MC@NLO
Matching NLO-calculations with Parton Showers at HERA
DIS 2008

Tobias Toll, DESY
advised by Hannes Jung and Stefano Frixione
Overview Monte Carlo $e p \rightarrow e + X$
What is an MC@NLO?

- NLO calculation of ME for heavy quark production
- Parton Showers and Hadronisation from MC
- Matching the NLO ME with the PS
- The result is unweighted events

Here the HERWIG MC (G. Corcella et al.) is used and the NLO calculations are taken from FMNR (S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi).
Why MC@NLO?
Next to Leading Order MEs for BGF

- Amplitudes for Born and Virtual Corrections interfere:

\[
|A_m|^2 = B^* B + (B^* V + V^* B) + V^* V
\]
\[
\propto \alpha_s \quad \propto \alpha_s^2 \quad \propto \alpha_s^4
\]

\[
|A_{m+1}|^2 = R^* R
\]
\[
\propto \alpha_s^2
\]
\[ \sigma = \int_{m+1} \left( d\sigma^{\text{Real}} \right) + \int_{m} \left( d\sigma^{\text{Born}} + d\sigma^{\text{Virtual}} \right) \]

Divergent \quad \text{Divergent}
NLO calculation Subtraction

\[ \sigma = \int_{m+1} \left( d\sigma^{\text{Real}} - d\sigma^{\text{subtr}}_{m+1} \right) + \int_{m} \left( d\sigma^{\text{Born}} + d\sigma^{\text{Virtual}} + d\sigma^{\text{subtr}}_{m} \right) \]

Event \hspace{1cm} Counter Event
**MC@NLO: Double Counting**

Real emission from NLO ME or Born term + Parton Shower?
**MC@NLO: Modified Subtraction**

\[
\sigma = \int_{m+1} (d\sigma^{\text{Real}} - d\sigma_{MC}) + \\
+ \int_{m} (d\sigma^{\text{Born}} + d\sigma^{\text{Virtual}} + d\sigma_{MC})
\]

With the addition and subtraction of the PS emission both integrals become finite!!!
Some can still be negative counter events.
MC-subtraction terms for ep-scattering

In ep-scattering two parts have to be considered separately:
- the hadronic (resolved) interaction
- the direct (pointlike) interaction

Hadronic Case is not completely new
- For direct case MC subtraction terms need to be calculated
Calculation of direct MC-subtr. terms

- The MC subtraction terms all have the same general structure:
  \[ \sigma_{MC} = \sigma_{\text{Born}}^{(s,t,u)} \times P_{A.P.}(z) \times \{\text{PhaseSpace, couplings, PS - regions etc.}\} \]
- Two main processes at Born level for direct case:
  - Photon-Gluon scattering
  - Photon-Quark/Antiquark scattering
MC subtraction terms $\gamma g$-scattering

- Two diagrams at Born level
- Emissions possible from "−" leg and from outgoing legs (no QCD-emission from photon)
**MC subtraction terms \( \gamma g \)-scattering**

Initial state radiation:  
"-" leg:  
\[ d\sigma_{\gamma g} \cdot P_{gg} \]

Final state radiation:  
"Q" leg:  
\[ d\sigma_{\gamma g} \cdot P_{qq} \]

"\overline{Q}" leg:  
\[ d\sigma_{\gamma g} \cdot P_{qq} \]
**MC subtraction terms \( \gamma q \text{-scattering} \)**

- In the first two diagrams only radiation from the "–" leg. Born is photon-gluon.

- In the third diagram only radiation from "+" leg. Here electromagnetic "splitting function" has to be used. Born is quark-antiquark annihilation.
MC subtraction terms $\gamma q$-scattering

"-" leg: $d\sigma_{\gamma g} \cdot P_{gq}$

"+" leg: $d\sigma_{\bar{q}g} \cdot P_{\gamma \rightarrow q\bar{q}}$

$P_{\gamma \rightarrow q\bar{q}} = \frac{T_f}{N_C} \cdot P_{qg}$
Internal Test of MC-terms

\[ \frac{MC_{\text{subtr.}}(\cos \theta \rightarrow -1)}{MC_{\text{subtr.}}(\cos \theta = -1)} \]

Each iteration closer to the limit.

Example collinear - : \( \cos(\theta) = -1 + 0.1^n \)

<table>
<thead>
<tr>
<th>n</th>
<th>**** Collinear- limit</th>
<th>**** Soft limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.911385659</td>
<td>1.0209289</td>
</tr>
<tr>
<td>2</td>
<td>0.963471603</td>
<td>0.999248357</td>
</tr>
<tr>
<td>3</td>
<td>0.988041227</td>
<td>0.999897717</td>
</tr>
<tr>
<td>4</td>
<td>0.996217561</td>
<td>0.999989494</td>
</tr>
<tr>
<td>5</td>
<td>0.998803796</td>
<td>0.999998902</td>
</tr>
<tr>
<td>6</td>
<td>0.99999995</td>
<td>1.00000232</td>
</tr>
<tr>
<td>7</td>
<td>0.99999995</td>
<td>1.00000023</td>
</tr>
<tr>
<td>8</td>
<td>0.99999995</td>
<td>1.00000002</td>
</tr>
</tbody>
</table>
### Test of Divergency Cancellation

\[
\sigma = \int_{m+1} (d\sigma^{\text{Real}} - d\sigma^{\text{MC}}) + \int_m (d\sigma^{\text{Born}} + d\sigma^{\text{Virtual}} + d\sigma^{\text{MC}})
\]

\[
\frac{MC_{\text{subtr.}}(\cos \theta \rightarrow -1)}{ME_{2\rightarrow3}(\cos \theta = -1)}
\]

**Collinear limit**
- 0.974061006
- 1.004122
- 1.00254968
- 1.00093199
- 1.00030953
- 0.999999501
- 0.9999995
- 0.99999995

\[
\frac{MC_{\text{subtr.}}(x \rightarrow 0)}{ME_{2\rightarrow3}(x = 0)}
\]

**Soft limit**
- 1.00412524
- 0.998628304
- 0.999845295
- 0.999984345
- 0.999995661
- 0.999996662
- 0.999999666
- 0.999999967

Important test of cancellation of divs. **point by point!!!
Test of total rates - direct

- Comparison of NLO-rates between MC@NLO and FMNR. When implementation is correct these should be equal.
- This is a test of over all cancellation of divergencies!!!

- Charm production [mb]
  - Total Rate
    - MC@NLO: 0.8448 +/- 0.003
    - FMNR: 0.8423 +/- 0.003
  - Ratio
    - MC@NLO: 1.003 +/- 0.005
    - FMNR: 1.000 +/- 0.002

- Beauty production [pb]
  - Total Rate
    - MC@NLO: 5199 +/- 30
    - FMNR: 5215 +/- 10
  - Ratio
    - MC@NLO: 0.997 +/- 0.006
    - FMNR: 1.000 +/- 0.002

\[ m_c = 1.55 \]
\[ m_b = 4.95 \]
\[ f_{ren} = f_{fac} = 1 \]
\[ cteq5m \]
Reminder

Solid: MC@NLO
Dashed: Herwig
Dotted: NLO
Reminder

Solid: MC@NLO
Dashed: Herwig
Dotted: NLO
Large \( Pt \) – shape comparison

- We see what part of phase space is subtracted.
- The differences are expected to be filled by PS.
- For large \( pt > 2M_b \) the PS is expected to stop.
- For the large pt tale the distributions should agree.

These distributions don't show physics!!!!
We see what part of phase space is subtracted.

The differences are expected to be filled by PS.

For large $pt > 2M_b$ the PS is expected to stop.

For the large pt tale the distributions should agree.

These distributions don't show physics!!!!
Small $P_t$ distribution

- Low $P_t$ is dominating both calculations.
- For $P_t=0$ the virtual contribution dominates FMNR.
- In MC@NLO the virtual divergent part is subtracted, the calculation is here dominated by the born term.
No significant difference in rapidity distributions.

Low pt is dominating both calculations, so this is consistent.
Very preliminary results!

\[ \log_{10}(p_t^{bb}) \]
Very preliminary results!
Summary and Outlook

- When combining NLO ME and Parton showers there is a problem with double counting.
- In MC@NLO this problem is solved with process dependent MC Subtraction Terms. These terms also cancel the divergences in the NLO calculation.
- I have successfully constructed and tested MC Subtraction Terms for Heavy Quark production in eP collisions, both for divergences and double counting!

- The program is just finished and need some further testing.
- MC@NLO for HERA will be ready soon for use in your analyses!!!