Monte Carlo challenges for the future

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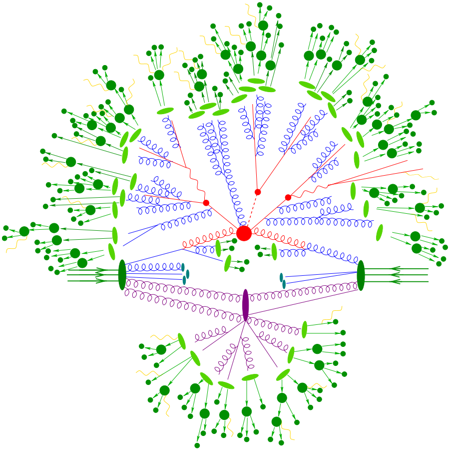
Higgs 2020

Online, 10/30/2020

State of the art

- LO Matrix Element generators and Loop-ME Generators
- Parton showers, mostly based on dipole/antenna picture
- Multiple interaction models possibly interleaved with shower
- Hadronization models string/cluster fragmentation
- Hadron decay packages
- Photon emission generators YFS formalism or QED shower



Much of the development focused on increase in perturbative precision

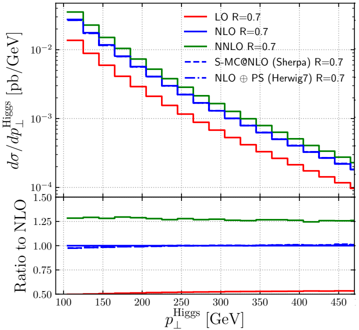
$\rightarrow$ Incorporation of higher orders in α_s, $\alpha_s L$, $1/N_c$, ... expansion while maintaining local, fully differential event generation paradigm

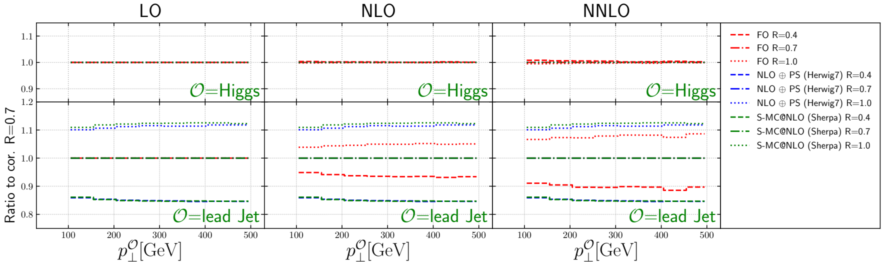
This talk: A sample of results and developments, and a (biased) outlook

Where do we stand? $\mathrm{N}^{(2)}\mathrm{LO}$ / MC comparison in gg→Hj

[Bellm at al.] arXiv:1903.12563

- Good agreement between MC@NLO (Herwig / Sherpa) and fixed-order pQCD for inclusive observables in $pp \to Hj$
- Radius dependence of cross section well modeled by MC in comparison to NNLO
- Spurious reduction of uncertainties at small R, more pronounced at NNLO than NLO → alternative prescription needed, e.g. [Dasgupta,Dreyer,Salam,Soyez] arXiv:1602.01110

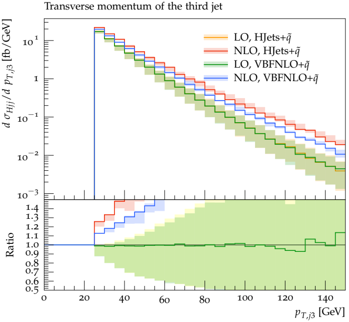


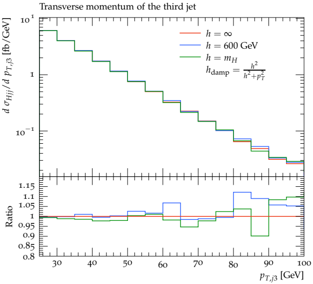


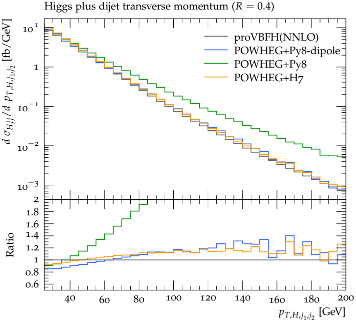
Where do we stand? N$^{(2)}$LO / MC comparison in VBF

[Jäger,Scheller,Plätzer,Karlberg,Zaro] arXiv:2003.12435

- Comparison between common tools Herwig/HJets, POWHEG/Pythia, and fixed-order NNLO
- Uncertainties of order 10% for more inclusive observables, order 20% for observables sensitive to radiative effects
- VBF process quite insensitive to form of Sudakov in POWHEG-BOX $\rightarrow$ little impact of hdamp parameter



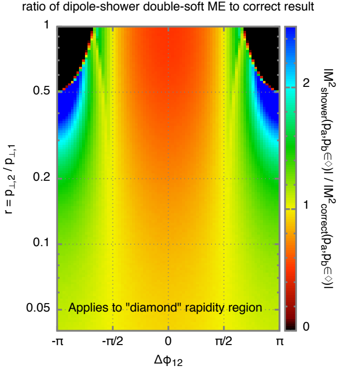


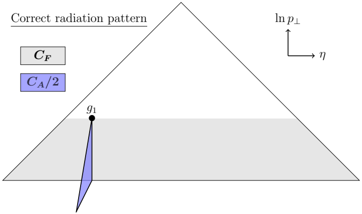


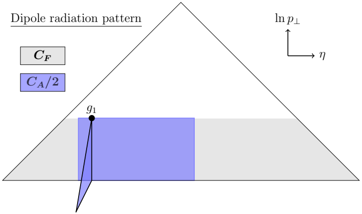
Parton showers beyond LL accuracy

[Dasgupta,Dreyer,Hamilton,Monni,Salam] arXiv:1805.09327

- Two problems in commonly used parton showers when compared to analytic NLL resummation:
  - Angular correlations across multiple emissions due to recoil strategy and choice of evolution variable spoil accuracy
  - Average color charge of initial $q\bar{q}$ dipole after radiation not reflected correctly in commonly used dipole shower approaches
- Both issues in strongly ordered soft limit







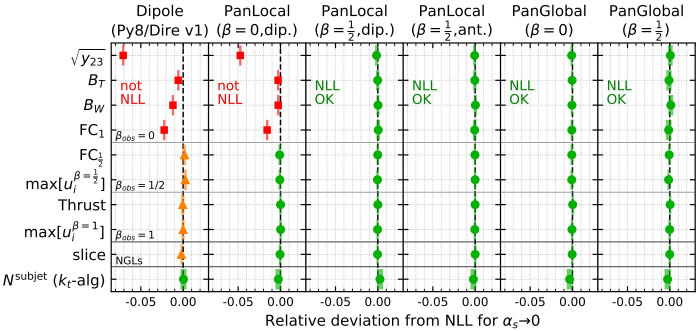
Parton showers beyond LL accuracy

[Dasgupta,Dreyer,Hamilton,Monni,Salam,Soyez] arXiv:2002.11114

- Both problems solved by partitioning of antenna radiation pattern and choosing a suitable evolution variable ($\beta \sim 1/2$)

$$k_T = \rho v e^{\beta|\bar{\eta}|} \qquad \rho = \left(\frac{s_i s_j}{Q^2 s_{ij}}\right)^{\beta/2}$$

- Three different recoil schemes lead to NLL result if β chosen appropriately: Local dipole, local antenna, and global antenna
- First provably NLL correct parton shower for $e^+e^- \to$hadrons

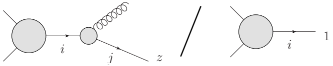


Towards parton showers at NLO

- Collinear limit: Higher-order DGLAP kernels obtained by factorization

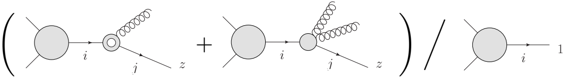
$$D_{ji}^{(0)}(z,\mu) = \delta_{ij}\delta(1-z) \qquad \leftrightarrow$$

$$D_{ji}^{(1)}(z,\mu) = -\frac{1}{\varepsilon}P_{ji}^{(0)}(z) \qquad \leftrightarrow$$



$$D_{ji}^{(2)}(z,\mu) = -\frac{1}{2\varepsilon}P_{ji}^{(1)}(z) + \frac{\beta_0}{4\varepsilon^2}P_{ji}^{(0)}(z) + \frac{1}{2\varepsilon^2}\int_z^1 \frac{\mathrm{d}x}{x}P_{jk}^{(0)}(x)P_{ki}^{(0)}(z/x)$$

$\leftrightarrow$

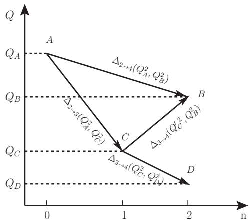


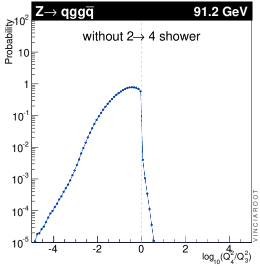
- Being able to compute $P_{ji}^{(1)}$ fully differentially in the parton shower is a prerequisite for NNLL accuracy in an observable-independent way
- $P_{ji}^{(1)}$ not probabilities, but sum rules hold ($\leftrightarrow$ unitarity constraint) In particular: Momentum sum rule identical between LO & NLO
- Soft limit schematically identical, but beware of overlap with collinear!

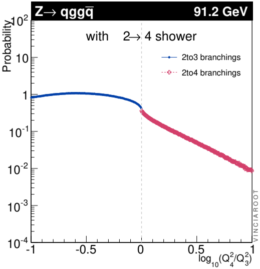
Towards parton showers at NLO

[Hartgring,Laenen,Skands] arXiv:1303.4974, [Li,Skands] arXiv:1611.00013

- ME-corrected showers (e.g. Vincia) predict correct 2-emission pattern $\rightarrow$ possibility to extend to full NLO by including virtual corrections
- Result depends on evolution variable due to phase-space restrictions in real emission integrals that arise from ordering (e.g. $A \rightarrow B \rightarrow C$)
- If missing phase space region is filled by direct $2 \rightarrow 4$ transitions ($A \rightarrow B$) obtain complete NLO antenna shower framework





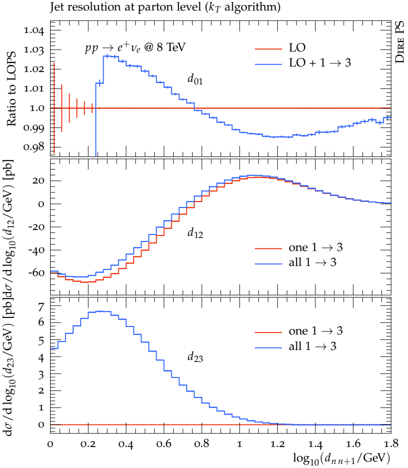


Towards parton showers at NLO

- Alternative approach based on standard parton shower:
  - Subtracted $2 \to 4$ splitting function in ordered phase-space region
  - Complete $2 \to 4$ splitting function in unordered phase-space region
- Structurally identical to fixed-order subtraction (e.g. Catani-Seymour)

$$P^{(1)}_{qq'}(z) = \mathrm{C}_{qq'}(z) + \mathrm{I}_{qq'}(z) + \int \mathrm{d}\Phi_{+1} \Big[\mathrm{R}_{qq'}(z, \Phi_{+1}) - \mathrm{S}_{qq'}(z, \Phi_{+1}) \Big]$$

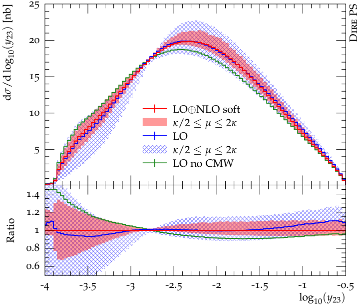
- Shown to reproduce known NLO splitting functions in collinear limit
  [Curci,Furmanski,Petronzio] NPB175(1980)27

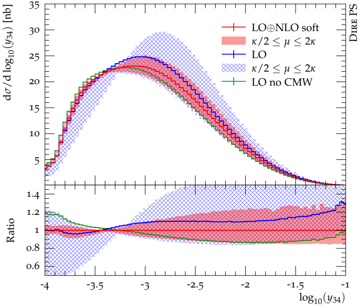


Towards parton showers at NLO

[Dulat,Prestel,SH] arXiv:1805.03757

- Alternative approach for soft radiation
  - ME correction implements kinematic corrections, angular correlations and first non-trivial sub-leading color contributions
  - Complete $2 \to 4$ splitting function in unordered phase-space region
- Reproduces benchmark given by soft gluon resummation at 2 loops
  [Belitsky] hep-ph/9808389
- CMW factor generated differentially by endpoint contributions, yields good agreement with inclusive CMW scheme

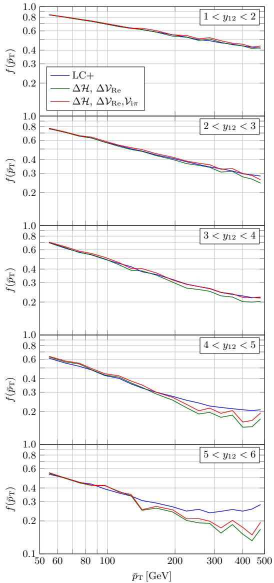




Parton showers beyond LC accuracy

[Nagy,Soper] arXiv:1902.02105, arXiv:1905.07176

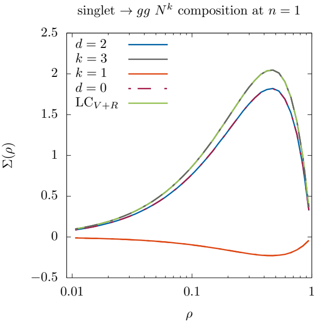
- Systematic expansion of shower operator acting on statistical space
- Starts with LC+ approximation $\rightarrow$ simplify color insertion operators $T_i T_k \rightarrow T_i^2$ but retain bra/ket states exactly
- Extension to higher number of terms in $1/N_c$ by means of additional operators
  - $\Delta\mathcal{H}$ - real-emission
  - $\Delta\mathcal{V}_{Re}$ - virtual correction (real part)
  - $\mathcal{V}_{i\pi}$ - virtual correction (imaginary part)
- Threshold resummation possible
  [Nagy,Soper] arXiv:1711.02369

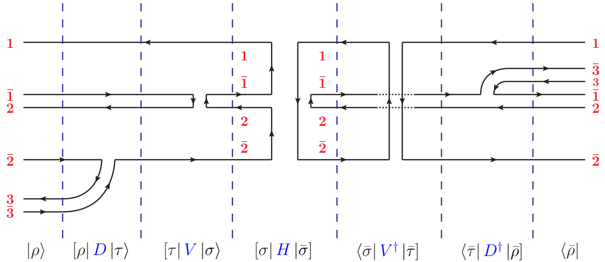


Parton showers beyond LC accuracy

[DeAngelis,Forshaw,Plätzer] arXiv:2007.09648

- Amplitude based evolution using color flow decomposition
- Systematic expansion in $1/N_c$ terms related to number of swaps of color lines

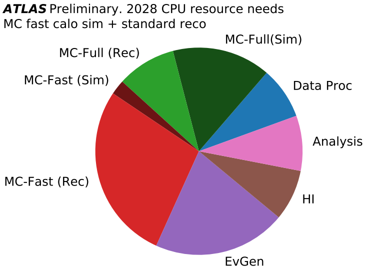


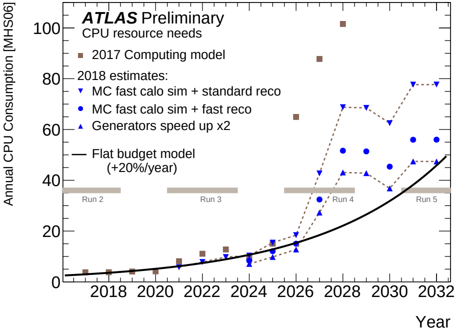


Computing challenges

[HSF Generator WG] arXiv:2001.10028

- Event generation will consume significant fraction of resources at LHC soon
- Need to scrutinize both generator usage and underlying algorithms
- Dedicated effort in HEP Software Foundation (HSF)

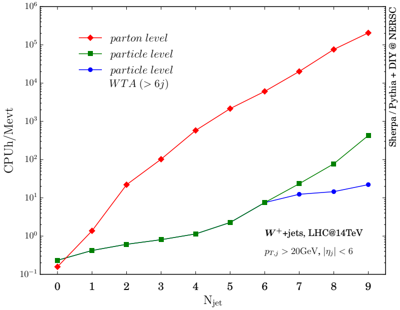




[ATLAS] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ComputingandSoftwarePublicResults

Computing challenges

- Hard scattering simulation much more demanding than parton shower & hadronization in multi-jet merged simulations
- Complexity of merging ME&PS grows quickly due to inherent N! scaling of algorithms, but still negligible compared to hard scattering calculation



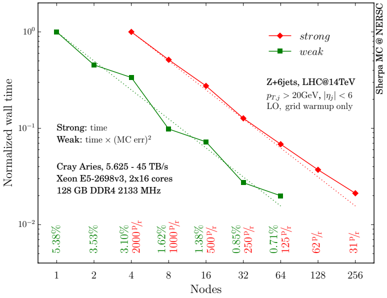
Origin of the problem

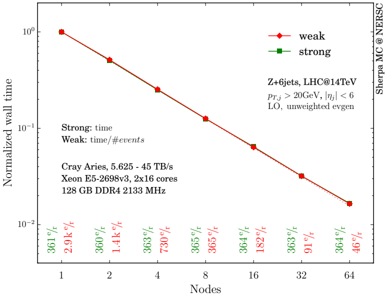
- Best case ME computation naively scales as $\approx \mathcal{O}(3^N)$
- Monte-Carlo unweighting efficiency degrades quickly due to high dimensionality of phase-space integral (3N-4)
- Overall scaling $\approx \mathcal{O}(4^N)$ if not taking cuts into account
- Cut inefficiencies worsen the picture significantly

Parallel computing

[Prestel,Schulz,SH] arXiv:1905.05120

- Integration / event generation performed on multiple cores
- Vegas grid warmup step scales (strong & weak) up to $\sim$ 2048 cores
- Event generation step scales (strong & weak) up to $\sim$ 2048 cores
- Performance limited by number of events being processed per rank (Average timing can only be expected if statistics is large enough)





Improved NLO matching

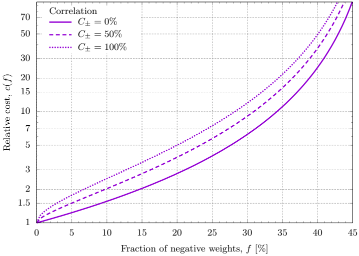
[Frederix,Frixione,Prestel,Torrielli] arXiv:2002.12716

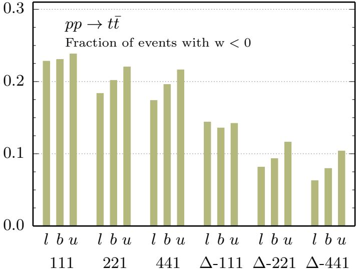
- For NLO matched simulations, efficiency largely depends on negative weight fraction in hard cross section calculation
- Negative weights can be significantly reduced by performing partial merging, schematically

$$\mathbb{H} \to (R - S)\Delta$$

$$\mathbb{S} \to B + V + I + \int S\Delta + \int R(1 - \Delta)$$

- Convergence of additional contribution to $\mathbb{S}$-events can be improved by folding

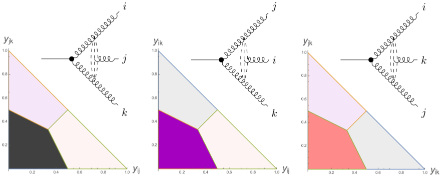




Sectorization

[Brooks,Preuss,Skands] arXiv:2003.00702

- Renewed interest in sector showers using antenna approach
- May provide avenue to more efficient merging due to unique branching history
- Novel implementation of algorithm in Vincia for hadron colliders and decays [Brooks,Skands] arXiv:1907.08980



	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
CS Dipole	2	8	48	384	3840	46080	645120
Global Antenna	1	2	6	24	120	720	5040

Summary

- Good agreement between different MC generators
  when using similar setups / assumptions
- NLL accurate evolution → direct comparison to analytic resummation
- NLO accurate evolution → first realistic uncertainty estimates
  Pathway to observable-independent, NNLL accurate resummation
- Sub-leading color evolution → improved predictions
  for processes with high jet multiplicity

- Most of the above improvements imply a certain fraction
  of negative weights or some other compute inefficiency
- It is possible that the theoretically improved MCs we desire
  will not be the tools to produce events for full simulation
- We might instead want to think about how to calibrate lower-precision
  (NLO+NLL,LC) MCs with higher-precision (NNLO+NNLL(?),NLC(?))
  and then propagate uncertainty predictions