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The automation of MC@NLO

in collaboration with
Stefano Frixione and Rikkert Frederix

PSI, June 2011

Outline

- Motivations
- Parton Showers and NLO
- Matching the two approaches: MC@NLO
- Automation: aMC@NLO
- Status and plans
- Outlook

Motivations

Why NLO computations

- LO computations describe reasonably well only inclusive quantities / total rates
- Differential NLO spectra often have shapes clearly different from LO ones (non constant K-factors)
- NLO both improves observables estimate (central value) and reduces theoretical uncertainty
- Weakness: poor description of the emissions in the soft - collinear region of the phase space

For the LHC is mandatory to know every observable at least at the NLO

(both for signal prediction and for background estimation)

Why Parton Showers (PSMC)

- Parton Showers Monte Carlos (PSMC's) offer resummation of large logarithms in the soft - collinear region at the LL accuracy
- PSMC is a realistic framework, including hadronisation, multiple interactions, non perturbative models and possibility of passing events through detector simulation
- Weaknesses: LO normalization and poor description on the hard region

Why matching

- NLO and PSMC are complementary approaches: the former good for hard emissions, the latter for soft - collinear ones
- Retain the virtues of the two discarding their weaknesses: give a prediction which is PSMC in the soft - collinear region, NLO for hard emission
- Attain NLO precision
- Achieve a smooth transition between the two predictions and avoid double counting

Matched computations are some of the most accurate / realistic predictions currently available

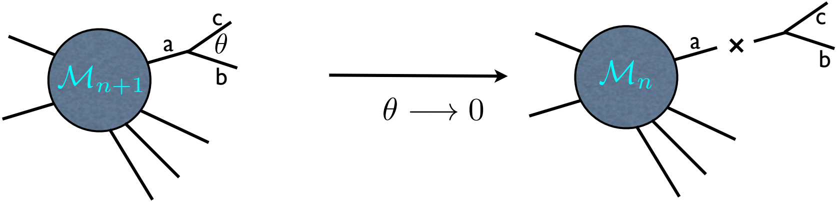
Why automation

- NLO computations conceptually easy but viable only for small multiplicities
- The core of the PSMC and of the matching machinery (see below) is process-independent
- Reduce bugs and avoid writing / debugging / validating one code each physical process
- Develop general tools that can be applied to any model and any multiplicity (up to CPU)

automation + PSMC + NLO = aMC@NLO

Parton Showers and NLO

PSMC I: collinear factorization

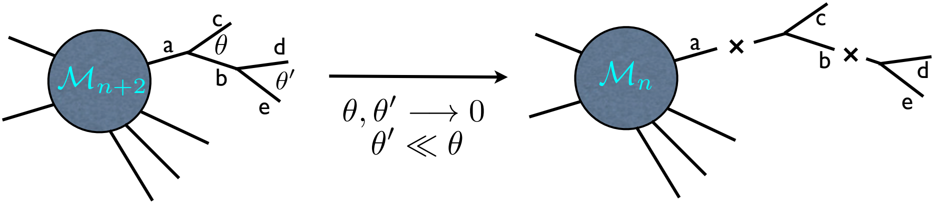


Cross section factorization in the collinear limit

$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \simeq |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

- $t =$ virtuality of particle a (could be its $p_\perp$ or $E_a\theta$ ...) it represents the hardness of the branching
- $z =$ energy fraction of parton b relative to a
- $P_{a\to bc}(z) =$ Altarelli - Parisi splitting kernel

PSMC II: multiple emission



$$|\mathcal{M}_{n+2}|^2 d\Phi_{n+2} \simeq |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z) \frac{dt'}{t'} dz' \frac{d\phi'}{2\pi} \frac{\alpha_S}{2\pi} P_{b\to de}(z')$$

Factorized rate for multiple emission

$$\sigma_{n+j} \propto \int_{Q_0^2}^{Q^2} \frac{dt}{t} \int_{Q_0^2}^{t} \frac{dt'}{t'} \cdots \int_{Q_0^2}^{t^{(j-2)}} \frac{dt^{(j-1)}}{t^{(j-1)}} \propto \sigma_n \left(\frac{\alpha_S}{2\pi}\right)^j \log^j(Q^2/Q_0^2)$$

Parton Shower Monte Carlo knows about the Leading Logarithmic (LL) collinear approximation of the total rate

PSMC III: emission probability

Differential probability for the branching $a \to bc$ at scale t:

$$dp(t) = \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

No emission probability between scales Q^2 and t:

$$\Delta_a(Q^2, t) = \lim_{dt_j \to 0} \prod_j \left[1 - \sum_{bc} \frac{dt_j}{t_j} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S(t_j)}{2\pi} P_{a\to bc}(z) \right] =$$

$$\exp\left[- \sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_S(t')}{2\pi} P_{a\to bc}(z) \right]$$

Probability of first branching at scale t:

$$dP_a(Q^2, t) = \Delta_a(Q^2, t)\; dp(t)$$

$\Delta_a(Q^2, t)$ is called Sudakov form factor

PSMC IV: unitarity

Cross section for 0 or 1 emission in the Parton Shower

$$\sigma_a^{(MC)} = \sigma_B \left(\Delta_a(Q^2, Q_0^2) + \Delta_a(Q^2, t) \sum_{bc} dz \frac{dt}{t} \frac{d\phi}{2\pi} \frac{\alpha_S(t)}{2\pi} P_{a \to bc}(z) \right)$$

normalization (LO) → σ_B

no-emission → $\Delta_a(Q^2, Q_0^2)$

1 emission at scale t → $\Delta_a(Q^2, t) \sum_{bc} dz \frac{dt}{t} \frac{d\phi}{2\pi} \frac{\alpha_S(t)}{2\pi} P_{a \to bc}(z)$

Expand at first order in α_S

$$\frac{\sigma_a^{(MC)}}{\sigma_B} \simeq 1 - \sum_{bc} \int_{Q_0^2}^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_S(t')}{2\pi} P_{a \to bc}(z) + \sum_{bc} dz \frac{dt}{t} \frac{d\phi}{2\pi} \frac{\alpha_S(t)}{2\pi} P_{a \to bc}(z)$$

virtual contribution (approximate) → the $-\sum_{bc} \int$ term

real contribution (approximate) → the $+\sum_{bc}$ term

PSMC V: practical implementation

- Extract the evolution scale of the branching by solving the equation $\Delta_a(Q^2, t) = R_\#$, with $R_\#$ a flat random number between 0 and 1

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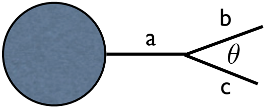
- Extract the energy sharing z and the daughters identities b and c according to $P_{a \to bc}(z)$
- Extract ϕ
- Reiterate until all ‘external’ partons have scale smaller than a threshold
- Put partons on shell and hadronise

PSMC VI: differences

Mainly : choice of the evolution variable



- **HERWIG6:** $$t = \frac{p_b \cdot p_c}{E_b E_c} \simeq 1 - \cos\theta$$
- **Herwig++:** $$t = \frac{(p_{b\perp})^2}{z^2(1-z)^2}\,, \quad z = \frac{n \cdot p_a}{n \cdot (p_a + p_c)}$$
- **PYTHIA6:** $$t = (p_b + p_c)^2$$
- **Pythia 8:** $$t = z(1-z)(p_b + p_c)^2\,, \quad z = \frac{E_b}{E_b + E_c}$$

NLO: cross section

Oversimplified structure of an NLO cross section

$$d\sigma_{\text{NLO}} = d\Phi_B \left(B + V + \int d\Phi_{(+1)} \; R \right)$$

$d\Phi_B$: n-bodies phase space

$d\Phi_B d\Phi_{(+1)}$: n+1-bodies phase space

B : Born matrix element squared

V : Virtual-emission matrix element squared (infinite)

R : Real-emission matrix element squared (infinite)

$V + \int d\Phi_{(+1)} \; R$ finite (KLN theorem)

Matching the two approaches: MC@NLO

Naive matching at NLO I

Take NLO cross section and PSMC formulae

$$d\sigma_{\rm NLO} = d\Phi_B \left(B + V + \int d\Phi_{(+1)}\ R \right)$$
$$d\sigma_{\rm MC} = d\Phi_B B I^{(n)}_{\rm MC}$$

$I^{(k)}_{\rm MC}$ is the PSMC emission probability obtained showering from a $k-$ bodies hard kinematics

Example: $I^{(n)}_{\rm MC}$ for 0 or 1 emission is

$$\Delta_a(Q^2,Q_0^2) + \Delta_a(Q^2,t)\sum_{bc} dz \frac{dt}{t}\frac{d\phi}{2\pi}\frac{\alpha_{\rm S}(t)}{2\pi} P_{a\to bc}(z)$$

Naive matching definition

$$d\sigma_{\rm MC@NLO} = \left[d\Phi_B(B+V)\right] I^{(n)}_{\rm MC} + \left[d\Phi_B d\Phi_{(+1)}\ R\right] I^{(n+1)}_{\rm MC}$$

Naive matching at NLO II

$$d\sigma_{\mathrm{MC@NLO}} = \left[d\Phi_B (B+V)\right] I_{\mathrm{MC}}^{(n)} + \left[d\Phi_B d\Phi_{(+1)} \; R\right] I_{\mathrm{MC}}^{(n+1)}$$

This simple approach does not work:

- Instability: weights associated to $I_{\mathrm{MC}}^{(n)}$ and $I_{\mathrm{MC}}^{(n+1)}$ are separately divergent (regulate them, but inefficient unweighting)

Naive matching at NLO II

$$d\sigma_{\mathrm{MC@NLO}} = [d\Phi_B(B+V)]\, I_{\mathrm{MC}}^{(n)} + \left[d\Phi_B d\Phi_{(+1)}\ R\right] I_{\mathrm{MC}}^{(n+1)}$$

This simple approach does not work:

- Instability: weights associated to $I_{\mathrm{MC}}^{(n)}$ and $I_{\mathrm{MC}}^{(n+1)}$ are separately divergent (regulate them, but inefficient unweighting)
- Double counting: $d\sigma_{\mathrm{MC@NLO}}^{(naive)}$ expanded at NLO does not coincide with NLO rate. Some configurations are dealt with by both the NLO and the PSMC

MC@NLO I: modified subtraction

Frixione, Webber: hep-ph/0204244

Modify the naive formula

$$d\sigma_{\rm MC@NLO} = \left[d\Phi_B (B + V + \int d\Phi_{(+1)} MC) \right] I_{\rm MC}^{(n)} + \left[d\Phi_B d\Phi_{(+1)} \; (R - MC) \right] I_{\rm MC}^{(n+1)}$$

Rough structure of the Monte Carlo counterterm:

$$MC = \left| \frac{\partial(t^{\rm MC}, z^{\rm MC}, \phi)}{\partial \Phi_{(+1)}} \right| \frac{1}{t^{\rm MC}} \frac{\alpha_{\rm S}}{2\pi} \frac{1}{2\pi} P(z^{\rm MC}) B$$

- It is the cross section for the first emission in the MC (more on its details later)

- It essentially depends on PSMC one is interfacing to

MC@NLO II: FKS

Deal with infinite cancellations: subtraction method.
MC@NLO uses Frixione-Kunszt-Signer formalism

Frixione, Kunstz, Signer: hep-ph/9512328
Frixione: hep-ph/9706545

- Partition the phase space with a set of functions ('S') each of which selects one soft and one collinear singularity and whose sum is 1

$$R = \sum_{ij} R_{ij}, \qquad R_{ij} = S_{ij} R$$

$$\sum_{ij} S_{ij} = 1$$

$$\sum_{j} S_{ij} \to 1 \quad \text{when} \quad k_i \to 0$$

$$S_{ij} \to 1 \quad \text{when} \quad k_i \parallel k_j$$

$$S_{ij} \to 0 \quad \text{for all other singularities}$$

MC@NLO II: FKS

- Perform analytically the cancellation of the IR poles in each singular region separately:

$$R_{ij} d\Phi_B d\Phi_{(+1)} \to \left(\frac{1}{E_i}\right)_+ \left(\frac{1}{1-\cos\theta_{ij}}\right)_+ E_i(1-\cos\theta_{ij}) R_{ij} d\Phi_B d\Phi_{(+1)}$$

- Exploit symmetries so that the number of subtraction terms scales mildly with the multiplicity (slower than the naive n^2)
  Example: for $2 \to n$ gluons one has only 3 subtractions

- FKS subtraction method has better 'scaling' properties with respect to other methods like dipole subtraction

MC@NLO III: properties

Nice features of the modified subtraction:

- Stability: weights associated to different kinematics are now separately finite. The MC term has the same collinear poles as the real (subtlety: soft poles)

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- Double counting avoided: the rate expanded at NLO coincides with the total NLO cross section

MC@NLO IV: properties

$$d\sigma_{\mathrm{MC@NLO}} = \left[d\Phi_B (B + V + \int d\Phi_{(+1)} MC)\right] I_{\mathrm{MC}}^{(n)} + \left[d\Phi_B d\Phi_{(+1)} \ (R - MC)\right] I_{\mathrm{MC}}^{(n+1)}$$

- More on (no) double counting

$$I_{\mathrm{MC}}^{(1^{st}\mathrm{em})} = 1 - \int_{Q_0^2}^{Q^2} \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_{\mathrm{S}}}{2\pi} P(z) + dz \frac{dt}{t} \frac{d\phi}{2\pi} \frac{\alpha_{\mathrm{S}}}{2\pi} P(z) \equiv 1 - \int d\Phi_{(+1)} \frac{MC}{B} + d\Phi_{(+1)} \frac{MC}{B}$$

Expand at NLO

$$\begin{aligned} d\sigma_{\mathrm{MC@NLO}} &= \left[d\Phi_B (B + V + \int d\Phi_{(+1)} MC)\right] \left[1 - \int d\Phi_{(+1)} \frac{MC}{B} + d\Phi_{(+1)} \frac{MC}{B}\right] \\ &+ \left[d\Phi_B d\Phi_{(+1)} \ (R - MC)\right] \simeq d\Phi_B (B + V + d\Phi_{(+1)} \ R) = d\sigma_{\mathrm{NLO}} \end{aligned}$$

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- Stability: weights associated to different kinematics are now separately finite. The MC term has the same collinear poles as the real (subtlety for the soft poles)
- Double counting avoided: the rate expanded at NLO coincides with the total NLO cross section
- Smooth matching: MC@NLO predictions coincide with the MC in shape in the soft and collinear region, with the NLO in the hard region

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$$d\sigma_{\rm MC@NLO} = \left[d\Phi_B\left(B+V+\int d\Phi_{(+1)} MC\right)\right] I_{\rm MC}^{(n)} + \left[d\Phi_B d\Phi_{(+1)}\ (R-MC)\right] I_{\rm MC}^{(n+1)}$$

- More on (no) double counting

$$I_{\rm MC}^{(1^{st}{\rm em})} = 1 - \int_{Q_0^2}^{Q^2} \frac{dt}{t} dz \frac{d\phi}{2\pi}\frac{\alpha_S}{2\pi}P(z) + dz\frac{dt}{t}\frac{d\phi}{2\pi}\frac{\alpha_S}{2\pi}P(z) \equiv 1 - \int d\Phi_{(+1)}\frac{MC}{B} + d\Phi_{(+1)}\frac{MC}{B}$$

Expand at NLO

$$\begin{aligned} d\sigma_{\rm MC@NLO} &= \left[d\Phi_B\left(B+V+\int d\Phi_{(+1)} MC\right)\right]\left[1 - \int d\Phi_{(+1)}\frac{MC}{B} + d\Phi_{(+1)}\frac{MC}{B}\right] \\ &+ \left[d\Phi_B d\Phi_{(+1)}\ (R-MC)\right] \simeq d\Phi_B(B+V+d\Phi_{(+1)}\ R) = d\sigma_{\rm NLO} \end{aligned}$$

- More on smooth matching
  - ✦ Soft-collinear region: $R \simeq MC \implies d\sigma_{\rm MC@NLO} \propto I_{\rm MC}^{(n)}$
  - ✦ Hard region: sensible α_S expansion $\implies d\sigma_{\rm MC@NLO} \simeq d\Phi_B d\Phi_{(+1)}\ R$

    (shower effects cancel at $\mathcal{O}(\alpha_S)$ and NLO = Real)

MC@NLO III: properties

Nice features of the modified subtraction:

- Stability: weights associated to different kinematics are now separately finite. The MC term has the same collinear poles as the real (subtlety for the soft poles)
- Double counting avoided: the rate expanded at NLO coincides with the total NLO cross section
- Smooth matching: MC@NLO predictions coincide with the MC in shape in the soft and collinear region, with the NLO in the hard region
- Normalization: MC@NLO is normalized to NLO

Integrands associated with $n-$ and $(n+1)-$ kinematics are called S (for standard) and H (for hard), respectively

MC@NLO V: implementation

$$d\sigma_{\mathrm{MC@NLO}} = \left[d\Phi_B \left(B + V + \int d\Phi_{(+1)} MC \right) \right] I_{\mathrm{MC}}^{(n)} + \left[d\Phi_B d\Phi_{(+1)} \, (R - MC) \right] I_{\mathrm{MC}}^{(n+1)}$$

S- and H- integrands can be negative somewhere : MC@NLO is not positive-definite (negative weights)

- Compute S- and H- integrals ($I_{\mathbb{S}}, \; I_{\mathbb{H}}$) and integrals of the absolute value of the S- and H- integrands ($J_{\mathbb{S}}, \; J_{\mathbb{H}}$)

- Generate events distributed according to $J_{\mathbb{S}}, \; J_{\mathbb{H}}$ (probability distributions are positive definite) but assign them a weight with sign $\pm$ depending on $I_{\mathbb{S}}, \; I_{\mathbb{H}}$ (unweighting up to a sign)

Fraction of negative weights : $f_{\mathbb{S},\mathbb{H}}^{(neg)} = \frac{1}{2} \left(1 - \frac{I_{\mathbb{S},\mathbb{H}}}{J_{\mathbb{S},\mathbb{H}}} \right)$

MC@NLO VI: negative weights

Negative fractions expected to be reasonably small (LO is dominant and positive definite)

Is it a problem to have negative weights?

NO : after showering MC@NLO distributions are positive definite (asymptotically) and physical

Fraction of negative weights just affects the efficiency, i.e. the ‘threshold’ beyond which smooth spectra are obtained (the less the negative weights the smoother the spectrum)

MC@NLO VII: old limitations

- Possibly different parametrizations for different processes: unease in extensions
- Approximations here and there
- Lack of a systematic approach
  - One code per process / simple processes only
  - Necessary slowness in including new processes
  - Necessary slowness in adding a new PSMC

Fortran HERWIG: from 2002, O(30) processes

Herwig++: from 2007, the same

Frixione, Stoeckli, Webber, P.T.: hep-ph/10100568

Frixione, Stoeckli, Webber, White, P.T.: hep-ph/10100819

Fortran PYTHIA: from 2008, 1(+1) processes

Frixione, P.T.: hep-ph/10024293

Slide by S. Frixione

MC@NLO 4.0 [Oct 10]

IPROC	IV	IL$_1$	IL$_2$	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL} l_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL} l_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL} l_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l_{IL}^+ \nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l_{IL}^- \bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^* (\to \sum_i f_i \bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2030		7	7	×	$H_1H_2 \to tW^-/\bar{t}W^+ + X$
–2031		7	7	×	$H_1H_2 \to \bar{t}W^+ + X$
–2034		7	7	×	$H_1H_2 \to tW^- + X$
–2040		7	7	×	$H_1H_2 \to tH^-/\bar{t}H^+ + X$
–2041		7	7	×	$H_1H_2 \to \bar{t}H^+ + X$
–2044		7	7	×	$H_1H_2 \to tH^- + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l_i^+ \nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l_i^- \bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i l_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO

Slide by S. Frixione

MC@NLO 4.0 [Oct 10]

IPROC	IV	IL_1	IL_2	Spin	Process
–1706		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i' (\bar{t} \to)b_l f_j f_j' + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' / (\bar{t} \to)b_k f_i f_i' + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to)b_k f_i f_i' + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' + X$
–2030		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i' (W^- \to) f_j f_j' /$ $(\bar{t} \to)\bar{b}_k f_i f_i' (W^+ \to) f_j f_j' + X$
–2031		i	j	✓	$H_1H_2 \to (\bar{t} \to)b_k f_i f_i' (W^+ \to) f_j f_j' + X$
–2034		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i' (W^- \to) f_j f_j' + X$
–2040		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' H^- /$ $(\bar{t} \to)\bar{b}_k f_i f_i' H^+ + X$
–2041		i		✓	$H_1H_2 \to (\bar{t} \to)b_k f_i f_i' H^+ + X$
–2044		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' H^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^+ \nu_i (W^- \to) l_j^- \bar{\nu}_j + X$
–2870		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^+ \nu_i (Z^0 \to) l_j' l_j' + X$
–2880		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^- \bar{\nu}_i (Z^0 \to) l_j' l_j' + X$

http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO

MC@NLO 3.4 is in GENSER (thanks to M. Kirsanov and A. Ribon). A GENSERisation script is now available (F. Stoeckli) and is being tested

Automation: aMC@NLO

From MC@NLO to aMC@NLO

- MC@NLO framework is solid and mature
- Limitations only in the implementation not in the method

To overtake old weaknesses

- Compute automatically NLO cross sections
  - ✦ MadGraph: Born contribution
  - ✦ MadFKS: poles subtraction and finite part of the Real
  - ✦ MadLoop: finite part of the Virtual
- Compute automatically MC counterterms: aMC@NLO

MadFKS

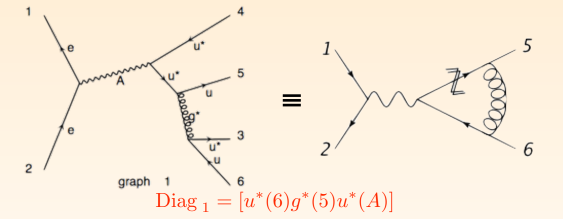
Frederix, Frixione, Maltoni, Stelzer: hep-ph/09084272

- A new MadGraph module to perform an NLO computation up to the finite part of the Virtual
- Automatic generation of Born an Real emission diagrams by MadGraph
- Analytical subtraction of IR singularities using the FKS formalism
- Efficient phase space integration
- Completely general and automatic

MadLoop I

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau: hep-ph/1103062I

- A new MadGraph module to compute the finite part of the Virtual (UV and IR regularized)
- Generates loop diagrams exploiting the ability of MadGraph of generating tree level diagrams ('L-cut diagrams')



- Instructs MadGraph to treat starred particles
- Automatically computes the numerator of the loop integrand

MadLoop II

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau: hep-ph/11030621

- Performs many sanity checks (IR poles, Ward, ...) and exploits many symmetry properties (cyclic, mirror, ...)
- Passes the numerator of the integrand to CutTools
- CutTools automatically implements the OPP reduction at the integrand level: evaluates the numerator at various points and numerically solves algebraic equations to obtain the coefficients of master scalar integrals and gives the integrals themselves

Ossola, Papadopoulos, Pittau: hep-ph/0609007
Ossola, Papadopoulos, Pittau: hep-ph/07113596

- MadLoop UV renormalizes and gives the finite part of the Virtual

aMC@NLO I: structure

$$MC = \sum_{pq,c,l\in c} \frac{\delta_{p\in l}}{N_p} \frac{\alpha_S}{(2\pi)^2} \left| \frac{\partial(t_p^{(l)}, z_p^{(l)}, \phi)}{\partial\Phi_{(+1)}} \right| \frac{P_{p\to qr}(z_p^{(l)})|\overline{\mathcal{M}_c}|_B^2 + Q_{p\to qr}(z_p^{(l)})|\overline{\widetilde{\mathcal{M}}_c}|^2}{t_p^{(l)}} \times$$

$$\times\Theta(DZ) d\Phi_B (1 - \mathcal{G}(\Phi_{(+1)})) + d\Phi_B d\Phi_{(+1)}\ R\, \mathcal{G}(\Phi_{(+1)})$$

- $c,\ l\ =$ color flow / color line
- $|\overline{\mathcal{M}_c}|_B^2 \equiv B|\mathcal{M}_c|_B^2 / \sum_{c'} |\mathcal{M}_{c'}|_B^2 =$ barred Born amplitude squared - to recover the full Born summing only on leading color

Odagiri: hep-ph/9806531

- $Q_{p\to qr}(z_p^{(l)}) =$ azimuthal kernel
- $|\overline{\widetilde{\mathcal{M}}_c}|^2 =$ barred azimuthal amplitude
- $\Theta(DZ) =$ dead zone (built-in for HERWIG, imposed to PYTHIA)
- $\mathcal{G}(\Phi_{(+1)}) =$ to recover correct soft limit

aMC@NLO II: structure

$$MC = \sum_{pq,c,l\in c} \frac{\delta_{p\in l}}{N_p} \frac{\alpha_{\rm S}}{(2\pi)^2} \left| \frac{\partial(t_p^{(l)}, z_p^{(l)}, \phi)}{\partial\Phi_{(+1)}} \right| \frac{P_{p\to qr}(z_p^{(l)})|\overline{\mathcal{M}_c}|^2_{\rm B} + Q_{p\to qr}(z_p^{(l)})|\widetilde{\overline{\mathcal{M}_c}}|^2}{t_p^{(l)}} \times$$

$$\times\Theta(DZ)d\Phi_B(1-\mathcal{G}(\Phi_{(+1)})) + d\Phi_B d\Phi_{(+1)}\ R\,\mathcal{G}(\Phi_{(+1)})$$

- Assignment of color flow and color partner (MC scales and variable definitions may depend on it)
- Assign splitting type (ISR from leg 1 or 2, FSR from massive or massless leg)
- Shower variables definitions and jacobian computation
- Computation of barred amplitudes
- Compute the G-function
- Compute the AP kernels
- Compute the MC counterterms
- Compute S- and H- integrands

aMC@NLO II: structure

$$MC = \sum_{pq,c,l\in c} \frac{\delta_{p\in l}}{N_p} \frac{\alpha_S}{(2\pi)^2} \left| \frac{\partial(t_p^{(l)}, z_p^{(l)}, \phi)}{\partial \Phi_{(+1)}} \right| \frac{P_{p\to qr}(z_p^{(l)}) |\overline{\mathcal{M}_c}|_B^2 + Q_{p\to qr}(z_p^{(l)}) |\widetilde{\overline{\mathcal{M}}_c}|^2}{t_p^{(l)}} \times$$
$$\times \Theta(DZ) d\Phi_B (1 - \mathcal{G}(\Phi_{(+1)})) + d\Phi_B d\Phi_{(+1)} \; R\, \mathcal{G}(\Phi_{(+1)})$$

- Assignment of color flow and color partner (MC scales and variable definitions may depend on it)
- Computation of barred amplitudes
- Shower variables definitions and jacobian computation
- Assign splitting type (ISR from leg 1 or 2, FSR from massive or massless leg)
- Compute the G-function
- Compute the AP kernels
- Compute the MC counterterms
- Compute S- and H- integrands

Structure fully general and process-independent

aMC@NLOIII: checks / validation

Checks

- IR limits / finiteness of S- and H- integrals
- Total cross section
- Symmetry properties (done for simple processes)

aMC@NLO III: checks / validation

Checks

- IR limits / finiteness of S- and H- integrals
- Total cross section
- Symmetry properties (done for simple processes)

Validation

- Fixed process and parameters, all spectra have to coincide with MC@NLO (helped spotting a small mistake in the non-automatic implementation)

Status and plans

aMC@NLO IV: status for HERWIG6

- Validated for all kinds of emission types (ISR, FSR massive...) against benchmark MC@NLO processes

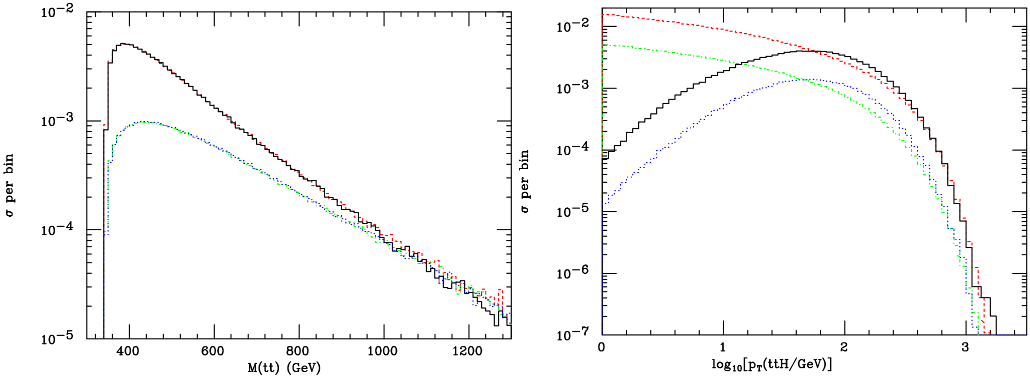
  Agreement for all spectra

  Non trivial since structure completely different!

- Moved to new complex processes (first time more than 2 final state particles)
  - $pp \to t\bar{t}H \ / \ t\bar{t}A + X$ Frederix, Frixione, Hirschi, Maltoni, Pittau, P.T.: hep-ph/11045613
  - $pp \to b\bar{b}(W^{\pm *})/b\bar{b}(Z^{*}) \to b\bar{b}ll + X$ (massive b, spin corr.)
  - $pp \to 2(\gamma^{*}/Z^{*}) \to e^{+}e^{-}\mu^{+}\mu^{-} + X$ (spin corr., interf.)
  - $pp \to b\bar{b}H + X$ (massive b)
  - ...

Slide by S. Frixione

$Ht\bar{t}$ and $At\bar{t}$ with aMC@NLO



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

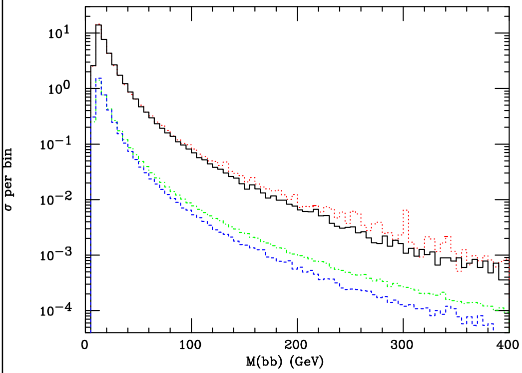
Dotted: NLO scalar. Dotdashed: NLO pseudoscalar

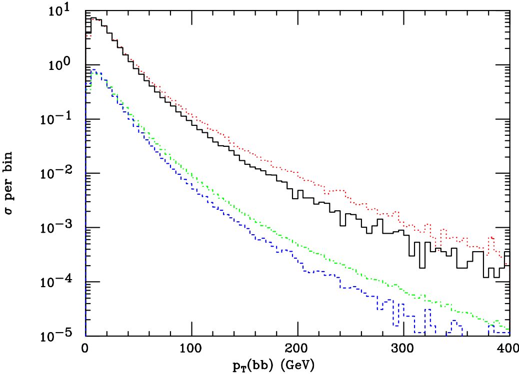
Left: $t\bar{t}$ invariant mass. Right: $t\bar{t}H$ p_T

$$m_H = m_A = 120 \text{ GeV}$$

Slide by S. Frixione

$(W \to) e\nu b\bar{b}$ with aMC@NLO





Solid: aMC@NLO. Dashed: aMC@LO Dotted: NLO. Dotdashed: LO

Left: $b\bar{b}$ invariant mass (LO rescaled). Right: $b\bar{b}$ p_T (LO rescaled)

aMC@NLO V: status for PYTHIA6

- Only virtuality-ordered shower at the moment

- Validated for half of the emission types (ISR) against the only available MC@NLO processes
  Agreement for all spectra

- Last checks for FSR: still one subtlety missing about PSMC maximum scale (intense activity)

aMC@NLOVI: status for other PSMC's

- Herwig++: all needed formulae known (from MC@NLO 4.0), just need to implement them and debug / check / validate Frixione, Stoeckli, Webber, White, P.T.: hep-ph/10100819

aMC@NLO VI: status for other PSMC's

- Herwig++: all needed formulae known (from MC@NLO 4.0), just need to implement them and debug / check / validate Frixione, Stoeckli, Webber, White, P.T.: hep-ph/10100819
- PYTHIA6 - pT: formulae known for ISR (very similar to virtuality - ordered case) just need to type them and debug / check / validate

aMC@NLO VI: status for other PSMC's

- Herwig++: all needed formulae known (from MC@NLO 4.0), just need to implement them and debug / check / validate Frixione, Stoeckli, Webber, White, P.T.: hep-ph/10100819

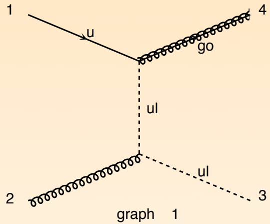
- PYTHIA6 - pT: formulae known for ISR (very similar to virtuality - ordered case) just need to type them and debug / check / validate

- Pythia8: nothing done yet (but no conceptual obstacles)

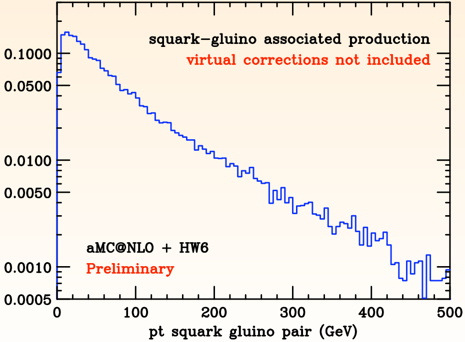
aMC@NLO project: future plans

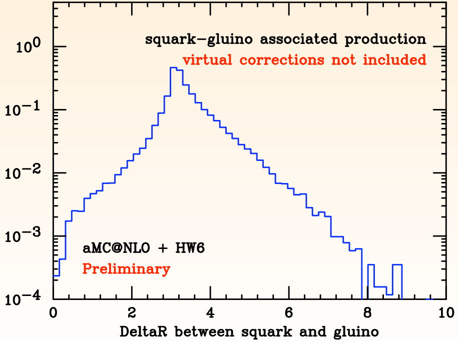
- Complete implementation for Herwig++ and Pythia
- Produce results for BSM (something already available !)

Also BSM



- squark-gluino associated production
- real emission corrections included, but virtual correction not (yet)





aMC@NLO project: future plans

- Complete implementation for Herwig++ and Pythia
- Produce results for BSM (something already available !)
- Move completely to MadGraph5: Alwall, Herquet, Maltoni, Mattelaer, Stelzer: hep-ph/11060522
  There will be huge benefits in terms of
  - Speed
  - Flexibility
  - Possibility to implement new models
  - Possibility to overtake current limitations (mainly in MadLoop)
- Dedicate large amount of time to studying exciting phenomenology
- Improve the code to make it more and more usable for experimental collaborations

Outlook

Outlook

- MC@NLO is well established theoretically: currently it provides some of the most accurate predictions for large classes of processes
- aMC@NLO is reaching maturity and will bring theoretical analyses to a new level of accuracy
- We are rapidly approaching the era of fully matched, automatic NLO + PSMC computations !

Thank you