MadGraph 5 Developments and Plans

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ATLAS/CMS/LPCC MC workshop, CERN
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(Most slide from Johan Alwall)

ATLAS/CMS/LPCC MC workshop, CERN
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Huge news!

Completely automated simulations at next-to-leading order in QCD, matched to shower, now public (aMC@NLO in MG5 v. 2.0 beta)!

- No-need-for-theorist NLO simulations that can be immediately interfaced to detector sim, for any $2 \rightarrow 3$ and many $2 \rightarrow 4$ and higher processes within the SM, at reasonable computer time

- You will hear (and have already heard!) much more about this from other speakers at this meeting!
• So I will focus on “LO” developments
• As per request, special focus on matching with b-quarks (public, but still under validation)
• Also present some exciting upcoming developments in the next few months!
Core news since MG5 release - Quick list

- Lots of speedups and improvements, including
  - Huge speedup of gridpacks
  - Vast speedup for long decay chains with multiparticle decays
  - Huge improvements in user interface
  - Multi cluster support

- New 4-flavor matching and VBF-type matching

- 4 fermion vertices in FR+MG5 (except Majorana)

- Spin 3/2 particles in FR+MG5

- Complex mass scheme

- Feynman gauge

- Handling of negative weights

- On-the-fly 2-body decay width calculations (“Auto width”)
News from our friends

- **FeynRules** (C. Duhr, B. Fuks et al)
  - SLagrangians in superspace formalism
  - Automatic 2-body width expressions
  - Automatic renormalization group equations (soon!)
  - Automatic mass matrix diagonalization (soon!)

- **MadAnalysis 5** (B. Fuks et al)
  - Super flexible, fast, user friendly analysis suite
  - Arbitrary weights (also negative)
  - Automatic systematics uncertainty bands (soon!)

- **MadGolem** (Goncalves-Netto, Plehn et al)
  - Automated NLO SUSY production cross sections
“LO” upcoming developments - Quick list

- Automatic matching to Pythia 8
  - CKKW-L matching (S. Pretzel et al)

- Automatic scale/PDF/matching systematics (A. Kalogeropoulos et al)

- Fast multiparton processes using color-ordered recursion

- MadSpin (full spin correlations for LO&NLO decays) (P. Artoisenet et al)
  - Combined with MadSpin for full spin correlations

- MadDecay: Automatic BSM decay width suite (including needed 3- and 4-body widths and decay of event file) (C-H Shen et al)
  - Combined with MadSpin for full spin correlations

- MadDM: Relic density calculations and direct detection limits for any BSM model (K.C. Kong et al)

- MadWeight5: Matrix-Element Method (P. Artoisenet et al)
Recap: “What is MG5”

• MadGraph 5 is a completely new (released spring 2011) matrix element generator written in Python
  • Can handle ANY model (that can be written as a Lagrangian), conveniently output by FeynRules
    ➡ Any Lorentz structure for any spin (up to 2) and color (6tets, $\varepsilon^{ijk}$)
    ➡ Multiparticle vertices for any multiplicity, multifermion vertices
• Super fast process generation
• Unlimited-length decay chains with full BW and spin effects
• Event generation speedups by orders of magnitude
• Output in multiple languages and formats (including Pythia 8)
• Super-user-friendly command line interfaces
Decay chains

Results for $g g \rightarrow g g g$, $(g g \rightarrow t_1 t^-, t^- \rightarrow b^- a l l \ a l l / h^+, (t_1 \rightarrow t n_1, t \rightarrow b a l l \ a l l / h^+))$ in the mssm

Available Results

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<th>Events</th>
<th>Tag</th>
<th>Run</th>
<th>Collider</th>
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</tr>
</tbody>
</table>

(See backup slides for discussion about physics validity)
User Interface

- Nice Interactive session
- Auto-completion
- Tutorial
- interactive help

- Simple command set
- import model sm
- generate p p > e+ e-
- output FORMAT MY_DIR
- launch
User Interface

- Nice Interactive session
- Auto-completion
- Tutorial
- Interactive help

If you test it, you are going to like it!

- Simple command set
- Import model sm
- Generate p p \rightarrow e^+ e^-
- Output FORMAT MY_DIR
- Launch

**Welcome to MadGraph 5**

**Version 1.3.16**

The MadGraph Development Team - Please visit us at 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
Matching in MG + Pythia 6

J.A. et al. [arXiv:0706.2569],
J.A., de Visscher, Maltoni [arXiv:0810.5350],
MadGraph wiki

- MLM-style matching
  - Classic cone-jet matching (à la AlpGen),
    $k_T$-jet matching, and “shower-$k_T$” matching

- Easily adopted to different shower algorithms
  (e.g., virtuality- and $p_T$-ordered showers in Pythia 6)

- Official CMS SM background simulation
  - Excellent agreement with data across the line

- Fully supports matching for any NP process

- Restriction: Matching of jets from core process, not from
  decay products (let Pythia ME corr. take care of that)
MLM algorithm in a nutshell

1. Generate ME events (with different parton multiplicities) using parton-level cuts ($p_T^{ME}/\Delta R$ or $k_T^{ME}$)

2. Cluster each event and reweight $\alpha_s$ and PDFs based on the scales in the corresponding clustering vertices

3. Run the parton shower with starting scale $t_0 = m_T$.

4. Check that the number of jets after parton shower is the same as ME partons, and that all jets after parton shower are matched to the ME partons at a scale $Q^{\text{match}}$. If yes, keep the event. If no, reject the event. $Q^{\text{match}}$ is called the matching scale.

5. For highest multiplicity, allow radiation $<$ lowest ME scale

(See backup slides for pedagogic discussion)
Matching with b-quarks

- When matching with b-quarks, two options:
  1. b as any parton (5-flavor scheme)
     
        No special treatment needed, just use regular matching

  2. b as massive final-state particle only (4-flavor scheme)
Matching with b-quarks

- In 5-flavor matching, just need to pick out events with b:s from all-inclusive sample
  - Below $Q^{\text{match}}$, b’s given by shower gbb splittings

- In 4-flavor matching, no cut on b:s (allowing, 0, 1 or 2 energetic b’s in event)
  - Need to remove b’s from Sudakov treatment (Pythia clustering), but make sure to veto too-hard FSR from b
  - Question: How to deal with alpha_s reweighting of b vertices and factorization scales?
Matching with b-quarks

- If this configuration given by shower, scale for the $b$ and $\bar{b}$ vertices would be given by $m_{Tb}$ and $m_{T\bar{b}}$

- Shower prescription works well in 5-flavor matching, so let's use the same also for the 4-flavor scheme

- Special difficulty: Factorization scale. In principle, parton line stops at the $gbb$ vertex, however, $Z$ sets central scale for process
  - Use geometric average $m_{TZ}m_{Tb}$ for factorization scale
  - Gives smooth matching to Pythia PS
Matching with b-quarks

Shower ➡ ME

→ Gives smooth matching to Pythia PS
Summary

• MadGraph 5 is a heavily used matrix element generator and MC simulator for both SM and BSM
• Jet matching in SM and any BSM model
• News include 4-flavor b and VBF matching, new gauges and mass schemes, even more BSM functionality
• Biggest news (this month!): aMC@NLO
• Lots of news upcoming in the next few months, including: MadDecay, MadSpin, MadDM, Pythia 8 matching, automatic systematics bands, fast multipartons, ...
• Keep updated at http://launchpad.net/madgraph5!
Backup slides
Decay chains

- Decay chains retain **full matrix element** for the diagrams compatible with the decay
- Full spin correlations (within and between decays)
- Full width effects
- However, no interference with non-resonant diagrams
  - Description only valid “near” pole mass
  - Cutoff at $|m \pm n\Gamma|$ where $n$ is set in run_card.
B Matching

- $bb\sim W$ matching with scale $m_t(W)$

- Gives NOT smooth matching to Pythia PS
Matching in New Physics production

- Matching necessary also in NP production whenever QCD radiation jets are important
  - When small mass differences in hadronic decays make decay jets softer than radiated jets
  - When recoil of NP system against initial state radiation is important

- Special difficulty: Double-counting due to onshell decays to jets

J.A., de Visscher, Maltoni [arXiv:0810.5350]
Double counting of decays

- Special difficulty in e.g. SUSY matching:
  Double counting due to on-shell decays to jets!

Decays double-counted
with on-shell gluino
production and subsequent
decay
Double counting of decays

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Decays double-counted with on-shell gluino production and subsequent decay
Double counting of decays

- This has been solved in MadGraph 5 by the “$” syntax
  
  \begin{verbatim}
  mg5> import model mssm
  mg5> generate p p > dr dr~ j j $ go
  \end{verbatim}

- This removes any on-shell gluinos from the event generation (where on-shell is defined as \( m \pm n \cdot \Gamma \) with \( n \) set by \texttt{bwcutoff} in the run\_card.dat)

- The corresponding region is exactly filled if you run gluino production with gluinos decaying to dr j (using the same \texttt{bwcutoff}).
Double counting of decays

Invariant mass distributions of $d_r$ squark and $d$ quark

$p\ p > dr\ dr~d \& go$

$p\ p > dr\ go, go > dr~d$
Double counting of decays

Invariant mass distributions of $d_r$ squark and $d$ quark

$$p\ p > \ dr\ dr~ d \ $ go$$

$$p\ p > \ dr\ go,\ go > \ dr~ d$$
Matching for initial state radiation
Matching for initial state radiation

- Look at what Parton Shower gives us
Matching for initial state radiation

- Look at what Parton Shower gives us
- Modify ME to ensure smooth matching near $Q^{\text{match}}$

$$\mathcal{P} = (\Delta_{Iq}(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{gq}(z)}{z} \frac{f_q(x_1, t_1)}{f_q(x_1', t_1)} \frac{\alpha_s(t_2)}{2\pi} \frac{P_{qg}(z')}{z'}$$

$$\times \hat{\sigma}_{q\bar{q}\rightarrow e\nu}(\hat{s}, \ldots) f_q(x_1', t_0) f_{\bar{q}}(x_2, t_0)$$
Matching for initial state radiation

- Look at what Parton Shower gives us
- Modify ME to ensure smooth matching near $Q^{\text{match}}$

$$\mathcal{P} = \left( \Delta I_q(t_{\text{cut}}, t_0) \right)^2 \Delta g(t_2, t_1) \Delta q(t_{\text{cut}}, t_2) \frac{\alpha_s(t_1)}{2\pi} \frac{P_{q\bar{q}}(z)}{z} \frac{f_q(x_1, t_1)}{f_{\bar{q}}(x'_1, t_1)} \frac{\alpha_s(t_2)}{2\pi} P_{q\bar{q}}(z')$$

$$\times \hat{\sigma}_{q\bar{q} \rightarrow e\nu} (\hat{s}, \ldots) f_q(x'_1, t_0) f_{\bar{q}}(x_2, t_0)$$
Matching for initial state radiation

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\[ P = (\Delta I_q(t_{\text{cut}}, t_0))^2 \Delta g(t_2, t_1)(\Delta q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} P_{gq}(z) \frac{f_q(x_1, t_1)}{f_q(x'_1, t_1)} \frac{\alpha_s(t_2)}{2\pi} P_{qg}(z') \]

\[ \times \hat{\sigma}_{q\bar{q} \rightarrow e\nu}(\hat{s}, \ldots) f_q(x'_1, t_0) f_{\bar{q}}(x_2, t_0) \]
Matching for initial state radiation

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- Modify ME to ensure smooth matching near $Q^{\text{match}}$

\[ \mathcal{P} = (\Delta_{Iq}(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{gq}(z)}{z} \frac{f_q(x_1, t_1)}{f_\bar{q}(x'_1, t_1)} \frac{\alpha_s(t_2)}{2\pi} P_{qg}(z') \times \hat{\sigma}_{q\bar{q} \rightarrow e\nu} (\hat{s}, ...) f_q(x'_1, t_0) f_\bar{q}(x_2, t_0) \]
Matching for initial state radiation

- Look at what Parton Shower gives us
- Modify ME to ensure smooth matching near $Q^{\text{match}}$

$$\mathcal{P} = (\Delta_I q(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1) (\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{qg}(z)}{z} \frac{f_q(x_1, t_1)}{f_q(x_1', t_1)} \frac{\alpha_s(t_2)}{2\pi} \frac{P_{gq}(z')}{z'}$$

$$\times \hat{\sigma}_{q\bar{q} \rightarrow e\nu}(\hat{s}, ...) f_q(x_1', t_0) f_{\bar{q}}(x_2, t_0)$$
Matching for initial state radiation

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Matching for initial state radiation

\[
(\Delta_{Iq}(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{gq}(z)}{z} \frac{f_q(x_1, t_1)}{f_q(x'_1, t_1)} \frac{\alpha_s(t_2)}{2\pi} P_{qg}(z') \\
\times \hat{\sigma}_{q\bar{q}\rightarrow e\nu}(\hat{s}, \ldots) f_q(x'_1, t_0) f_{\bar{q}}(x_2, t_0)
\]
Matching for initial state radiation

\[
(\Delta_{Iq}(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1) (\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{gq}(z)}{z} \frac{f_q(x_1, t_1)}{2\pi} \frac{\alpha_s(t_2)}{2\pi} \frac{P_{gq}(z')}{z'} \times \hat{\sigma}_{q\bar{q} \to e\nu}(\hat{s}, \ldots) f_q(x'_1, t_0) \bar{f}_q(x_2, t_0)
\]

ME with \(\alpha_s\) evaluated at the scale of each splitting
Matching for initial state radiation

\[
(\Delta_{Iq}(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{gq}(z)}{z} \frac{f_q(x_1, t_1)}{2\pi} \frac{\alpha_s(t_2)}{2\pi} P_{qg}(z') \\
\times \hat{\sigma}_{q\bar{q} \rightarrow e\nu}(\hat{s}, \ldots) f_q(x'_1, t_0) f_{\bar{q}}(x_2, t_0)
\]

ME with $\alpha_s$ evaluated at the scale of each splitting

PDF reweighting
Matching for initial state radiation

\[(\Delta_Iq(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q(t_{\text{cut}}, t_2))^2 \frac{\alpha_s(t_1)}{2\pi} \frac{P_{gq}(z)}{z} \frac{f_q(x_1, t_1)}{f_q(x_1', t_1)} \frac{\alpha_s(t_2)}{2\pi} \frac{P_{gq}(z')}{z'} \times \hat{\sigma}_{q\bar{q} \rightarrow e\nu}(\hat{s}, \ldots) f_q(x_1', t_0) f_{\bar{q}}(x_2, t_0)\]

ME with $\alpha_s$ evaluated at the scale of each splitting

PDF reweighting

Sudakov suppression due to non-branching above scale $t_{\text{cut}}$
Matching for initial state radiation

We want to simulate $pp \rightarrow Z + \text{jets}$. We pick (according to the relative cross-section of the processes) a $u \bar{d} W_d \bar{d}$ event. We pick momenta according to the pdf-weighted matrix element

$$|M_{u \bar{d} W_d \bar{d}}(x_1, x_2, s(d_{\text{ini}}))|^2 \left[ f_{u}(x_1, d_{\text{ini}}) f_{\bar{d}}(x_2, d_{\text{ini}}) \right]$$

We cluster the event using the boost-invariant $k_T$ clustering scheme, to get nodes $d_1$, $d_2$, $d_3$ as shown.

We apply the $s$ and Sudakov weight $(s(d_3), d_{\text{ini}})$, $(s(d_2), d_{\text{ini}})$, $(s(d_1), d_{\text{ini}})$.

We apply initial-state radiation for the incoming $u$ and $\bar{d}$ starting at $d_3 = M_W$, and final-state radiation for the outgoing $d$ and $\bar{d}$ starting at $d_2$, but veto all emissions above $d_{\text{ini}}$ (in both initial- and final-state showers).
Matching for initial state radiation

- Again, use a clustering scheme to get a parton shower history
Matching for initial state radiation

- Again, use a clustering scheme to get a parton shower history

![Diagram of initial state radiation matching]
Matching for initial state radiation

- Again, use a clustering scheme to get a parton shower history
- Now, reweight both due to $\alpha_s$ and PDF

$$|\mathcal{M}|^2 \to |\mathcal{M}|^2 \frac{\alpha_s(t_1)}{\alpha_s(t_0)} \frac{\alpha_s(t_2)}{\alpha_s(t_0)} \frac{f_q(x'_1, t_0)}{f_q(x'_1, t_1)}$$
Matching for initial state radiation

- Again, use a clustering scheme to get a parton shower history
- Now, reweight both due to $\alpha_s$ and PDF

$$|\mathcal{M}|^2 \rightarrow |\mathcal{M}|^2 \frac{\alpha_s(t_1) \alpha_s(t_2)}{\alpha_s(t_0)^2} \frac{f_q(x'_1, t_0)}{f_q(x'_1, t_1)}$$

- Remember to use first clustering scale on each side for PDF scale: $\mathcal{P}_{\text{event}} = \hat{\sigma}(x_1, x_2, p_3, p_4, \ldots) f_q(x_1, t_1) f_{\bar{q}}(x_2, t_0)$
MLM matching

[ML. Mangano, ~2002, 2007]
[J.A. et al 2007, 2008]
MLM matching

- The simplest way to do the Sudakov suppression is to run the shower on the event, starting from \( t_0 \)!

\[
|M.L. \text{ Mangano, } \sim 2002, 2007| \\
|J.A. \text{ et al 2007, 2008}|
\]
MLM matching

- The simplest way to do the Sudakov suppression is to run the shower on the event, starting from $t_0$!

[$[M.L. \text{ Mangano}, \sim 2002, 2007]$  
[J.A. et al 2007, 2008]
MLM matching

- The simplest way to do the Sudakov suppression is to run the shower on the event, starting from $t_0$!

- Perform jet clustering after PS - if hardest jet $k_{T1} > t_{\text{cut}}$ or there are jets not matched to partons, reject the event
MLM matching

- The simplest way to do the Sudakov suppression is to run the shower on the event, starting from $t_0$!

- Perform jet clustering after PS - if hardest jet $k_{T1} > t_{cut}$ or there are jets not matched to partons, reject the event.

- The resulting Sudakov suppression from the procedure is
  
  $$\left(\Delta_{Iq}(t_{cut}, t_0)\right)^2 \left(\Delta_q(t_{cut}, t_0)\right)^2$$

  which turns out to be a good enough approximation of the correct expression

  $$\left(\Delta_{Iq}(t_{cut}, t_0)\right)^2 \Delta_g(t_2, t_1) \left(\Delta_q(t_{cut}, t_2)\right)^2$$
MLM matching

- The simplest way to do the Sudakov suppression is to run the shower on the event, starting from $t_0$!

- Perform jet clustering after PS - if hardest jet $k_{T1} > t_{cut}$ or
  ✓ Simplest available scheme
  ✓ Allows matching with any shower, without modification
  ➡ Sudakov suppression not exact, minor mismatch with shower

- Implemented in AlpGen, HELAC, MadGraph

[J.A. et al 2007, 2008]