Sherpa@NLO

QCD@LHC 2013, DESY, Hamburg

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Tradition (SHERPA 1.x): two lines of usage

SHERPA "Parton Shower"

Multi-purpose hadron-level
Monte-Carlo event generator

- parton shower
- hadronisation
- hadron decays
- multiple parton interactions
- QED corrections a la YFS

QCD corrections through
ME+PS merging

- high-multiplicity tree-level MEs from COMIX or AMEGIC
- dipole-based parton shower
- ME+PS merging for LO accuracy in jet observables in inclusive samples

SHERPA "NLO"

Parton-level event generator
at NLO QCD accuracy

- automated tree-level MEs
- dipole subtraction
- phase space integration and event generation
- 1-loop matrix-elements from external codes via standardised interfaces

  [Binoth et al.] arXiv:1001.1307, arXiv:1308.3462

Examples ($\rightsquigarrow$ later):
BlackHat, GoSam, NJet, OpenLoops, ...

External features

LHAPDF, FastJet, HepMC, Rivet, ROOT ...

Future (SHERPA 2.x): unification

SHERPA "Parton Shower"

Multi-purpose Monte-Carlo event generator

↓

SHERPA "NLO"

Parton-level event generator at NLO QCD accuracy

↓

SHERPA "ME+PS @ NLO"

Hadron-level event generator with NLO accuracy in multiple jet bins

- NLO+parton shower matching in fully colour-correct extension of basic MC@NLO idea
- merging of NLO+PS predictions in different jet multiplicities, e.g. W+0,1,2,3 jets
- Relies crucially on NLO and parton shower building blocks (subtraction terms)
- Fully automated within SHERPA except 1-loop-ME: interfaces to external (automated) codes as above

Tree-level ME+PS merging in SHERPA

[Höche, Krauss, Schumann, FS] JHEP 0905 (2009) 053

Main idea

Phase space slicing for QCD radiation in shower evolution

- Hard emissions $Q_{ij}(z,t) > Q_{\text{cut}}$
  - Events rejected
  - Compensated by events starting from higher-order ME regularised by Q_{cut}

  $\Rightarrow$ Splitting kernels replaced by exact real-emission matrix elements

  (But Sudakov form factors $\Delta^{(\text{PS})}$ remain unchanged)
- Soft/collinear emissions $Q_{ij,k}(z,t) < Q_{\text{cut}}$

  $\Rightarrow$ Retained from parton shower

Features

- Full hadron-level predictions
- Hard jet production with exact MEs
- Intra-jet evolution preserved
- Inclusive cross section still at LO accuracy

Features and shortcomings

Example

Diphoton production at Tevatron

- Measured by CDF Phys.Rev.Lett. 110 (2013) 101801
- Isolated hard photons
- Azimuthal angle between the diphoton pair

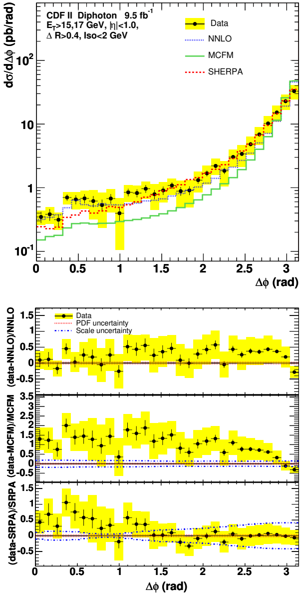
ME+PS simulation using SHERPA vs. (N)NLO

Conclusions

Shapes described very well even for this non-trivial process/observable for both:

- Hard region, e.g. $\Delta\Phi_{\gamma\gamma} \to 0$
- Soft region, e.g. $\Delta\Phi_{\gamma\gamma} \to \pi$

Scale variations high ⇒ NLO needed



Parton-level NLO predictions

NLO calculations

$$\sigma_{\text{NLO}} = \int \mathrm{d}\phi_B (\mathcal{B} + \mathcal{V} + \mathcal{I}) + \int \mathrm{d}\phi_R (\mathcal{R} - \mathcal{S})$$

Building blocks in SHERPA:

- Tree-level matrix elements $\mathcal{B}$, $\mathcal{R}$
- Automated Catani-Seymour dipole subtraction
- Interfaces to external 1-loop ME generators
- Multi-channel integration

Additional features

- Efficient ROOT ntuple event output
- cheap variations of scale/PDF/jet definition
- Highly efficient CPU parallelisation through MPI

Examples for recent calculations with SHERPA

GOSAM — Eur.Phys.J. C72 (2012) 1889

- $t\bar{t} + 0, 1$ jets
  [Höche, Huang, Luisoni, Schönherr, Winter] Phys.Rev. D88 (2013) 014040
- $gg \to H + 3$ jets
  [Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano] arXiv:1307.4737

→ next talk by E. Mirabella

NJet

- $pp \to 2, 3, 4(, 5)$ jets
  [Badger, Biedermann, Uwer, Yundin] Phys.Lett. B718 (2013) 965

→ talk yesterday by V. Yundin

OPENLOOPS — Phys. Rev. Lett. 108 (2012) 111601

- $pp \to 4$ leptons + 0,1 jets
  [Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, FS] arXiv:1309.0500

→ talk this afternoon by F. Cascioli

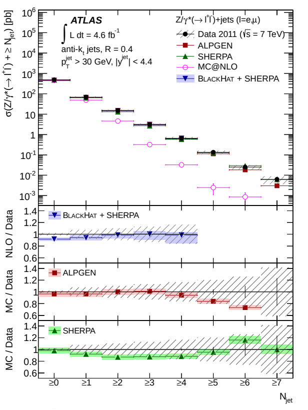
W + 5 jets with BlackHat + Sherpa

[Bern, Dixon, Febres Cordero, Höche, Ita, Kosower, Maitre, Ozeren] Phys.Rev. D88 (2013) 014025

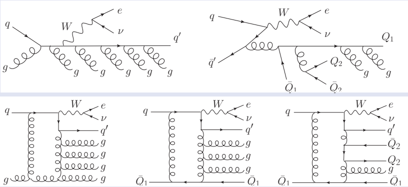
V+jets at the LHC

- Very high jet multiplicities, e.g. ATLAS $Z + 7$ jets
  JHEP 1307 (2013) 032

$\Rightarrow$ quest for precise predictions



$W + 5$ jets with BLACKHAT+SHERPA



Approximations in the following:

- leading-colour for virtual diagrams
  estimated uncertainty $< 3\%$
- real corrections only ≤ 3 quark pairs
  estimated uncertainty $< 1\%$
- no diagrams involving top-quark loops
- parton-level only
  no non-perturbative corrections applied

W + 5 jets: Total cross sections

[Bern, Dixon, Febres Cordero, Höche, Ita, Kosower, Maitre, Ozeren] Phys.Rev. D88 (2013) 014025

$W + 5$ jets at the LHC (7 TeV)

- scale choice: $\hat{H}'_{\rm T} \equiv \sum_{\rm partons} p_{\rm T}^{\rm parton} + \sqrt{M_W^2 + (p_{\rm T}^W)^2}$
- MSTW2008 (N)LO PDFs
- anti-k_t jets with $R = 0.5$ and $p_\perp > 25$ GeV

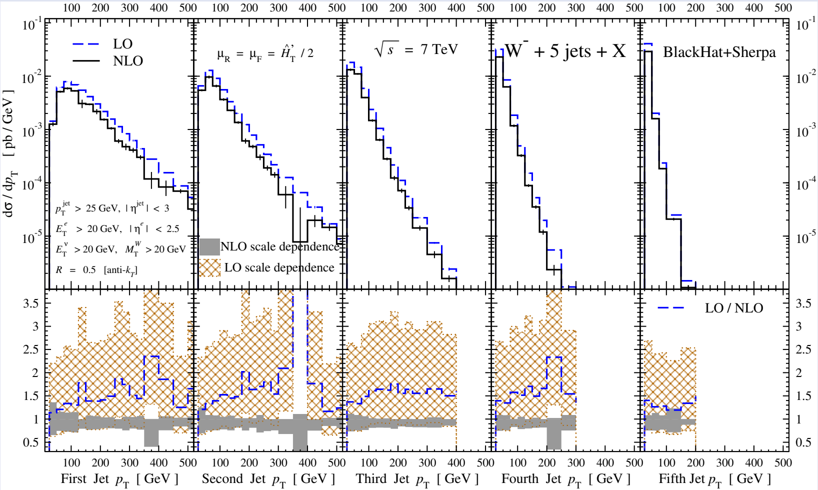
Jets	W^- LO	W^- NLO	W^+ LO	W^+ NLO
1	$284.0(0.1)^{+26.2}_{-24.6}$	$351.2(0.9)^{+16.8}_{-14.0}$	$416.8(0.6)^{+38.0}_{-35.5}$	$516(3)^{+29}_{-23}$
2	$83.76(0.09)^{+25.45}_{-18.20}$	$83.5(0.3)^{+1.6}_{-5.2}$	$130.0(0.1)^{+39.3}_{-28.1}$	$125.1(0.8)^{+1.8}_{-7.4}$
3	$21.03(0.03)^{+10.66}_{-6.55}$	$18.3(0.1)^{+0.3}_{-1.8}$	$34.72(0.05)^{+17.44}_{-10.75}$	$29.5(0.2)^{+0.4}_{-2.8}$
4	$4.93(0.02)^{+3.49}_{-1.90}$	$3.87(0.06)^{+0.14}_{-0.62}$	$8.65(0.01)^{+6.06}_{-3.31}$	$6.63(0.07)^{+0.21}_{-1.03}$
5	$1.076(0.003)^{+0.985}_{-0.480}$	$0.77(0.02)^{+0.07}_{-0.19}$	$2.005(0.006)^{+1.815}_{-0.888}$	$1.45(0.04)^{+0.12}_{-0.34}$

- uncertainty reduction estimated by scale variations:
  $\sigma(W^- + 5j)$: LO $^{+91\%}_{-45\%}$ $\rightarrow$ NLO $^{+9\%}_{-25\%}$
- Estimate for $W + 6j$ from scaling patterns: [Gerwick, Plehn, Schumann, Schichtel] JHEP 1210 (2012) 162
  $W^- + 6$ jets: 0.15 ± 0.01 pb
  $W^+ + 6$ jets: 0.30 ± 0.03 pb

W + 5 jets: $p_\perp$ spectra

[Bern, Dixon, Febres Cordero, Höche, Ita, Kosower, Maitre, Ozeren] Phys.Rev. D88 (2013) 014025

Leading five jet $p_\perp$ in W^- + 5 jets events



Matching and merging NLO and parton showers in Sherpa

Matching NLO and parton showers: Extended MC@NLO

- Basis: MC@NLO algorithm [Frixione, Webber] JHEP 0206 (2002) 029
- Extend with full CS subtraction terms instead of parton shower kernels
  - ⇒ Fully colour-correct simulation
  - ⇒ Rigorous solution for soft gluons
  - ⇒ Negative "splitting kernels" ⇒ modified Sudakov veto algorithm necessary

  [Höche, Krauss, Schönherr, FS] JHEP 1209 (2012) 049

MENLOPS

- First step towards combining NLO+PS and ME+PS:
  Add higher tree-level simulations to MC@NLO core simulation
  [Hamilton, Nason] JHEP 1006 (2010) 039, [Höche, Krauss, Schönherr, FS] JHEP 1108 (2011) 123

MEPS@NLO merging [Höche, Krauss, Schönherr, FS] JHEP 1304 (2013) 027

- basic concepts continued from tree-level ME+PS merging
- double counting in $\mathbb{S}$-events avoided by truncated "NLO-vetoed" shower:
  First hard emission is only ignored, no event veto

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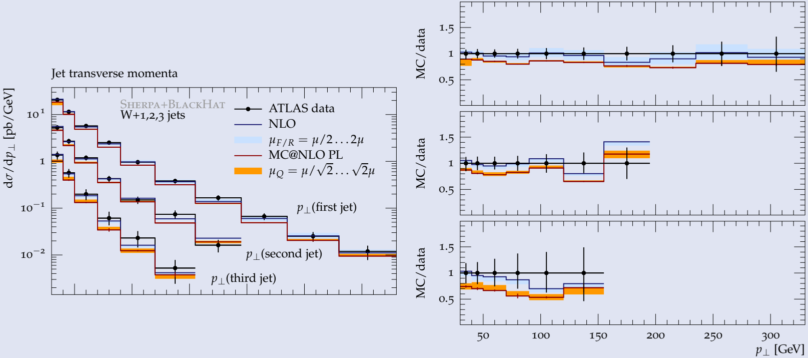
State-of-the-art application: W + 3 jets at NLO with parton showers

Comparison to ATLAS data



Physical assessment of resummation uncertainty: Variation of resummation scale μ_Q

ATLAS measurement

Phys.Rev. D85 (2012) 092002

SHERPA+BLACKHAT NLO+PS predictions

[Höche, Krauss, Schönherr, FS] Phys.Rev.Lett. 110 (2013) 052001

Off-shell top-pair production

Basis: NLO calculation

[Denner, Dittmaier, Kallweit, Pozzorini] JHEP 1210 (2012) 110, Phys.Rev.Lett. 106 (2011) 052001

- Parton-level NLO QCD calculation for $\ell\ell\nu\nu bb$ final states
- Includes all non-resonant diagrams, interferences and top offshell effects

⇒ relevant for Higgs/BSM background

- Dynamical scale $\mu \sim E_T = \sqrt{\sqrt{m_t^2 + p_{\perp,t}^2}\sqrt{m_t^2 + p_{\perp,\bar{t}}^2}}$

Matching to parton shower

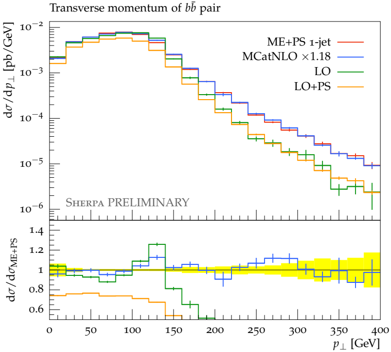
WORK IN PROGRESS!

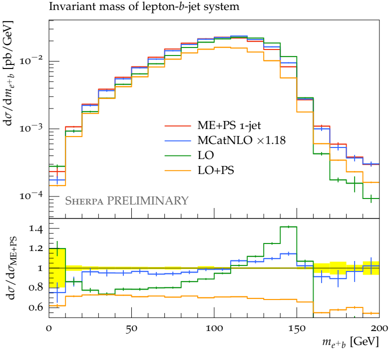
[Denner, Dittmaier, Kallweit, Pozzorini, FS]

- Use SHERPA's matching implementation based on Catani-Seymour dipole subtraction
- Interface virtual matrix elements from standalone code and OPENLOOPS

Off-shell top-pair production: PRELIMINARY results

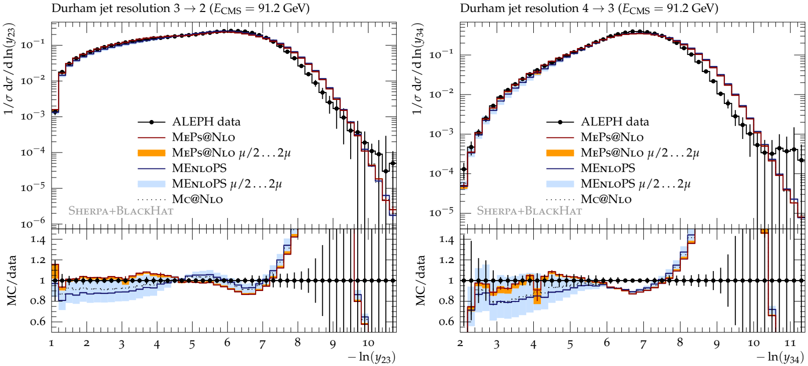
[Denner, Dittmaier, Kallweit, Pozzorini, FS] in preparation





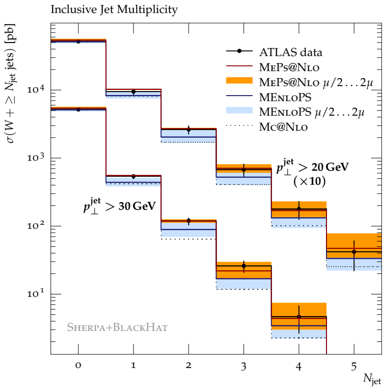
Merging multiple jet multiplicities at NLO: e^+e^- collisions

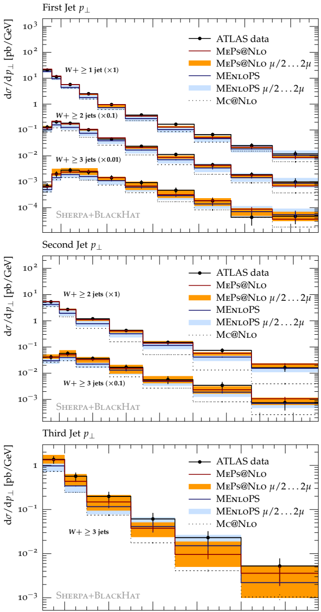
[Gehrmann, Höche, Krauss, Schönherr, FS] JHEP 1301 (2013) 144



- ME+PS@NLO predictions with $ee \to 2, 3, 4$ partons at NLO
- Significant reduction of ME+PS@NLO scale uncertainties in perturbative region
- Improved agreement with experimental data

Merging multiple jet multiplicities at NLO: W + jets again





- Comparison to ATLAS measurement
  Phys.Rev. D85 (2012), 092002
- Significant reduction of ME+PS@NLO scale uncertainties in "NLO" multiplicities ($pp \to W + 0, 1, 2$ jets)
- Improved agreement with data

[Höche, Krauss, Schönherr, FS] JHEP 1304 (2013) 027

Conclusions

Summary

- SHERPA features traditionally in two complementary areas: hadron-level ME+PS and parton-level NLO QCD calculations
- Several state-of-the-art predictions in these areas have been reviewed
- Combination of both to bring NLO to the hadron level also for complex final states: ME+PS@NLO in SHERPA 2.x

Outlook

- Public SHERPA 2.0.beta2 already contains many of the newest features
- Final release 2.0.0 just around the corner, only waiting for tuning of parton shower/hadronisation/MPI