Event Generation for the LHC
Joshua Isaacson
Based on: Snowmass White Paper (arxiv:2203.11110)
Seattle Snowmass Summer Meeting 2022: EF-TF Cross Frontier
19 July 2022
The success of HEP experiments critically relies on advancements in physics modelling and computational techniques, driven by a close dialogue between large experimental collaborations and small teams of event generator authors.

Development, validation, and long-term support of event generators requires a vibrant research program at the interface of theory, experiment, and computing.
Introduction

- White paper brought together all event generator communities in HEP for the first time.
- Need to continue this collaboration through the creation of a joint theoretical-experimental working group cross-cutting through all experiments.
- For a discussion on the computing aspects see my talk in the CompF2 parallel from Monday.
- For a discussion on the impact of ML on event generation see the talk from Tilman following this one and the ML WP (2203.07460).
Why do we need generators?

- Precision understanding of Standard Model
- Ability to model BSM processes
- Essential role in planning and design of future experiments
- Connects the theory and experimental community
- Modelling non-perturbative effects
Computing Bottlenecks

- Unweighting efficiency
- Handling (reducing) negative weights
- Alternative event weights for parton showers to estimate uncertainties
- Matching / merging schemes have factorial growth problem
### Fixed Order Calculations

- Automation has been achieved for tree level and next-to-leading order calculations
- Large development in fully-differential NNLO calculations
- A few processes at \( N^3 \)LO accuracy

<table>
<thead>
<tr>
<th>Higgs</th>
<th>SM candles</th>
<th>Jets</th>
<th>Other</th>
</tr>
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<tbody>
<tr>
<td>( H )</td>
<td>( W^\pm )</td>
<td>dijets</td>
<td>single top</td>
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<tr>
<td>( W^\pm H )</td>
<td>( Z )</td>
<td>3 jets</td>
<td>( t \bar{t} )</td>
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<td>( ZH )</td>
<td>( \gamma \gamma )</td>
<td>( Z + \text{jet} )</td>
<td>( b \bar{b} )</td>
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<tr>
<td>( H \text{ (VBF)} )</td>
<td>( W^\pm \gamma )</td>
<td>( \gamma + \text{jet} )</td>
<td>( H \rightarrow b \bar{b} )</td>
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<tr>
<td>( HH )</td>
<td>( Z \gamma )</td>
<td>( Z + b )</td>
<td>( t \text{ decay} )</td>
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<tr>
<td>( HHH )</td>
<td>( W + W^- )</td>
<td>( W^\pm c )</td>
<td>( e^+e^- \rightarrow 3j )</td>
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<td>( H + \text{jet} )</td>
<td>( WZ )</td>
<td>( \gamma \gamma + \text{jet} )</td>
<td>DIS (di-)jets</td>
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<tr>
<td>( W^\pm H + \text{jet} )</td>
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<td>( \gamma \gamma )</td>
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Calculations available differentially at NNLO or higher in QCD (for \( pp \) initial state). References to the first time the process has been calculated can be found in Table 1 of the white paper.
QCD factorization and parton evolution

- Factorize into short and long distance physics:

\[ \sigma[J] \approx \sum_{a,b} \int dx_a \int dx_b \ f_{a/A}(x_a, \mu_J^2) \ f_{b/B}(x_b, \mu_J^2) \ \hat{\sigma}[J] \]

- QCD evolution given by:

\[
\frac{d x f_{a/A}(x, \mu_J^2)}{d \ln \mu_J^2} = \sum_{b=q,g} \int_0^1 \ d\tau \int_0^1 \ dz \ \frac{\alpha_s}{2\pi} [z P_{ab}(z)] + \tau f_{b/A}(\tau, \mu_J^2) \delta(x - \tau z)
\]

- PDFs and fragmentation functions are not always consistent

- Improving PDF understanding for neutrino experiments and the EIC are vital

- Work on using lattice to improve PDF accuracy
**QCD factorization and parton evolution**

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Hadronization

**Lund String Model**
- Basic assumption: linear confinement potential approximated by a string stretched between $q\bar{q}$ pairs
- Stored energy in string used to produce new $q\bar{q}$ pairs
- Baryons introduced by splitting to an antidiquark-diquark pair
- Gluons treated as kinks on the string
- Many improvements over the years, but still much work is needed

**Cluster Model**
- Guided by local parton-hadron duality and preconfinement
- Evolution based on formation and decay of color-neutral clusters interpreted as resonances of hadrons with a continuous mass spectrum
- Baryons introduced by introduction of diquarks
- Gluons are split into flavor-antiflavor pairs at end of parton shower
- Need to revisit questions of very forward hadronization and color reconnections
### New-physics models

<table>
<thead>
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<th>Generator</th>
<th>singlet</th>
<th>triplet</th>
<th>octet</th>
<th>( \epsilon^{ijk} )</th>
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<table>
<thead>
<tr>
<th>Generator</th>
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<th>Lorentz structures</th>
<th>Other aspects</th>
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<tr>
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<td>Spin 2</td>
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- FeynRules package allows for the generation of Feynman rules from nearly arbitrary Lagrangians
- UFO file format very successful
Higher-order QCD and EW computations

- MADLOOP: One loop automated, work on two-loops
- MATRIX: NNLO accuracy through $q_T$ subtraction, mixed NNLO QCD-EW corrections
- MCFM: NNLO accuracy, recently added resummation using CuTe, interface to general purpose generators
- NNLOJet: NNLO accuracy, using antenna subtraction, work towards $N^3$LO
- OPENLOOPS: Automated generator of tree and one-loop amplitudes, stability techniques for one-loop contributions in unresolved regions of phase space for NNLO calculations.
- RECOLA: Automated generator of tree and one-loop amplitudes for full SM and BSM.
QCD parton and dipole showers

- Many tools exist for parton showers, but are limited in accuracy
- Ongoing work to evaluate formal precision of parton showers
- First NLL shower completed
- Several proposals to include sub-leading color effects into parton showers
- Ongoing work on including higher order / higher logarithmic corrections
- Major questions on how you handle mass effects in a shower

\[ \Delta \psi_{12}, \alpha_s \rightarrow 0 \]

\[ \frac{\Delta \psi_{12}}{\Sigma_{MC}^{\text{Next-to-Next-to-Leading Order}}(\Delta \psi_{12}, k_1, k_2)} \]

- $-0.6 < \alpha_s \log \frac{k_{11}}{Q} < -0.5$, $0.3 < \frac{k_{22}}{k_{11}} < 0.5$

[2002.11114]
Matching fixed-order to parton showers

- **NLO Matching:**
  - MC@NLO: Standard for general purpose generators
  - POWHEG: Combines matrix-element corrected parton showers
  - KRKNLO: Crucial advantage is its simplicity

- **(N)LO multijet merging:**
  - Combines strengths of matrix element calculations and parton showers
  - Soft and collinear radiation captured by shower
  - Hard radiation captured by higher multiplicity matrix element
  - VINCIA uses sector showers which reduce complexity of matching, merging, and matrix-element correction schemes
Matching fixed-order to parton showers

- **NNLO Matching**
  - **GENEVA**: Use SCET to match fixed order to parton shower
  - **NNLOPS and MiNNLO\_PS**: No reweighting required, and parton shower based on POWHEG method
  - Need work in direction of fully differential matching

- **TOMTE method for N\textsuperscript{3}LO matching**, process independent, and constructed with a simple procedure
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![Graph showing transverse momentum of Z-boson with ratio and data points](image)
General-purpose resummation tools

- **CAESAR Formalism**: provides NLL’+NLO accuracy, plugin available to interface with SHERPA
- Possible extensions to NNLL accuracy via the ARES formalism.
- **SHERPA** has framework for a \( q_T \) resummation for \( W \) and \( Z \) at N^3LL’ accuracy based on SCET
Event Generators are vital for the success of high energy experiments

Event Generators bridge theory, experiment, and computing