Aspects of MC event generation for e^+p collisions

Stefan Höche

Fermi National Accelerator Laboratory

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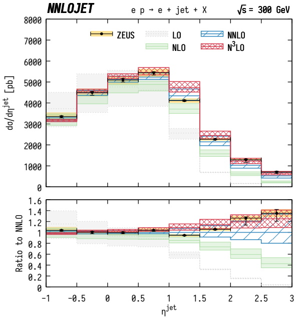
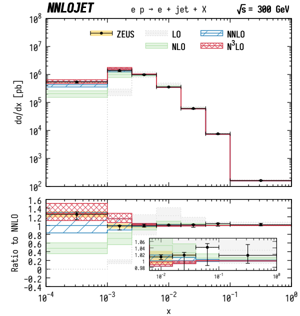
Precision QCD calculations

- 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

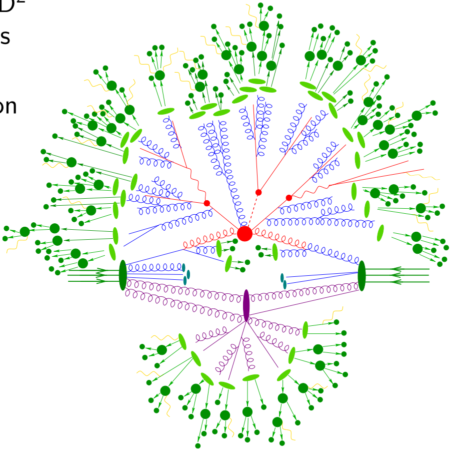




Fixed-order calculations vs event generators

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



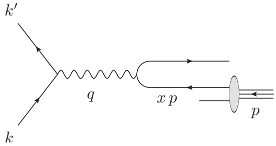
Comparison to fixed order (FO)

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

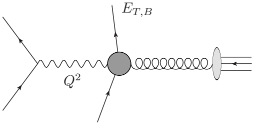
[1] via interfaces to 1-loop generators
[2] for selected processes

Peculiarities of DIS

- Leading order $e^{\pm}p$ - scattering in collinear factorization
  - No jets, sole kinematical variables are
    $$Q^2 = q^2 = (k' - k)^2 \text{ and } x = \frac{Q^2}{2\,q \cdot p}$$
  - Hadronic cm energy
    $W = Q\sqrt{(1-x)/x}$



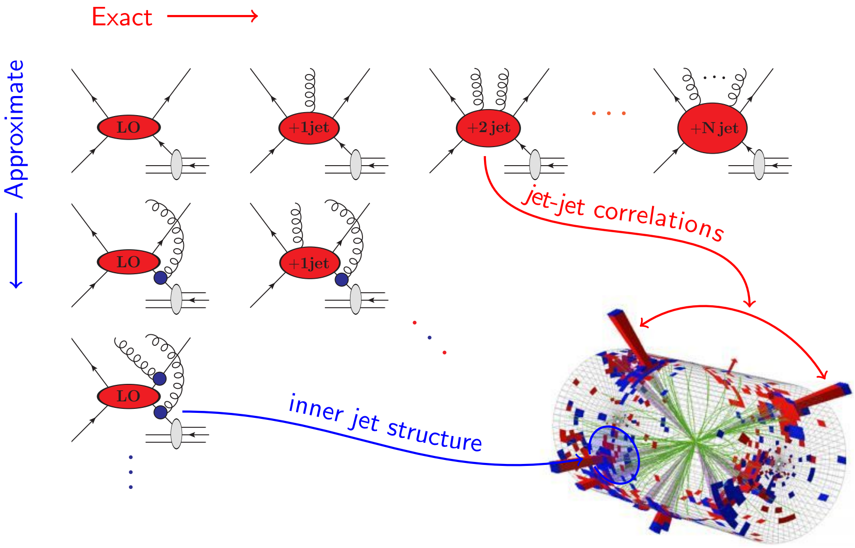
- QCD dynamics at higher orders



  - Multiple scales, e.g. $E^2_{T,B}$
  - $e^{\pm}q \to e^{\pm}q$ if $E^2_{T,B} \lesssim Q^2$
    $\gamma^* g \to jets$ if $Q^2 \lesssim E^2_{T,B}$

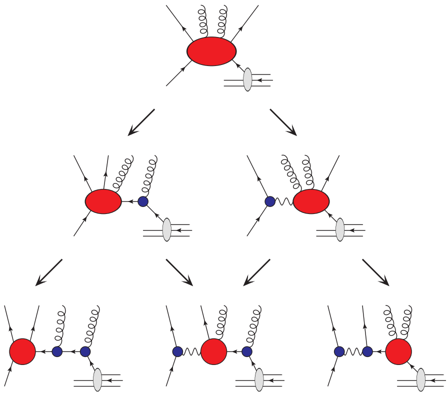
- What makes DIS different from $e^+e^- \to jj$ and $pp \to e^+e^-$ is that the virtuality of the exchanged photon tends to be close to zero
- Also the case in low-mass Drell-Yan $pp \to e^+e^-$,
  but recent experimental studies usually focus on $m_{l\bar{l}} \approx m_Z$

Merging fixed-order calculations and parton-showers



Merging fixed-order calculations and parton-showers

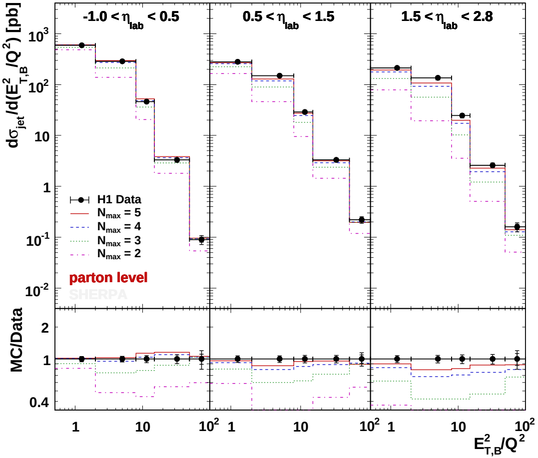
- QCD dynamics of the multi-jet final state must be reflected accurately when identifying parton-shower branching history
  [Carli,Gehrmann,SH] arXiv:0912.3715
  - $e^{\pm}q \to e^{\pm}q$ if $E_{T,B}^2 \lesssim Q^2$
  - $\gamma^* g \to$ jets if $Q^2 \lesssim E_{T,B}^2$
  - $qg \to$ jets if $Q^2 \ll E_{T,B}^2$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

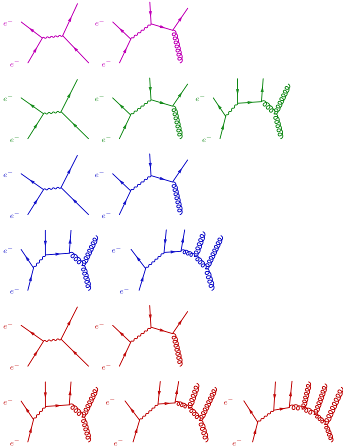


Comparison to HERA data

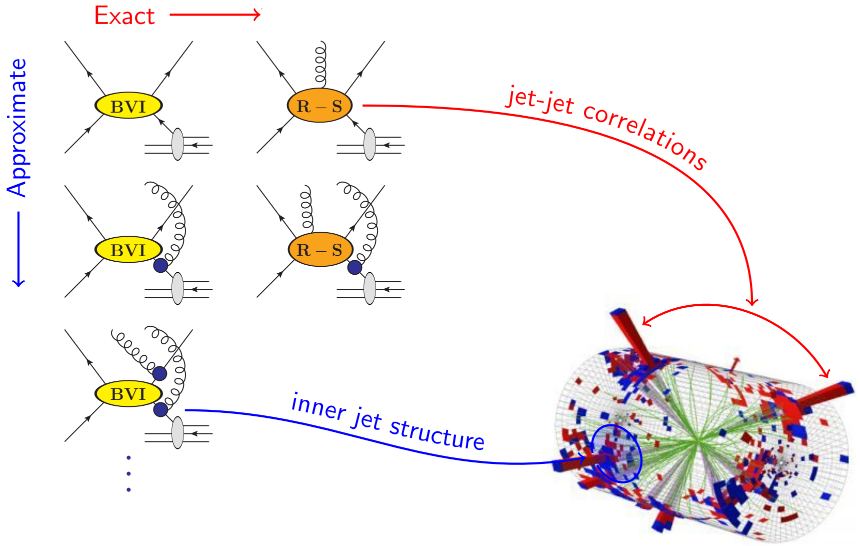
[Carli,Gehrmann,SH] arXiv:0912.3715

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





Matching fixed-order NLO calculations to parton-showers



Matching fixed-order NLO calculations to parton-showers

Two possible ways 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

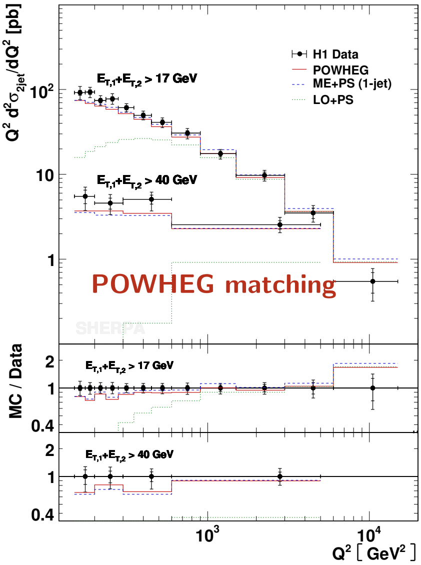
[Nason] hep-ph/0409146

- 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)

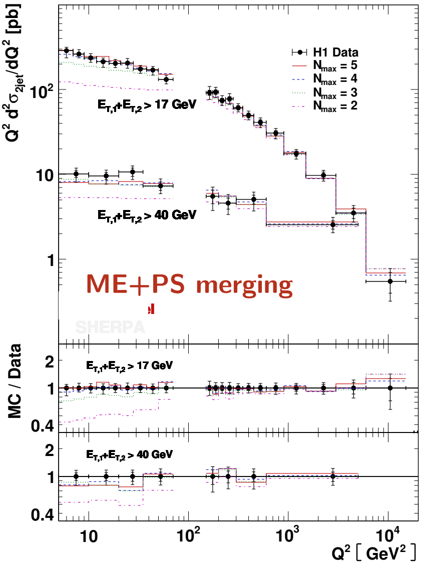
Both cases: Beware of sub-leading color terms and spin correlations!

Matching vs Merging

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



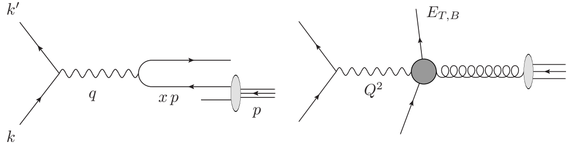
[Carli,Gehrmann,SH] arXiv:0912.3715



Matching at NNLO accuracy

[Kuttimalai,Li,SH] arXiv:1809.04192

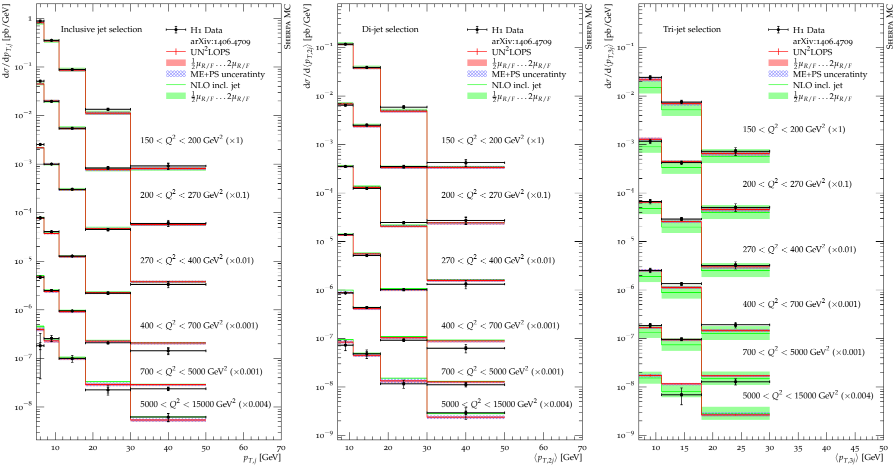
- New Sherpa module for computation of inclusive DIS at NNLO QCD
- Projection-to-Born method for fully differential fixed order predictions
  [Zijlstra,vanNeerven] NPB383(1992)525, PLB297(1992)377 [Moch,Vermaseren,Vogt] hep-ph/0504242
  [Bern,Dixon,Kosower] hep-ph/9708239, [Berger et al.] arXiv:0803.4180
- 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 $\to \mu^2_{R/F} = (Q^2 + (H_T/2)^2)/2$



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

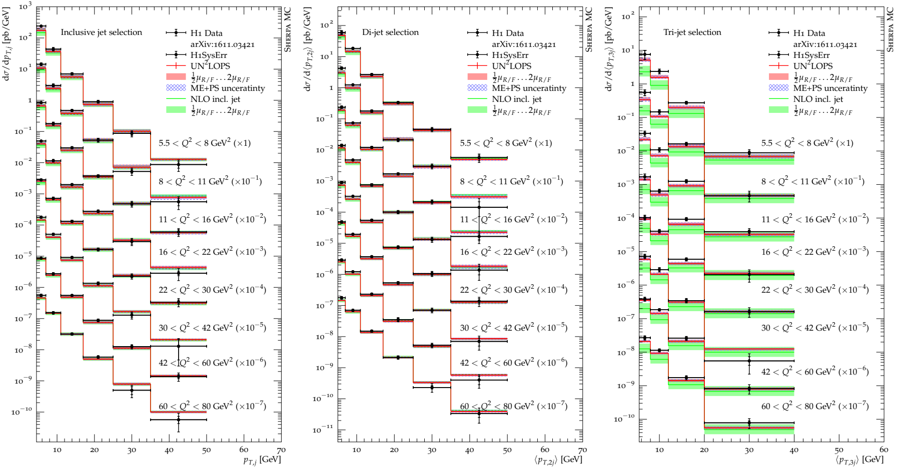
NNLO particle-level simulation vs. H1 high-Q^2 data

[Kuttimalai,Li,SH] arXiv:1809.04192



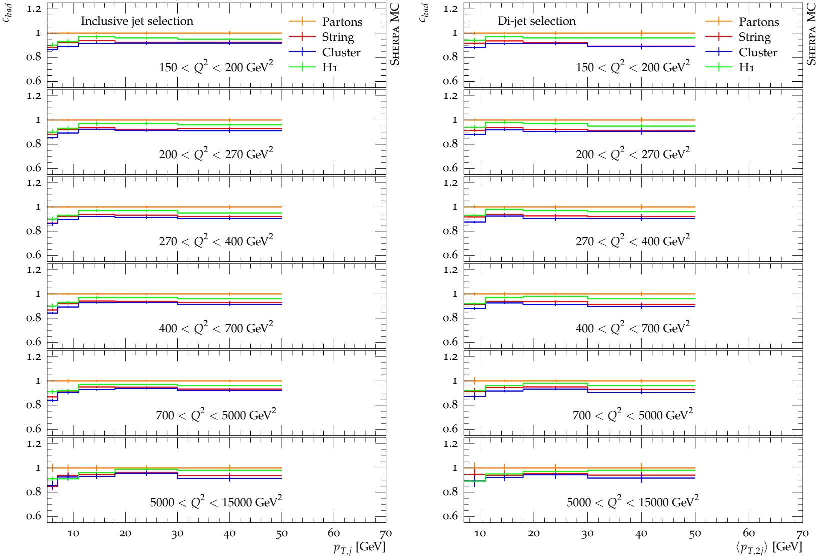
NNLO particle-level simulation vs. H1 low-Q^2 data

[Kuttimalai,Li,SH] arXiv:1809.04192



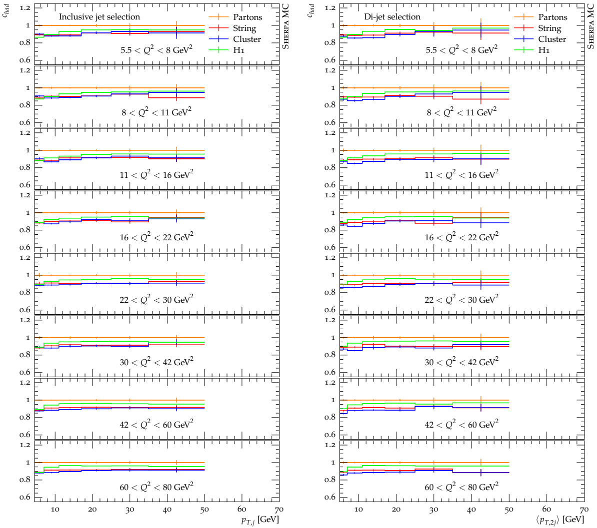
Hadronization corrections at high Q^2

[Kuttimalai,Li,SH] arXiv:1809.04192



Hadronization corrections at low Q^2

[Kuttimalai,Li,SH] arXiv:1809.04192

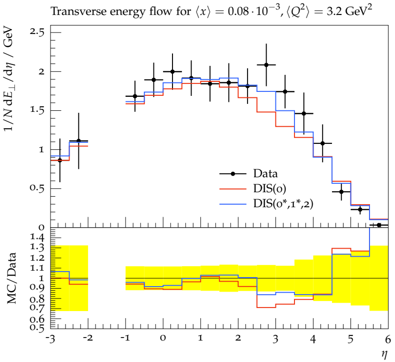


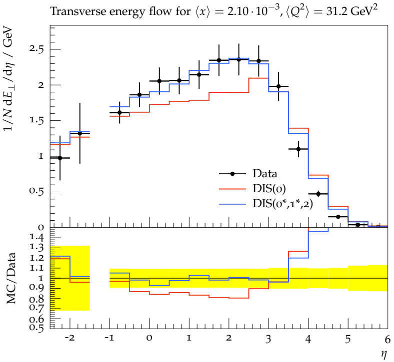
Availability of DIS simulations

- **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

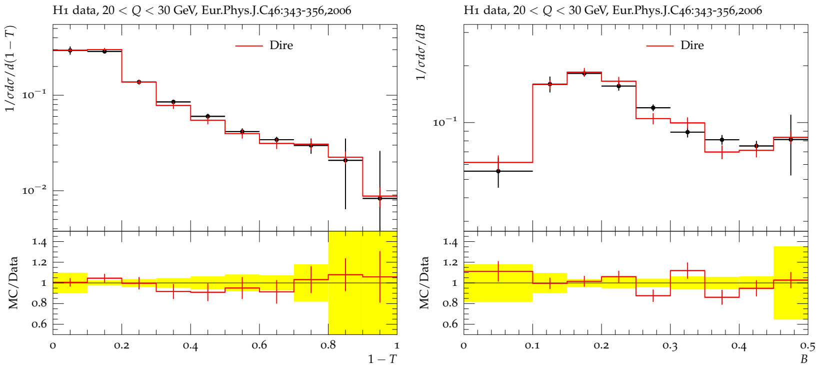
- NLO Merged calculation vs data from hep-ex/9907027





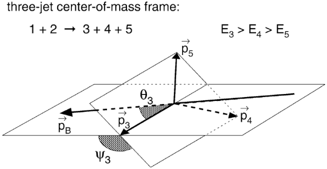
Performance examples – Pythia

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

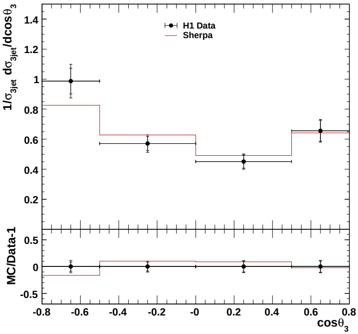


Performance examples – Sherpa

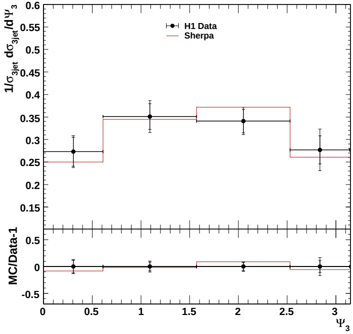
[Carli,Gehrmann,SH] arXiv:0912.3715



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

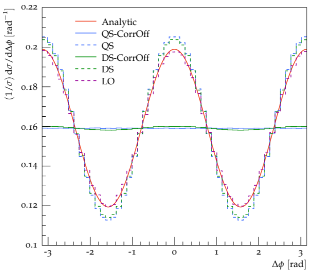


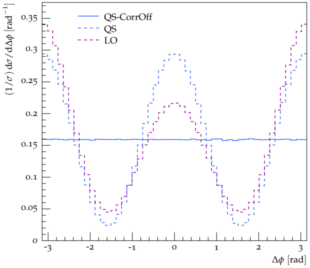
Ψ_3 $Q^2 > 150$ GeV^2



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

Summary

- DIS simulations available in all three event generation frameworks
- NLO matching & merging standard, NNLO matching available
- Peculiarities of DIS require careful selection of clustering history
- Very good description of wide range of experimental data
- Hadronization corrections fairly model independent
- Spin-correlated parton showers now becoming available