Monte Carlo generators and parton showers

– status and trends –

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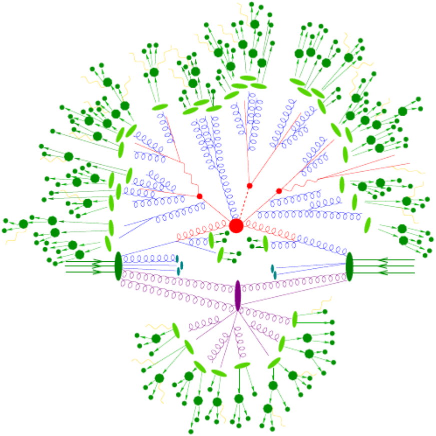
Monte Carlo Event Generators – work horses

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 8.240)

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

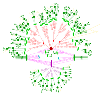
- collider setup
- PDFs (built-in, LHAPDF)
- beam spectra

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



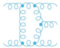
Matrix Elements

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

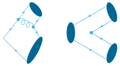
NNLO QCD with parton showers

- selected processes only

Soft Physics

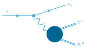
Hadronisation

- 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

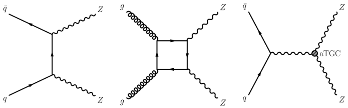
sherpa.hepforge.org

gitlab.com/sherpa-team/sherpa

Signals and backgrounds for SM measurements and BSM searches

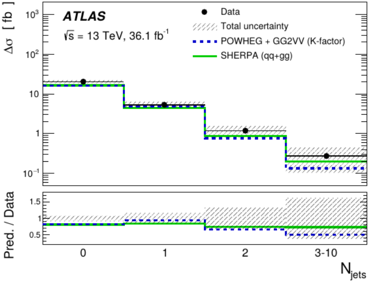
[Aaboud et al.: arXiv:1905.07163 [hep-ex]]

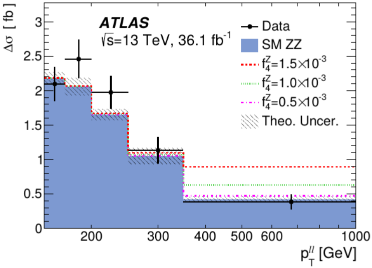
- direct & loop-induced channels
- sensitivity to aTGC



$\hookrightarrow$ uncertainty estimates needed

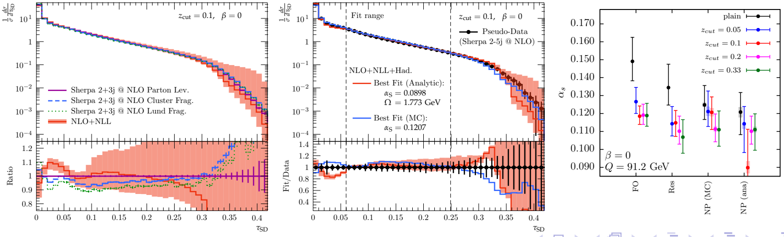
Process	Generator	Simulation accuracy	Cross-section accuracy
$qqZZ$	Powheg-Box v2 + Pythia8.186	NLO QCD	NNLO QCD + NLO EW
	Sherpa2.2.2	NLO QCD 0-1p, LO QCD 2-3p	
$ggZZ$	gg2vv3.1.6 + Pythia8.186	LO QCD	NLO QCD
	Sherpa2.1.1	LO QCD 0-1p	
$qqZZ$ (aTGCs)	Sherpa2.1.1	NLO QCD 0-1p, LO QCD 2-3p	
WZ	Powheg-Box v2 + Pythia8.186	NLO QCD	
	Powheg-Box v2 + Herwig++		
WW	Powheg-Box v2 + Pythia8.186	NLO QCD	
$qqZZ \to 4\ell$	Powheg-Box v2 + Pythia8.186	NLO QCD	NNLO QCD + NLO EW
$ggZZ \to 4\ell$	gg2vv3.1.6 + Pythia8.186	LO QCD	NLO QCD
Z + jets	Sherpa2.2.1	NLO QCD 0-2p, LO QCD 3-5p	NNLO QCD
$t\bar{t}$	Powheg-Box v2 + Pythia6.428	NLO QCD	NNLO QCD
Wt	Powheg-Box v2 + Pythia6.428	NLO QCD	NNLO QCD
VVV	Sherpa2.1.1	NLO QCD	
$t\bar{t}V$	MadGraph5_aMC@NLO + Pythia8.186	LO QCD	NLO QCD





α_s fits affected by non-perturbative corrections

- resummed predictions with hadronization corrections from Monte Carlo
- uncertainty estimate via different generators/fragmentation models
  ↪ pitfall, PS lacks higher-order terms
- Jet-rates @ NNLO+NNLL [Verbytskyi et al.: arXiv:1902.08158 [hep-ph]]
  $\alpha_s(M_Z) = 0.11881 \pm 0.00063(exp.) \pm 0.00101(hadr.) \pm 0.00045(ren.) \pm 0.00034(res.)$
- Soft-drop thrust @ NLO+NLL [Marzani et al.: arXiv:1906.XXYY [hep-ph]]
  - consider thrust shape with soft-drop grooming [Baron et al.]
  - features reduced hadronization corrections
    ↪ uncertainty estimated from cluster model vs. Lund string



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 et al.]
  - perturbative color reconnection [Bellm; Gieseke et al.]
- higher-order corrections [Dulat et al.]

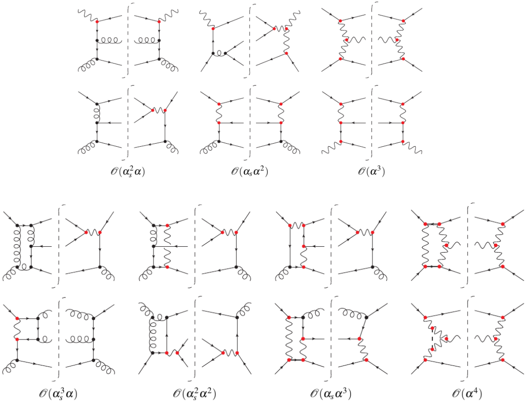
spin-offs

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

Electroweak Corrections

parametrically $\alpha_s^n \alpha \approx \alpha_s^{n+2}$, Sudakov enhancements

$\hookrightarrow$ photonic initial states, EW Born & Loop corrections, QED reals



Full NLO corrections to hadronic 3-jet production

[Reyer, Schönherr, S.: Eur. Phys. J. C **79** (2019) no.4, 321]

- QCD & QED dipole subtraction [Schönherr]
- virtuals from RECOLA [Actis et al.]

$$\sigma_{nj} = \sum_{i=0}^{n} \sigma_{nj}^{\mathrm{LO}_i} + \sum_{i=0}^{n+1} \sigma_{nj}^{\Delta\mathrm{NLO}_i}$$

$$\mathcal{O}\left(\sigma_{nj}^{\mathrm{LO}_i}\right) = \alpha_s^{n-i}\alpha^i$$

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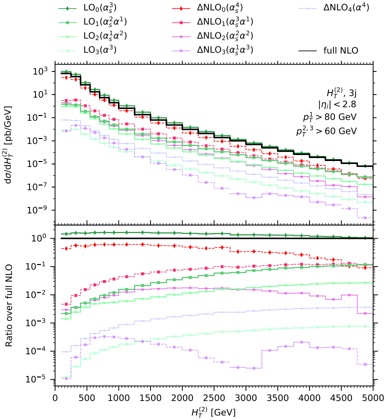

↪ subleading EW tree-level and one-loop contributions sizeable

↪ challenge for matching & merging

Pushing Frontiers: 3-jet production at full SM NLO

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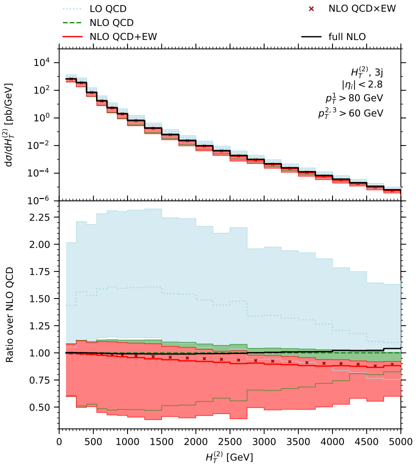


Shower improvements

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

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

$\hookrightarrow$ preserve spin correlations

$\hookrightarrow$ $N_C = 3$ corrections

$\hookrightarrow$ higher-order splitting functions

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

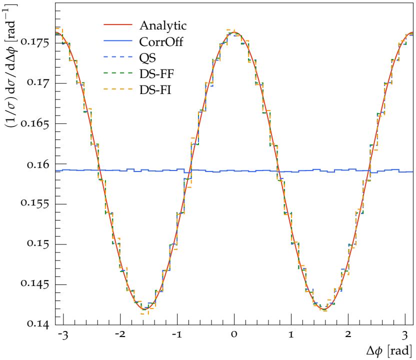
$$\rho_{g_1}^{\lambda_{g_1}\lambda'_{g_1}} \propto \mathcal{M}_{h^0\to gg}^{\lambda_{g_1}\lambda_{g_2}}\mathcal{M}^{*\,\lambda'_{g_1}\lambda_{g_2}}_{h^0\to gg}$$

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

↪ 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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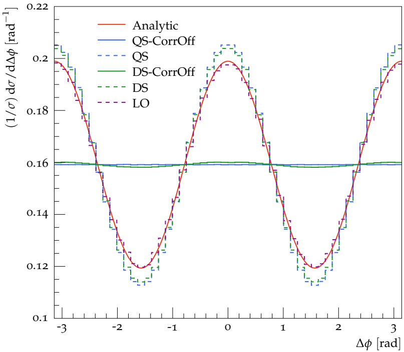
$$h^0 \overset{\mathsf{ME}}{\longrightarrow} g_1 g_2 \overset{\mathsf{PS}}{\longrightarrow} q\bar{q}q'\bar{q}'$$



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

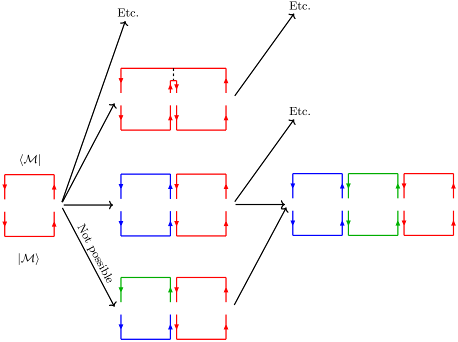
[Isaacson, Prestel: Phys. Rev. D **99** (2019) no.1, 014021]

full-color (FC) shower based on DIRE

- trace color assignments in *color flow basis*
- sample flows for emissions above $t_{\rm FC}^{\rm cut} > t_0$ according to

  $$\langle \mathcal{M}' | t_k^{\alpha} t_{ij}^{\beta} | \mathcal{M} \rangle$$
- LC shower below $t_{\rm FC}^{\rm cut} > t_0$
- keep track of large-N_C flow for LC shower and hadronization

possible color configurations



↪ possibly large weight fluctuations

↪ lack of kinematic corrections

↪ no virtual color rearrangements

Pushing Frontiers: $N_C = 3$ corrections

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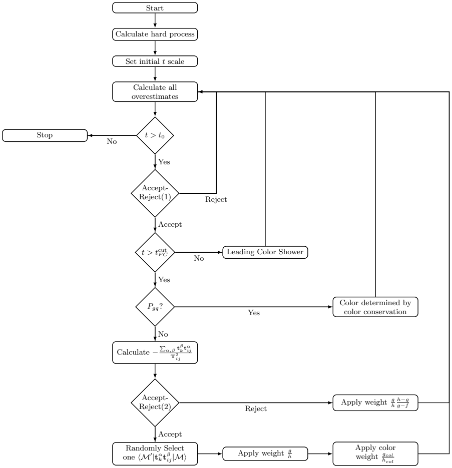

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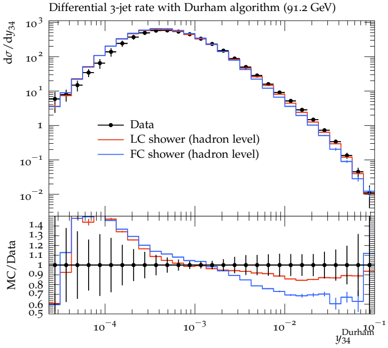

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Color matrix element corrections

[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

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

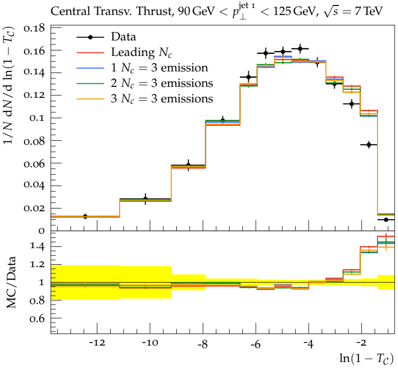
- evolve full color structure, LC shower beyond $N_{\max}$ emissions
- available for final- and initial state

↪ limited to first few emissions

↪ possibly large weight fluctuations

↪ rather mild corrections observed

transverse thrust @ LHC



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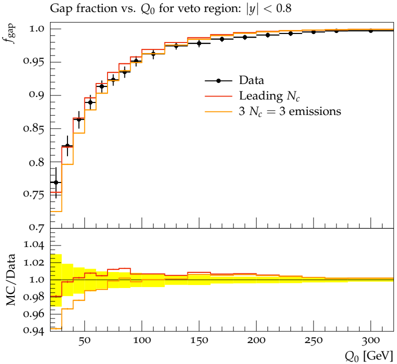
gap fraction in $t\bar{t}$ events @ LHC



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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]

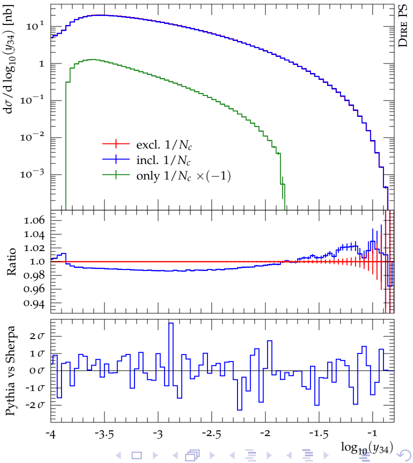
correct DIRE emission pattern for NLO soft-gluon radiation

- 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

$\hookrightarrow$ meaningfull uncertainty estimate

y_{34} – impact of subleading color



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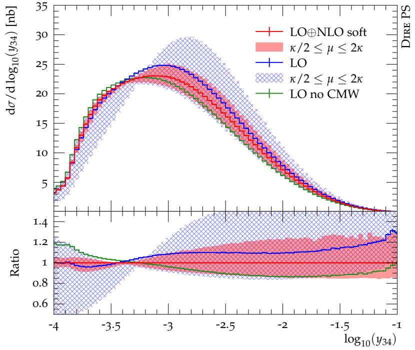
y_{34} – full distribution



Conclusions

- NLO QCD matching/merging prescriptions routinely used for LHC pheno
- automation NLO EW achieved, more and more public tools emerging
- focus moving towards improvements of shower algorithms

  $\hookrightarrow$ sophisticated reweighting techniques for applying corrections (SVA)
  - uncertainty evaluations
  - approximate NLO EW contributions
  - subleading color
  - spin correlations
  - NLO QCD splitting function
- towards full amplitude evolution equations

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Looking forward to a productive workshop!