MC Event Generators and Phenomenology

With a special focus on DIS

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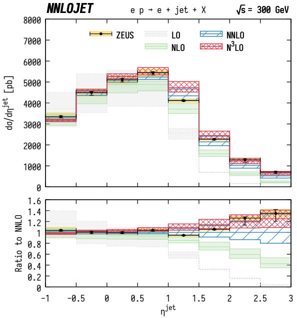
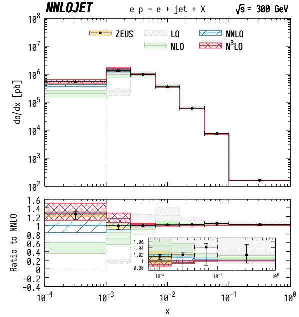
DIS as a precision test of QCD

- Inclusive DIS at NLO QCD
  [Bardeen,Buras,Duke,Muta] PRD18(1978)3998
  [Altarelli,Ellis,Martinelli] NPB143(1978)521
  [Humpert,van Neerven] NPB184(1981)225
- ... at N^{2}LO QCD [Zijlstra,vanNeerven]
  NPB383(1992)525, PLB297(1992)377
  [Moch,Vermaseren] hep-ph/9912355
- ... at N^{3}LO QCD [Moch,Vermaseren,Vogt]
  hep-ph/0504242, arXiv:0812.4168
- Di-jet production at NLO QCD
  [Mirkes,Zeppenfeld] hep-ph/9511448
  [Graudenz] hep-ph/9710244
  [Nagy,Trocsanyi] hep-ph/0104315
- ... at N^{2}LO QCD
  [Abelof,Boughezal,Liu,Petriello] arXiv:1607.04921
  [Currie,Gehrmann,Niehues] arXiv:1606.03991
  [Currie,Gehrmann,Huss,Niehues] arXiv:1703.05977
- DIS at N^{3}LO QCD, fully exclusive
  [Currie,Gehrmann,Glover,Huss,Niehues,Vogt]
  arXiv:1803.09973





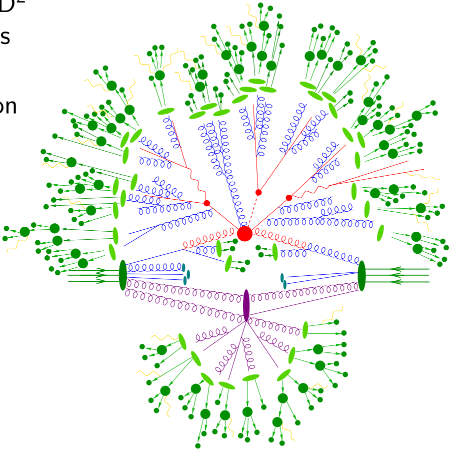
Fixed-order calculations vs event generators

Anatomy of MC simulations

- **Hard interaction**
  LO, NLO QCD/EW[1], NNLO QCD[2]
  Generic matrix-element generators
- **Radiative corrections**
  Parton Showers, YFS resummation
- **Hadronization** & **Decays**
  Cluster / String model
  Phase space or EFTs + YFS

Comparison to fixed order (FO)

- **Hard interaction**
  Lower precision than FO
- **Radiative corrections**
  Resummed & matched to FO
- **Hadronization** & **Decays**
  Not accessible at FO



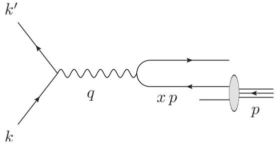
[1] via interfaces to 1-loop generators
[2] for selected processes

DIS as a precision test of QCD dynamics

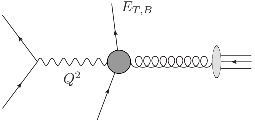
- Inclusive DIS, computed in collinear factorization
  - Just a form factor! Described by

    $$Q^2 = q^2 = (k' - k)^2 \text{ and } x = \frac{Q^2}{2\, q \cdot p}$$

  - Hadronic cm energy
    $W = Q\sqrt{(1-x)/x}$



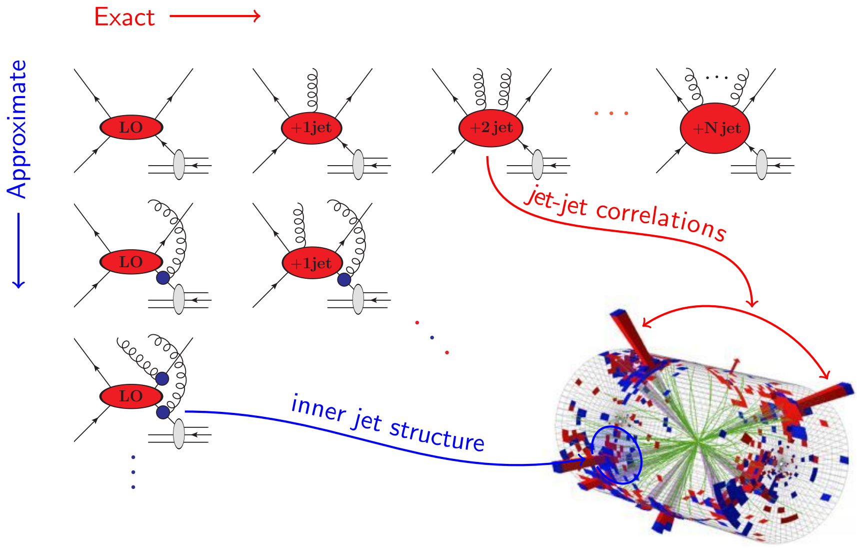
- QCD dynamics in more differential measurements



  - A multi-scale problem
  - $e^{\pm}q \to e^{\pm}q$ if $E^2_{T,B} \lesssim Q^2$
    $\gamma^* g \to jets$ if $Q^2 \lesssim E^2_{T,B}$

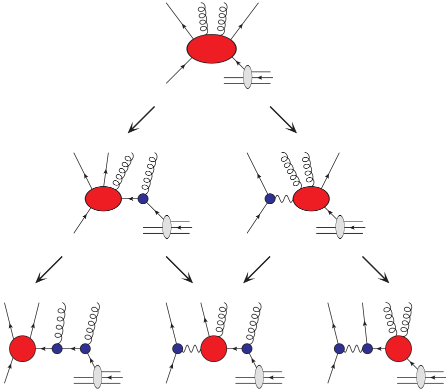
- What makes DIS different from $e^+e^- \to jj$ and $pp \to e^+e^-$ is that the virtuality of the exchanged photon tends to be close to zero

How to simulate it? Merging multiple LO calculations



Getting the physics right: Topology selection

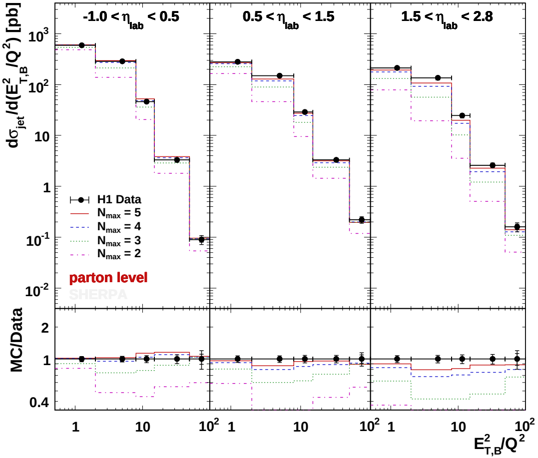
- QCD dynamics of the multi-jet final state must be reflected accurately when identifying a parton-shower branching tree
  [Carli,Gehrmann,SH] arXiv:0912.3715
  - $e^{\pm}q \to e^{\pm}q$ if $E_{T,B}^2 \lesssim Q^2$
  - $\gamma^* g \to \text{jets}$ if $Q^2 \lesssim E_{T,B}^2$
  - $qg \to \text{jets}$ if $Q^2 \ll E_{T,B}^2$
- Similar to taking direct and fragmentation component into account in hard photon production at hadron colliders
  [Schumann,Siegert,SH] arXiv:0912.3501

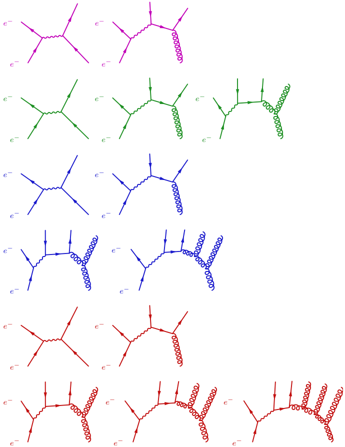


Comparison to HERA data

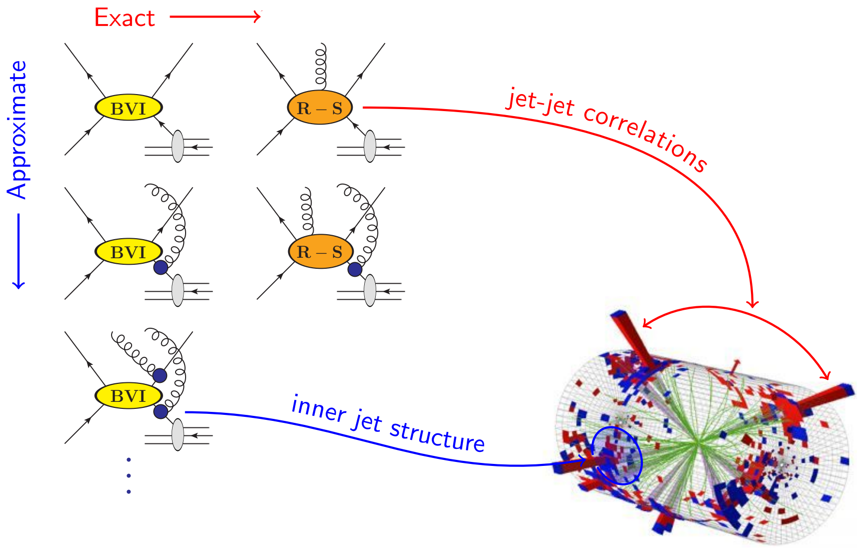
[Carli,Gehrmann,SH] arXiv:0912.3715

Variation of maximum matrix-element multiplicity, N_{max}





How to simulate it? Matching NLO to parton showers



How to simulate it? Matching NLO to parton showers

Two major techniques to match NLO calculations and parton showers

MC@NLO

[Frixione,Webber] hep-ph/0204244

- Use parton-shower splitting kernel as infrared subtraction term
- Multiply LO event weight by Born-local K-factor including integrated subtraction term and virtual corrections
- Add hard remainder function consisting of subtracted real-emission correction

POWHEG

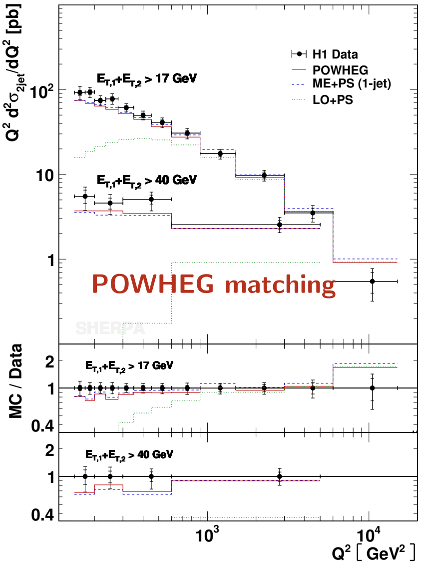
[Nason] hep-ph/0409146

- Use matrix-element corrections to replace parton-shower splitting kernel by full real-emission matrix element in first shower branching
- Multiply LO event weight by Born-local NLO K-factor (integrated over real corrections that can be mapped to Born according to parton-shower kinematics)

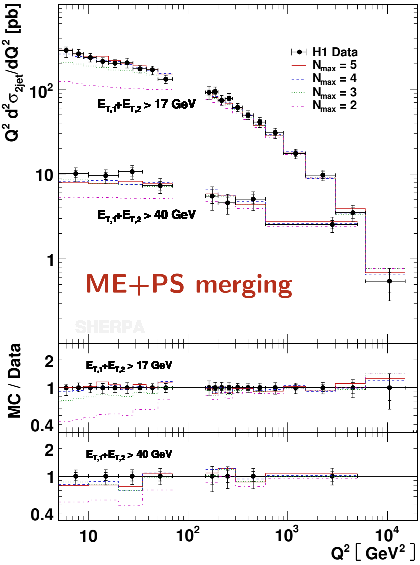
Both cases: Beware of sub-leading color terms and spin correlations!

Matching vs Merging: Which one is right for your purpose?

[Krauss,Schönherr,Siegert,SH] arXiv:1008.5399



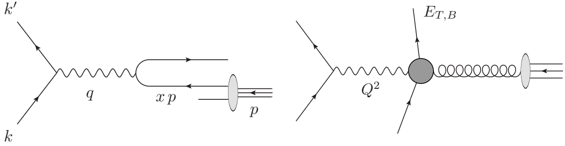
[Carli,Gehrmann,SH] arXiv:0912.3715



How to simulate it? Matching NNLO to parton showers

[Kuttimalai,Li,SH] arXiv:1809.04192

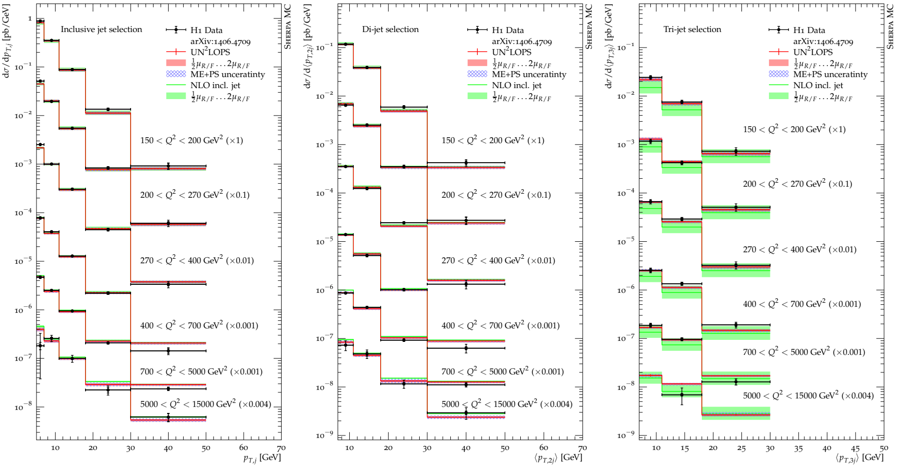
- Relatively straightforward to compute inclusive DIS at NNLO QCD
  [Zijlstra,vanNeerven] NPB383(1992)525, PLB297(1992)377 [Moch,Vermaseren,Vogt] hep-ph/0504242
- Combined with Projection-to-Born method → fully differential NNLO
- UN^{2}LOPS matching to parton shower for particle-level simulations
  [Lönnblad,Prestel] arXiv:1211.7278, [Li,Prestel,SH] arXiv:1405.3607
- Scale choice appropriate for simultaneous description of inclusive DIS and inclusive jet / di-jet / tri-jet production → $\mu^2_{R/F} = (Q^2 + (H_T/2)^2)/2$



- Good agreement with H1 measurements in both high-Q^2 and low-Q^2 region [Andreev et al.] arXiv:1406.4709, arXiv:1611.03421

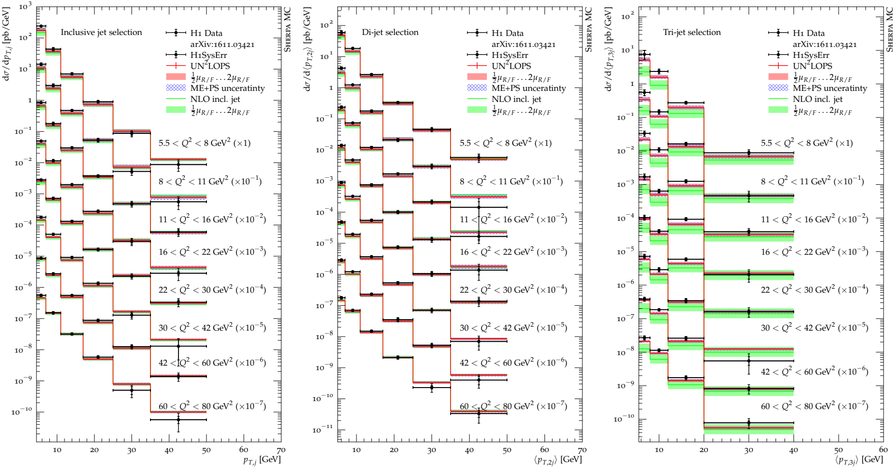
NNLO particle-level simulation vs. H1 high-Q^2 data

[Kuttimalai,Li,SH] arXiv:1809.04192



NNLO particle-level simulation vs. H1 low-Q^2 data

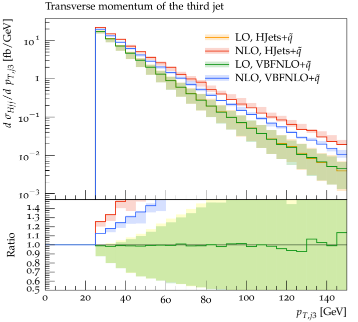
[Kuttimalai,Li,SH] arXiv:1809.04192

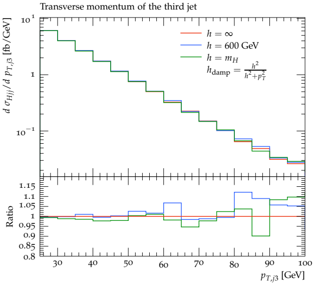


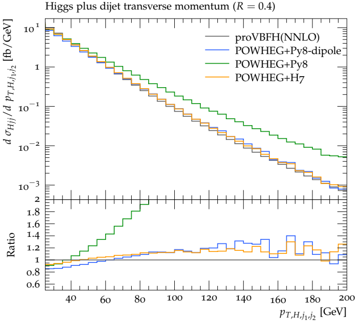
Where do we stand? N$^{(2)}$LO / MC comparison in VBF

[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



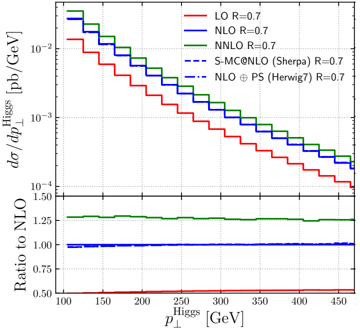


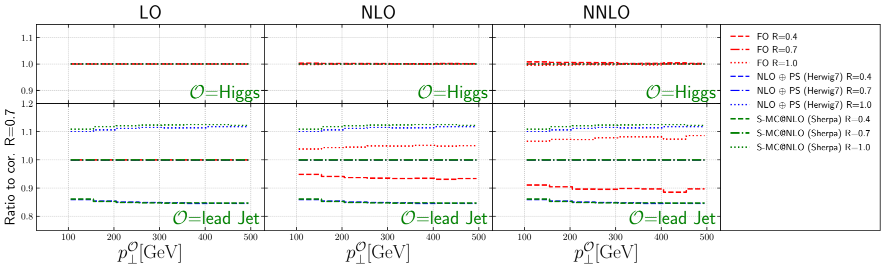


Where do we stand? $N^{(2)}LO$ / MC comparison in gg→Hj

[Bellm at al.] arXiv:1903.12563

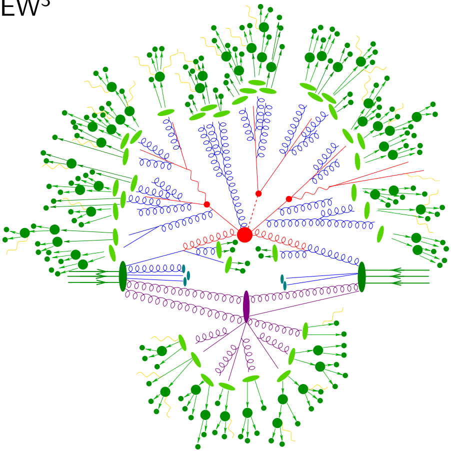
- Good agreement between MC@NLO (Herwig / Sherpa) and fixed-order pQCD for inclusive observables in $pp \to Hj$
- Radius dependence of cross section well modeled by MC in comparison to NNLO
- Spurious reduction of uncertainties at small R, more pronounced at NNLO than NLO → alternative prescription needed,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





Current developments

- **Hard interaction**
  Extension of capabilities at NLO EW[3]
  EW Sudakov resummation
- **Radiative corrections**
  Matching at NLO QCD$\oplus/\otimes$EW
  Extension of parton showers to
  NLO, NLL, NLC and beyond
- **Hadronization** & **Decays**
  Hadronization at finite N_c
  Dense QCD environments
  Collective effects

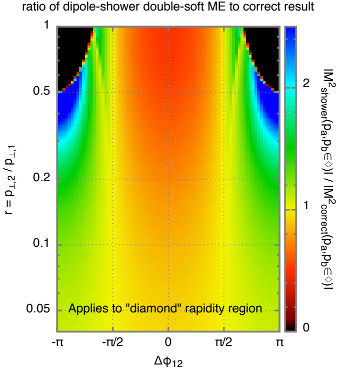


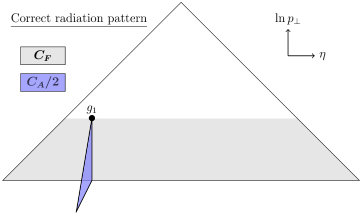
[3] via interfaces to 1-loop generators

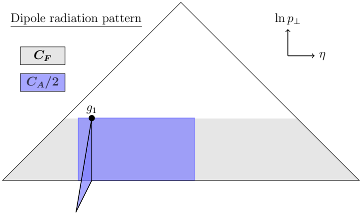
Parton showers beyond LL accuracy

[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







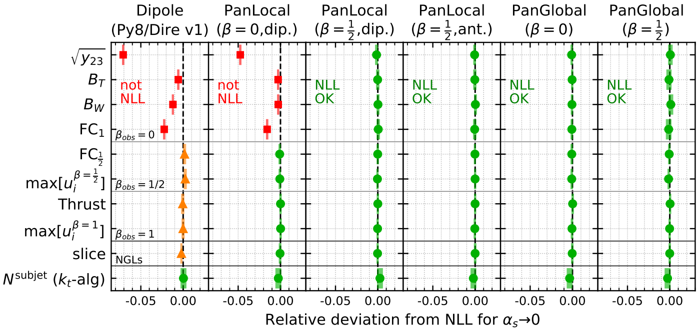
Parton showers beyond LL accuracy

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

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

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

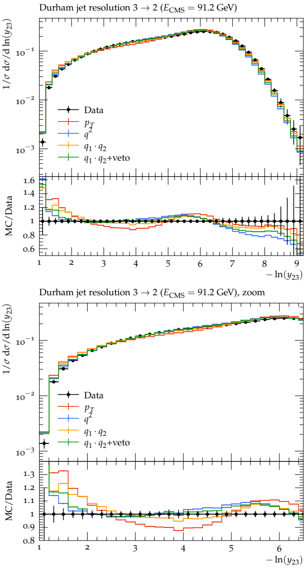
- Three different recoil schemes lead to NLL result if β chosen appropriately: Local dipole, local antenna, and global antenna
- First provably NLL correct parton shower for $e^+e^- \rightarrow$hadrons



Parton showers beyond LL accuracy

[Bewick,Ferrario-Ravasio,Richardson,Seymour] arXiv:1904.11866

- Recoil schemes affect logarithmic accuracy but impact also phase-space coverage
- In context of angular ordered Herwig 7 (NLL accurate for global observables)
  - q_T preserving scheme:
    Maintains logarithmic accuracy
    Overpopulates hard region
  - q^2 preserving scheme:
    Breaks logarithmic accuracy
    Good description of hard region
  - Dot product preserving scheme (new):
    Maintains logarithmic accuracy
    Good description of hard radiation

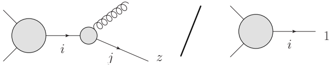


Towards parton showers at NLO

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

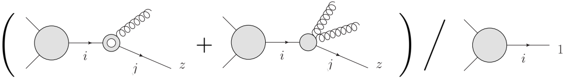
$$D^{(0)}_{ji}(z,\mu) = \delta_{ij}\delta(1-z) \qquad \leftrightarrow$$

$$D^{(1)}_{ji}(z,\mu) = -\frac{1}{\varepsilon}P^{(0)}_{ji}(z) \qquad \leftrightarrow$$



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

$$\leftrightarrow$$

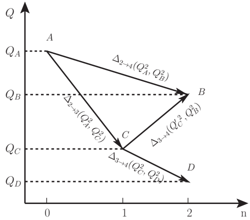


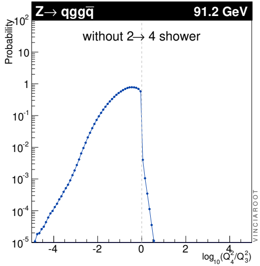
- Being able to compute $P^{(1)}_{ji}$ fully differentially in the parton shower is a prerequisite for NNLL accuracy in an observable-independent way
- $P^{(1)}_{ji}$ not probabilities, but sum rules hold ($\leftrightarrow$ unitarity constraint)
  In particular: Momentum sum rule identical between LO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

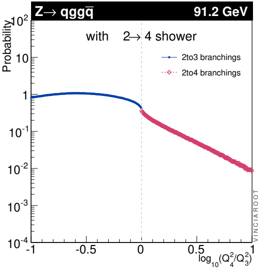
Towards parton showers at NLO

[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





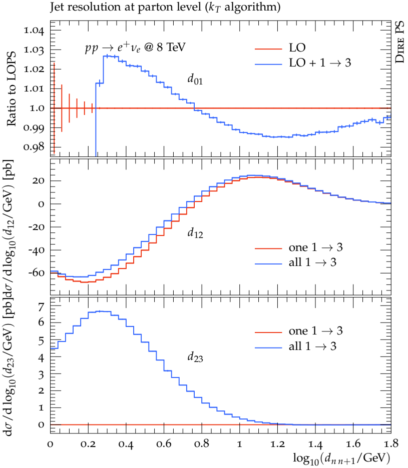


Towards parton showers at NLO

- 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)

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

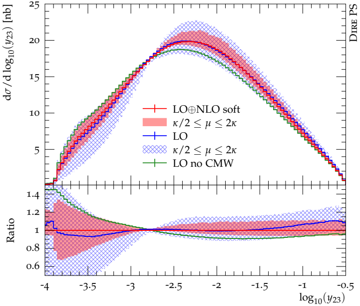
- Shown to reproduce known NLO splitting functions in collinear limit
[Curci,Furmanski,Petronzio] NPB175(1980)27

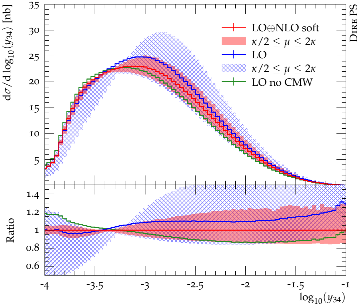


Towards parton showers at NLO

[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

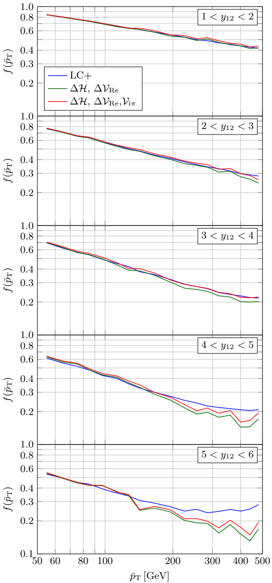




Parton showers beyond LC accuracy

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

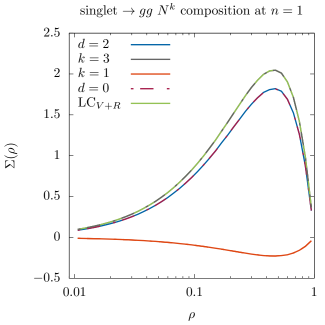
- Systematic expansion of shower operator acting on statistical space
- Starts with LC+ approximation → simplify color insertion operators $T_i T_k \to T_i^2$ but retain bra/ket states exactly
- Extension to higher number of terms in $1/N_c$ by means of additional operators
  - $\Delta\mathcal{H}$ - 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

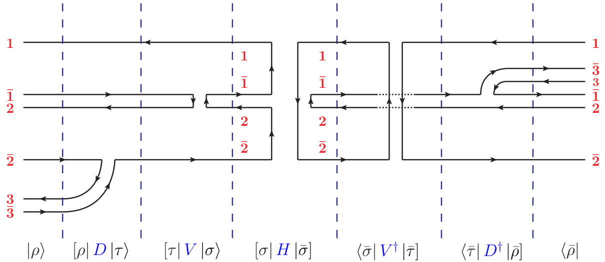


Parton showers beyond LC accuracy

[DeAngelis,Forshaw,Plätzer] arXiv:2007.09648
[Forshaw,Holguin,Plätzer] arXiv:1905.08686

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

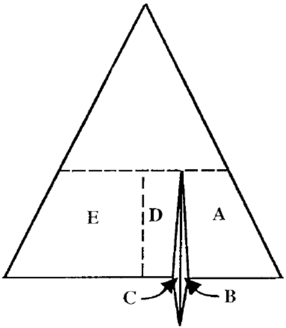




Parton showers beyond LC accuracy

[Gustafsson] Nucl.Phys.B392(1993)251-280
[Hamilton,Medves,Salam,Scyboz,Soyez] arXiv:2011.10054

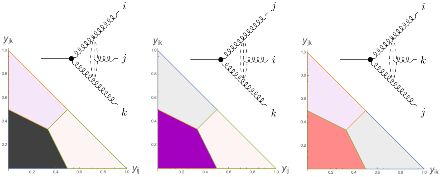
- Different parts of phase space for coherent emission off a $q\bar{q}g$ system can be associated with individual hard partons (jets)
- Best visualized in Lund plane
  - Region A: q jet
  - Region B&C: g jet
  - Region E: $\bar{q}$ jet
- Region D: Coherent emission off $\bar{q}g$ system
  Color charge is that of "mother" $\bar{q}$-jet $\rightarrow C_F$
- Extension to all orders: Emissions in Lund "back-plane" have color factor C_F, even if emitting large-N_c dipole is gluon pair



Sector showers

[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

Deep Inelastic Scattering

- A precision laboratory for validating and calibrating MCs
- Simulations possible up to NNLO QCD precision
- NLO (merged) simulations available in all major generators
- Incorporation of QED/EW corrections one of next milestones

More generally

- Good agreement between different MC generators when using similar setups & assumptions (not trivial!)
- 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

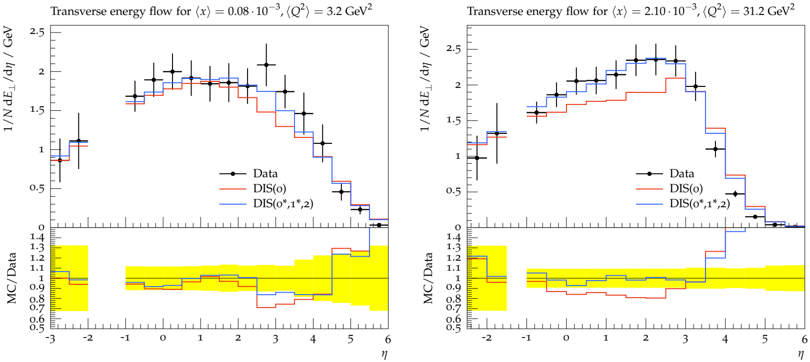
Thank you for your attention!

Availability of DIS simulations

- **Herwig**
  - Matching fully automated [Gieseke,Plätzer] arXiv:1109.6256
  - External 1-loop providers & builtin loop library
  - Merging in modified unitarized approach
    [Plätzer] arXiv:1211.5467, [Bellm,Gieseke,Plätzer] arXiv:1705.06700
  - QED & mixed higher-order corrections work in progress
- **Pythia**
  - New parton shower Dire [Prestel,SH] arXiv:1506.05057
  - Unitarized merging under development [Prestel,Lönnblad] arXiv:1211.4827
  - Matching via interface to POWHEG / MC@NLO
- **Sherpa**
  - Matching fully automated [Krauss,Schönherr,Siegert,SH] arXiv:1008.5399, arXiv:1111.1220
  - External 1-loop providers & builtin loop library
  - Merging in non-unitarized approach [Krauss,Schönherr,Siegert,SH] arXiv:1207.5030
  - NNLO matching [Kuttimalai,Li,SH] arXiv:1809.04192

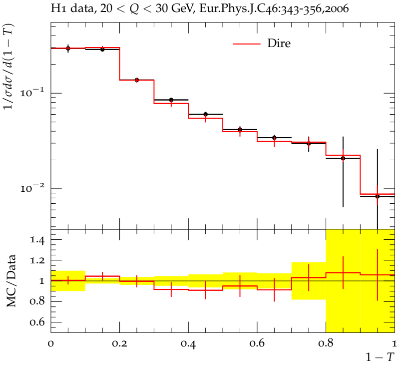
Performance examples – Herwig

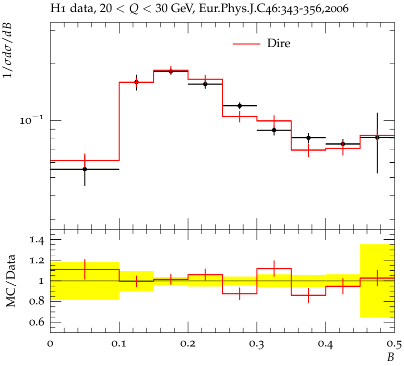
- NLO Merged calculation vs data from hep-ex/9907027



Performance examples – Pythia

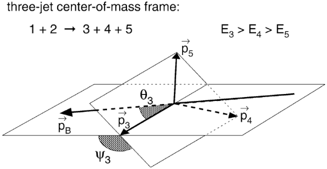
- Parton-shower calculation vs data from hep-ex/0512014



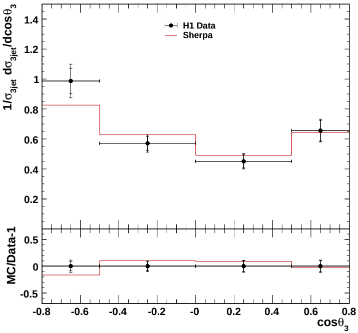


Performance examples – Sherpa

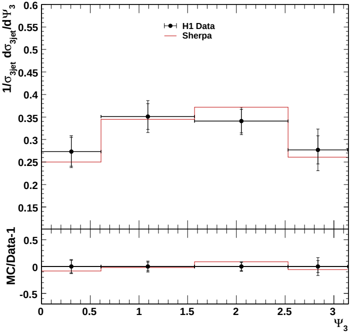
[Carli,Gehrmann,SH] arXiv:0912.3715



$\cos\theta_3$ $Q^2 > 150$ GeV^2

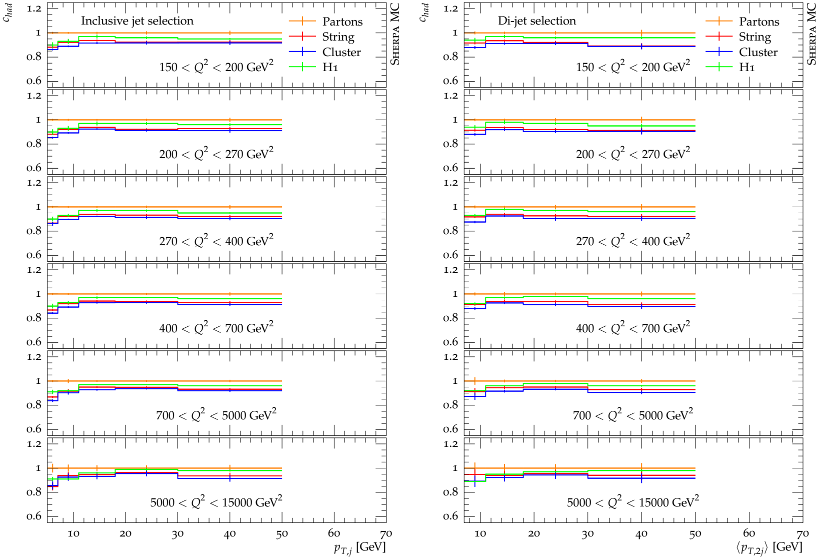


Ψ_3 $Q^2 > 150$ GeV^2



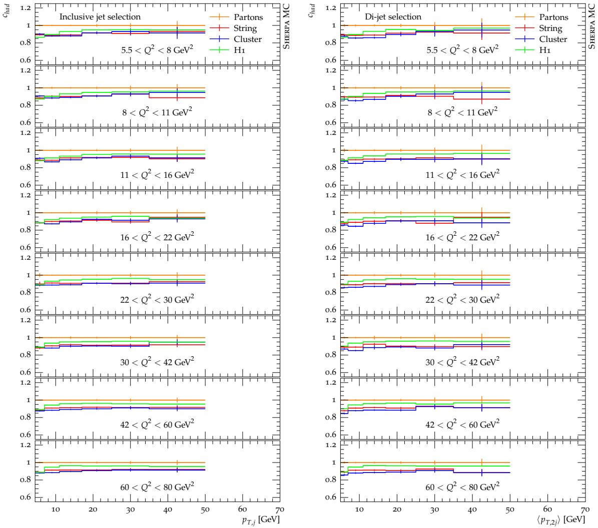
Hadronization corrections at high Q^2

[Kuttimalai,Li,SH] arXiv:1809.04192



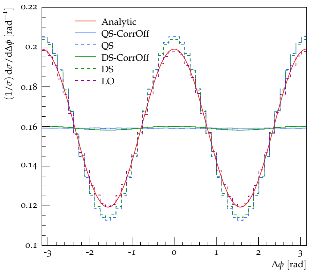
Hadronization corrections at low Q^2

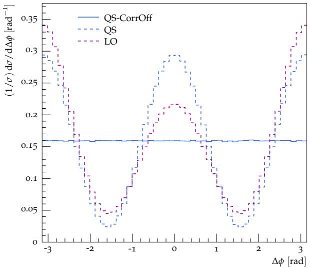
[Kuttimalai,Li,SH] arXiv:1809.04192



Spin correlations in decays and showers

[Richardson,Webster] arXiv:1807.01955





- Spin-correlation algorithms known since '80s [Collins] NPB304(1988)794, [Knowles] CPC58(1990)271, [Richardson] hep-ph/0110108
- Decay correlations in $\sim$ all generators [Gigg,Richardson] hep-ph/0703199 [Artoisenet, Frederix,Mattelaer,Rietkerk] arXiv:1212.3460 [Kuttimalai,Schumann,Siegert,SH] arXiv:1412.6478
- Spin-dependent parton showers
  Herwig [Richardson,Webster] arXiv:1807.01955
  Vincia [Fischer,Lifson,Skands] arXiv:1708.01736

Improved NLO matching

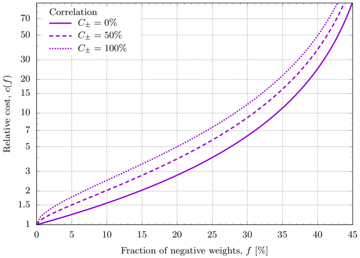
[Frederix,Frixione,Prestel,Torrielli] arXiv:2002.12716

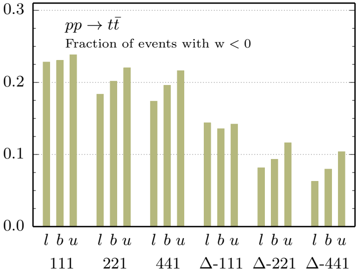
- For NLO matched simulations, efficiency largely depends on negative weight fraction in hard cross section calculation
- Negative weights can be significantly reduced by performing partial merging, schematically

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

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

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

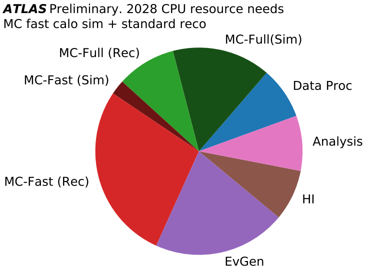


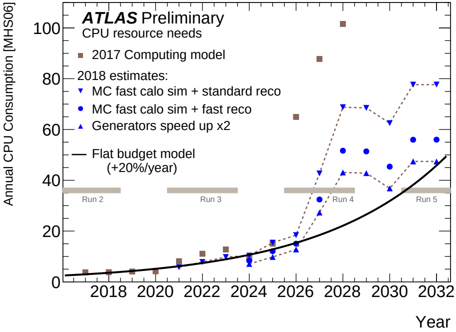


Computing challenges

[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)

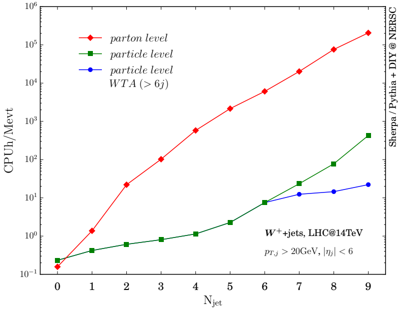




[ATLAS] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ComputingandSoftwarePublicResults

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 ∼ 2048 cores
- Event generation step scales (strong & weak) up to ∼ 2048 cores
- Performance limited by number of events being processed per rank
  (Average timing can only be expected if statistics is large enough)