Geneva: Event Generation at NLO

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Outline

- Report on progress towards Event Generation at NLO
- Important Features of Monte Carlos
- Why merging NLO with Resummation is important and challenging
- Current Approaches
- Geneva Approach
- First Results
- Conclusions
Important Features of MC

- **Monte Carlos indispensable at colliders**

  Goal: Connect most precise theory predictions possible to experiment.

- **Key Feature: Monte Carlos are exclusive**

  Basic role of event generator: return weight for each point in N-body phase space $d\sigma/d\Phi_N$

  ➤ Can implement arbitrary experimental cuts $\{\eta_{\text{cut}}, p_T^{\text{cut}}, R\}$

  Major challenge for analytic calculations.

  ➤ Leading small $p_T$ resummation and large $p_T$ fixed order

  ➤ Allows one to be exclusive in jet multiplicities

  Eg. $pp \rightarrow H + 0, 1, 2 \text{jets}$ have different backgrounds and sensitivities

  ➤ Fully hadronized events
Parts of the Monte Carlo

\[ d\sigma^{MC} = \text{Hard Interaction} \otimes \text{Parton Shower} \otimes \text{Hadronization/UE} \]

- **Hard Interaction**: Fixed order partonic matrix elements. Legs + Loops.

- **Parton Shower**: Collinear and soft splittings. High Multiplicity final state. Logs \( \alpha_s \ln^2 \frac{\mu_{PS}}{\mu_H} \).

- **Hadronization/UE**: Model non-perturbative physics. Partons to hadrons.
Combining Fixed Order and Resummation

- **Example** $pp \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\nu$:
  Large fixed order corrections. Vary with $p_T^{\text{cut}}$

- **FO $\alpha_s$ expansion** describe large $p_T^{\text{cut}}$ region
  Unreliable at small $p_T^{\text{cut}}$

- Need $\alpha_s \ln \frac{p_T^{\text{cut}}}{m_H}$ resummation (parton shower)

- **Combine** Hard Matrix Element NLO with Resummation (parton shower)

- **Goal of Geneva:**
  Combine different jet multiplicities all at NLO with resummation
Challenge: Fixed Order and Parton Shower

At LO:

<table>
<thead>
<tr>
<th>$d\Phi_n$</th>
<th>$d\Phi_{n+1}$</th>
<th>$d\Phi_{n+2}$</th>
<th>$d\Phi_{n+3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO Matrix Element</td>
<td>Parton Shower</td>
<td>Parton Shower</td>
<td>Parton Shower</td>
</tr>
</tbody>
</table>

- Beyond LO: N-body Phase Space $\neq$ N-parton Phase Space

IR finite NLO $=$ $d\Phi_n$ + $d\Phi_{n+1}$

- Make each weight well defined.

- Both Parton Shower and NLO ME include real emission corrections
  FO: exact n+1 body, PS collinear/soft limit.

At NLO:

<table>
<thead>
<tr>
<th>$d\Phi_n$</th>
<th>$d\Phi_{n+1}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>LO +Virtual</td>
<td>Real</td>
<td>PS</td>
<td>Parton Shower</td>
</tr>
</tbody>
</table>

Avoid Double Counting
Current Approaches: Fixed Order $\otimes$ Parton Shower

*touch on just a few

- **MC@NLO/ POWHEG** (NLO for single jet multiplicity) $\otimes$ (LL Parton Shower)

  - Divergences: Define Subtraction
    \[
    d\Phi_n \left[ V_n + \int d\Phi_{n+1|n} S \right] + d\Phi_{n+1} \left[ R_{n+1} - S \right]
    \]

  Maps N-Body Phase Space to N-Parton Phase Space

  [Frixione, Webber; Nason; Frixione, Nason, Oleari]

- Double Counting: Modify 1st emission of parton shower. **Inclusive** jet observable at NLO

- **Multi-jets at LO** (LO for all jet multiplicities) $\otimes$ (LL Parton Shower)

  - Hard matrix element combined with Sudakov to cancel $\mu_{\text{res}}$ dependence.

    [Catani, Krauss, Kuhn, Webber; Lönnblad; Mangano]

  - MENLOPS (NLO single jet + LO rest jet multiplicities) $\otimes$ (LL Parton Shower)

  [Bauer, Tackmann, Thaler; Hamilton, Nason; Hoche, Krauss, Schonherr, Siegert]
The Geneva Approach

- **Goal:** Exclusive jet multiplicities all at NLO + resummation $pp \rightarrow H/W + 0, 1, 2$ jets
  Start with $e^+e^- \rightarrow 2, 3, 4$ jets.
  Naively 4 jets NLO would require 2 jet to N$^3$LO to be IR finite.
  Geneva: relevant pieces obtained from resummation

- **Divergences:** Map N-jet Phase Space to N-body Phase Space

- **Divide Phase Space:** Resolution variable, N-jettiness $\mathcal{T}_N$: Vetos $> N$ jets. Well defined for any number of partonic final states.

[Stewart, Tackmann, Waalewijn]

\[
d\sigma_{2}^{\text{excl}} : \mathcal{T}_\text{cut} > \mathcal{T}_2
\]
\[
d\sigma_{3}^{\text{excl}} : \mathcal{T}_2 > \mathcal{T}_\text{cut} > \mathcal{T}_3
\]
\[
d\sigma_{4}^{\text{incl}} : \mathcal{T}_3 > \mathcal{T}_\text{cut}
\]
Systematic Improvement of MC Using EFT

- For given N-jet

- Small $\mathcal{T}_2$: Soft Collinear Effective Theory - framework to calculate resummed QCD distributions.

Systematically include: $\alpha_s^n$ matching and resum renormalization group $\alpha_s^n \ln^m(\mathcal{T}/Q)/\mathcal{T}$

\[
\frac{d\sigma_2^s}{d\Omega \, d\mathcal{T}} = \frac{d\sigma_B}{d\Omega} H_2(E_{cm}^2, \mu) \int ds_1 ds_2 J_1(s_1, \mu) J_2(s_2, \mu) S_2 \left( \mathcal{T} - \frac{s_1}{Q_1} - \frac{s_2}{Q_2}, \mu \right)
\]

Hard Function: NLO matrix elements

Jet and Soft functions: Collinear and soft limit
Systematic Improvement of MC Using EFT

- Combine with large $T_2$ in 2-jet bin

\[
\frac{d\sigma_2}{d\Omega \, dT} = \frac{d\sigma_2^s}{d\Omega \, dT} + \left[ \frac{d\sigma_2^{QCD}}{d\Omega \, dT} - \frac{d\sigma_2^s}{d\Omega \, dT} \right]_{\text{exp}}
\]

Resummed NLL' = NLO FO+ $\alpha_s^n L^{2n-1}$

![Graph showing the variation of $\sigma_2(T_{\text{cut}})$ with $T_{\text{cut}}$ for different orders of corrections. The graph has a horizontal axis labeled $T_{\text{cut}}$ [GeV] ranging from 0 to 300, and a vertical axis labeled $\sigma_2(T_{\text{cut}})$ [pb] ranging from 0 to 1.4. The graph includes data points for $E_{\text{cm}} = 500$ GeV. The curves represent different orders of corrections: NLO, NLL, NLL' + NLO.]

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Combining Higher Jet Multiplicities

- Focus on 2-jet NLL+NLO, 3 jet LO (MC@NLO/POWHEG equivalent)

- Distribute events according to:

\[
\frac{d\sigma_2}{d\Phi_2}(T_{\text{cut}}) = \int_0^{T_{\text{cut}}} dT_2 \frac{d\sigma_2}{d\Omega dT_2} + \frac{d\sigma_{\geq 3}}{d\Phi_3} = \left( \frac{d\sigma_2}{d\Omega_2 dT_2} \bigg|_{\exp} \right) \frac{d\sigma_{\geq 3}^{FO}}{d\Phi_3} \theta(T_2 > T_{\text{cut}})
\]

2-body events

- Constant \( T_2 \) dependence for 2-body events
- Has full \( \Phi_3 \) dependence

3-body events

- Large \( T_2 \) : Resummation starts to turn off.
- Ratio starts at \( \mathcal{O}(\alpha_s^2) \)

- Small \( T_2 \) : Resummation important
- Ratio starts at NNLL

- Now straightforward to extend to 3 jet NLO.
First Results

- Distribute events according to \( \frac{d\sigma}{d\Phi_3} \)

- Monte Carlo with theory (scale) uncertainties not MC statistics!
  Exactly matches analytic central value + uncertainty.

\[ T_2 = 2(1 - T') \]

\[ E_{cm} = 500 \text{ GeV} \]

\( \text{NLL'} + \text{NLO} \)

\( \text{NLL} \)

\( \text{GENEVA} \)
First Results

- Consider variable sensitive to $\Phi_3$ angular dependence.

Using

$$
\frac{d\sigma_{\geq 3}}{d\Phi_3} = \left( \frac{d\sigma_2}{d\Omega_2 \, dT_2} \left|_{\exp} \right. \frac{d\sigma_2}{d\Omega_2 \, dT_2} \right) \frac{d\sigma_{\geq 3}^{FO}}{d\Phi_3} \theta(T_2 > T_{cut})
$$

- Should reproduce shape. $d\Phi_3 = d\Phi_2 \, dz \, dT_2 \, d\phi$

Definition of variables consistent for 3-jets (at any order).

![Graph showing the relationship between $d\sigma/dz$ and $z$ for various values of $E_{cm}$ and $T_2$. The graph includes data points and a curve, with annotations for singular behavior and terms indicating a shift from resummed terms.](image-url)
Conclusions

• Want event generators with best possible accuracy to connect theory and experiment

• Goal of Geneva: Combining several jet multiplicities at NLO with resummation/parton shower

• Method: Use resummed exclusive cross-sections from SCET

• Status: 2 jet NLL’+ NLO and 3 jet LO; 3 jet NLO almost complete.

• Expect \( pp \rightarrow H + 0, 1 \text{jets}, \ pp \rightarrow W + 0, 1 \text{jets} \) at NLO soon!
END
Back Up Slides
$\alpha_s^2$ corrections are large

- NLL' much larger than $\alpha_s$ contribution

[Abbate, Fickinger, Hoang, Mateu, Stewart]
Perturbative Structure

- Perturbative structure of hard interaction \( \otimes \) parton shower

\[
\sigma \sim \begin{cases} 
1 \\
\alpha_s L^2 + \alpha_s L + \alpha_s & \text{NLO} \\
\alpha_s^2 L^4 + \alpha_s^2 L^3 & \text{N}^2\text{LO} \\
\alpha_s L^2 + \alpha_s L + \alpha_s^2 & \text{N}^2\text{LO}
\end{cases}
\]

\[L \sim \ln \frac{\mu_{\text{PS}}}{\mu_{\text{hard}}}\]