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# The automation of MC@NLO

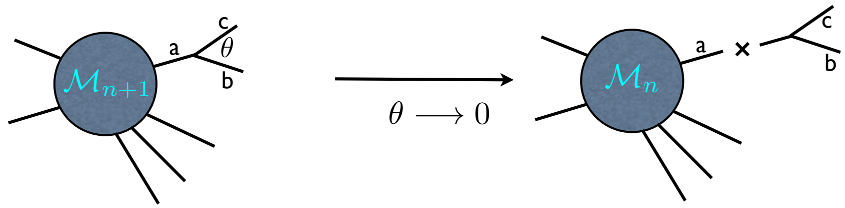
in collaboration with
Stefano Frixione and Rikkert Frederix

MadGraph Workshop, May 2011

# Outline

- Generalities of PSMC
- MC@NLO
- aMC@NLO
- Implementation and status of aMC@NLO
- Outlook

# Collinear factorization

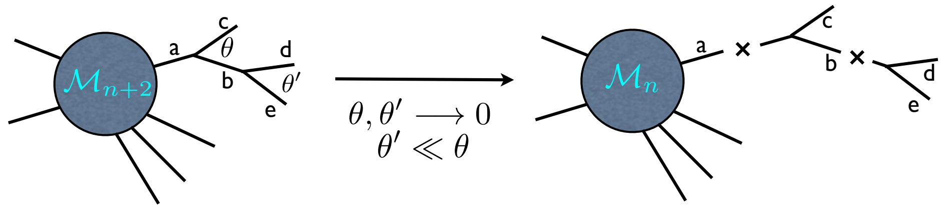



Cross section factorization in the collinear limit

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

- $t \;=$ 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

# Multiple emission




$$\theta, \theta' \longrightarrow 0$$
$$\theta' \ll \theta$$

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

Factorized rate for multiple emission

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

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

# 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

# Properties I: Sudakov form factor

$$d\Delta_a(Q^2,t) = \Delta_a(Q^2,t)\frac{dt}{t}dz\frac{d\phi}{2\pi}\frac{\alpha_S}{2\pi}P_{a\to bc}(z) = dP_a(Q^2,t)$$

$$\Longrightarrow \int_t^{Q^2} dP_a(Q^2,t') = \int_t^{Q^2} d\Delta_a(Q^2,t') = 1-\Delta_a(Q^2,t)$$

- Sudakov form factor $\Delta_a(Q^2,t)$ is the probability of no-emission between scales $Q^2$ and $t$

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- Sudakov form factor $\Delta_a(Q^2,t)$ is the probability of no-emission between scales $Q^2$ and $t$
- Emission probability only depends on particle identity and scales (Markov chain)

# Properties I: Sudakov form factor

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

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- Sudakov form factor $\Delta_a(Q^2,t)$ is the probability of no-emission between scales $Q^2$ and $t$
- Emission probability only depends on particle identity and scales (Markov chain)
- Branching + no-branching probability = 1 (unitarity): all virtual emissions automatically taken into account (approximately)

# Properties II: unitarity

Cross section for 0 or 1 emission in the Parton Shower

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

normalization (Born)

no-emission

1 emission at scale $t$

Expand at first order in $\alpha_S$

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

virtual contribution (approximate)

real contribution (approximate)

# 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 $\phi$ uniformly between 0 and $2\pi$

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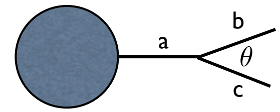
- Extract $\phi$ uniformly between 0 and $2\pi$

- Reiterate the procedure until $t \geq Q_0^2$: if $t < Q_0^2$ put partons on-shell and hadronize (non perturbative)

# Differences among PSMC's

Mainly : choice of the evolution variable




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

# Naive matching at NLO I

Structure of an NLO cross section

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

Born

Real (infinite)

Virtual (infinite)

Finite (KLN)

Naive definition

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

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

# 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)

# 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)

- 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

Modify the naive formula

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

Rough structure of the Monte Carlo counterterm:

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

- It is the cross section for the first emission in the MC (more on the 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

- Partition the phase space with a set of functions each of which selects one soft and one collinear singularity and whose sum is 1
- Perform analytically the cancellation of the IR poles (MC is a local counterterm) in each singular region separately
- Sum the finite leftovers

A different parametrization in each region is possible

# 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

# 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 IV: properties

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

- More on (no) double counting

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

Expand at NLO

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

# 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

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

- More on smooth matching
  - ✦ Soft-collinear region: $MC \simeq R \implies d\sigma_{\mathrm{MC@NLO}} \propto I_{\mathrm{MC}}^{(n)}$
  - ✦ Hard region: sensible $\alpha_{\mathrm{S}}$ expansion $\implies d\sigma_{\mathrm{MC@NLO}} \simeq d\Phi_B d\Phi_{(+1)}\ R$
    (shower effects cancel at $\mathcal{O}(\alpha_{\mathrm{S}})$ and NLO = Real)

# MC@NLO V: implementation

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

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
- 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
Fortran PYTHIA: from 2008, 2 processes

Slide by S. Frixione

# MC@NLO 4.0 [Oct 10]

| IPROC | IV | $IL_1$ | $IL_2$ | Spin | Process |
|---|---|---|---|---|---|
| –1350–IL | | | | ✓ | $H_1H_2 \to (Z/\gamma^* \to)l_{\rm IL}l_{\rm IL} + X$ |
| –1360–IL | | | | ✓ | $H_1H_2 \to (Z \to)l_{\rm IL}l_{\rm IL} + X$ |
| –1370–IL | | | | ✓ | $H_1H_2 \to (\gamma^* \to)l_{\rm IL}l_{\rm IL} + X$ |
| –1460–IL | | | | ✓ | $H_1H_2 \to (W^+ \to)l^+_{\rm IL}\nu_{\rm IL} + X$ |
| –1470–IL | | | | ✓ | $H_1H_2 \to (W^- \to)l^-_{\rm IL}\bar\nu_{\rm IL} + X$ |
| –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 | | | | | $H_1H_2 \to bb + X$ |
| –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 | × | $H_1H_2 \to tW^-/\bar tW^+ + X$ |
| –2031 | | 7 | 7 | × | $H_1H_2 \to \bar tW^+ + X$ |
| –2034 | | 7 | 7 | × | $H_1H_2 \to tW^- + X$ |
| –2040 | | 7 | 7 | × | $H_1H_2 \to tH^-/\bar tH^+ + X$ |
| –2041 | | 7 | 7 | × | $H_1H_2 \to \bar tH^+ + X$ |
| –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 | $i$ | | ✓ | $H_1H_2 \to H^0(Z \to)l_i\bar l_i + X$ |
| –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

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| IPROC | IV | $IL_1$ | $IL_2$ | Spin | Process |
|---|---|---|---|---|---|
| –1706 | | $i$ | $j$ | ✓ | $H_1H_2 \to (t \to)b_k f_i f_i'(\bar{t} \to)\bar{b}_l f_j f_j' + X$ |
| –2000–IC | | $i$ | | ✓ | $H_1H_2 \to (t \to)b_k f_i f_i'/(\bar{t} \to)\bar{b}_k f_i f_i' + X$ |
| –2001–IC | | $i$ | | ✓ | $H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i' + X$ |
| –2004–IC | | $i$ | | ✓ | $H_1H_2 \to (t \to)b_k f_i f_i' + X$ |
| –2030 | | $i$ | $j$ | ✓ | $H_1H_2 \to (t \to)b_k f_i f_i'(W^- \to)f_j f_j'/$ <br> $(\bar{t} \to)\bar{b}_k f_i f_i'(W^+ \to)f_j f_j' + X$ |
| –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 | | $i$ | | ✓ | $H_1H_2 \to (t \to)b_k f_i f_i' H^-/$ <br> $(\bar{t} \to)\bar{b}_k f_i f_i' H^+ + X$ |
| –2041 | | $i$ | | ✓ | $H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i' H^+ + X$ |
| –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

# 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 (4) for the Born
  MadFKS for the poles subtraction and for the finite part of the Real
  MadLoop (or other) for the finite part of the Virtual

- Compute automatically MC counterterms: aMC@NLO

# aMC@NLO I: structure

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

- $p,\ q\ =$ mother and sister particles
- $c,\ l\ =$ color flow / color line
- $N_p\ =$ symmetry factor (1 for quarks, 2 for gluons)
- $|\overline{\mathcal{M}_c}|_B^2 \equiv \frac{|\mathcal{M}_c|_B^2}{\sum_{c'} |\mathcal{M}_{c'}|_B^2} B\ =$ barred Born amplitude squared (Odagiri's prescription)

# aMC@NLO II: structure

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

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

- $Q_{p\to qr}(z_p^{(l)}) \ =$ 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 III: structure

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

- Assignment of color flow and color partner (MC scales and variable definitions may depend on it)
- Computation of barred amplitudes (from jamp2)
- 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
- Modify fks_singular.f to compute S- and H- integrands

# aMC@NLO IV: events generation

- Madfks/trunk/Template
- Set parameters for MadGraph, MadLoop, ...
- ./bin/newprocess_fks_orig
- ./compile_madfks.sh with option ‘mintMC’
- It generates the so-called ‘P-directories (basically one per FKS phase-space partition)
- ./run_madfks.sh steps 0, 1, 2 (see below): specify the PSMC at this stage
- Collect (not yet physical) events in LHE files

# aMC@NLO V: events generation

Uses the MINT integrator (adapted to handle negative weighted events)

Generates events in three steps:

- 0) Compute physical integral and integral of the absolute value to set up grids (channel by channel)
  Combine results: possibility to discard small channels

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Uses the MINT integrator (adapted to handle negative weighted events)

Generates events in three steps:

- 0) Compute physical integral and integral of the absolute value to set up grids (channel by channel)
  Combine results: possibility to discard small channels
- 1) Refine integrals
  Combine results: compute how many events per channel
- 2) Generate unweighted (up to sign) events
  Collect events in a LHE file to be showered

Possibility to run separately B, S, H, V, R, no-V

# aMC@NLO VI: showering phase

Same structure as MC@NLO 4.0

- Set physics parameters in
  Madfks/trunk/MCatNLO/MCatNLO_MadFKS.inputs

- Set PSMC parameters in
  Madfks/trunk/MCatNLO/srcXX/madfks_XXdriver.f

- Define analyses routines in (topdrawer)

- Run . /MCatNLO_MadFKS.inputs (and get physical plots)

# aMC@NLO VII: checks / validation

## Checks

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

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## Validation

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

# aMC@NLO VIII: status for HERWIG6

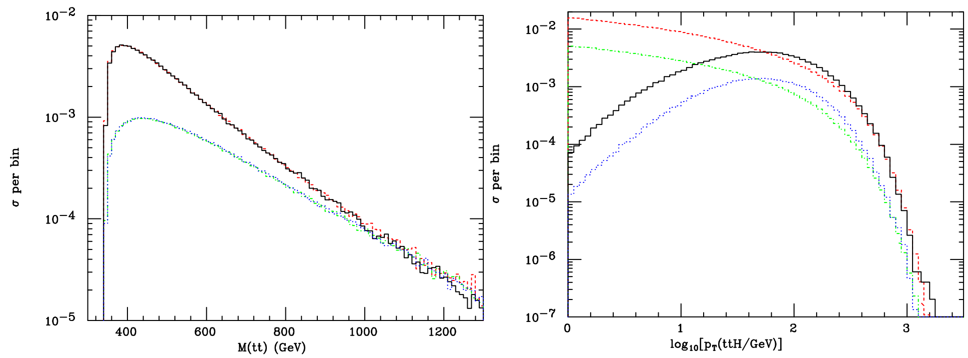
- Validated for all kinds of emission types (ISR, FSR massive...) against benchmark MC@NLO processes
  Agreement for all spectra

- Moved to new more complex processes (first time more than 2 final state particles)

  - $pp \to t\bar{t}H \ / \ t\bar{t}A + X$ (paper)
  - $pp \to (\gamma^*/Z^*) \to e^+e^-\mu^+\mu^- + X$
  - $pp \to b\bar{b}H + X$ (massive bottom: under way)
  - $pp \to b\bar{b}W^\pm + X$

Slide by S. Frixione

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




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

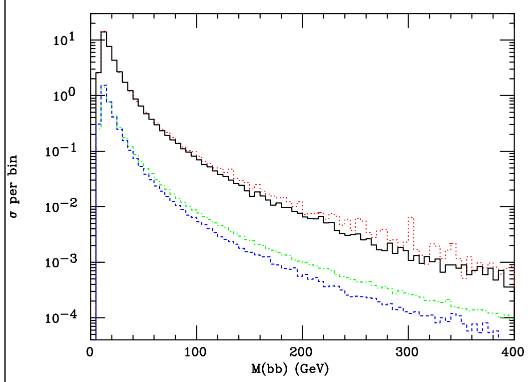
Dotted: NLO scalar. Dotdashed: NLO pseudoscalar

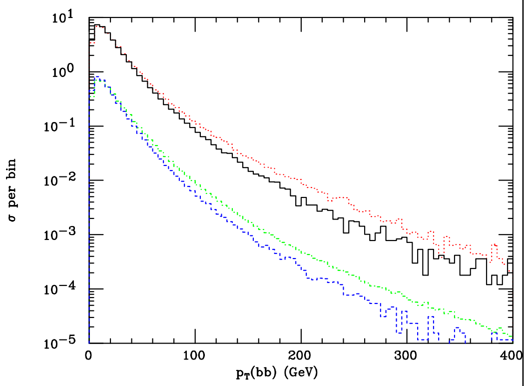
Left: $t\bar{t}$ invariant mass. Right: $t\bar{t}H$ $p_T$

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

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 IX: 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@NLO X: status for other PSMC's

- Herwig++: all needed formulae known (from MC@NLO 4.0), just need to implement them and debug / check / validate

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# aMC@NLO X: status for other PSMC's

- Herwig++: all needed formulae known (from MC@NLO 4.0), just need to implement them and debug / check / validate

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

- Pythia8: nothing done (but no conceptual obstacles)

# Outlook

- MC@NLO well established theoretically
- aMC@NLO is reaching maturity
- Will receive huge benefits form MG5
- Approaching the era of fully matched NLO+PSMC computations!

Thank you