A critical appraisal of NLO+PS methods

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General NLO+PS matching

- NLO calculation with subtraction methods

$$\sigma^{\text{NLO}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big] + \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{S})}(\Phi_R)\Big]$$

- introduce another set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$

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- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

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- use $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels
- resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
  → starting scale of parton shower evolution
  → should be of the order of the hard resummation scale
- choice of coupling scales:
  - fixed order parts: μ_R
  - resummation: needs $\mu_{\text{exp}} \to p_\perp$ as $p_\perp \to 0$, otherwise arbitrary

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POWHEG

Special choices: Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R}$ with $\rho_i = \mathrm{D}_i^{(\mathsf{S})} / \sum_i \mathrm{D}_i^{(\mathsf{S})}$
  $\rightarrow$ each R_i contains only one divergence structure as defined by $\mathrm{D}_i^{(\mathsf{S})}$

Consequences:

- no $\mathbb{H}$-events, resummation scale μ_Q^2 at kinematic limit $\frac{1}{2}\,s_{\text{had}}$
- in CS-subtraction instabilities in ρ_i due to different cuts on R and $\mathrm{D}_i^{(\mathsf{S})}$
- exponentiation of R through matrix element corrected parton shower NLO accuracy depends crucially on presence of exact same terms in subtraction and parton shower

Modifications:

- introduce suppression function $f(p_\perp) = h^2/(p_\perp^2 + h^2)$ Alioli et.al. JHEP04(2009)002
  $\rightarrow \mathrm{D}_i^{(\mathsf{A})} = \mathrm{R}_i \cdot f(p_\perp)$
  $\rightarrow$ continuous dampening of resummation kernel at large $p_\perp$

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MC@NLO – traditional scheme

Special choices: Frixione, Webber JHEP06(2002)029

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{B} \cdot \mathcal{K}_i$ with $\mathcal{K}_i$ parton shower kernels

Consequences:

- resummation scale $\mu_Q^2 = t_{\mathsf{max}}$ parton shower starting scale
- in general, $\mathrm{D}_i^{(\mathsf{A})}$ only leading colour approximation
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- introduce soft modification function $f(p_\perp)$ such that

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Special choices: SH, FK, MS, FS arXiv:1111.1220

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- simplification of $\bar{\mathrm{B}}^{(\mathsf{A})}$-integral
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Implemented in SHERPA – full-colour first parton shower emission

Tricky point: $\mathrm{D}_i^{(\mathsf{A})} < 0$ e.g. for subleading colour dipoles

Use modified Sudakov veto algorithm SH, FK, MS, FS arXiv:1111.1220

- Assume $f(t)$ as function to be generated, and overestimate $g(t)$
  Standard probability for *one* acceptance with n rejections

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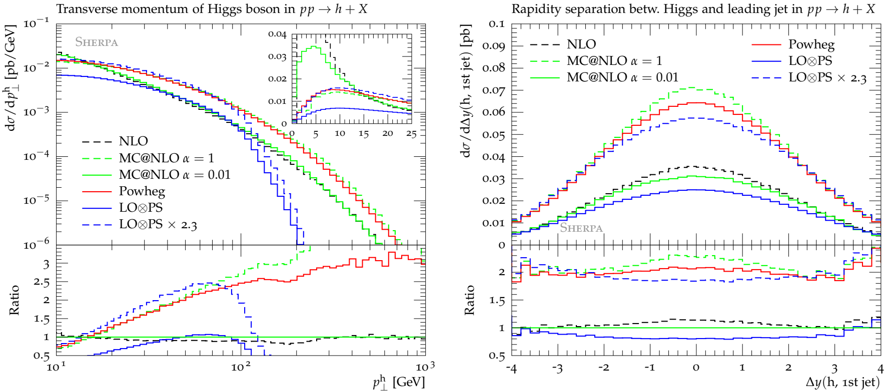
Identify $f(t)$, $g(t)$, $h(t)$:

- $f(t)$ determined by MC@NLO $\Rightarrow D_i^{(A)}$
- $h(t)$ determined by parton shower $\Rightarrow D_i^{(PS)}$
- $g(t)$ **can be chosen freely** $\Rightarrow$ const. $\cdot\, f$
  constraints: $\text{sign}(f) = \text{sign}(g)$, $|f| \leq |g|$

Automation in SHERPA framework

- easy to automate and process independent
  only virtual correction V needs to be supplied
- leading order pieces and phase space generation taken care of by well-tested automated tree-level matrix element generators AMEGIC++ and/or COMIX
- based on Catani-Seymour subtraction
- using dipole-like parton shower
- parton showers are easy to correct with matrix elements
  $\mathrm{D}_i^{(\mathsf{A})}/\mathrm{B}$ always non-zero and close to pure parton shower result
  deviations in soft-gluon regime limited by parton shower cut-off

Results – $h + X$ production in gluon fusion



Sanity checks:

- Sudakov shape of LO⊗PS result for $\alpha_{\text{cut}} \to 1$
- High-$p_\perp$ tail of NLO reproduced for $\alpha_{\text{cut}} \ll 1$

Ideally both simultaneously, as in traditional MC@NLO, but currently limited by inappropriate choice of μ_Q^2 through α_{cut}

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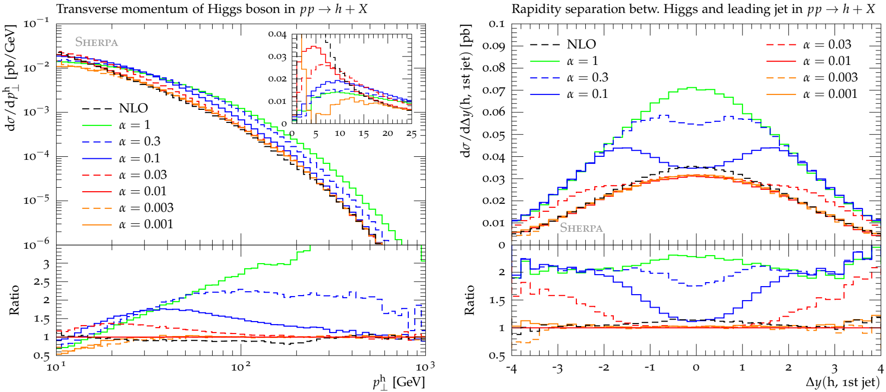
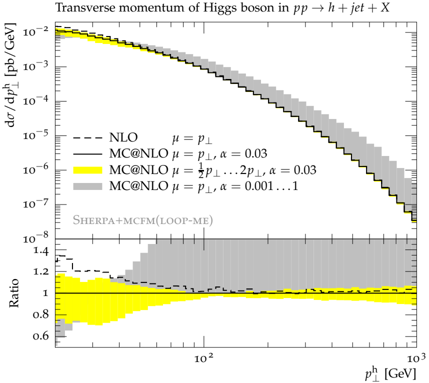


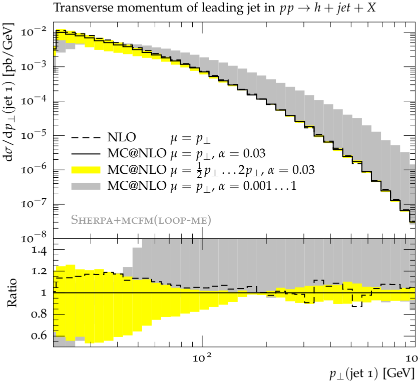
Essential features of Alioli et.al. JHEP04(2009)002 reproduced

- hardness of POWHEG/MC@NLO $\alpha_{\text{cut}} = 1$
- dip in Δy for intermediate α_{cut}

Purely academic, rather define $\mathrm{D}^{(\mathsf{A})}$ properly $\Rightarrow$ **phase space separation in t**

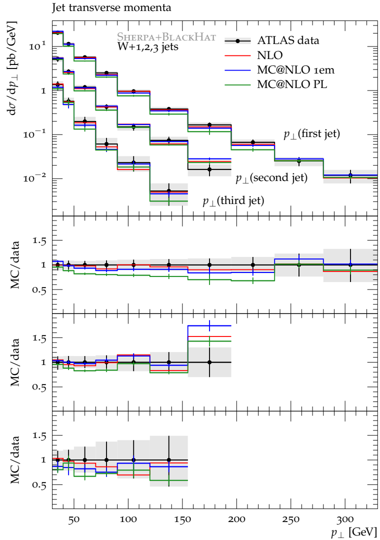
Results – $\mathrm{h}+\mathrm{j}+\mathrm{X}$ production





- increased parton multiplicity worsens problems
- large dependence on exponentiated phase space
- unphysical results for $\mu_Q^2 \to \frac{1}{2}\, s_{\text{had}}$

Results – $W + n$ jet production



$W + 1, 2, 3$ jets at LHC (ATLAS data)

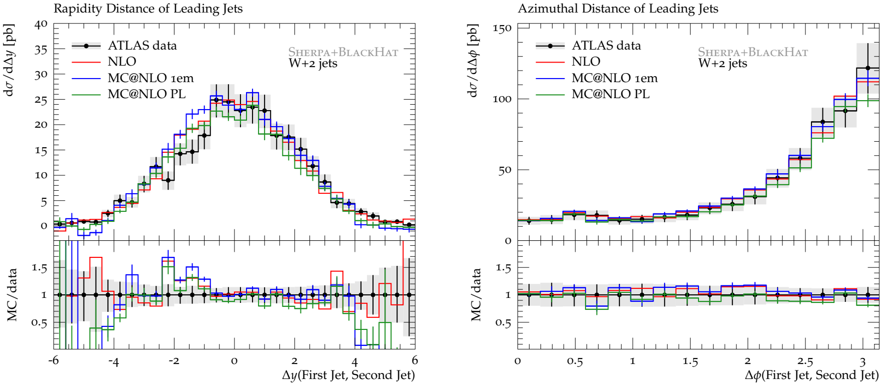
- complexity not a problem
- speed limited by the virtual amplitude in $W + 3j$
- scales:

$$\mu_R = \mu_F = \frac{1}{2}\hat{H}'_T$$

$$\mu_{\text{exp}} = \frac{1}{(1/p_\perp^2 + 1/\mu_R^2)^{\frac{1}{2}}}$$

- fixed order behaviour at high $p_\perp$ $\rightarrow$ smoother transition to $\mathbb{H}$-events

Results – $W + n$ jet production



Conclusions

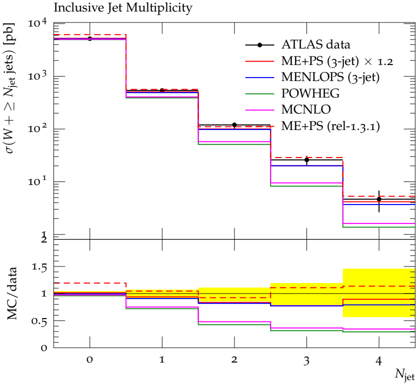
- care must be taken to preserve the correct resummation properties as not to introduce large spurious subleading logarithms

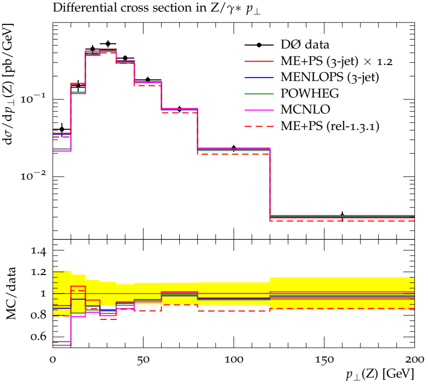
  Banfi, Salam, Zanderighi JHEP08(2004)062

- MC@NLO $\mathrm{D}^{(\mathsf{A})} = \mathrm{D}^{(\mathsf{S})}$ scheme facilitates implementation of process independent correct soft-gluon limit needed for NLO accuracy
- no conceptual problems for high-multiplicity processes
- independent check of POWHEG ↔ MC@NLO differences
- both MC@NLO and POWHEG can be trivially combined with ME+PS merging ⇒ MENLOPS

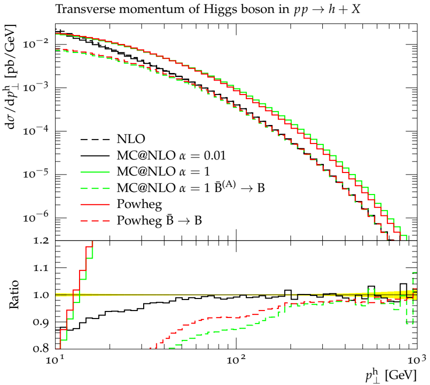
SHERPA-1.4.0

MENLOPS with MC@NLO





Additional Sudakov suppression by inappropriately sized resummation phase space



- first emission only
- $\mu_{\text{exp}}^2 = \min(p_\perp^2, \mu_R^2)$ and $\mu_R = m_h$, such that $\mu_{\text{exp}} = \mu_R$ for $p_\perp > m_h$
- already 10% suppression at m_h