Sherpa NLO and multileg developments

ATLAS MC NLO/MultiLeg Mini-Workshop

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Based on

- arXiv:1111.1220 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)
- arXiv:1201.5882 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)
- in preparation (Stefan Höche, Marek Schönherr)
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Current status in Sherpa 1.4.0

- Automatic tree-level ME+PS merging, including heavy-flavour treatment
- QED ME+PS merging, and interleaved QCD/QED ME+PS for hard photon production ("fragmentation component")
- QCD NLO+PS matching with MC@NLO-like algorithm
- MENLOPS on top of NLO+PS for higher-multi tree-level accuracy
  $\rightarrow$ even unweighted event generation possible (weights ± 1)

This talk

- Features of our NLO+PS implementation
- Resummation improvements in NLO+PS and uncertainty assessment
- Some last-minute sneak preview slides – stay tuned . . . :-)

Reminder: NLO calculations

- Contributions to NLO cross section: $\mathcal{B}$orn, $\mathcal{V}$irtual and $\mathcal{R}$eal emission
- $\mathcal{V}$ and $\mathcal{R}$ divergent in separate phase space integrations
  $\Rightarrow$ Subtraction method for expectation value of observable O at NLO:

$$\langle O\rangle^{(\mathrm{NLO})} = \int \mathrm{d}\Phi_B \left[\mathcal{B}(\Phi_B) + \tilde{\mathcal{V}}(\Phi_B) + \sum_{\widetilde{ij}} \mathcal{I}^{(\mathrm{S})}_{\widetilde{ij}}(\Phi_B)\right] O(\Phi_B)$$
$$+ \int \mathrm{d}\Phi_R \left[\mathcal{R}(\Phi_R)\, O(\Phi_R) - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{S})}_{ij}(\Phi_R)\, O(b_{ij}(\Phi_R))\right]$$

- Subtraction terms $\mathcal{D}$ and their integrated form $\mathcal{I}$
  e.g. Frixione, Kunszt, Signer (1995); Catani, Seymour (1996)
- Subtraction defines phase space factorisation $\Phi_R \underset{r_{\widetilde{ij}}}{\overset{b_{ij}}{\rightleftharpoons}} \left(\Phi_B, \Phi^{ij}_{R|B}\right)$

Modifications for NLO+PS

Following Frixione, Webber (2002): Introduce additional subtraction terms $\mathcal{D}^{(\mathrm{A})}$

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, \bar{\mathcal{B}}^{(\mathrm{A})} \left[\underbrace{\Delta^{(\mathrm{A})}(t_0)}_{\text{unresolved}} O(\Phi_B) + \sum_{\{\widetilde{ij}\}} \int_{t_0} \mathrm{d}\Phi^{ij}_{R|B} \underbrace{\frac{\mathcal{D}^{(\mathrm{A})}_{ij}}{\mathcal{B}} \Delta^{(\mathrm{A})}(t)}_{\text{resolved, singular}} O(r_{\widetilde{ij}}(\Phi_B)) \right]$$

$$+ \int \mathrm{d}\Phi_R \underbrace{\left[\mathcal{R} - \sum_{ij} \mathcal{D}^{(\mathrm{A})}_{ij} \right]}_{\text{resolved, non-singular}} O(\Phi_R)$$

with $\bar{\mathcal{B}}^{(\mathrm{A})}$ defined as:

$$\bar{\mathcal{B}}^{(\mathrm{A})} = \mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{\widetilde{ij}\}} \mathcal{I}^{(\mathrm{S})}_{\widetilde{ij}} + \sum_{\{\widetilde{ij}\}} \int \mathrm{d}\Phi^{ij}_{R|B} \left[\mathcal{D}^{(\mathrm{A})}_{ij} - \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

Features

- Reproduces $\langle O \rangle^{(\mathrm{NLO})}$ to $\mathcal{O}(\alpha_s)$
- Event generation techniques for $\langle O \rangle$
  - Line 1: Events with Born kinematics, weight $\bar{\mathcal{B}}^{(\mathrm{A})}$ and shower algorithm using $\mathcal{D}^{(\mathrm{A})}$
  - Line 2: Real-emission events with divergences subtracted by $\mathcal{D}^{(\mathrm{A})}$
- Choice of $\mathcal{D}^{(\mathrm{A})}$ fixes matching algorithm (MC@NLO, Powheg, ...)

Subtleties

To prove NLO accuracy:
$\mathcal{D}^{(\mathrm{A})}$ needs to be identical in shower algorithm and real-emission events

Original idea: $\mathcal{D}^{(\mathrm{A})}$ = PS splitting kernels

Frixione, Webber (2002)

- \+ Shower algorithm for Born-like events easy to implement
- – "Non-singular" piece $\mathcal{R} - \sum_{ij} \mathcal{D}_{ij}^{(\mathrm{A})}$ is actually singular:
  - Collinear divergences subtracted by splitting kernels
  - Remaining soft divergences as they appear in non-trivial processes at sub-leading N_c

Workaround: $\mathcal{G}$-function dampens soft limit in non-singular piece
⇔ Loss of formal NLO accuracy
(but heuristically only small impact)

Alternative idea: $\mathcal{D}^{(\mathrm{A})}$ = Catani-Seymour dipole subtraction terms $\mathcal{D}^{(\mathrm{S})}$

Höche, Krauss, Schönherr, FS (2011)

- \+ "Non-singular" piece fully free of divergences
- \+ $\bar{\mathcal{B}}^{(\mathrm{A})}$ function simplifies
- – Splitting kernels in shower algorithm become negative

Solution: Weighted $N_C = 3$ one-step PS based on subtraction terms

⇓

Used in the following

Example application: $W+1,2,3$-jet production with SHERPA

Höche, Krauss, Schönherr, FS (2012)

Event generation setup

- SHERPA's MC@NLO for $W+0$, $W+1$, $W+2$ and $W+3$-jet production
- Virtual corrections from BLACKHAT Berger et al. (2008),
  leading-colour approximation for the $W+3$-jet virtual
- For $n>0$ regularise requiring k_T jets with $p_\perp > 10$ GeV
- Exponentiation region restricted using $\alpha = 0.01$-cut in dipole terms Nagy (2003) (cf. outlook)
- CTEQ6.6 NLO PDF
- $\mu_R = \mu_F = 1/2\,\hat{H}'_T$, where $\hat{H}'_T = \sqrt{\sum p_{T,j}^2 + E_{T,W}^2}$.
- Three levels of event simulation:

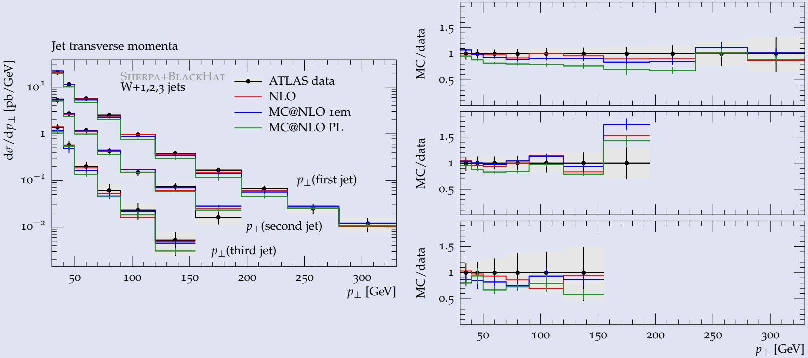
"NLO"	Fixed-order
"MC@NLO 1em"	MC@NLO including hardest emission
"MC@NLO PL"	MC@NLO including full PS

Analysis setup

- Comparing to ATLAS W+jets measurement arXiv:1201.1276
- Implementation in Rivet arXiv:1003.0694

Results for $W + n$-jet production at the LHC (arXiv:1201.5882)

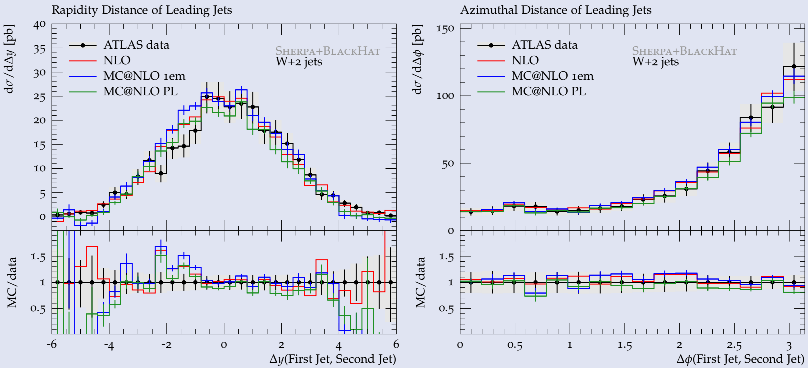
Transverse momenta of jets



Transverse momentum of the first, second and third jet (from top to bottom) in $W^\pm + \geq 1, 2, 3$ jet production as measured by ATLAS compared to predictions from the corresponding fixed order and MC@NLO simulations.

Results for $W + n$-jet production at the LHC (arXiv:1201.5882)

Angular correlations of leading jets



Angular correlations of the two leading jets in $W^{\pm} + \geq 2$ jet production as measured by ATLAS compared to predictions from the $W^{\pm} + 2$ jet fixed order and MC@NLO simulations.

More subtleties

Recall NLO+PS expression and its resummation evolution:

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, \bar{\mathcal{B}}^{(\mathrm{A})} \left[\underbrace{\Delta^{(\mathrm{A})}(t_0)}_{\text{unresolved}} O(\Phi_B) + \sum_{\{\widetilde{ij}\}} \int_{t_0} \mathrm{d}\Phi_{R|B}^{ij} \underbrace{\frac{\mathcal{D}_{ij}^{(\mathrm{A})}}{\mathcal{B}} \Delta^{(\mathrm{A})}(t)}_{\text{resolved, singular}} O(r_{\widetilde{ij}}(\Phi_B)) \right]$$

$$+ \int \mathrm{d}\Phi_R \underbrace{\left[\mathcal{R} - \sum_{ij} \mathcal{D}_{ij}^{(\mathrm{A})} \right]}_{\text{resolved, non-singular}} O(\Phi_R)$$

- Upper limit of this integration $\hat{=}$ Starting scale in traditional parton shower
- Determines how much emission phase space is exponentiated

How to implement and vary this consistently in NLO+PS?

k_T cuts in dipole terms

Höche, Schönherr (in preparation)

Idea

Implement upper cut-off $k_T < \mu_Q$ in resummation kernels $\mathcal{D}_{ij}^{(\mathrm{A})}$

- Consistently restricts resummation region in the PS evolution variable k_T
- Dipole subtraction terms $\mathcal{D}_{ij}^{(\mathrm{S})}$ remain unchanged
  $\Rightarrow$ Integral in $\bar{\mathcal{B}}^{(\mathrm{A})}$ has to be re-instated
  (Alternatively: Re-integrate dipole subtraction terms with k_T cut-off parameter)

Variation of resummation scale μ_Q

Experience from analytic resummation:

- Choose central scale specific for each process (e.g. $\mu_Q = m_H$)
- Variation: Typically by factors of $\sqrt{2}$ up and down

Variation gives handle on resummation uncertainty in NLO+PS

Application of k_T cut dipoles: QCD jet production

Höche, Schönherr (in preparation)

Event generation setup

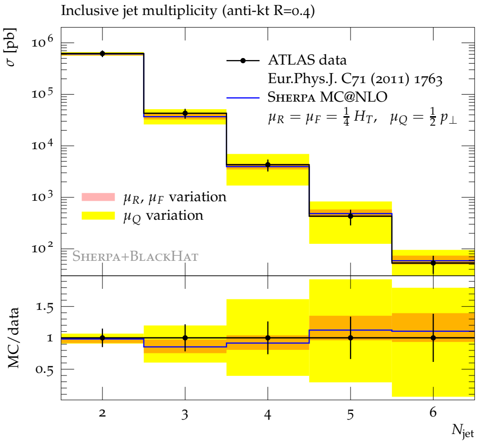
- $2 \to 2$ QCD jet production
- MC@NLO like algorithm as implemented in SHERPA
- Central scales:
  $\mu_R = \mu_F = 1/4 H_T = 1/4 \sum_{i \in jets} p_{\perp,i}$
  $\mu_Q = 1/2 p_\perp$
- Virtuals provided by BlackHat library Berger et al. (2008)
- Fully hadronised and including MPI with the Sherpa 1.4.0 CT10 tune

Analyses

- Various inclusive/di/multi-jet measurements from ATLAS and CMS

Preview: QCD jet production with Sherpa's MC@NLO (preliminary)

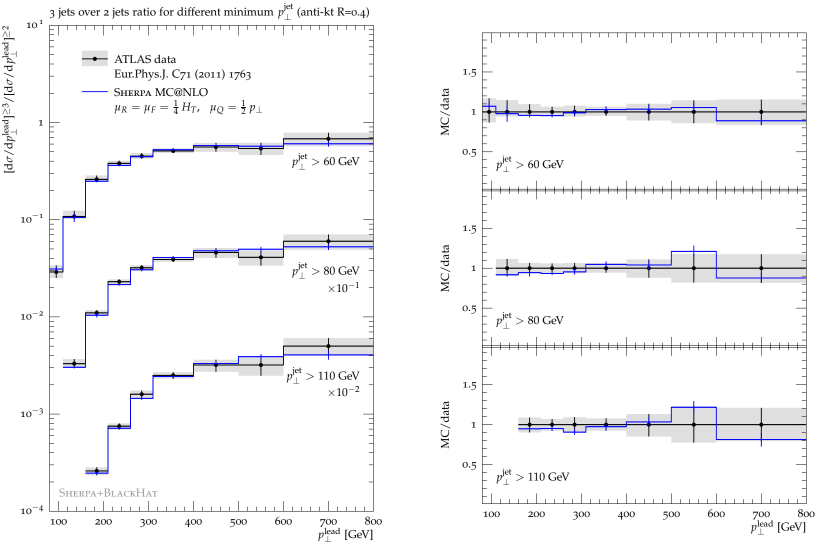
Uncertainties from scale variations:
$\mu_{R,F}$ by factor 2, μ_Q by factor $\sqrt{2}$



Comparison to ATLAS jet multiplicity measurement arXiv:1107.2092

Preview: QCD jet production with Sherpa's MC@NLO (preliminary)

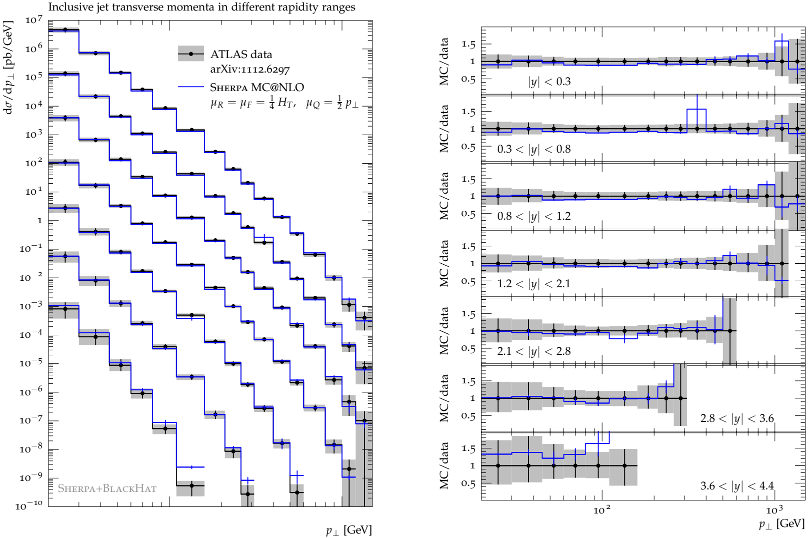
Predictions for central scales



Comparison to ATLAS R_{32} measurement arXiv:1107.2092

Preview: QCD jet production with Sherpa's MC@NLO (preliminary)

Predictions for central scales



Comparison to ATLAS inclusive jet measurement arXiv:1112.6297

Conclusions

Summary

- Presented recent progress in SHERPA with respect to NLO+PS matching
- Implementation of alternative MC@NLO algorithm applied to non-trivial processes: $W + 1, 2, 3$-jet production
- Assessment of uncertainties with respect to resummation scale demonstrated for example of QCD jet production

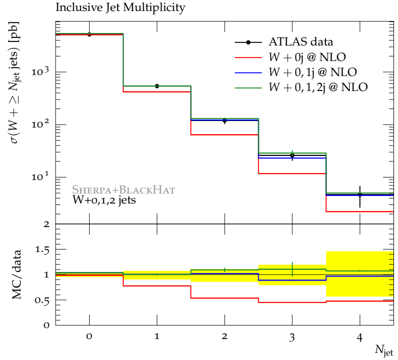
Outlook

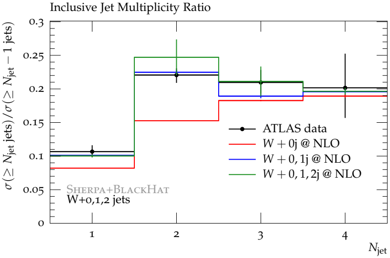
- It would be nice to have NLO+PS accuracy for $W + 0, 1, 2, \ldots$ jet production not separately but in one inclusive "NLO-merged" sample.

  Ah, hang on …

Sneak preview: NLO merging for $W + 0, 1, 2$-jet production SHERPA

NLO merging predictions compared to ATLAS W+jets measurement (arXiv:1201.1276)





Höche, Krauss, Schönherr, FS (in preparation)

Sneak preview: NLO merging for $W + 0, 1, 2$-jet production SHERPA

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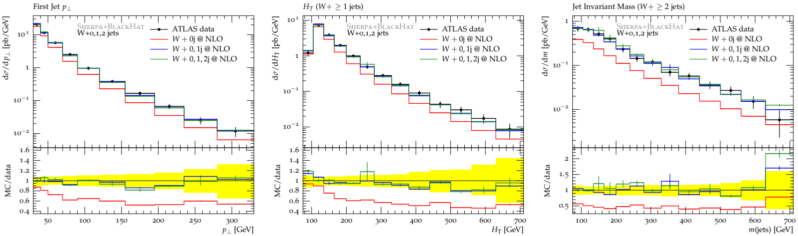

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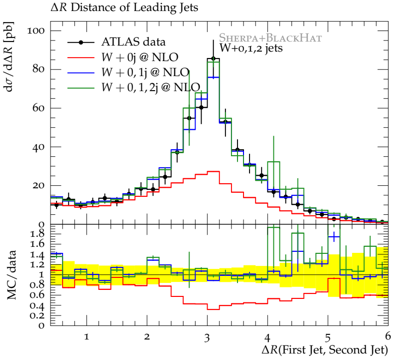
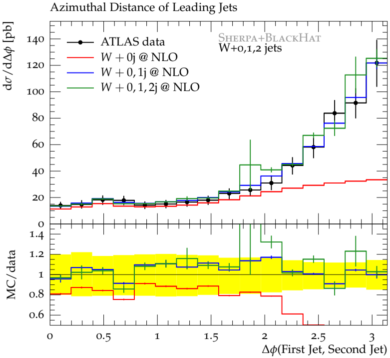
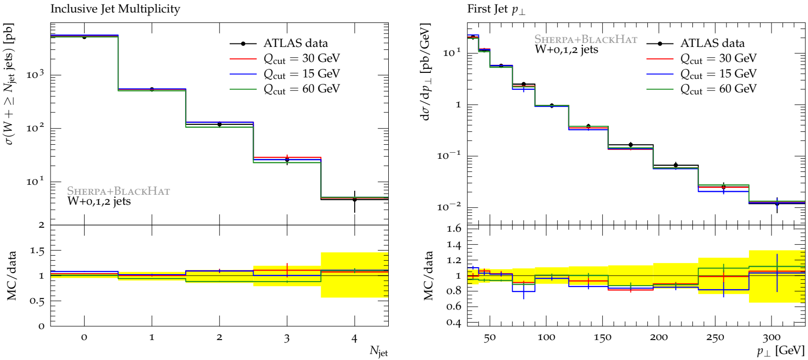




Höche, Krauss, Schönherr, FS (in preparation)

Sneak preview: NLO merging for $W + 0, 1, 2$-jet production in SHERPA

Uncertainties from Q_{cut} variations



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