Event Generation for the LHC

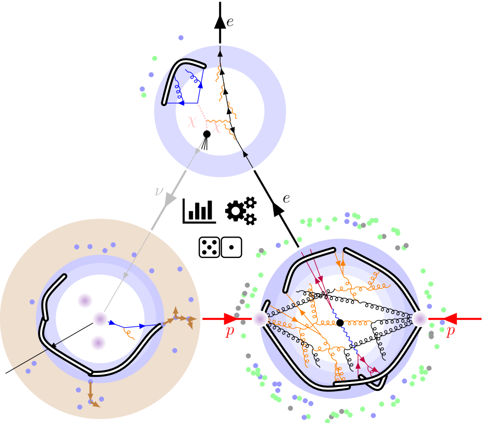
Joshua Isaacson

Based on: Snowmass White Paper (arxiv:2203.11110)

Seattle Snowmass Summer Meeting 2022: EF-TF Cross Frontier

19 July 2022

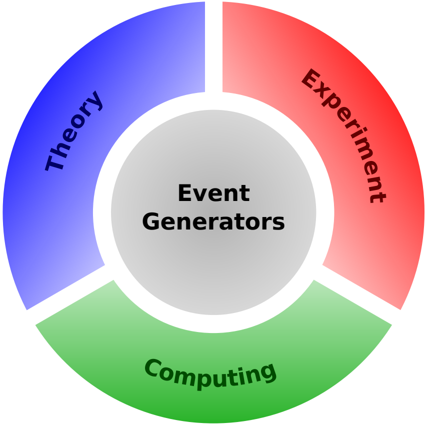
Introduction



- 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

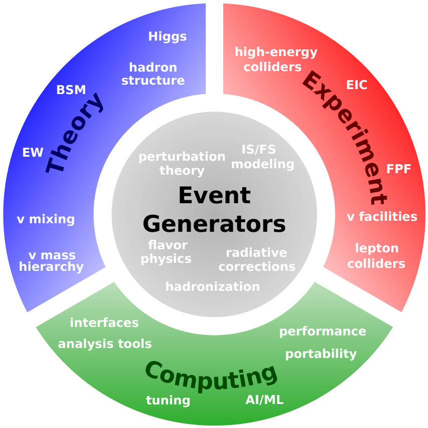
Introduction

- 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).

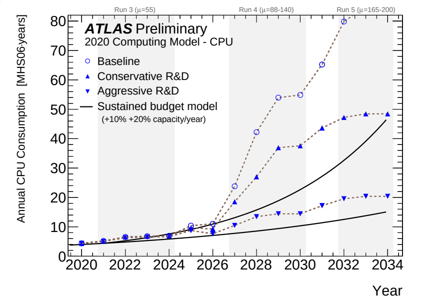


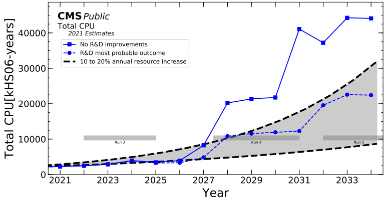
Why do we need generators?

- 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^3LO accuracy

Higgs	SM candles	Jets	Other
H	$W^\pm$	dijets	single top
$W^\pm H$	Z	3 jets	$t\bar{t}$
ZH	$\gamma\gamma$	$W^\pm$+jet	$b\bar{b}$
H (VBF)	$W^\pm\gamma$	Z+jet	$H \to b\bar{b}$
HH	$Z\gamma$	γ+jet	t decay
HHH	W^+W^-	$Z + b$	$e^+e^- \to 3j$
H+jet	WZ	$W^\pm c$	DIS (di-)jets
$W^\pm H$+jet	ZZ	$\gamma\gamma$+jet	
ZH+jet	$\gamma\gamma\gamma$		

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.

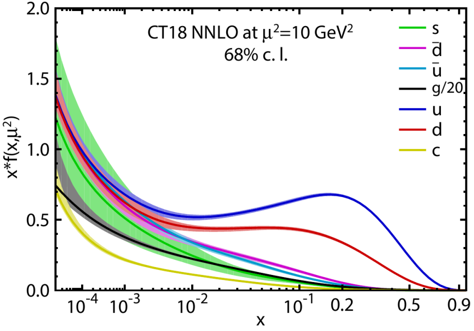
QCD factorization and parton evolution

- Factorize into short and long distance physics:

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

- QCD evolution given by:

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



- 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

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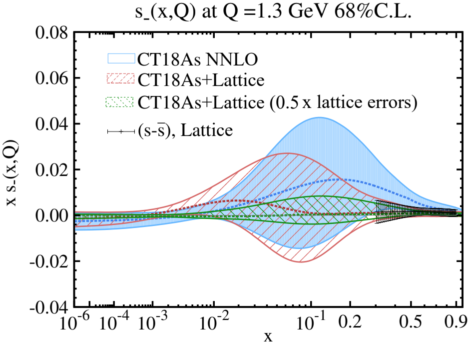

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Hadronization

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 a 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

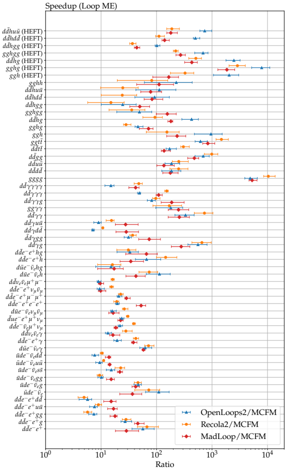
Generator	Representation					
	singlet	triplet	octet	ϵ^{ijk}	6	10
MG5aMC	✓	✓	✓	✓	✓	
SHERPA	✓	✓	✓			
WHIZARD	✓	✓	✓			

Generator	Representations			Lorentz structures			Other aspects			
	SM	Spin $\frac{3}{2}$	Spin 2	Custom	Majorana	4-Fermi	Propagator	Running	Form factor	Unitarity
MG5aMC	✓	✓	✓	✓	✓	(✓)	✓	EFT	✓	
SHERPA	✓		(✓)	✓	✓	(✓)				
WHIZARD	✓	✓	✓	✓	✓	✓	✓		✓	✓

- FeynRules package allows for the generation of Feynman rules from nearly arbitrary Lagrangians
- UFO file format very successful

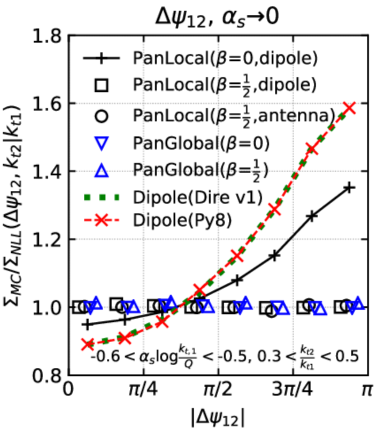
Higher-order QCD and EW computations

- 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.



[2107.04472]

QCD parton and dipole showers



[2002.11114]

- 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

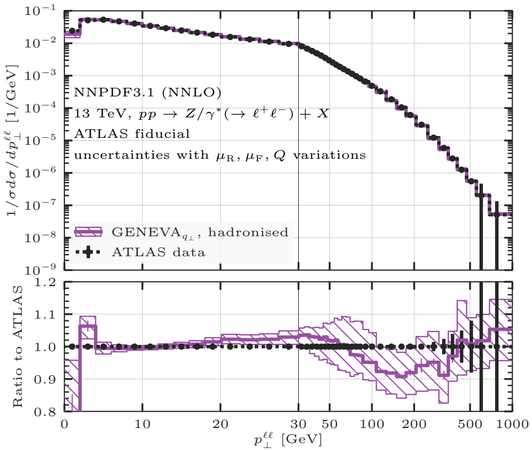
Matching fixed-order to parton showers

- 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 POWHEGmethod
  - Need work in direction of fully differential matching
- TOMTE method for N^{3}LO matching, process independent, and constructed with a simple procedure



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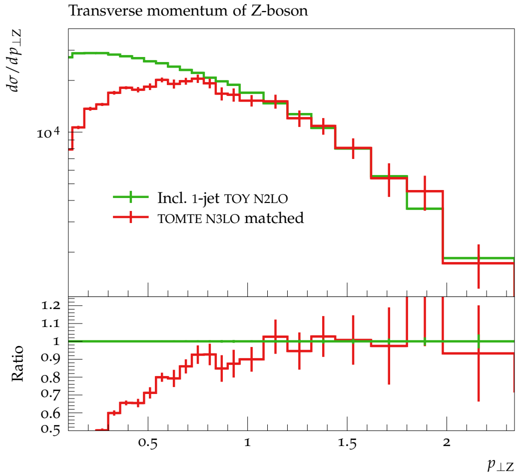
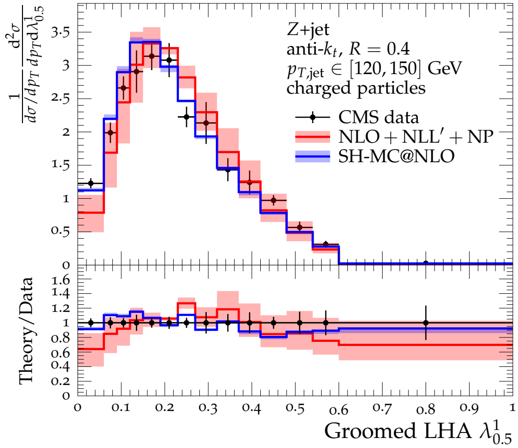
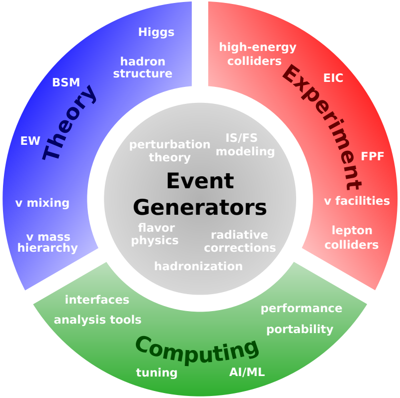


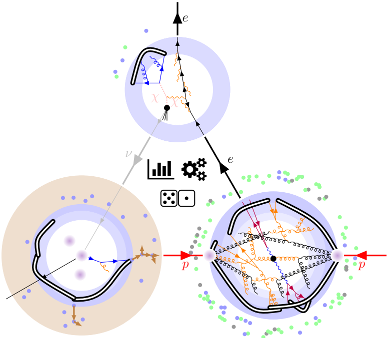
General-purpose resummation tools



- 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^{3}LL' accuracy based on SCET

Conclusions





- **Event Generators are vital for the success of high energy experiments**
- **Event Generators bridge theory, experiment, and computing**