# Parton showers and Resummation

– jet resolutions as a testbed –

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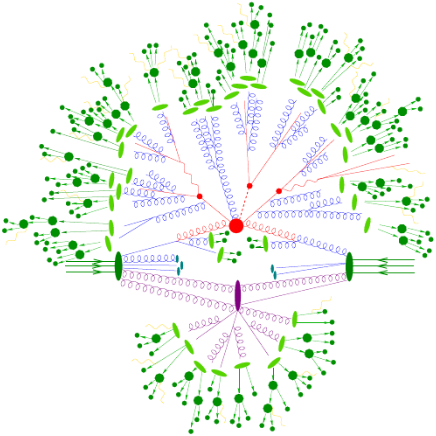
# Monte Carlo Event Generators – work horses

## Stochastic simulation of fully exclusive collision events

[Buckley *et al.* Phys. Rept. **504** (2011) 145]

↪ factorize short- & long range physics

- perturbative phases
  - **Hard interaction**
    exact matrix elements $|\mathcal{M}|^2$
    LO,NLO,NNLO – QCD, NLO – EW
  - **Radiativ corrections**
    parton showers in the initial and final state
    resummation of soft-collinear logs: LL, NLL
- non-perturbative phases
  - **Hadronization**
    parton–hadron transition
  - **Hadron Decays**
    phase space or effective theories
  - **Underlying Event**
    beyond factorization: modelling



- general purpose generators: PYTHIA, HERWIG, SHERPA
- dedicated to matching/merging: POWHEGBOX, MADGRAPH5-AMC@NLO

# Monte Carlo Event Generators – work horses

**PYTHIA** (latest release 8.243)

- $p_T$ ordered (dipole inspired) parton shower
- automatic shower variations [Mrenna, Skands]
- string fragmentation model
- sophisticated underlying event, non-perturbative models
- VINCIA and DIRE showers as plugins

**HERWIG** (latest release 7.1.5)

- angular-ordered and CS dipole shower
- interfaces to ME generators
- on-the-fly uncertainty variations [Bellm et al.]
- cluster hadronization model
- generic matching/merging implementations
- underlying event & soft interactions

# The SHERPA 2.2 event generator framework

## User Inputs

### Initial Beams

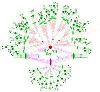
- collider setup
- PDFs (built-in, LHAPDF)
- beam spectra

### Parameters/Models

- FeynRules/UFO
- couplings
- masses
- variations
- shower settings
- non-perturbative parameters

### Physics Process

- parton level
- perturbative order (QCD/EW)
- selectors
- matching/merging
- partonic decays



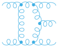
## Matrix Elements

### Matrix Element Generators

- AMEGIC
- COMIX
- CS subtraction

### 1-loop Amplitudes

- OpenLoops
- Recola
- GoSam
- BLHA



## Parton Showers

### CS-Shower (default)

- dipole shower
- fully massive
- QED splittings

### DIRE

- hybrid dipole-parton shower algorithm
- fully massive

## Matching and Merging

**Automated MC@NLO style matching**

**Multijet-merging algorithms**

- based on truncated showers
- tree-level and one-loop matrix elements: MEPS@LO and MEPS@NLO
- approximate electroweak corrections

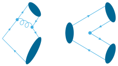
**NNLO QCD with parton showers**

- selected processes only

## Soft Physics

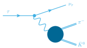
### Hadronisation

- AHADIC: a cluster fragmentation model
- interface to Pythia string fragmentation



### Hadron Decays

- decay tables for hadronic resonances
- dedicated form-factor models, e.g. τ, B, Λ
- spin correlations
- YFS QED corrections
- partonic channels



### Underlying Event

- multiple parton interactions
- beam-remnant colours
- intrinsic transverse momentum

## Interfaces/Outputs

### Output Formats

- HepMC
- LHEF
- Root Ntuple

### Interfaces

- RIVET analyses
- C++/Python ME access
- MCgrid
- integration into ATLAS/CMS


### Code/Docu

- HepForge
- GitLab
- online documentation

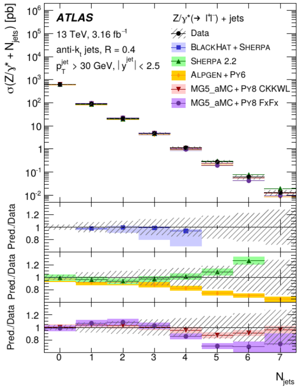
sherpa.hepforge.org

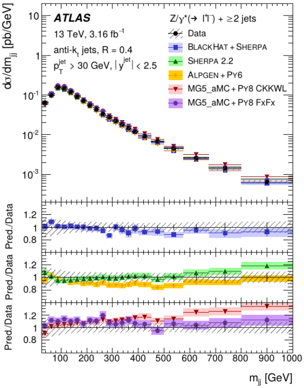
gitlab.com/sherpa-team/sherpa

# Status Quo

## NLO QCD phenomenology

- NLO QCD + PS matched/merged routinely used in LHC experiments
  $\hookrightarrow$ account for multiple hard emissions, reduced scale uncertainties
- probabilistic simulation of exclusive hadronic final states
  $\hookrightarrow$ address 'arbitrary' observables with one event sample



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**Some open questions in perturbative parts**

- inclusion of (mixed) electroweak corrections in shower simulations
- formal accuracy of showers for specific observables
- quality of approximations, e.g. large-$N_c$ limit, spin averaging
- systematic improvements of shower algorithms
  ↪ NLO QCD, (N)NLL resumation, reduced uncertainties

# Pushing Frontiers

**Electroweak Physics**

- automation of NLO EW corrections [Frederix et al.; Schönherr et al.]
- approximate NLO EW in MEPS@NLO simulations [Kallweit et al.]

**QCD Shower Improvements**

- new shower-development platforms: DEDUCTOR [Nagy, Soper], DIRE [Höche, Prestel], HEJ [Andersen et al.], VINCIA [Skands et al.]
- shower logarithmic accuracy [Dreyer et al.; Richardson et al.; Reichelt et al.]
- spin correlations [Richardson et al.]
- resonance-aware subtraction/matching [Ježo, Nason; Liebschner et al.]
- beyond leading color
    - $N_C = 3$ corrections for real emissions [Plätzer et al.; Isaacson, Prestel]
    - evolution beyond LC+ with DEDUCTOR [Nagy, Soper]
    - amplitude-based evolution [Forshaw, Plätzer et al.]
    - perturbative color reconnection [Bellm; Gieseke et al.]
- higher-order corrections [Höche et al., Dulat et al.]

**spin-offs**

- frameworks for automated resummation [Becher et al.; Reichelt et al.]

## Shower improvements

$$|\mathcal{M}_{n+1}|^2 \approx \sum_{i,j,k\neq i,j} \frac{1}{2p_i \cdot p_j} \langle \mathcal{M}_n | \frac{\mathbf{T}_{ij} \cdot \mathbf{T}_k}{\mathbf{T}_{ij}^2} \mathbf{V}_{ij,k} | \mathcal{M}_n \rangle$$

conventional shower: average spins, '$N_C \to \infty$'

$\hookrightarrow$ preserve spin correlations

$\hookrightarrow$ $N_C = 3$ corrections

$\hookrightarrow$ higher-order splitting functions

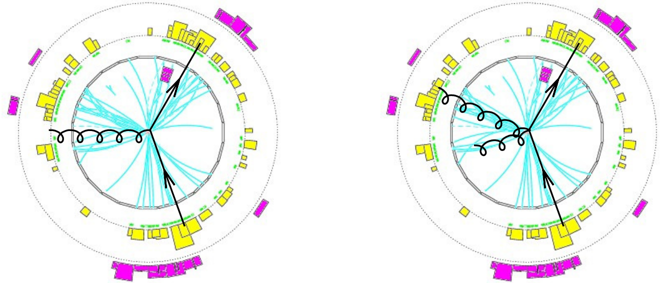
$\hookrightarrow$ NLL resummation for multi-jet resolutions

# Jet resolutions as a testbed

**consider jet-resolution scales in $k_T$ algorithm**

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)}{Q^2}(1 - \cos\theta_{ij})$$

- differential probe of pQCD jet production: $y_{n,n+1}$ resolutions
  $\hookrightarrow$ sensitive to non-perturbative corrections
- measured by LEP experiments, hadron-collider equivalents at LHC
- used for $\alpha_s$ extractions, benchmark for parton showers, MC tuning, ...



# Pushing Frontiers: Spin Correlations in the Parton Shower

**Spin-density formalism in HERWIG showers (angular and dipole)**

[Richardson, Webster: arXiv:1807.01955 [hep-ph]]

helicity amplitudes for branchings

(i) azimuthal correlations in parton splittings

$$\frac{1}{2\pi}\left(1 + AB\cos 2\Delta\phi\right)$$

(ii) correlations between shower, hard process and decays

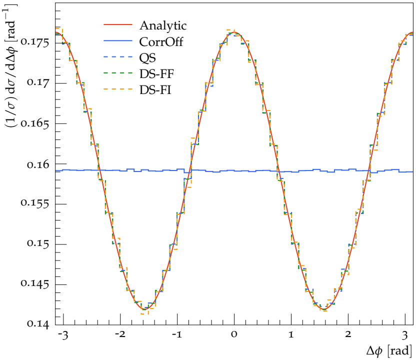
$$\rho_{g_1}^{\lambda_{g_1}\lambda'_{g_1}} \propto \mathcal{M}_{h^0\to gg}^{\lambda_{g_1}\lambda_{g_2}} \mathcal{M}^{*\,\lambda'_{g_1}\lambda_{g_2}}_{h^0\to gg}$$

$$f(\phi) \propto \rho_{g_1}^{\lambda_{g_1}\lambda'_{g_1}} \mathcal{M}_{g\to q\bar{q}}^{\lambda_{g_1}\lambda_q\lambda_{\bar{q}}} \mathcal{M}_{g\to q\bar{q}}^{*\lambda'_{g_1}\lambda_q\lambda_{\bar{q}}}$$

↪ improved description of spin-correlated decays

↪ available from HERWIG 7.2

FS $q \to qg_1$ with $g_1 \to gg$



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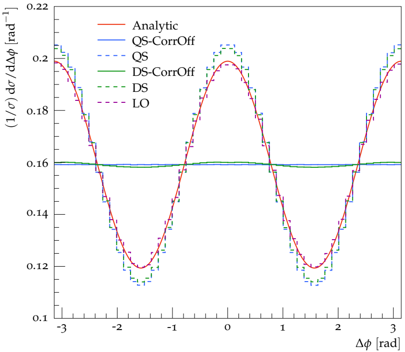
$$h^0 \stackrel{\text{ME}}{\longrightarrow} g_1 g_2 \stackrel{\text{PS}}{\longrightarrow} q\bar{q}q'\bar{q}'$$

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# Pushing Frontiers: $N_C = 3$ corrections

**Color matrix element corrections**
[Plätzer, Sjödahl, Thorén: JHEP **1811** (2018) 009]

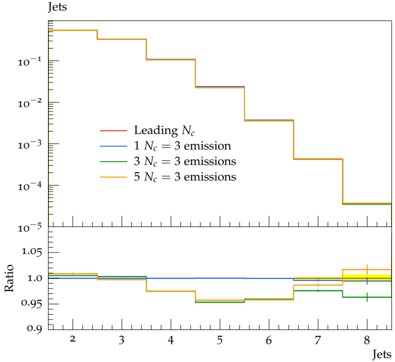
color corrections for first few emissions in HERWIG dipole shower

- use *trace basis* color representation
- color correction weight

$$\omega^n_{\tilde{ij}\tilde{k}} = \frac{-1}{T^2_{\tilde{ij}}} \frac{\langle \mathcal{M}_n | T_{\tilde{ij}} \cdot T_{\tilde{k}} | \mathcal{M}_n \rangle}{|\mathcal{M}_n|^2}$$

- evolve full color structure, LC shower beyond $N_{\max}$ emissions
- available for final- and initial state

jet multiplicity @ LEP




$\hookrightarrow$ limited to first few emissions
$\hookrightarrow$ possibly large weight fluctuations
$\hookrightarrow$ rather mild corrections observed

towards full amplitude evolution [Forshaw, Holguin, Plätzer: JHEP **1908** (2019) 145]

# Pushing Frontiers: $N_C = 3$ corrections

**Stochastically sample $\mathbf{N_C = 3}$ configurations**

[Isaacson, Prestel: Phys. Rev. D **99** (2019) no.1, 014021]

full-color (FC) shower based on DIRE

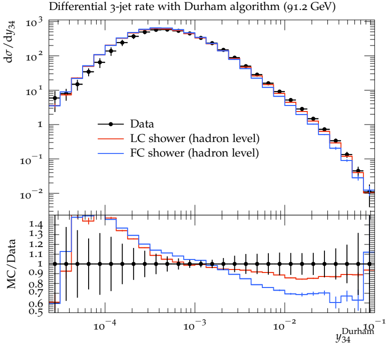
- trace color assignments in *color flow basis*
- sample flows for emissions above $t_{\mathrm{FC}}^{\mathrm{cut}} > t_0$ according to
  $$\langle \mathcal{M}' | t_k^\alpha t_{ij}^\beta | \mathcal{M} \rangle$$
- LC shower below $t_{\mathrm{FC}}^{\mathrm{cut}} > t_0$
- keep track of large-$N_C$ flow for LC shower and hadronization

$\hookrightarrow$ possibly large weight fluctuations

$\hookrightarrow$ lack of kinematic corrections

$\hookrightarrow$ no virtual color rearrangements

$y_{34}$ @ LEP



# Pushing Frontiers: towards NLO precision

**Fully differential two-loop soft corrections in dipole showers**

[Dulat, Höche, Prestel: Phys. Rev. D **98** (2018) no.7, 074013]

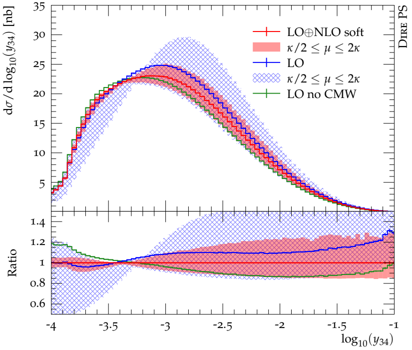
correct DIRE emission pattern for NLO soft-gluon radiation

- differential in one-emission phase space
- correction weights for
  - phase-space coverage
  - spin correlations
  - subleading color
- final- and initial state emissions
- two independent implementations PYTHIA and SHERPA

$\hookrightarrow$ good agreement with CMW

$\hookrightarrow$ meaningful uncertainty estimate

$y_{34}$ @ LEP



**The CAESAR formalism for soft-gluon NLL resummation**
[Banfi, Salam, Zanderighi: JHEP **0503** (2005) 073]

- consider rIRC safe observable $V(\{\tilde{p}\}, k_1, \ldots, k_n)$, Born limit $V(\{p\}) = 0$
- resummed cummulant distribution for $V \leq v$ ($L \equiv \ln(1/v)$) given by

$$\begin{aligned}\Sigma_{\mathcal{H}}(v) &= \sum_\delta \int d\mathcal{B} \frac{d\sigma_\delta}{d\mathcal{B}} f_{\delta,\mathcal{B}}(v) \mathcal{H}(\{p\}) \\ &\sim (1 + C(\alpha_s)) \exp\left(L g_1^{(\delta)}(\alpha_s L) + g_2^{(\delta,\mathcal{B})}(\alpha_s L) + \ldots\right)\end{aligned}$$

$$f_{\delta,\mathcal{B}}(v) \sim \exp\left(-\sum_l R_l^{(\delta,\mathcal{B})}(v)\right) \mathcal{S}^{(\delta,\mathcal{B})} \mathcal{F}^{(\delta,\mathcal{B})}$$

$\hookrightarrow$ $\mathcal{F}$: accounts for correlated/multiple emissions (observable specific)
$\hookrightarrow$ $\mathcal{S}$: accounts for soft wide-angle emissions

- largely automated for multi-leg processes in SHERPA framework
  [Gerwick, Höche, Marzani, S.: JHEP **1502** (2015) 106]

**NLO+NLL accurate predictions for multi-jet resolution scales**

[Baberuxki, Preuss, S., Reichelt: to appear]

- employ CAESAR implementation in SHERPA framework
  ↪ colour-decomposed matrix elements and colour insertions for $\mathcal{S}$
  ↪ numerical evaluation of multiple-emission function $\mathcal{F}$

- consider jet production in $e^+e^-$ annihilation at $\sqrt{s} = 91.2$ GeV
  ↪ NLO+NLL predictions for 3−, 4−, 5−, 6−jet resolutions NEW
  ↪ emissions off $2, 3, 4, 5$ hard legs with $y_\mathrm{cut}$=0.02, respectively
- resummation scale given by last hard splitting, i.e. for $y_{n,n+1}$

$$\mu_Q^2 = y_{n-1,n} Q^2$$

- renormalisation scale according to CKKW, i.e. for $y_{n,n+1}$ this yields

$$\alpha_s^{n-2}(\mu_R^2) = \alpha_s(y_{23}Q^2)\ldots\alpha_s(y_{n-1,n}Q^2)$$

# Pushing Frontiers: jet resolutions at NLO+NLL accuracy

**validation of soft-function $\mathcal{S}$**

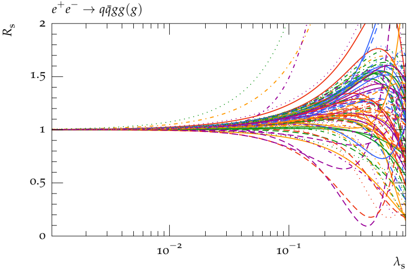
- consider ratio of soft-eikonal approx. to exact real-emission matrix element

$$R_s = \frac{Tr[\Gamma c_n H_n]}{Tr[c_{n+1} H_{n+1}]} \quad \text{(Born process in trace-basis } \{|b_\alpha\rangle\}\text{)}$$

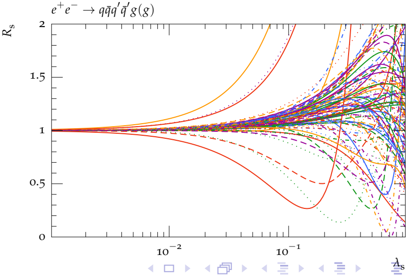
$$\Gamma = -2g_s^2 \sum_{i<j} \frac{p_i \cdot p_j}{(p_i \cdot k_s)(p_j \cdot k_s)} \sum_{\alpha,\beta} \langle b_\alpha | \boldsymbol{T}_i \boldsymbol{T}_j | b_\beta \rangle c^{\alpha\beta}$$

- ratio should approach 1 for soft-gluon emission, probes colour correlators
  $\hookrightarrow$ consider 100 random non-collinear phase-space points $\{p_{n+1}\}$
  $\hookrightarrow$ one gluon to become soft, i.e. $k_s \mapsto \lambda_s k_s$ with $\lambda_s \to 0$

five-jet channel




six-jet channel

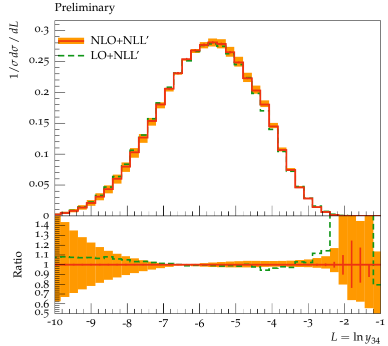


# Pushing Frontiers: jet resolutions at NLO+NLL accuracy

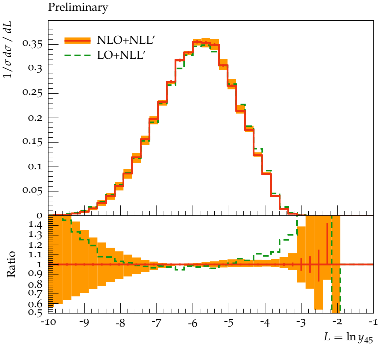
**patching-up hard emissions: matching to NLO matrix elements**

- use log-R matching scheme [Catani et al. Nucl. Phys. B **407** (1993) 3] (endpoints at respective $y_{n-1,n}$)
- NLO QCD matrix elements from OpenLoops, Recola
- uncertainties shown cover $\mu_Q$ variations only

four-jet resolution $y_{34}$

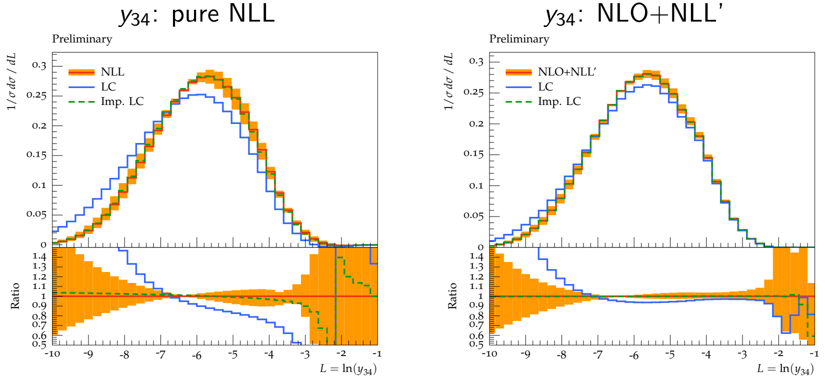



five-jet resolution $y_{45}$



**impact of subleading colors**

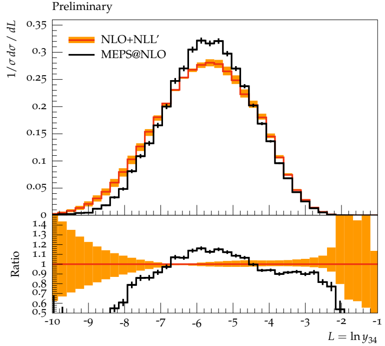
- strict leading color (LC) only, i.e. $N_c \to \infty$, $\alpha_s/N_c = \text{const.}$
- shower-like improved LC scheme (Imp. LC)
  e.g. $g \to q\bar{q}$, $C_F$ for quark legs, $n_f = 5$ in $\alpha_s$ running



## comparison to Monte Carlo predictions

- SHERPA MEPS@NLO simulation:
  - ↪ NLO QCD matrix elements for $e^+e^- \to 2, 3, 4, 5$jets
  - ↪ matched to Catani–Seymour dipole shower [S., Krauss: JHEP **0803** (2008) 038]

four-jet resolution $y_{34}$

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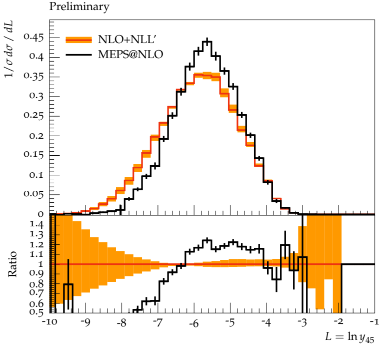

# Conclusions/Outlook

**Monte Carlo generators workhorses for LHC physics**

- NLO QCD pheno, including parton showers and non-perturbative models
- automated NLO QCD/EW subtractions, full SM NLO calculations

**Lots of recent shower developments**

- sophisticated matching/merging with exact QCD/EW matrix elements
- focus moving towards improvements of shower algorithms
  - uncertainty evaluations
  - approximate NLO EW contributions
  - subleading colour
  - spin correlations
  - NLO QCD splitting functions

**Towards automation of NLL resummation for multi-jet final states**

- implementation of CAESAR formalism in SHERPA framework

  $\hookrightarrow$ application to jet resolutions in $e^+e^- \to$ jets

  $\hookrightarrow$ allows for tuned comparison to parton showers

  $\hookrightarrow$ generalisation to hadronic initial states