

HIGGS CHARACTERIZATION WITH aMC@NLO AND MADGRAPH5

FABIO MALTONI CENTRE FOR COSMOLOGY, PARTICLE PHYSICS AND PHENOMENOLOGY (CP3)





* Predictive = "QCD>tuning"



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MC = a code that can generate (unweighted) events



- Accurate and experimental friendly predictions for collider physics range from being very useful to strictly necessary.
- Confidence on possible excesses, evidences and eventually discoveries builds upon an intense (and often non-linear) process of description/prediction of data via MC's.
- Both measurements and exclusions rely on accurate predictions.
- Predictions for both SM and BSM on the same ground.

* Predictive = "QCD>tuning"

MC = a code that can generate (unweighted) events





MC (SIMPLIFIED) PROGRESS







- There are various ways to improve a Parton Shower Monte Carlo event generator with matrix elements:
 - ME+PS merging: Include matrix elements with more [Catani, Krauss, Kuhn, Webber, 2001] final state partons to describe hard, well-separated [M.L. Mangano, 2002] radiation better.





Matrix









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Works amazingly well...!!! Mature. Available in Alpgen, MadGraph and Sherpa. Studies/Improvements/developments for procs with b quarks on going.

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PREDICTIVE MC'S

- There are various ways to improve a Parton Shower Monte Carlo event generator with matrix elements:
 - ME+PS merging: Include matrix elements with more [Car final state partons to describe hard, well-separated radiation better.

[Catani, Krauss, Kuhn, Webber, 2001] [M.L. Mangano, 2002]

 NLO+PS matching: Include full NLO corrections to the matrix elements to reduce theoretical uncertainties in the matrix elements. The real-emission matrix elements will describe the hard radiation.

[Frixione & Webber (2002)] [Nason (2004)]



NLOWPS IN A NUTSHELL

$$d\sigma^{\text{NLO}+\text{PS}} = d\Phi_B \bar{B}^s(\Phi_B) \left[\Delta^s(p_{\perp}^{\min}) + d\Phi_{R|B} \frac{R^s(\Phi_R)}{B(\Phi_B)} \Delta^s(p_T(\Phi)) \right] + d\Phi_R R^f(\Phi_R)$$

with
$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B}) \right] \quad \stackrel{\text{Full cross section (if F=1) at fixed Born}}{\underset{\text{kinematics}}{\text{Kinematics}}} \right]$$

This formula is valid both for both MC@NLO and POWHEG

MC@NLO: $R^{s}(\Phi) = P(\Phi_{R|B}) B(\Phi_{B})$ Needs exact mapping $(\Phi_{B}, \Phi_{R}) \rightarrow \Phi$ POWHEG: $R^{s}(\Phi) = FR(\Phi), R^{f}(\Phi) = (1 - F)R(\Phi)$ F=1 = Exponentiates the Real.It can be damped by hand.



$PP \rightarrow H+JETS$ with finite mass corrections

H+jets MERGED in the HEFT available since a long time in Alpgen, Madgraph, Sherpa.

In total rates we know that large-m_{top} approximation works extremely well up (differences of the order of 0.5 % for mh<300 GeV !) [Harlander et al. (2009,2010), Steinhauser et al. (2009)]. In differential rates corrections show up only for very hard kinematics.



7 TeV-LHC

Illustrative example of **CONSISTENT** event-by-event reweighting: single events are generated in the HEFT, and then one by one reweighted by $|M_{loop}|^2$ / $|M_{HEFT}|^2$. (VERY DIFFERENT from reweighting based on one distribution!!)



$PP \rightarrow H+JETS$ WITH FINITE MASS CORRECTIONS

Application: Changes in the p_T spectrum of a mh=120 GeV with respect to the HEFT.



mh=120GeV@7TeV-LHC

Possible to extend this study to a pseudo scalar.



HIGGS PT : HEFT VS FULL THEORY

Heavy quark mass effects in $pp \rightarrow H + X$ at LHC7 (MC@NLO)



Beware : significant differences at small pT for the Higgs! This is due to the different treatment of the probability of the first emission within the two methods. Note that POWHEG has been now tuned to HqT at high pT.



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X=J^P WITH MADGRAPH5

[De Aquino et al. for HC2012]

$$0^{+} \qquad \mathcal{L}_{h} = -\frac{1}{4} g_{h} G^{a}_{\mu\nu} G^{\mu\nu,a} \Phi$$

$$0^{-} \qquad \mathcal{L}_{A} = \frac{1}{2} g_{A} G^{a}_{\mu\nu} \tilde{G}^{\mu\nu,a} \Phi_{A}$$

$$|^{-/+} \qquad \mathcal{L}_{V} = \bar{\psi} (a + b\gamma_{5}) \gamma^{\mu} \psi V^{\mu} + \operatorname{Int}(V_{\mu}, W^{+}_{\nu}, W^{-}_{\rho}) + \operatorname{Int}(V_{\mu}, Z_{\nu}, Z_{\rho})$$

$$2^{+} \qquad \mathcal{L}_{G} = -\frac{1}{\Lambda} T_{\mu\nu} \mathcal{T}^{\mu\nu}$$

Any other state/interaction comes from higher-dimensional operators and it is therefore suppressed. For all the above interactions **production and decay**, (possibly including interference with SM processes), can be inherited by **FEYNRULES** and then simulated in **MADGRAPH5** as inclusive merged samples for any production channel (which works out of the box).

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X=J^P WITH MADGRAPH5

[De Aquino et al. for HC2012]

You can now plot all you are interested in for production....



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X=J^P WITH MADGRAPH5

[De Aquino et al. for HC2012]

and production with SPIN CORRELATED decays:



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X=J^P WITH MADGRAPH5 : MADWEIGHT

[Artoisenet, De Aquino, FM, Mattelaer, in progress]

Since a few years, MadGraph has the possibility to test hypotheses using an automatized implementation of the Matrix Element Method using **MadWeight** [Artoisenet, Lemaitre, FM, Mattelaer, 1007.3300]

This can be applied to ANY process in the SM and BSM, including the effects of ISR.

Easy to apply the method to the spin and parity of $pp \rightarrow X \rightarrow VV + jets$ production.

X=J^P WITH MADGRAPH5 : MADWEIGHT

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aMC@NLO

[Alwall, Hirschi, Frederix, Frixione, FM, Mattelaer, Pittau, Torrielli, Zaro]

Mini-Higgs meeting Louvain

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aMC@NLO

[Alwall, Hirschi, Frederix, Frixione, FM, Mattelaer, Pittau, Torrielli, Zaro]



Modular structure in the **MADGRAPH5** framework:

Mini-Higgs meeting Louvain

aMC@NLO

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[Alwall, Hirschi, Frederix, Frixione, FM, Mattelaer, Pittau, Torrielli, Zaro]



Modular structure in the **MADGRAPH5** framework:

- MadLoop (w/ Cuttools)
- MadFKS for subtractions
- MC@NLO counterterms for Pythia6Q², Herwig, HW++. (Pythia8 validation on-going).

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aMC@NLO

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aMC@NLO POSSIBILITIES

The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power. It basically encompasses (and goes beyond) the current MCFM and POWHEG-Box libraries.

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Here you find a subset of processes that we have toind to test ANCHED to be able to access the liths in the table, resince in the seder-



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aMC@NLO possibilities

The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power. It basically encompasses (and goes beyond) the current MCFM and POWHEG-Box libraries.

- Signal simulation in the SM:
 - Automatic : e.g., $pp \rightarrow VBF, WH(+j), ZH(+j), ttH,...$
 - Available : pp→H +0,1,2 extra jets + FxFx (NLO) merging.
- Bkg simulation:
 - Automatic : e.g., pp→tt, tj, V V, V V, Vbb, V, Vj, Vjj, ttV,....
 - Available: QCD rich final states.
- Spin correlated decays can be obtained after event generation via MadSpin.
- Higgs characterization $pp \rightarrow X(J^P)$ +jets: codes publicly available.
- Extended Higgs sectors straightforward (in progress).





Mini-Higgs meeting Louvain

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Suppose now you are interested in studying HH production in VBF:

- ./bin/mg5
- > generate p p > H H j j [QCD]
- > output HHvbf
- > launch

or in studying spin-2 production in association with a vector boson:

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- ./bin/mg5
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- > launch

or in studying spin-2 production in association with a vector boson:

- > import model RS_NLO
- > generate p p > Gr Z, Gr > b b~ [QCD]
- > output vbf_gr
- > launch





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or in studying spin-2 production in association with a vector boson:

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- > output vbf_gr
- > launch

The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power so it improves with time. It already encompasses and goes beyond the currently public tools based on libraries (MCFM, POWHEG-BOX,..)



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aMC@NLO APPLICATIONS TO HIGGS PHYSICS

 $(Z/W \rightarrow ||/|_V)bb \qquad VV \rightarrow 4|$

For H, NLO results known (but no public code available) for scalar Higgs since some time. No results for pseudoscalar A were known.

ttH/tt/

First fully automatic results for both H and A.

Experimental grade distributions for decaying tops and Higgs can be plotted. Spin correlated decays included via MadSpin. Combinatorics very hard to manage, is improved in the boosted case.

10^{-2} aMC@NLO σ per bin [pb] at LHC 7 TeV= 5 H 120 no cuts, def. a no cuts, def. b p_{T}^{H} >200 GeV, def. a >200 GeV, def. b 10-3 5 10^{-4} 5 10^{-5} 0 50 100 150 200 m_{BB} [GeV]

[aMC@NLO:1104.5613]



aMC@NLO APPLICATIONS TO HIGGS PHYSICS

Z/W→II/Iv)bb

Extremely interesting QCD laboratory and background to the Higgs searches. Historically source of TH/EXP discrepancies at Tevatron and now at the LHC. Topological difference between Z and W.

ttH/ttA

Very different m_{bb} distributions. Full simulation for signal and background at NLOwPS!!



√→4|

aMC@NLO APPLICATIONS TO HIGGS PHYSICS

Several NLO and NLO+PS results available (Herwig++ and POWHEG-BOX).

NLO calculation includes γ^*/Z interference, full spin correlations and single resonant diagrams + one-loop gg channel.

First fully automatic NLO+PS results including automatic theoretical uncertainty band



aMC@NLO APPLICATIONS TO $X(J^{\mathsf{P}})$ physics

[P.Artoisenet, P. de Aquino, R. Frederix, F. Maltoni, M.~K. Mandal, P. Mathews, V. Ravindran, S. Seth, P.Torrielli, M. Zaro, for HC2012]

| Process | Codes | Plots | Extra info | | | | |
|---|-------|----------------------------------|--|--|--|--|--|
| Higgs characterization. Comparison plots: <u>pt of the "Higgs"</u> <u>rapidity of the "Higgs"</u> <u>jet rates</u> | | | | | | | |
| $pp \rightarrow 0^+ + X$ | Code | aMC@NLO+Pythia aMC@NLO+Herwig | Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Scalar resonance. Process generated in the HEFT model | | | | |
| $pp \rightarrow 0^- + X$ | Code | aMC@NLO+Pythia aMC@NLO+Herwig | Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Pseudo scalar resonance. Process generated in the HEFT model | | | | |
| $pp \rightarrow 1^- + X$ | Code | aMC@NLO+Pythia aMC@NLO+Herwig | Fully automatic in aMC@NLO. Vector resonance (Obtained from the Z using only vector coupling to quarks). | | | | |
| $pp \rightarrow 1^+ + X$ | Code | aMC@NLO+Pythia aMC@NLO+Herwig | Fully automatic in aMC@NLO. Pseudo vector resonance (Obtained from the Z using only axial coupling to quarks). | | | | |
| $pp \rightarrow (2^+ \rightarrow \gamma \gamma) + X$ | Code | aMC@NLO+Pythia aMC@NLO+Herwig | Virtuals Provided by Frederix et al. <u>arXiv:1209.6527</u> Code generated using the RS model. Spin 2 (graviton like) | | | | |
| More to come soon | | | | | | | |

http://amcatnlo.cern.ch

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aMC@NLO APPLICATIONS TO $X(J^P)$ PHYSICS

Shapes for 0 and 2 very similar and different from 1.

aMC@NLO APPLICATIONS TO $X(J^P)$ PHYSICS

Comparison between MLM-KT merged and **aMC@NLO**

The p_T shapes and jet rates are harder in the merged samples.

aMC@NLO APPLICATIONS TO $X(J^P)$ PHYSICS

Comparison between MLM-KT merged and **aMC@NLO**

Quite different spectra between spin 0 and spin 2 hypothesis. Very consistent p_T shapes between k_T -MLM and **aMC@NLO**.

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CONCLUSIONS

- The MADGRAPH5 framework offers a flexible platform for LO and NLO automatic simulations in the SM and BSM.
- **aMC@NLO** is now public (8 Nov 2012).
- Many applications to Higgs physics available:
 - At LO, any production channel for X(J^P) is possible, including multi-jet merging.
 - Signal simulation **aMC@NLO**:
 - All SM procs:
 - $pp \rightarrow H + jets$ including b,t mass effects (at two loops) in <u>MC@NLOv4.09</u>.
 - $pp \rightarrow H + jets$ with FxFx (NLO) merging available.
 - pp→VBF,VH,ttH,...
 - Higgs characterization $pp \rightarrow X(J^P)$ +jets: codes publicly available.
 - Bkg simulation aMC@NLO: pp→VV,Vbb,Vjj,...

MERGING AT NLO

PREDICTIVE MC'S

- There are various ways to improve a Parton Shower Monte Carlo event generator with matrix elements:
 - ME+PS merging: Include matrix elements with more final state partons to describe hard, well-separated radiation better.
 - NLO+PS matching: Include full NLO corrections to the matrix elements to reduce theoretical uncertainties in the matrix elements. The real-emission matrix elements will describe the hard radiation.
 - NLO+PS matching+merging: Include full NLO for each jet multiplicity and merge the various multiplicities

[Catani, Krauss, Kuhn, Webber, 2001] [M.L. Mangano, 2002]

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[Frixione & Webber (2002)] [Nason (2004)]

[Hoche, Krauss, Schonherr, Sieger (2012)]

[Frixione, Frederix (2012)]

FXFX MULTI-JET MERGING IN aMC@NLO

[Frederix, Frixione, 1209.6215]

- **aMC@NLO** samples for S+0j, S+1j, S+2j, S+...j consistently without double counting (where S can be a Higgs, a ttbar pair, a W-boson, etc.)
- Use techniques from CKKW/MLM and multi-scale improved fixed order NLO or "MINLO" (Hamilton, Nason & Zanderighi, 2012) to define exclusive event samples for S+0j, S+1j, etc.
 - In such a way that the exclusive samples can simply be combined to one big event sample
- Special care needed for the highest multiplicity sample

FXFX MULTI-JET MERGING IN aMC@NLO

- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with H+0j at MC@NLO and H+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale

FXFX MULTI-JET MERGING IN aMC@NLO

• Differential jet rates for $I \rightarrow 0$ and $2 \rightarrow I$

FXFX MULTI-JET MERGING IN aMC@NLO

- Matching up to 2 jets at NLO : consistent with up to 1 more jet.
- Method works for ttbar+jets and W+jets equally well.

aMC@NLO LIMITATIONS AND PLANS (STATUS)

- QCD corrections only
- SM processes (+ weak BSM) only

NOW

- Pythia6Q², Herwig, HW++
- Rather simple final state with up to l or max 2 extra jets
- Loop induced procs not automatic yet
- FxFx merging not automatic yet

→NLO EW (development)

FUTURE (status)

- ⇒ SUSY (on-going)
- → Pythia8 (validation)
- Multiparton optimizations (development)
- → Automation (on-going)
- → Automation (to do)

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HEAVY HIGGS

(a)MC@NLO APPLICATIONS TO HIGGS PHYSICS

[Hirschi, Frixione, Laureys, Maltoni]

aMC@NLO web page

| The project | Special Needs | | | | | | |
|--|---|----------------------------|------------------|---|--|--|--|
| Home People Contact News | Here you find a collectio | ns of codes for special ne | eeds. | | | | |
| MC Tools | Process | Codes | Info | Comments | | | |
| (registration needed) | Inclusive Heavy Higgs in VV >4 leptons final states : codes for background+interference. MC@NLO code for the signal at NLO with full heavy quark dependence is available <u>here</u> . | | | | | | |
| Download aMC@NLO Help and FAQs Event samples DB Special Codes | g g > W+ W- > e+ ve mu- vm~ | Code | <u>More info</u> | Virtual provided by MCFM and MadLoop. Features the interference of the Higgs with the continuum WW background. | | | |
| Communication | g g > e+ e- mu+ mu- | Code | More Info | Virtual provided by MCFM and MadLoop. Features the interference of the Higgs with | | | |
| Citations | | | | the continuum 22 background. | | | |
| Publications Talks & Seminars | g g > e+ e- vm vm~ | Code | More Info | Virtual provided by MCFM and MadLoop. Features the interference of the Higgs with | | | |
| Resources | | | | the continuum 22 background. | | | |
| Useful links File Sharing | g g > e+ e- ve ve~ | Not yet available | <u>More Info</u> | In progress. Features the interference of the Higgs with the continuum WW/ZZ background. | | | |

(a)MC@NLO APPLICATIONS TO HIGGS PHYSICS

[Hirschi, Frixione, Laureys, Maltoni]

A MadLoop based code generates:

$\sigma_{\mathrm{S+i+B}}^{\mathrm{LO}} = |\mathcal{M}_{\mathrm{S}}|^2 + 2\operatorname{Re}(\mathcal{M}_{\mathrm{S}}\mathcal{M}_{\mathrm{B}}^*) + |\mathcal{M}_{\mathrm{B}}|^2$

Events for the signal at NLO accuracy can be generated via the latest MC@NLOv4.09 i.e. with the FULL TOP AND BOTTOM MASS DEPENDENCE UP TO TWO LOOPS (in the virtuals) and ONE LOOP in the real contributions.

One can combine Signal and Interference+Background ADDITIVELY, schematically:

$$\sigma_{\mathrm{S}}^{\mathrm{NLO}} + \sigma_{\mathrm{i+B}}^{\mathrm{LO}} = \sigma_{\mathrm{S}}^{\mathrm{NLO}} + 2\operatorname{Re}(\mathcal{M}_{\mathrm{S}}\mathcal{M}_{\mathrm{B}}^{*}) + |\mathcal{M}_{\mathrm{B}}|^{2}$$

(a) MC@NLO APPLICATIONS TO HIGGS PHYSICS

[Hirschi, Frixione, Laureys, Maltoni]

any loop induced proc in SM and BSM

(a) MC@NLO APPLICATIONS TO HIGGS PHYSICS

[Hirschi, Frixione, Laureys, Maltoni]

| Available : | | | ZZ invariant mass distribution |
|--|----------|------------------|---|
| $gg(\rightarrow H) \rightarrow ZZ \rightarrow 4 \ell$ | | 10 ⁻⁴ | $ \begin{bmatrix} \mathbf{r} & \mathbf{r} & \mathbf{r} \\ \mathbf{r}$ |
| $gg(\rightarrow H) \rightarrow ZZ \rightarrow l l NN$ | (nid/dq | 10 ⁻⁵ | $\begin{bmatrix} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\$ |
| $gg(\rightarrow H) \rightarrow WW \rightarrow ll N N$ | | | LHC@8TeV, cteq6m |
| gg →HH (SM) | sigma (j | 10 | $ m_{\rm h} = 600 \; {\rm GeV} $ $ \mu = \sqrt{m_{\rm h}^2 + p_{\rm T_{\rm h}}^2} $ |
| On going : | | 10 ⁻⁷ | $\begin{array}{c} m_{e-e+} > 30 \ \text{GeV} \\ p_{T}(e^{\pm}) > 20 \ \text{GeV} \\ \eta(e^{\pm}) < 2.5 \end{array}$ |
| $gg(\rightarrow H) \rightarrow WW/ZZ \rightarrow ll n n$ | | | 600 800 1000 |
| gg →H H' (BSM) | | | M(e-,e+,ve,vex) (GeV) |
| any loop induced proc in SM and BS | SM | | |

MADSPIN

[Artoisenet, Frederix, Mattelaer, Rietkerk. ready to go, to appear]

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THE MADSPIN DECAY PACKAGE

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Anything in between?

Mini-Higgs meeting Louvain

THE MADSPIN DECAY PACKAGE

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$$|M_{P+D}|^2 / |M_P|^2 > \text{Rand}() \max(|M_{P+D}|^2 / |M_P|^2)$$

• Validated with for t t~ and singletop

Frixione, Laenen, Motylinski & Webber, hep-ph/0702198

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σ∕bin (pb)

Fabio Maltoni