A critical appraisal of NLO+PS matching methods

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Contents

Introduction

Importance of matching NLO calculations with parton showers

- exclusive final states
- observable independent combination of fixed order and resummation
- problem double counting: both NLO and PS are approximations to higher order corrections

Two methods appeared in the literature: MC@NLO and POWHEG

- two sides of one medal
- differ in choices of division of resummation and fixed-order part

Uncertainties of NLO+PS matching

- usual μ_R and μ_F variation as in NLO calculations
- also μ_Q-variation as in analytic resummations

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General NLO calculations

- NLO calculation with subtraction methods

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Catani, Seymour Nucl.Phys.B485(1997)291-419

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\begin{aligned}
\langle O\rangle^{\text{NLO}} =& \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B) \\
&+ \int \mathrm{d}\Phi_R \Big[\qquad - \sum_i \mathrm{D}_i^{(\mathrm{S})}(\Phi_R) \qquad O(\Phi_{B_i})\Big] \\
&+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) \qquad \Big]\, O(\Phi_R)
\end{aligned}
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- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathrm{A})}$
- $\mathrm{D}_i^{(\mathrm{A})}$ and $\mathrm{D}_i^{(\mathrm{S})}$ need to have same momentum maps and IR limit

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$$\langle O\rangle^{(\text{A})}_{\text{corr}}=\int \mathrm{d}\Phi_R \sum_i \mathrm{D}_i^{(\text{A})}\big[O(\Phi_R)-O(\Phi_{B_i})\big]$$

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$$\langle O\rangle^{\mathsf{NLO}} = \int \mathrm{d}\Phi_B \;\; \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\; O(\Phi_B)$$

$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\mathsf{corr}}$$

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Parton showers and resummation

- parton shower/resummation kernel $\mathcal{K}_i(\Phi_1)$, $\Phi_1 = \{t, z, \phi\}$
  $\rightarrow \mathcal{K}_i$ incorporates divergent propagator and DGLAP splitting kernels

$$\langle O \rangle^{\mathsf{PS}} = \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \, O(\Phi_B)$$

$$= \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \, O(\Phi_B) +$$

- Sudakov form factor $\Delta^{(\mathcal{K})}(t, t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1 \, \mathcal{K}(\Phi_1)\right]$ contains resummation features
- $\langle O \rangle^{(\mathcal{K})}_{\mathsf{corr}}$ generated by one parton shower step

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$$\langle O \rangle^{\text{PS}} = \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \left[\Delta^{(\mathcal{K})}(t_0, \mu_F^2) \, O(\Phi_B) + \int\limits_{t_0}^{\mu_F^2} \mathrm{d}\Phi_1 \mathcal{K}(\Phi_1) \, \Delta^{(\mathcal{K})}(t, \mu_F^2) \, O(\Phi_R) \right]$$

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General NLO+PS matching

$$\langle O\rangle^{\text{NLO+PS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B) \Bigg[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\, O(\Phi_B) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathsf{A})}(t,\mu_Q^2)\, O(\Phi_R) \Bigg]$$

$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R) \Big] O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\text{corr}}$$

- use $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels
- resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
  - $\rightarrow$ starting scale of parton shower evolution
  - $\rightarrow$ should be of the order of the hard resummation scale
- **Powheg and Mc@Nlo now differ in choice of $\mathrm{D}_i^{(\mathsf{A})}$ and μ_Q^2**

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\end{aligned}
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$$
\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} \mathrm{d}\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]
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POWHEG

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

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

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 $\mathrm{D}_i^{(\mathrm{S})}$
- 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
  $\rightarrow \mathrm{D}_i^{(\mathrm{A})} = \rho_i \cdot \mathrm{R} \cdot f(p_\perp)$
  $\rightarrow$ 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
  NLO accuracy depends crucially on correctness of IR-limit

Modifications: Frixione, Nason, Webber JHEP08(2003)007

- introduce soft modification function $f(p_\perp)$ such that

$$\sum \mathrm{B} \cdot \mathcal{K}_i \cdot f(p_\perp) \xrightarrow{p_\perp \to 0} \sum \mathrm{D}_i^{(\mathsf{S})}$$

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MC@NLO – $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ scheme

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

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Consequences:

- simplification of $\bar{\mathrm{B}}^{(\mathsf{A})}$-integral
- resummation scale $\mu_Q^2 = t_{\mathsf{max}}$ set by phase space limitation of subtraction terms
  $\rightarrow$ subtraction constrained in parton shower t needed for physical resummation
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MC@NLO – $\mathrm{D}_i^{(\mathrm{A})} = \mathrm{D}_i^{(\mathrm{S})}$ scheme

Implemented in SHERPA – full-colour first parton shower emission

Tricky point: $\mathrm{D}_i^{(\mathrm{A})} < 0$ 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

$$\frac{f(t)}{g(t)}\,g(t)\exp\left\{-\int_t^{t_1}\mathrm{d}\bar{t}\,g(\bar{t})\right\}\prod_{i=1}^{n}\left[\int_{t_{i-1}}^{t_{n+1}}\mathrm{d}t_i\left(1-\frac{f(t_i)}{g(t_i)}\right)g(t_i)\exp\left\{-\int_{t_i}^{t_{i+1}}\mathrm{d}\bar{t}\,g(\bar{t})\right\}\right]$$

- Can split weight into MC and **analytic** part using auxiliary function $h(t)$

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$$w(t,t_1,\ldots,t_n) = \frac{g(t)}{h(t)}\prod_{i=1}^{n}\frac{g(t_i)}{h(t_i)}\,\frac{h(t_i)-f(t_i)}{g(t_i)-f(t_i)}$$

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

- Can split weight into MC and **analytic** part using auxiliary function $h(t)$

$$\frac{f(t)}{g(t)}\,h(t)\exp\left\{-\int_t^{t_1}\mathrm{d}\bar{t}\,h(\bar{t})\right\}\prod_{i=1}^{n}\left[\int_{t_{i-1}}^{t_{n+1}}\mathrm{d}t_i\left(1-\frac{f(t_i)}{g(t_i)}\right)h(t_i)\exp\left\{-\int_{t_i}^{t_{i+1}}\mathrm{d}\bar{t}\,h(\bar{t})\right\}\right]$$

$$w(t,t_1,\ldots,t_n) = \frac{g(t)}{h(t)}\prod_{i=1}^{n}\frac{g(t_i)}{h(t_i)}\,\frac{h(t_i)-f(t_i)}{g(t_i)-f(t_i)}$$

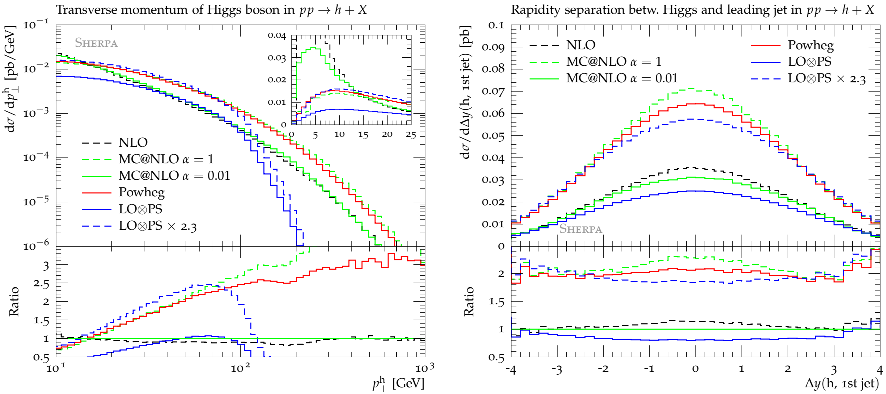
Identify $f(t)$, $g(t)$, $h(t)$:

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

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
  Krauss, Kuhn, Soff JHEP02(2002)044, Höche, Gleisberg JHEP12(2008)039
- based on Catani-Seymour subtraction Catani, Seymour Nucl.Phys.B485(1997)291-419
  Nagy PRD68(2003)094002, Gleisberg, Krauss EPJC53(2008)501-523
- using dipole-like parton shower Schumann, Krauss JHEP03(2008)038
  ⇒ phase space restriction of dipoles = starting scale for 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
  − larger analytic weights in soft-gluon regime limited by t_0

Results – $pp \to h + X$ production in gluon fusion

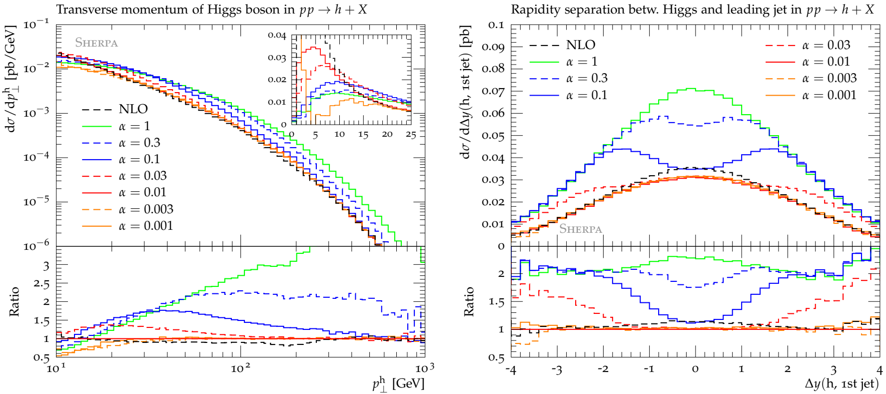


Sanity checks:

- 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}

Results – $pp \to h + X$ production in gluon fusion

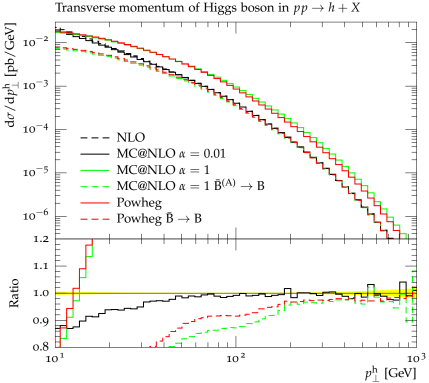


Essential features of Alioli et.al. JHEP04(2009)002 reproduced

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

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

Results – $\mathrm{pp} \to \mathrm{h} + \mathrm{X}$ production in gluon fusion



replace weight of $\mathbb{S}$-events by LO weight

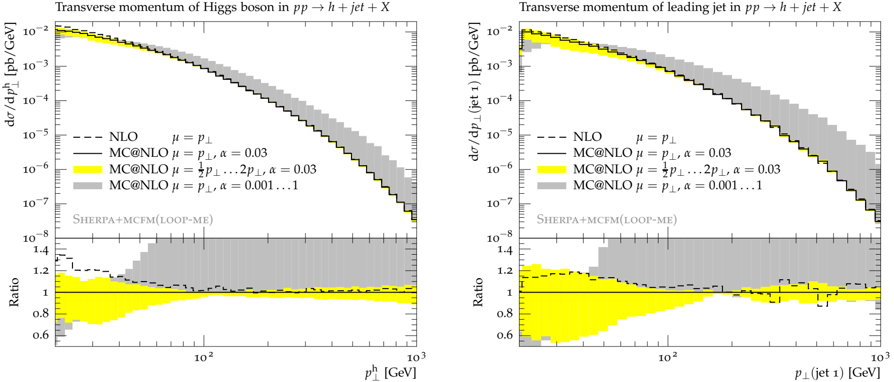
- for $t \to s_{\text{had}}$ approaches NLO result, but

$$\Delta^{(\mathrm{A})}(m_h^2, s_{\text{had}}) = \exp\left[-\int_{m_h^2}^{s_{\text{had}}} \mathrm{d}t\, \frac{\mathrm{R}(t)}{\mathrm{B}}\right] < 1$$

- non-negligible Sudakov suppression at $p_\perp \sim m_h \ll s_{\text{had}}$, induced by erroneous phase space boundaries for resummation
- spuriously large subleading logarithms

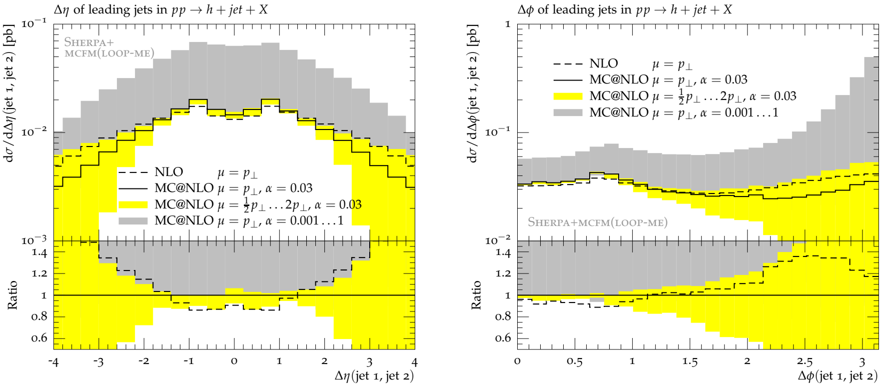
Banfi, Salam, Zanderighi JHEP08(2004)062

Results – $\mathrm{pp} \to \mathrm{h} + \mathbf{jet} + \mathrm{X}$ production in gl. fusion



- 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 – $pp \to h + jet + X$ production in gl. fusion



- increased parton multiplicity worsens problems
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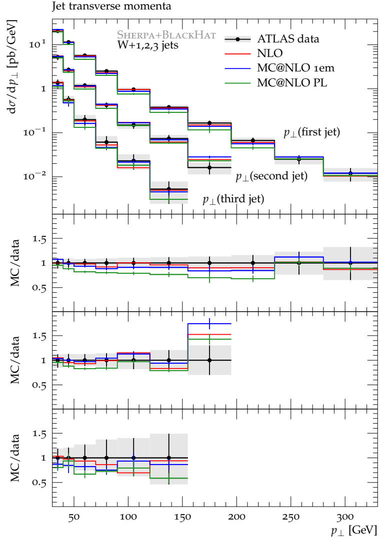
Results – $pp \to W + n$ jet $+ X$ production



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

SH, FK, MS, FS arXiv:1201.5882

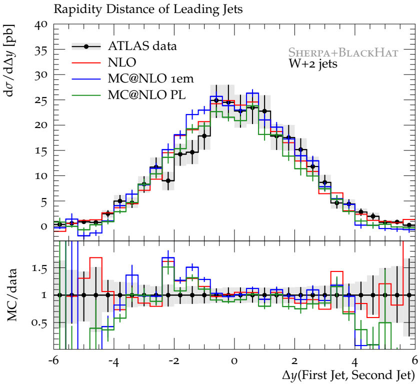
- complexity not a problem
- speed limited by the virtual amplitude in $W + 3$jet
- scales:

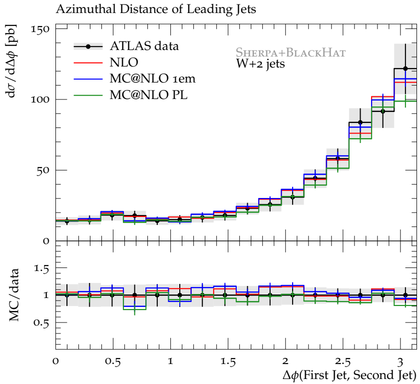
$$\mu_R = \mu_F = \frac{1}{2}\hat{H}'_T$$

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

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

Results – $pp \to W + n\ \text{jet} + X$ production





data: ATLAS arXiv:1201.1276

MENLOPS for MC@NLO

$$
\begin{aligned}
\langle O\rangle^{\text{MENLOPS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B) \Bigg[& \Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\, O(\Phi_B) \\
& + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathsf{A})}(t,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q) \Bigg] \\
+ \int \mathrm{d}\Phi_R \Bigg[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R) \Bigg] & O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q) \\
+ \int \mathrm{d}\Phi_R \Bigg[\frac{\bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)}{\mathrm{B}(\Phi_B)} \left(1 - \frac{\mathrm{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right) + \frac{\mathrm{H}(\Phi_R)}{\mathrm{R}(\Phi_R)} \Bigg] & \mathrm{R}(\Phi_R)\, \Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q-Q_{\text{cut}})
\end{aligned}
$$

- restrict MC@NLO expression to region $Q < Q_{\text{cut}}$
- add in real radiation explicitly, as in ME+PS
- restore logarithmic behaviour by explicit Sudakov
- local K-factor for continuity at Q_{cut}

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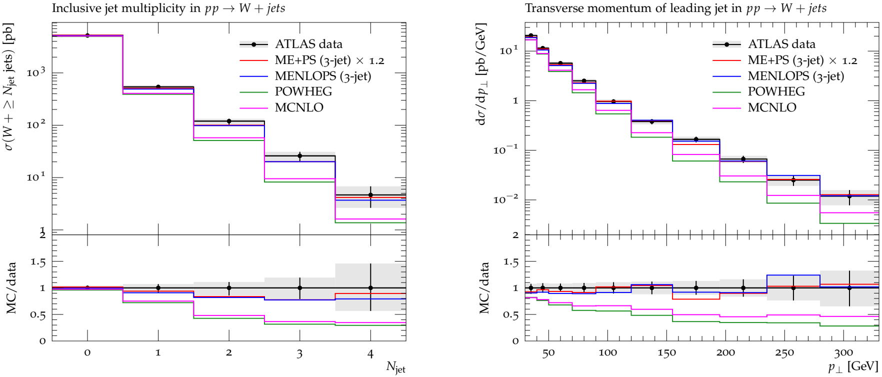
MENLOPS for MC@NLO – $pp \to W +$ jets production



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- good agreement with data ATLAS arXiv:1201.1276

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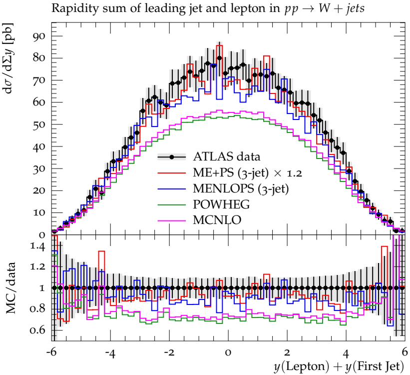

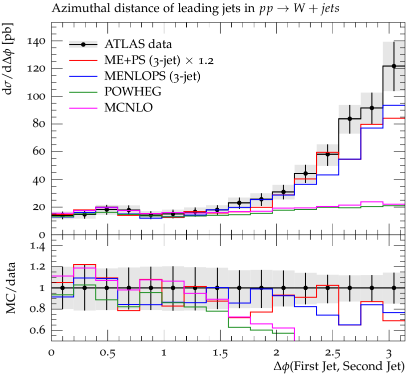

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Choice of exponentiated phase space

Assessment of uncertainties

- limit discussion to $gg \to h$ because effects are largest and cleanest here (large NLO k-factor, very simple colour/dipole structure)
  $\to$ large rate difference for $\mathbb{S}$ and $\mathbb{H}$ events
- setup: $k_\perp$-ordered parton shower based on Catani-Seymour dipoles
  $\to$ highlights what happens at resummation scale $\mathbf{k}_\perp^{\text{max}}$
- renormalisation scale $\mu_R = m_h$, $\mu_R^{\text{exp}} = \sqrt{\frac{1}{1/p_\perp^2 + 1/\mu_R^2}} \xrightarrow{p_\perp \to \infty} \mu_R$
- vary resummation scale $\mathbf{k}_\perp^{\text{max}}$, i.e. starting conditions of MC@NLO-shower
- starting conditions of POWHEG-shower fixed at $\mathbf{k}_\perp^{\text{max}} = \frac{1}{2}\sqrt{s_{\text{had}}}$
  - effect of suppression function not investigated
  - introduces arbitrary free parameter (not fixed to be of order of m_h)
  - uncertainties as large as with α variation
    $\to$ investigated in Alioli et.al. JHEP04(2009)002

$\Rightarrow$ uncertainties in (N)LL-LO matching in MC@NLO and POWHEG

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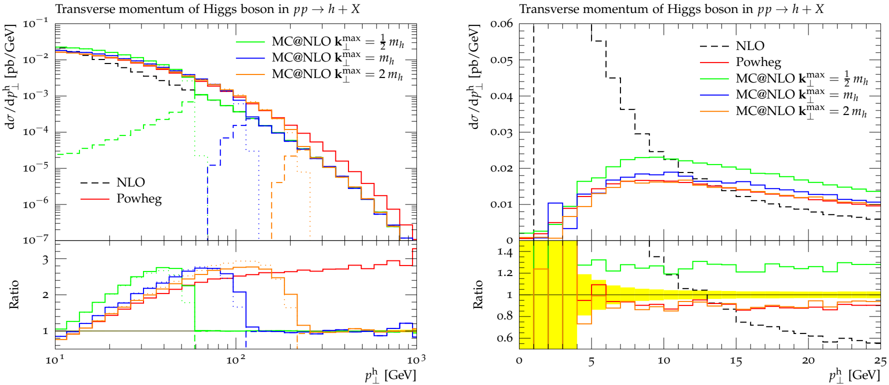
$\Rightarrow$ uncertainties in (N)LL-LO matching in Mc@Nlo and Powheg

Choice of splitting kernel – $\mathrm{D}^{(\mathsf{A})}/\mathrm{B}$

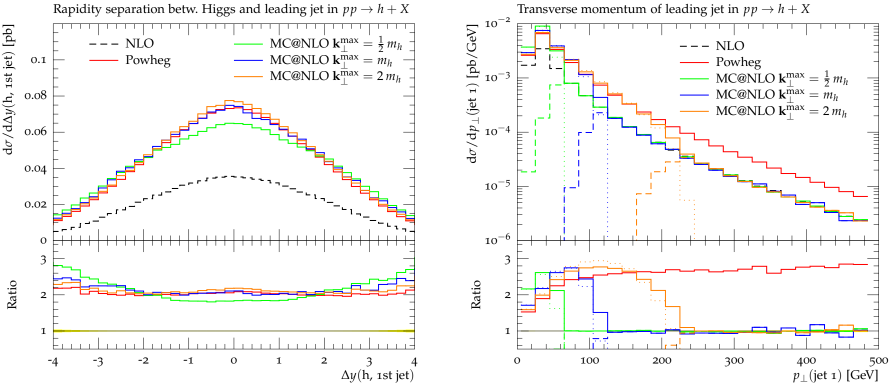
traditional MC@NLO and POWHEG choices of splitting kernels



- large uncertainties when varying $\mathbf{k}_\perp^{\max}$
- driven by diff. in normalisation of $\mathbb{S}$- and $\mathbb{H}$-events and size of $\ln^2(\mathbf{k}_\perp^2/\mu_Q^2)$
- shape difference driven by unitarity constraint

Choice of splitting kernel – $\mathrm{D}^{(\mathsf{A})}/\mathrm{B}$

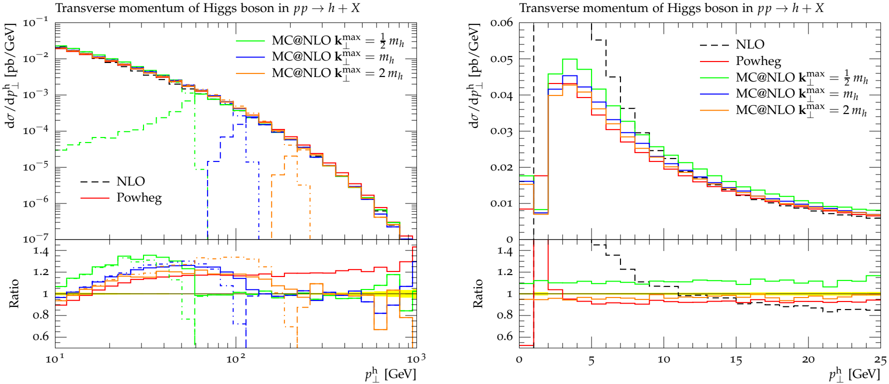
traditional MC@NLO and POWHEG choices of splitting kernels



- uncertainty on jet rates with $p_\perp \sim 100$GeV: 2.5
- no dip in Δy → originates in HERWIG's radiation pattern

Choice of splitting kernel – $\mathrm{D}^{(\mathbf{A})}/\bar{\mathrm{B}}^{(\mathbf{A})}$

here: change splitting kernels $\mathrm{K} \longrightarrow (1+\alpha_s \cdot \text{const.})\,\mathrm{K}$



- uncertainties much lower, smooth transition at μ_Q^2
- much closer to NLO fixed order result for "hard" emissions
- price of spuriously large LL prefactor → Sudakov peak differs

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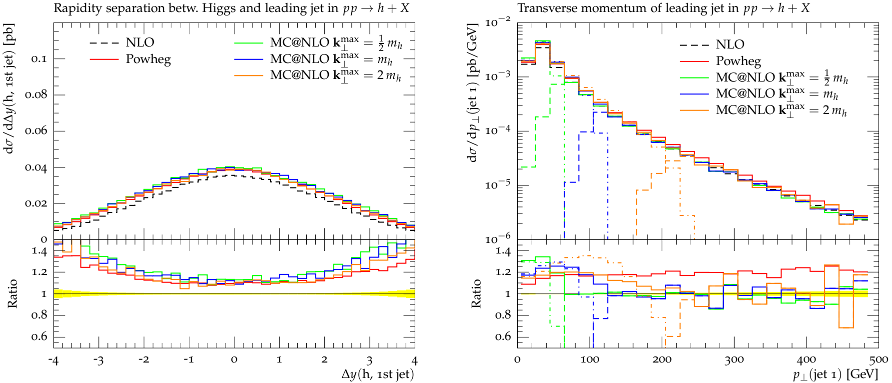

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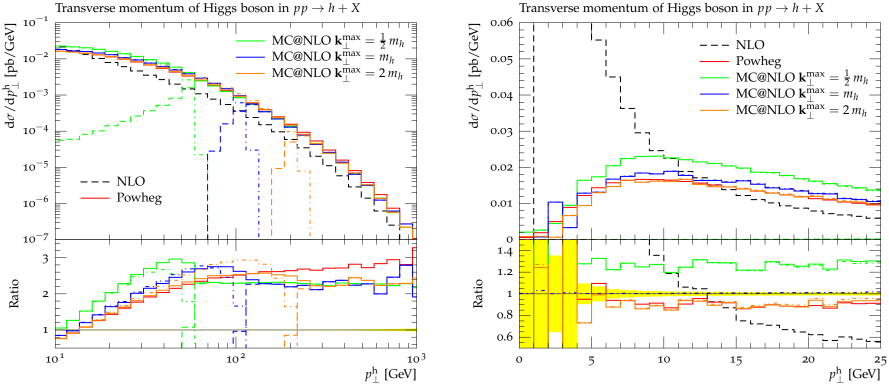
Choice of higher order correction – $\bar{\mathrm{B}}^{(\mathsf{A})}/\mathrm{B}\cdot\mathbb{H}$

here: modify $\mathbb{H}$-term with arbitrary higher order corrections $\mathbb{H} \to \frac{\bar{\mathrm{B}}^{(\mathsf{A})}}{\mathrm{B}}\,\mathbb{H}$



- PS resummation left void of higher order terms
- equivalent to MENLOPS prescription in Höche et.al. JHEP04(2011)024
- uncontrolled $\mathcal{O}(\alpha_s^2)$ terms in $\mathbb{H}$-events

Choice of higher order correction – $\bar{\mathrm{B}}^{(\mathsf{A})}/\mathrm{B} \cdot \mathbb{H}$

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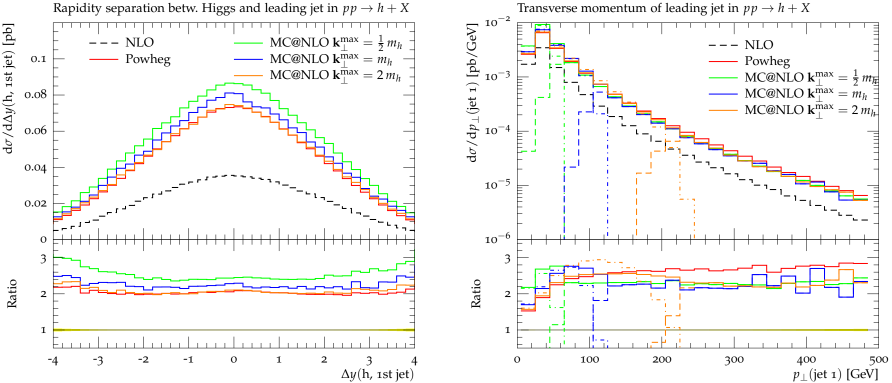

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- uncontrolled $\mathcal{O}(\alpha_s^2)$ terms in $\mathbb{H}$-events

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 $\leftrightarrow$ MC@NLO differences
- both MC@NLO and POWHEG can be trivially combined with ME+PS merging $\Rightarrow$ MENLOPS

SHERPA-1.4.0

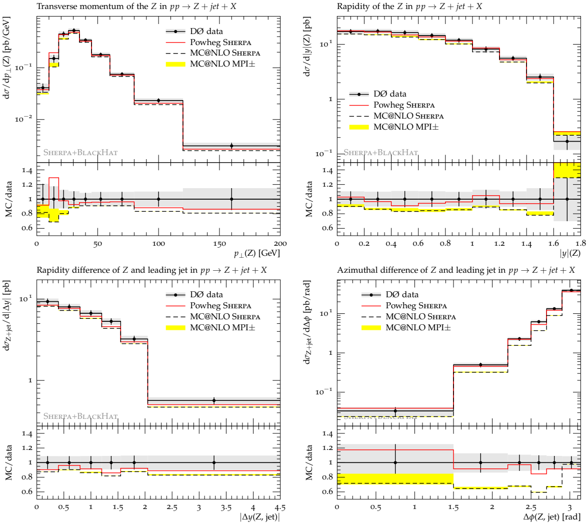
http://sherpa.hepforge.org/trac/wiki/SherpaDownloads/Sherpa-1.4.0

Conclusions

- NLO+PS is LO+(N)LL matching
- uncertainties studied occur in every process and are inherent to methods
  $\rightarrow gg \rightarrow h$ just presents a clean environment
- exploit freedom left at the respective level of accuracy
  $\rightarrow$ each with merrits and drawbacks
- choices constrained by adding higher order calculations
  - (N)NLL resummation
  - NNLO corrections
  - NLO$\otimes$NLO merging with $Q_{\text{cut}} < \mu_Q^2$

Thank you for your attention!

POWHEG and MC@NLO for $pp \to Z + \text{jet} + X$



POWHEG

- LC-NLO correct only
- too large emission probability calcelled by too soft MPI

MC@NLO

- $\alpha_{\text{cut}} = 0.03$
- rather large non-perturbative effects
- MPI too soft