Jet production and substructure in SHERPA

Marek Schönherr

Institute for Particle Physics Phenomenology

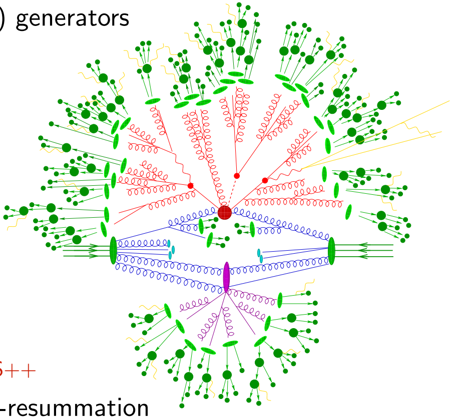
Glasgow, 15/10/2013

Contents

JHEP02(2009)007

The SHERPA event generator framework

- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044
  COMIX JHEP12(2008)039
  CS subtraction EPJC53(2008)501
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using YFS-resummation
  PHOTONS++ JHEP12(2008)018

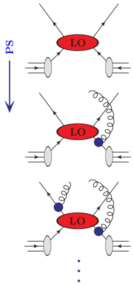


Sherpa's traditional strength is the perturbative part of the event

MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO

$\rightarrow$ full analytic control mandatory for consistency/accuracy

Recent developments – MEPS@NLO

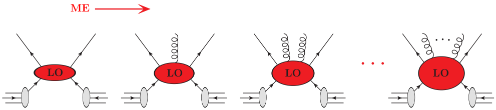


Parton showers

resummation of (soft-)collinear limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- MEPS@NLO combines multiple NLOPS – keeping either accuracy

Recent developments – MEPS@NLO

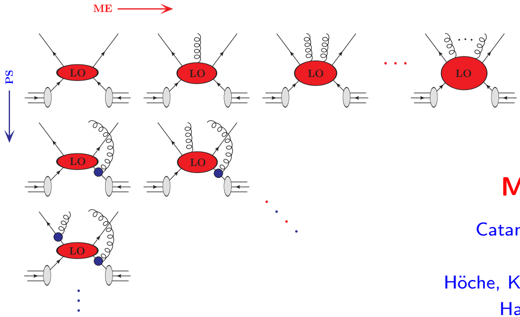


Matrix elements

fixed-order in α_s
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- MEPS@NLO combines multiple NLOPS – keeping either accuracy

Recent developments – MEPS@NLO

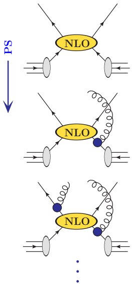


MEPS (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053
Hamilton, Richardson, Tully JHEP11(2009)038

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- MEPS@NLO combines multiple NLOPS – keeping either accuracy

Recent developments – MEPS@NLO

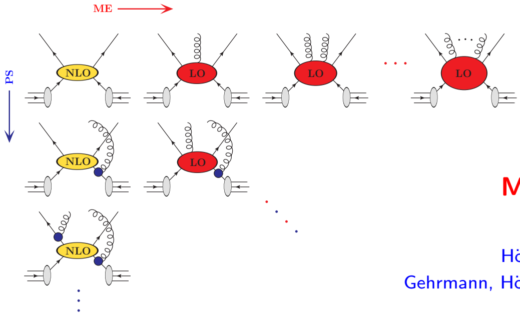


NLOPS (MC@NLO,POWHEG)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- **MEPS@NLO combines multiple NLOPS – keeping either accuracy**

Recent developments – MEPS@NLO

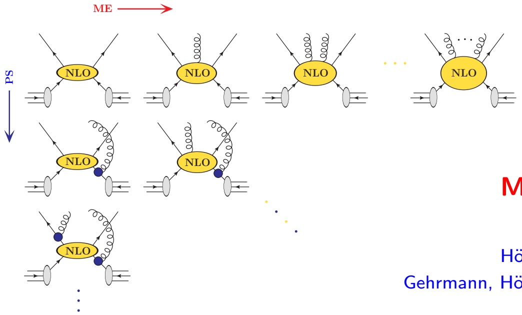


MENLOPS

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- MEPS@NLO combines multiple NLOPS – keeping either accuracy

Recent developments – MEPS@NLO



MEPS@NLO

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- **MEPS@NLO combines multiple NLOPS – keeping either accuracy**

Recent results

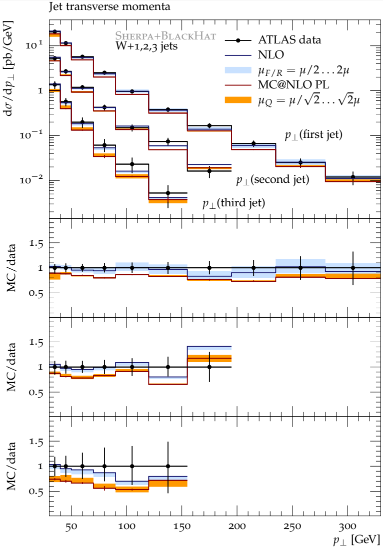
Fixed-mulitplicity NLOPS (MC@NLO)

- $pp \to W + 0, 1, 2, 3$jets – SHERPA+BLACKHAT
  Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001
- $pp \to$ jets – SHERPA+BLACKHAT Höche, MS Phys.Rev.D86(2012)094042
- $pp \to t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS
  Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

Multijet merging at NLO accuracy (MEPS@NLO)

- $pp \to W +$ jets – SHERPA+BLACKHAT Höche, Krauss, MS, Siegert JHEP04(2013)027
- $e^+e^- \to$ jets – SHERPA+BLACKHAT
  Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
- $pp \to h +$ jets – SHERPA+GOSAM Höche, Krauss, MS, Siegert, in YR3 arXiv:1307.1347
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM
  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS
  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

Recent results – $pp \to W + n$ jets MC@NLO



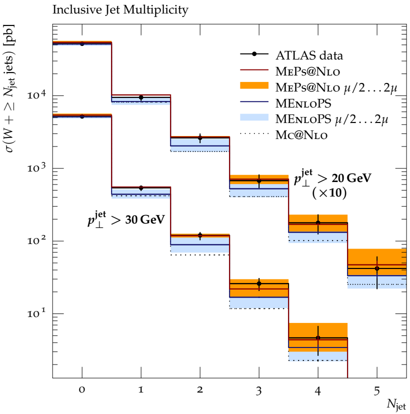
Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001

$pp \to W + 1, 2, 3$ jets

- 3 separate samples/calculations
- NLO accuracy for inclusive observables of respective jet multiplicity
- resummation of softest/LO jet, i.e. 4th jet in $pp \to W + 3$ jets
- no resummation of sample-defining jet multiplicity, i.e. first 3 jets in $pp \to W + 3$ jets
- scales: $\mu_{R/F} = \frac{1}{2}\,\hat{H}'_T$, $\mu_Q = p_\perp(j_n)$

ATLAS data Phys.Rev.D85(2012)092002

Recent results – $\mathrm{pp} \to \mathrm{W} + $ jets MEPS@NLO

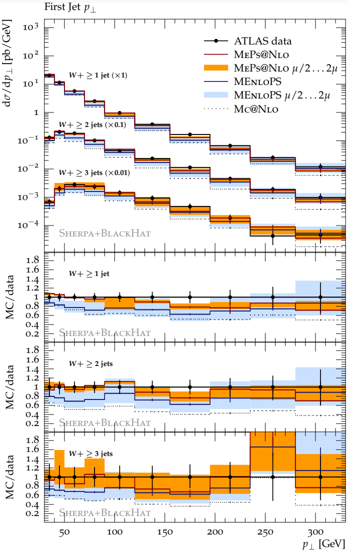


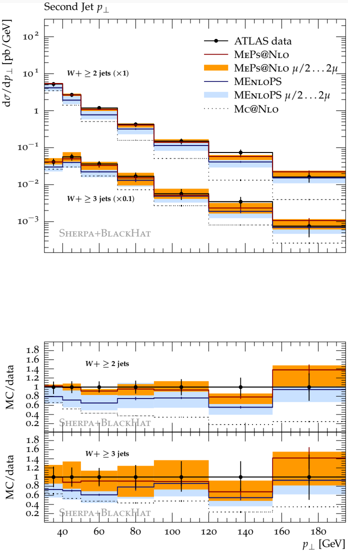
$pp \to W+$jets (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$ scale uncertainty much reduced
- NLO dependece for $pp \to W+$0,1,2 jets LO dependence for $pp \to W+$3,4 jets
- $Q_{\text{cut}} = 30$ GeV
- good data description

ATLAS data Phys.Rev.D85(2012)092002

Recent results – $pp \to W + \text{jets}$ MEPS@NLO





Recent results – $pp \to$ jets MC@NLO

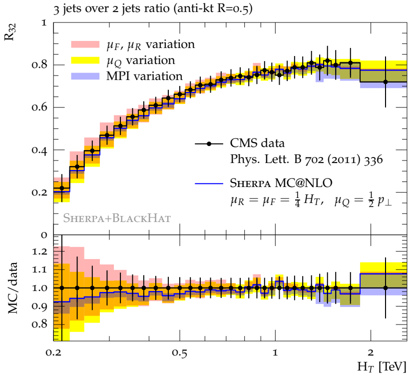
MC@NLO di-jet production:

- $\mu_{R/F} = \frac{1}{4}\,H_T,\ \mu_Q = \frac{1}{2}\,p_\perp$
- CT10 PDF ($\alpha_s(m_Z) = 0.118$)
- hadron level calculation, MPI
- virtual MEs from BLACKHAT
  Giele, Glover, Kosower Nucl.Phys.B403(1993)633-670
  Bern et.al. arXiv:1112.3940
- $p_\perp^{j_1} > 20$ GeV, $p_\perp^{j_2} > 10$ GeV

Uncertainty estimates:

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_Q^{\text{def}}$
- MPI activity in tr. region $\pm$ 10%

Höche, MS Phys.Rev.D86(2012)094042



Recent results – $\mathrm{pp} \to \mathrm{t}\bar{\mathrm{t}} + $ jets MEPS@NLO

- Definition of forward-backward asymmetry of an observable $\mathcal{O}$

$$A_{\mathsf{FB}}(\mathcal{O}) \;=\; \frac{\dfrac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}\mathcal{O}|_{\Delta y>0}} - \dfrac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}\mathcal{O}|_{\Delta y<0}}}{\dfrac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}\mathcal{O}|_{\Delta y>0}} + \dfrac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}\mathcal{O}|_{\Delta y<0}}}$$

- A_{FB} is ratio of expectation values
  $\to$ conventional scale variations by factor 2 will largely cancel for uncertainty on A_{FB}

$\Rightarrow$ use different functional forms of the scale defintion that behave differently in $\Delta y > 0$ and $\Delta y < 0$ for a realistic estimate of uncertainty

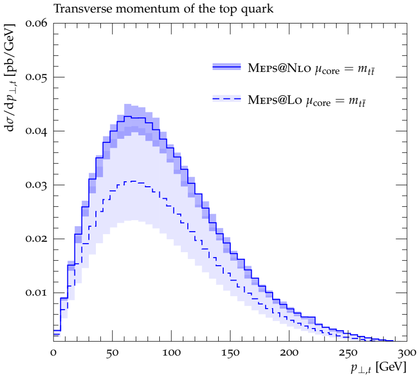
- applies to other ratio observables, e.g. normalised observables, as well

Recent results – $pp \to t\bar{t} + $ jets MEPS@NLO

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

Setup: $p\bar{p} \to t\bar{t} +$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV

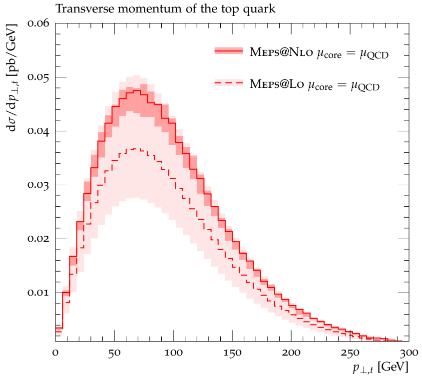


- scale choices: $\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\, \alpha_s(t_1) \cdots \alpha_s(t_n)$
  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

$\Rightarrow$ **different behaviour for forward/backward configurations**

Recent results – $pp \to t\bar{t} +$ jets MEPS@NLO

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703



Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices: $\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$

  1) $\mu_{\text{core}} = m_{t\bar{t}}$

  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j\ \ldots\ N_c \to \infty$ colour partners, chooses between s, t, u

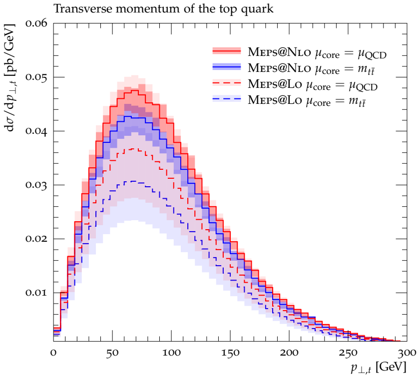
$\Rightarrow$ different behaviour for forward/backward configurations

Recent results – $pp \to t\bar{t} + $ jets MEPS@NLO

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV

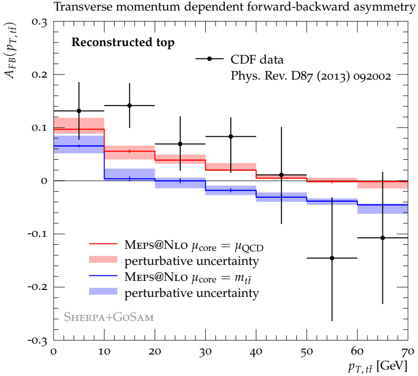


- scale choices: $\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j\ \ldots\ N_c \to \infty$ colour partners, chooses between s, t, u

$\Rightarrow$ different behaviour for forward/backward configurations

Recent results – $pp \to t\bar{t} + $ jets MEPS@NLO

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703



Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices: $\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

$\Rightarrow$ **different behaviour for forward/backward configurations**

Recent results – $pp \to t\bar{t}\,b\bar{b}$ MC@NLO

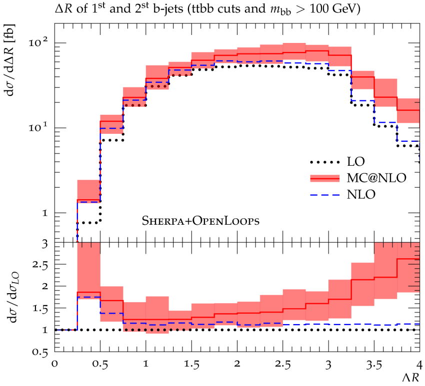
Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

MC@NLO $pp \to t\bar{t}\,b\bar{b}$ production:

- 4F scheme, finite m_b, m_t
- $\mu_R = \sqrt[4]{\prod_{i=t,\bar{t},b,\bar{b}} E_{\perp,i}}$
- $\mu_F = \frac{1}{2}\,\left(E_{\perp,t} + E_{\perp,\bar{t}}\right)$
- $\mu_Q = \mu_F$
- MSTW2008NLO PDF
- parton level calculation
- virtual MEs from OPENLOOPS

Uncertainty estimates:

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_Q^{\text{def}}$

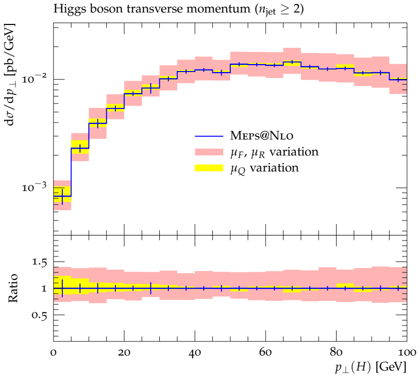


Recent results – $\mathrm{pp} \to \mathrm{h} + $ jets MEPS@NLO

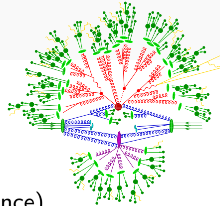
Höche, Krauss, MS, Siegert in preparation

$pp \to h$+jets (0,1,2 @ NLO; 3 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{def}}$
  $\mu_{\text{core}} = m_h$
- NLO dependence
  for $pp \to h$+0,1,2 jets
  LO dependence
  for $pp \to h$+3 jets
- $Q_{\text{cut}} = 20$ GeV



Jet properties



Jet production comprises contributions from all energy regimes:

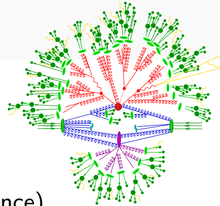
- perturbative contributions
  - hard seed parton(s) $\rightarrow$ fixed order matrix elements
  - soft & collinear emissions (parton shower w/ colour coherence)
- non-perturbative contributions
  - (uncorrelated) contributions from additional partonic interactions
  - hadronisation and hadron decays

$\Rightarrow$ **small scale contributions especially important for intrajet observables**

- necessity to describe intrajet observables well to be useful in jet substructure analysis
- need to describe hard emissions well
  - recoil to produce boosted heavy particles (production xsecs/dists)
  - good chance they will end up in same fat jet (Q_{cut} usally $k_\perp$-type)

$\Rightarrow$ **multijet merging necessary**

Jet properties



Jet production comprises contributions from all energy regimes:

- perturbative contributions
  - hard seed parton(s) $\rightarrow$ fixed order matrix elements
  - soft & collinear emissions (parton shower w/ colour coherence)
- non-perturbative contributions
  - (uncorrelated) contributions from additional partonic interactions
  - hadronisation and hadron decays

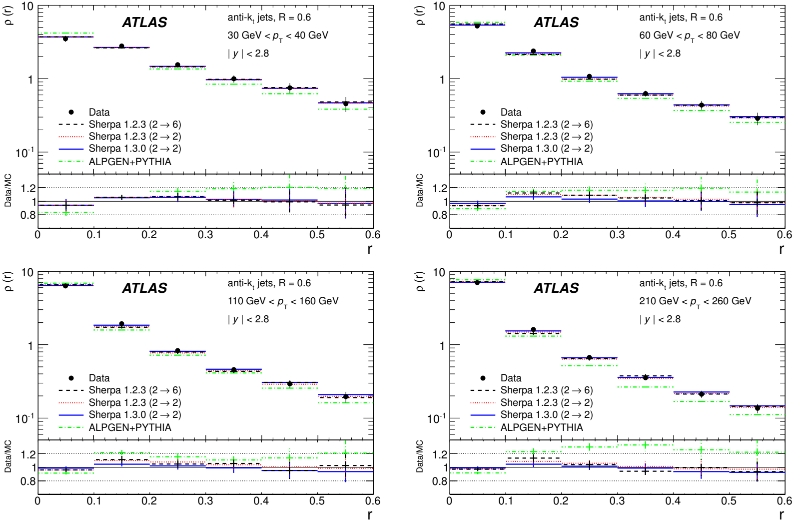
$\Rightarrow$ **small scale contributions especially important for intrajet observables**

- necessity to describe intrajet observables well to be useful in jet substructure analysis
- need to describe hard emissions well
  - recoil to produce boosted heavy particles (production xsecs/dists)
  - good chance they will end up in same fat jet (Q_{cut} usally $k_\perp$-type)

$\Rightarrow$ **multijet merging necessary**

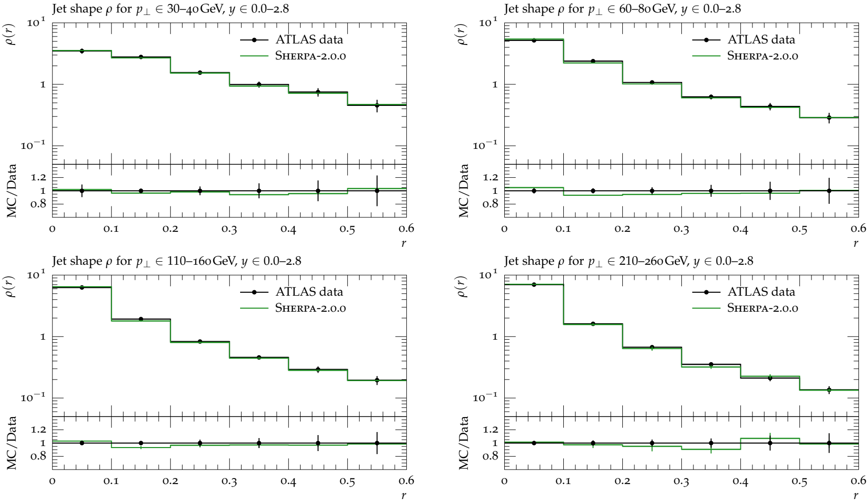
Jet shapes – differential jet shape $\rho(\mathrm{r})$

ATLAS collaboration Phys.Rev.D83(2011)052003, ATL-PHYS-PUB-2011-010



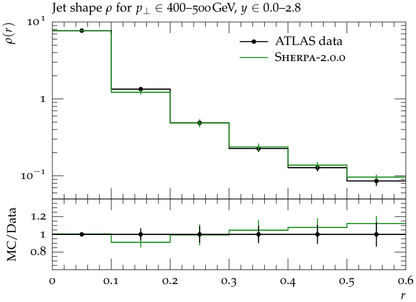
Jet shapes – differential jet shape $\rho(r)$

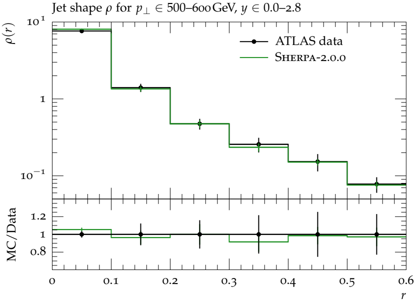
ATLAS data Phys.Rev.D83(2011)052003



Jet shapes – differential jet shape $\rho(\mathrm{r})$

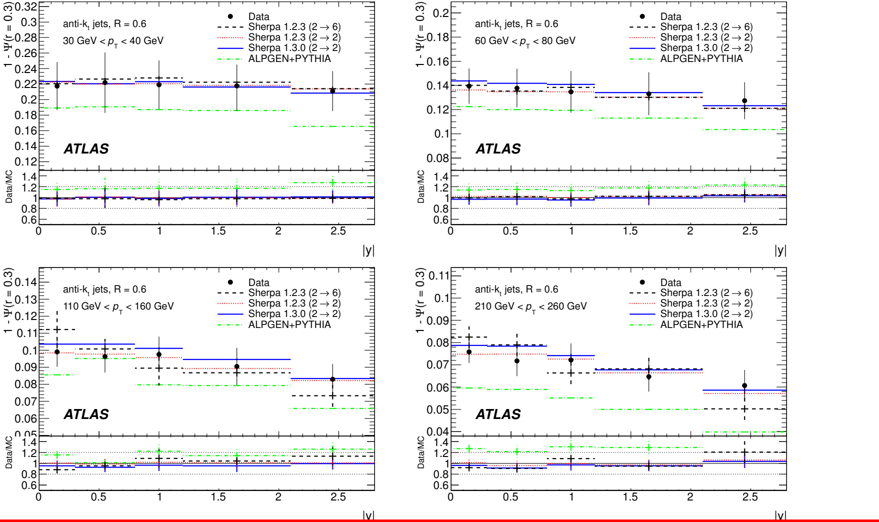
ATLAS data Phys.Rev.D83(2011)052003





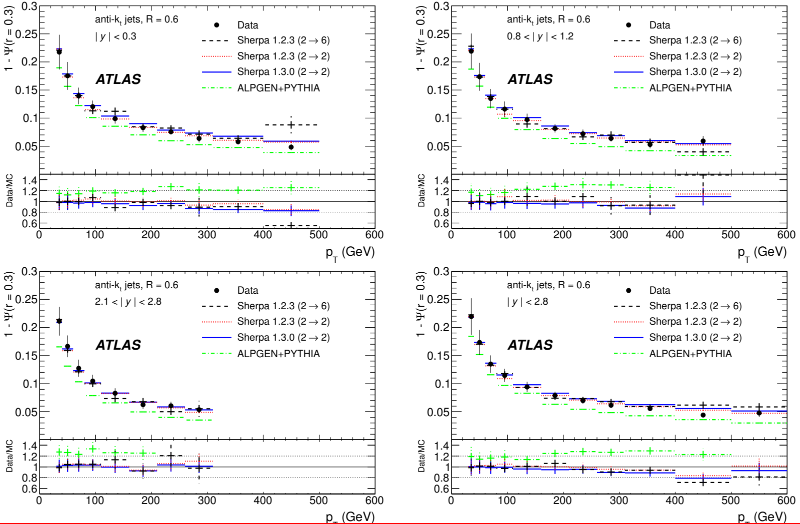
Jet shapes – integrated jet shape $1 - \Psi(r = 0.3)$

ATLAS collaboration Phys.Rev.D83(2011)052003, ATL-PHYS-PUB-2011-010



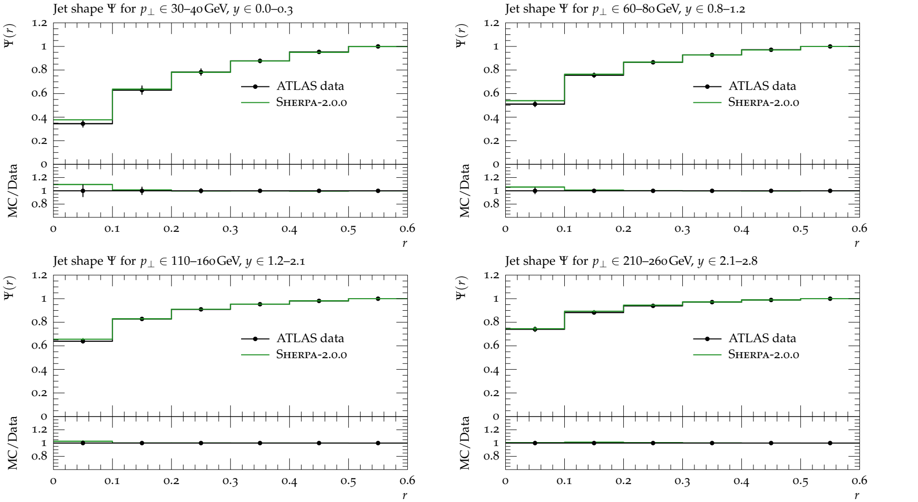
Jet shapes – integrated jet shape $1 - \Psi(r = 0.3)$

ATLAS collaboration Phys.Rev.D83(2011)052003, ATL-PHYS-PUB-2011-010



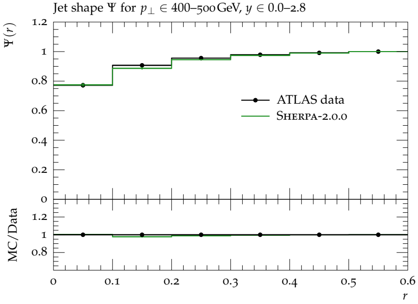
Jet shapes – integrated jet shape $\Psi(r)$

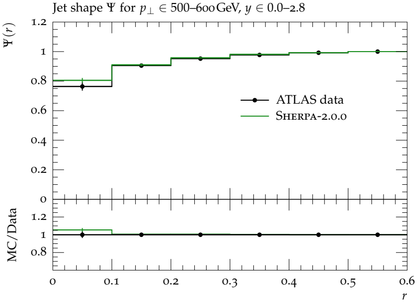
ATLAS data Phys.Rev.D83(2011)052003



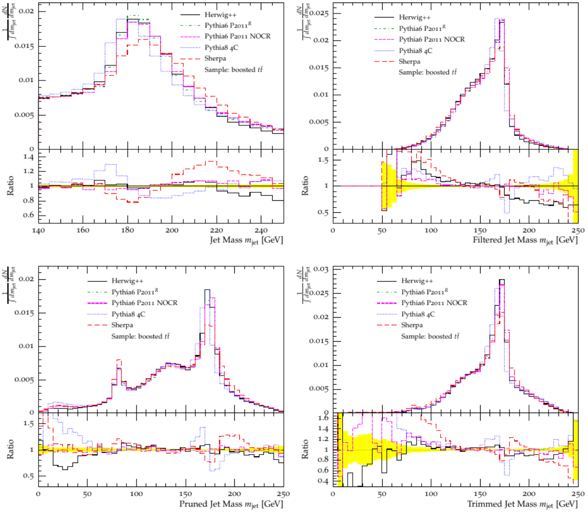
Jet shapes – integrated jet shape $\Psi(r)$

ATLAS data Phys.Rev.D83(2011)052003





Jet substructure



BOOST2012 to be published

$pp \to t\bar{t}$ + jets production

- NLO accuracy (MC@NLO, MEPS@NLO) of signal and background processes possible in SHERPA
- Hadronisation and Underlying Event contributions tuned

Matrix element weights and reweighting

SHERPA-2.0.0 will contain an Python interface
(available since SHERPA-2.0.β_2)

- gives access to SHERPA's matrix elements (AMEGIC++ & COMIX)
- takes external four momenta and flavours
- returns colour and helicity summed/averaged matrix elements including symmetry and flux factors

⇒ can be used to calculate the ME weight for a given configuration

- matrix element method (tree-level) can be used for any process
- reweight BSM sample to different BSM parameter points

Conclusions

- MC@NLO including exact soft-gluon colour coherence
- multijet merging at NLO accuracy (MEPS@NLO)
  → preserves NLO accuracy at every jet multiplicity and and all resummation properties of the parton shower
- jet shapes well modelled
- multijet topologies relevant in boosted regime
  → multijet merging needed
- tools for ME-reweighting provided

imminent release SHERPA-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!