

- Why ?
  - The MG5 `from_group` algorithm is already much faster for tree-level diagrams.
  - It is modified so that bubbles and tadpoles are not generated.
  - When generating diagrams for a given L-Cut particle, all previously considered L-Cut particles are vetoed from being loop-lines.

Final Word

Full Automation is at the door

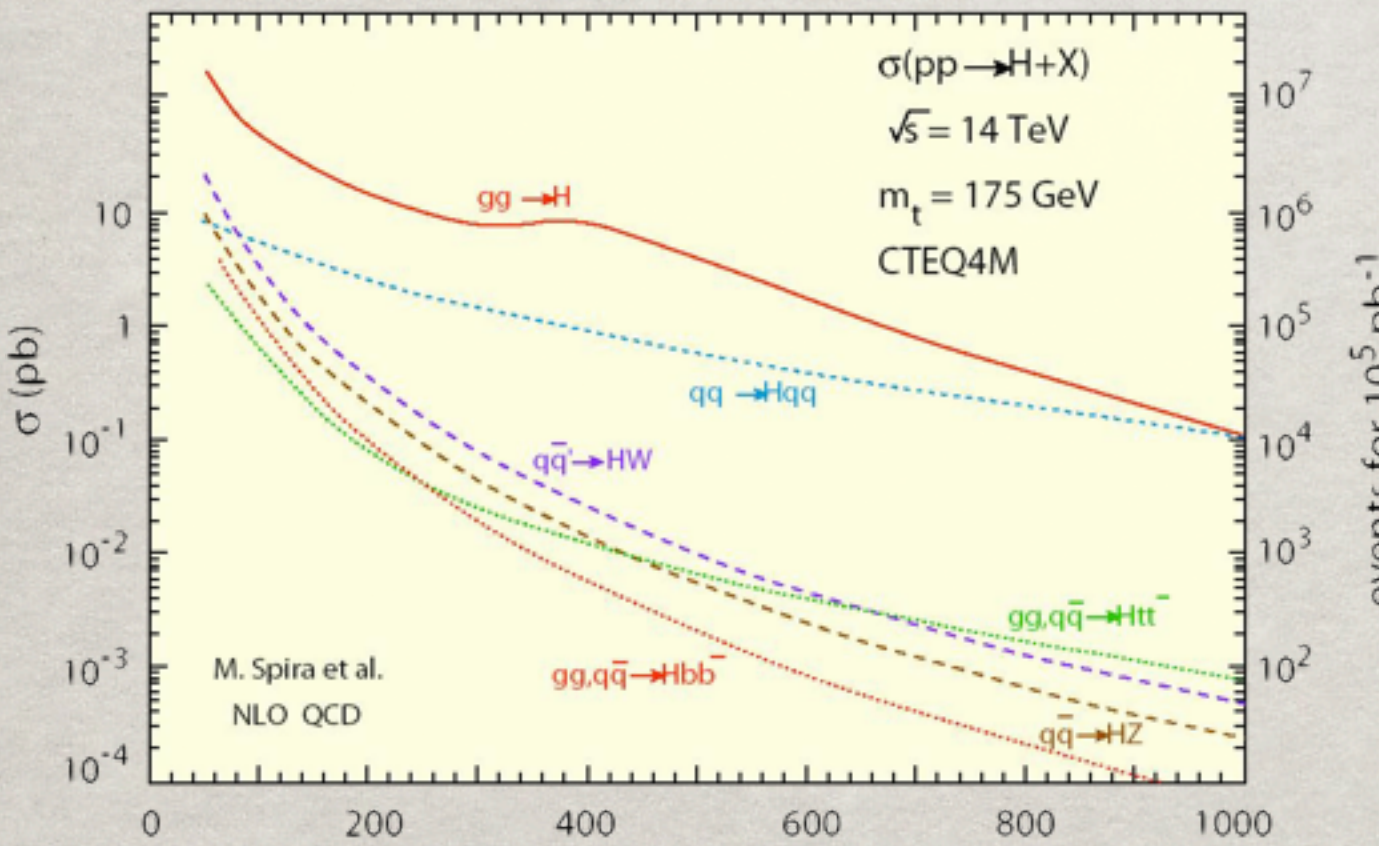
- aMC@NLO shows that an experimental analysis fully at NLO done without theory support is not science fiction any more !
- First fully working loop model in MG5: $N_f = 2$ massless QCD
- Have a look at our website! http://amcatnlo.cern.ch/, where you will find :
  - NLO event samples to be showered by the user
  - On-line running of validated aMC@NLO code for specific proc. (soon)
  - On-line running of MadLoop for a single phase-space point check.

Thanks

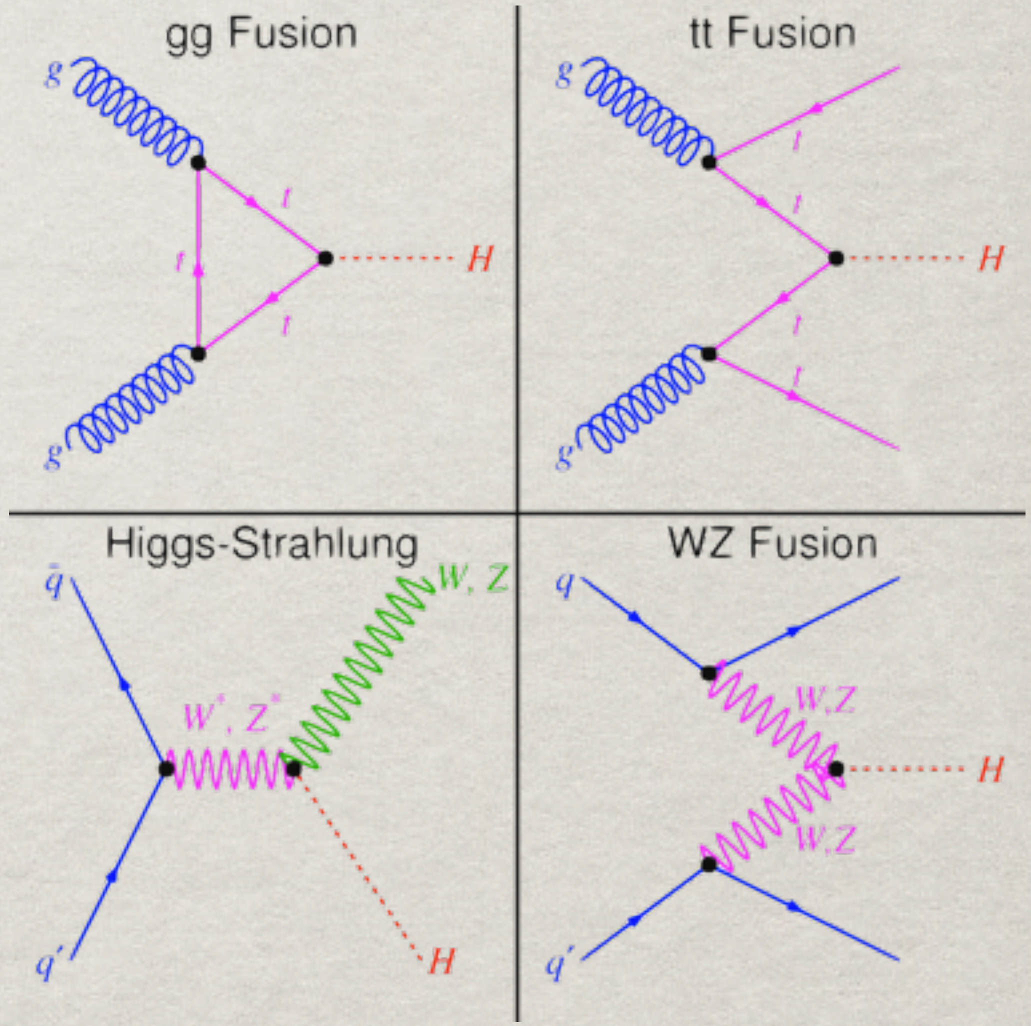
Additional Slides

Higgs Production

- Gluon fusion exclusively loop induce!
- Still very relevant compared to other production channels.



From CMS collaboration

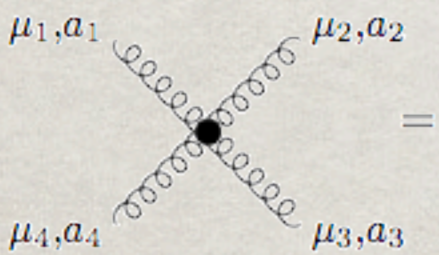


- But consider $H \to b\bar{b}$ and compare to $\sigma_{LHC}(b\bar{b}) = \mathcal{O}(10^8\ [pb])$!
- So accurate estimation of background process is crucial.

MadLoop in MG4

What it could not do

✓ No four-gluon vertex at born level :



$$= -\frac{ig^4 N_{col}}{96\pi^2} \sum_{P(234)} \Big\{ \Big[\frac{\delta_{a_1a_2}\delta_{a_3a_4} + \delta_{a_1a_3}\delta_{a_4a_2} + \delta_{a_1a_4}\delta_{a_2a_3}}{N_{col}} + 4\,Tr(t^{a_1}t^{a_3}t^{a_2}t^{a_4} + t^{a_1}t^{a_4}t^{a_2}t^{a_3})\,(3+\lambda_{HV}) - Tr(\{t^{a_1}t^{a_2}\}\{t^{a_3}t^{a_4}\})\,(5+2\lambda_{HV}) \Big] g_{\mu_1\mu_2}g_{\mu_3\mu_4} + 12\frac{N_f}{N_{col}} Tr(t^{a_1}t^{a_2}t^{a_3}t^{a_4}) \left(\frac{5}{3} g_{\mu_1\mu_3}g_{\mu_2\mu_4} - g_{\mu_1\mu_2}g_{\mu_3\mu_4} - g_{\mu_2\mu_3}g_{\mu_1\mu_4} \right) \Big\}$$

✓ All born contribution must factorize the same power of all coupling orders.

✓ No finite-width effects of unstable massive particles also appearing in the loop.

Set-up

- Three scenarios

  I) scalar Higgs H, with m_H = 120 GeV

  II) pseudo-scalar Higgs A, with m_A = 120 GeV

  III) pseudo-scalar Higgs A, with m_A = 40 GeV

- SM-like Yukawa coupling, $y_t/\sqrt{2}=m_t/v$

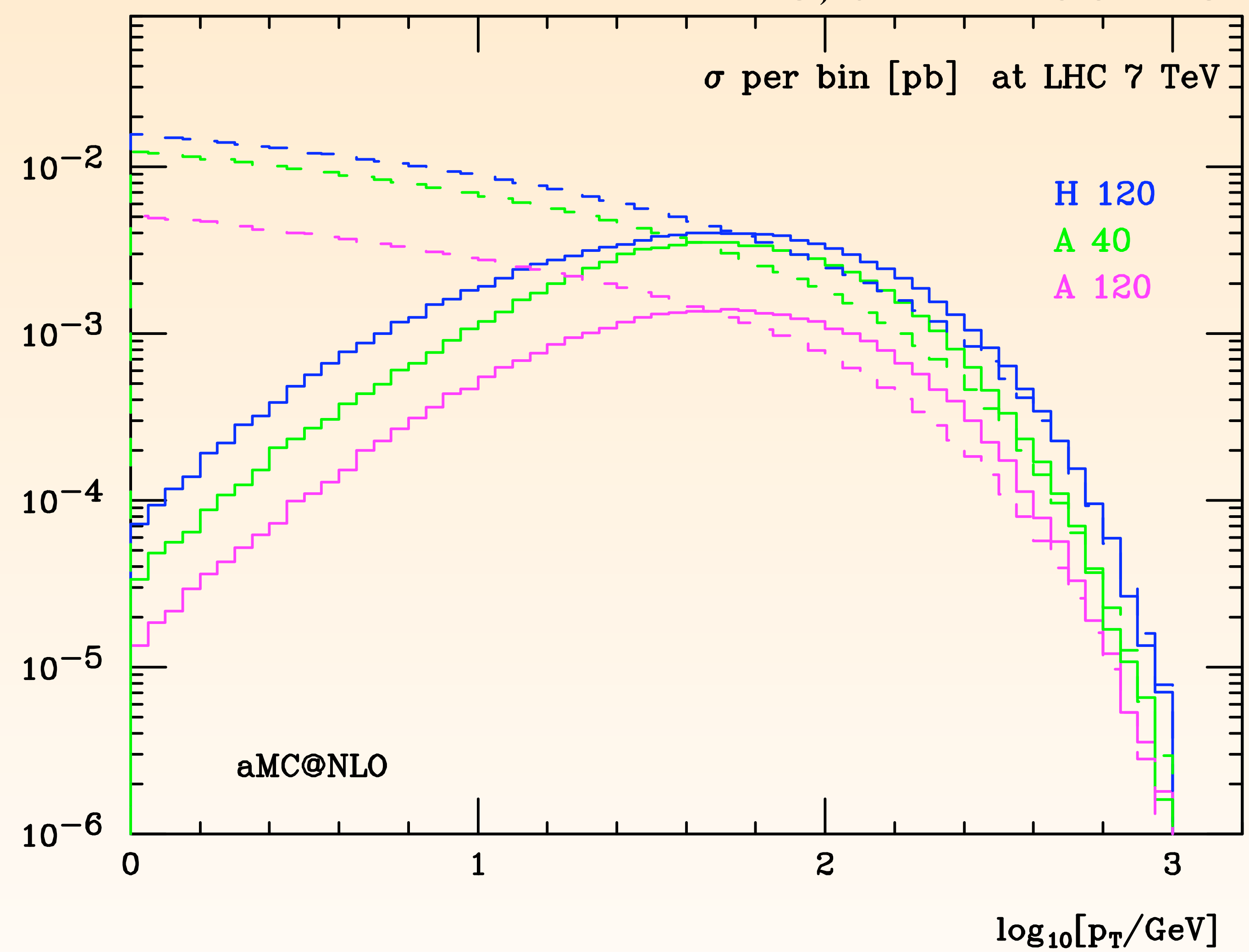
- Renormalization and factorization scales $\mu_F = \mu_R = \left(m_T^t m_T^{\bar{t}} m_T^{H/A}\right)^{\frac{1}{3}}$ with $m_T = \sqrt{m^2 + p_T^2}$ and $m_t^{pole} = m_t^{\overline{MS}} = 172.5$ GeV

- Note: first time that pp → ttA has been computed beyond LO

Impact of the shower

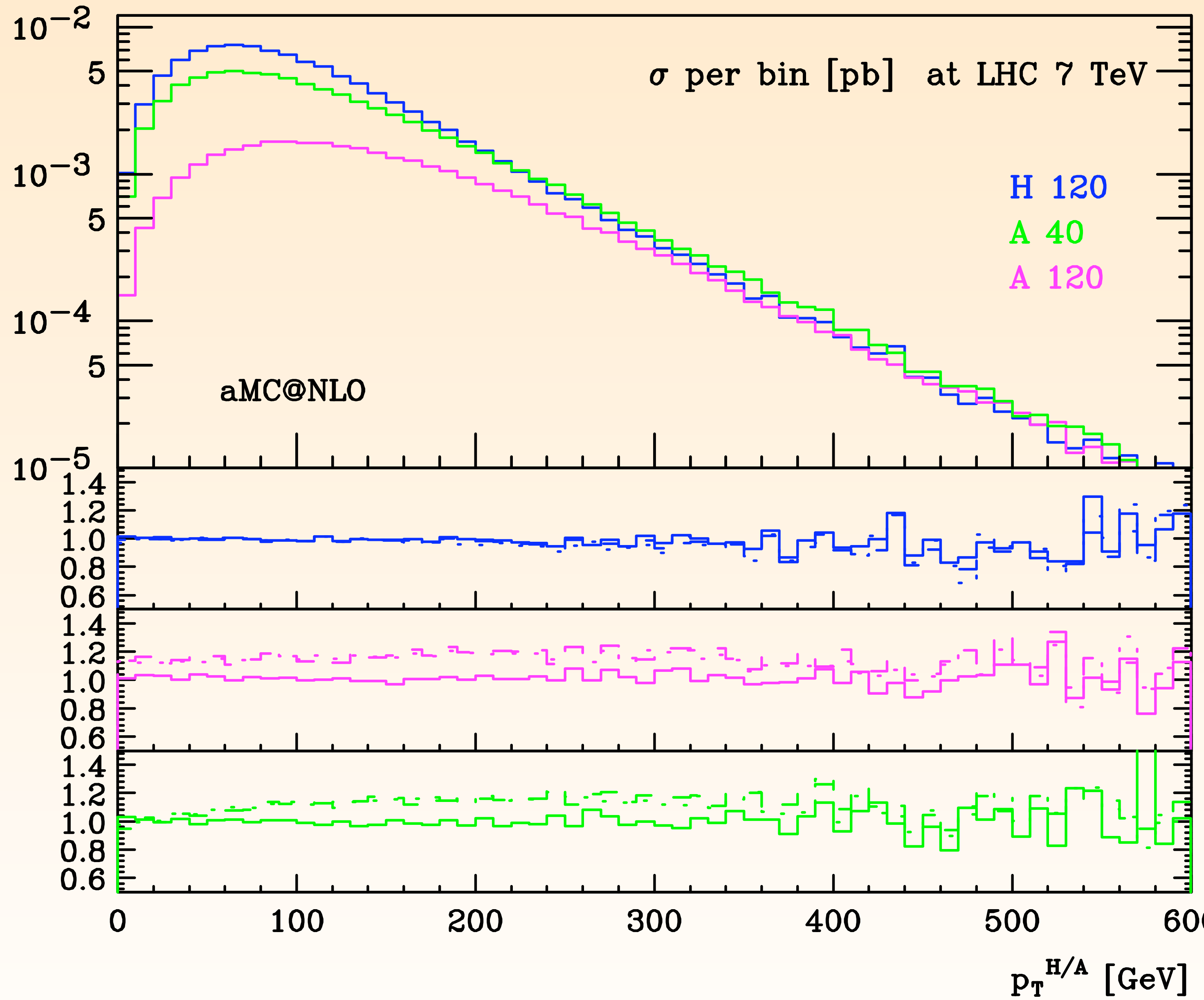
- Three particle transverse momentum, p_T(H/A t tbar), is obviously sensitive to the impact of the parton shower
- Infrared sensitive observable at the pure-NLO level for $p_T \to 0$
- aMC@NLO displays the usual Sudakov suppression
- At large p_T's the two descriptions coincide in shape and rate

Dashed: NLO, Solid: aMC@NLO



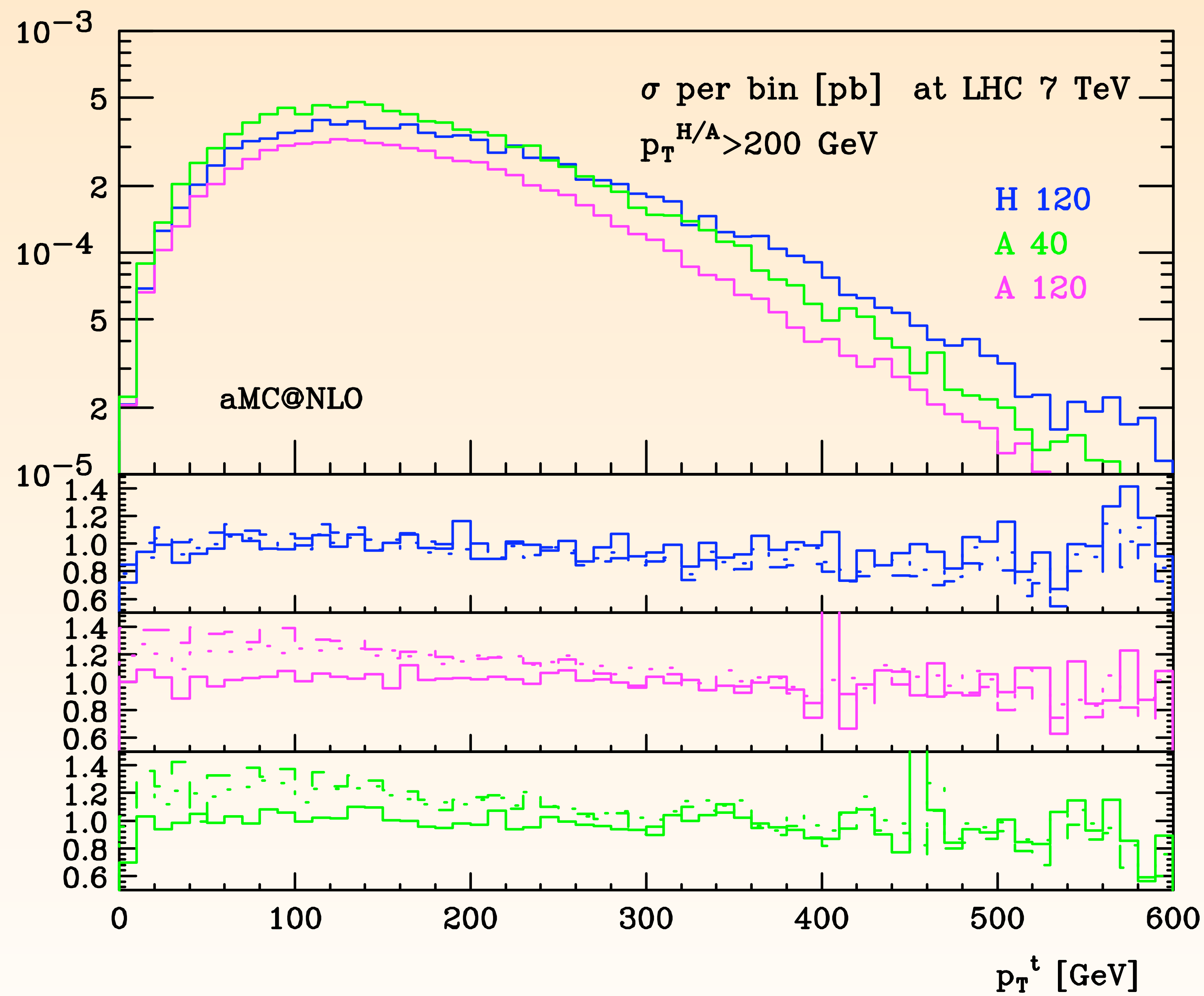
Higgs p_T

- Transverse momentum of the Higgs boson
- Lower panels show the ratio with LO (dashed), NLO (solid) and aMC@LO (dotted)
- Corrections are small and fairly constant
- At large p_T, scalar and pseudo-scalar production coincide: boosted Higgs scenario *[Butterworth et al., Plehn et al.]* should work equally well for pseudo-scalar Higgs



Boosted Higgs

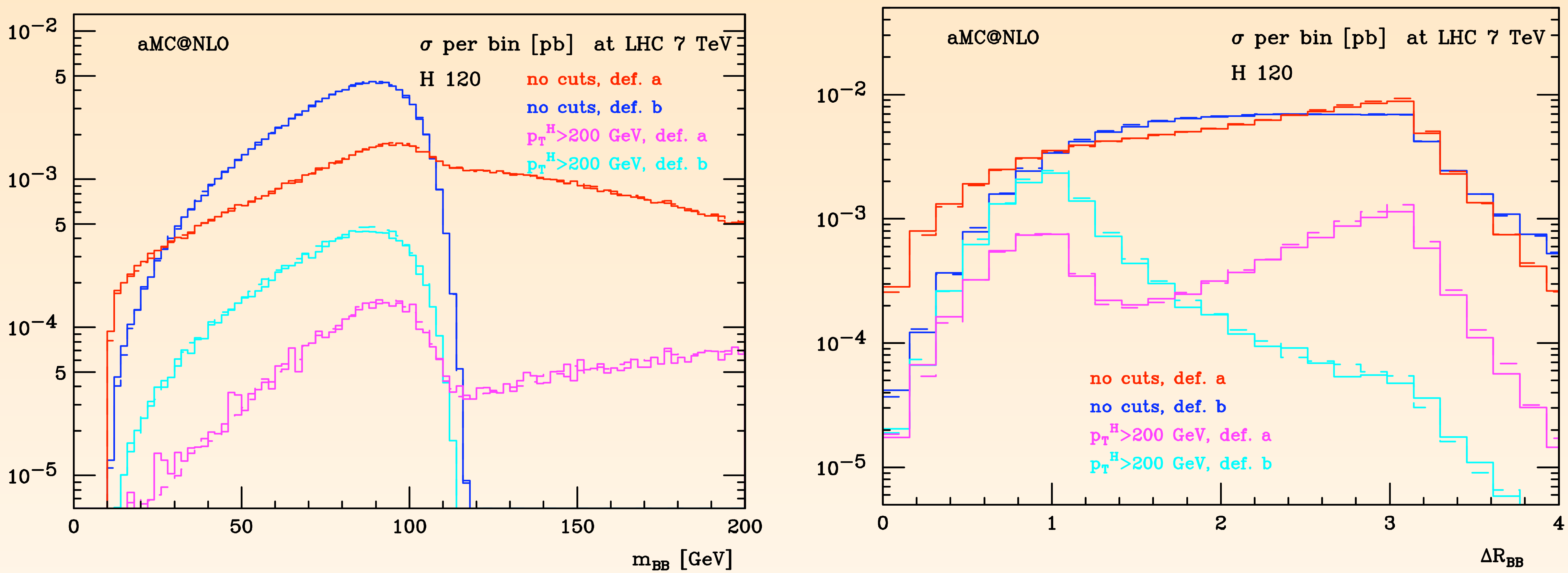
- Boosted Higgs: $p_T^{H/A} > 200$ GeV
- Transverse momentum of the top quark
- Lower panels show the ratio with LO (dashed), NLO (solid) and aMC@LO (dotted)
- Corrections compared to (MC@)LO are significant and cannot be approximated by a constant K-factor



Rikkert Frederix, May 5, 2011

TTH DECAYED

Dashed: aMC@LO, Solid: aMC@NLO



- Two definitions of the B hadron pair in these plots (assuming 100% b-tagging efficiency)
  - a) hardest pair in the event
  - b) decay products of the Higgs (uses MC truth)
- A cut on the p_T of the Higgs improves the selection of B hadrons from the Higgs decay