NLO+PS matching methods and systematic uncertainties

Marek Schönherr

Institute for Particle Physics Phenomenology

DESY, 30/05/2012

arXiv:1111.1220, arXiv:1201.5882
JHEP04(2011)024, JHEP08(2011)123*

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

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

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

General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

$$\langle O\rangle^{\text{NLO}} = \int d\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B)$$

$$+ \int d\Phi_R \Big[\sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\, O(\Phi_{B_i}) - \sum_i \mathrm{D}_i^{(\mathsf{S})}(\Phi_R)\, O(\Phi_{B_i})\Big]$$

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

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit
- $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels

General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

$$\langle O\rangle^{\text{NLO}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B)$$

$$+ \int \mathrm{d}\Phi_R \Big[\sum_i \mathrm{D}_i^{(\text{A})}(\Phi_R)\; O(\Phi_{B_i}) - \sum_i \mathrm{D}_i^{(\text{S})}(\Phi_R)\, O(\Phi_{B_i})\Big]$$

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

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

- introduce second set of subtraction functions $\mathrm{D}_i^{(\text{A})}$
- $\mathrm{D}_i^{(\text{A})}$ and $\mathrm{D}_i^{(\text{S})}$ need to have same momentum maps and IR limit
- $\mathrm{D}_i^{(\text{A})}$ as resummation kernels

General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

$$\langle O\rangle^{\mathsf{NLO}} = \int \mathrm{d}\Phi_B\;\; \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\;\; O(\Phi_B)\left[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\,O(\Phi_B)\right.$$
$$\left. + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathsf{A})}(t,\mu_Q^2)\,O(\Phi_R)\right]$$
$$+ \int \mathrm{d}\Phi_R\left[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\right] O(\Phi_R) + \langle O\rangle_{\mathsf{corr}}^{(\mathsf{A})}$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit
- $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels

General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

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

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit
- $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels

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 $\rho_i \cdot \mathrm{R}$ 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
  $\rightarrow \mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R} \cdot f(p_\perp)$
  $\rightarrow$ continuous dampening of resummation kernel at large $p_\perp$

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 $\rho_i \cdot \mathrm{R}$ 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
  $\rightarrow \mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R} \cdot f(p_\perp)$
  $\rightarrow$ continuous dampening of resummation kernel at large $p_\perp$

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 $\rho_i = \mathrm{D}_i^{(\mathsf{S})} / \sum_i \mathrm{D}_i^{(\mathsf{S})}$
  $\to$ each $\rho_i \cdot \mathrm{R}$ 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 $\frac{1}{2}\, s_{\mathsf{had}}$
- 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
  $\to \mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R} \cdot f(p_\perp)$
  $\to$ continuous dampening of resummation kernel at large $p_\perp$

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 $\mu_Q^2 = t_{\mathrm{max}}$ 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

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

- $f(p_\perp)$ process dependent in general

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

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

- $f(p_\perp)$ process dependent in general

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

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

- $f(p_\perp)$ process dependent in general

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

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

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$

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
  $\to$ subtraction constrained in parton shower t needed for physical resummation
  $\to$ instructive example: use α_{cut} to explore effects Nagy PRD68(2003)094002
- integrate difference of α_{cut} and t_{max} numerically
- trivially NLO correct independent of the process without arbitrary parameter choices

MC@NLO – $D_i^{(A)} = D_i^{(S)}$ scheme

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

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$

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
  $\rightarrow$ instructive example: use α_{cut} to explore effects Nagy PRD68(2003)094002
- integrate difference of α_{cut} and t_{max} numerically
- trivially NLO correct independent of the process without arbitrary parameter choices

Full-colour parton showering

- resummation kernels $\mathrm{D}_i^{(\mathsf{A})}$ need to have correct full-colour soft-collinear limit in order for modified subtraction to work
  $\rightarrow$ conventional large-N_C shower kernels not suitable
- independent of precise defintion of $\mathrm{D}_i^{(\mathsf{A})}$ (POWHEG or MC@NLO)
- implemented algorithm to incorporate all subleading-colour dipoles in Catani-Seymour dipole shower independent of sign
  $\rightarrow$ similar to Plätzer, Sjödahl Eur.Phys.J.Plus 127(2012)26, arXiv:1201.0260

Full-colour parton showering

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

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

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

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

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

Full-colour parton showering

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

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

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

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

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

Full-colour parton showering

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

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

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

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

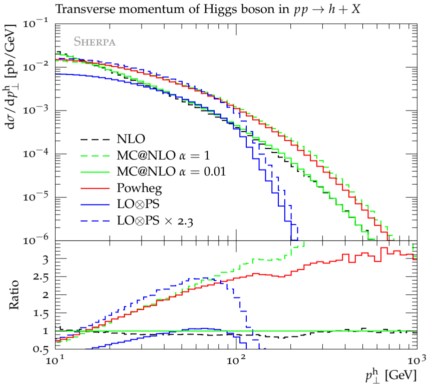
Identify $f(t)$, $g(t)$, $h(t)$:

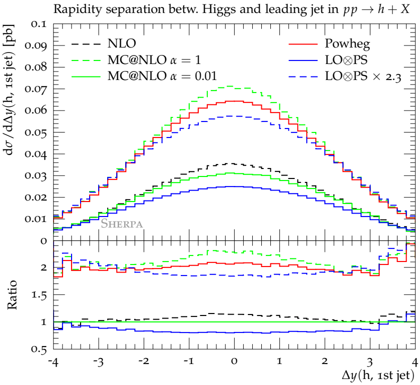
- $f(t)$ determined by MC@NLO $\Rightarrow \mathrm{D}_i^{(\mathsf{A})}$
- $h(t)$ determined by parton shower $\Rightarrow \mathrm{D}_i^{(\mathsf{PS})}$
- $g(t)$ **can be chosen freely** $\Rightarrow$ const. $\cdot f$
  constraints: $\mathrm{sign}(f) = \mathrm{sign}(g)$, $|f| \leq |g|$

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
  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
  $\Rightarrow$ 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 – $\mathrm{pp} \to \mathrm{h} + \mathrm{X}$ in gl. fusion

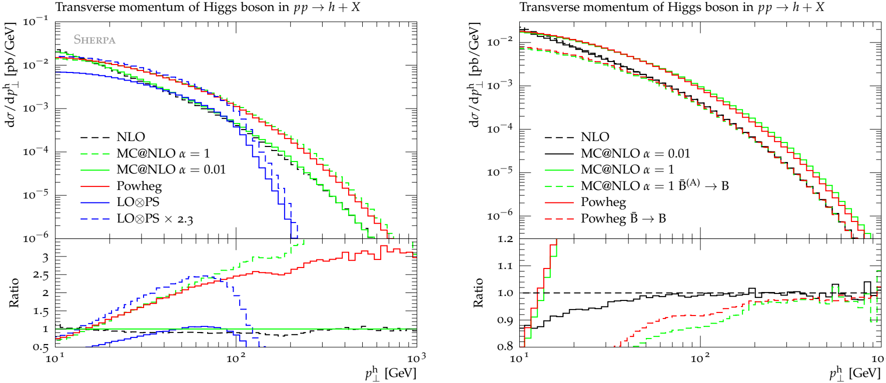




- NLO K-factor distributed over phase space filled by $\mathbb{S}$-events
- Powheg resums up to scale $\frac{1}{2}\sqrt{s_\mathrm{had}}$

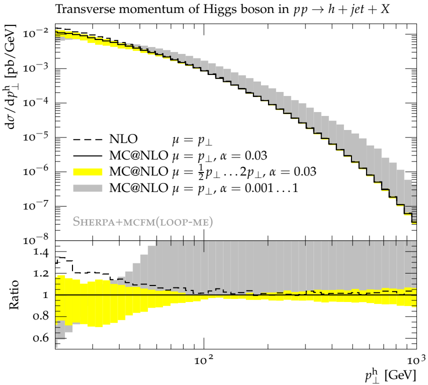
  → generates ~10% Sudakov suppression at m_h,
  as does Mc@Nlo when resumming up to $\frac{1}{2}\sqrt{s_\mathrm{had}}$
- Mc@Nlo w. restricted res. phase space follows fixed order result at large $p_\perp$

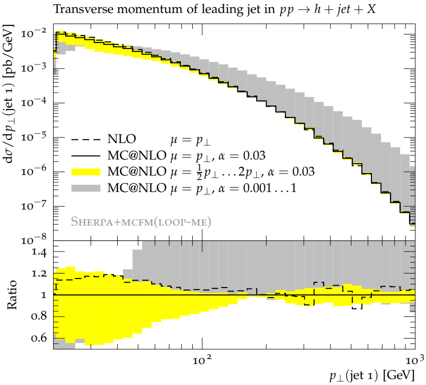
Results – $pp \to h + X$ in gl. fusion



- NLO K-factor distributed over phase space filled by $\mathbb{S}$-events
- POWHEG resums up to scale $\frac{1}{2}\sqrt{s_{\text{had}}}$
  $\to$ generates ~10% Sudakov suppression at m_h,
  as does MC@NLO when resumming up to $\frac{1}{2}\sqrt{s_{\text{had}}}$
- MC@NLO w. restricted res. phase space follows fixed order result at large $p_\perp$

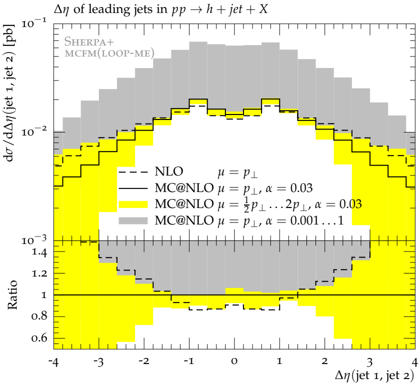
Results – $\mathrm{pp} \to \mathrm{h} + \textbf{jet} + \mathrm{X}$ production in gl. fusion

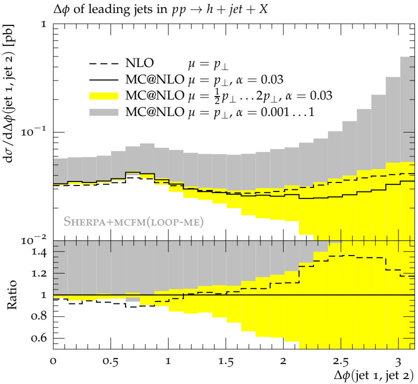




- increased parton multiplicity worsens problems
- large dependence on exponentiated phase space
- unphysical results for $\mu_Q^2 \to \frac{1}{4}\, s_{\mathrm{had}}$

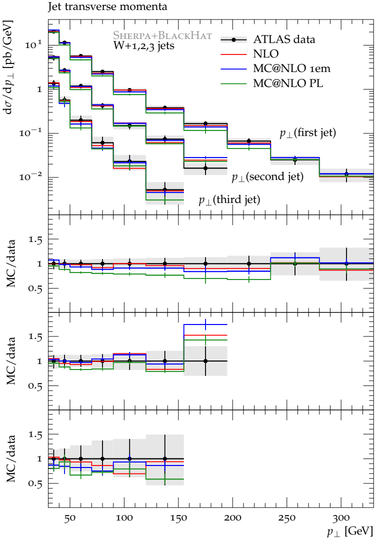
Results – $\mathrm{pp} \to \mathrm{h} + \mathbf{jet} + \mathrm{X}$ production in gl. fusion





- increased parton multiplicity worsens problems
- large dependence on exponentiated phase space
- unphysical results for $\mu_Q^2 \to \frac{1}{4}\, s_{\text{had}}$

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



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

SH, FK, MS, FS arXiv:1201.5882

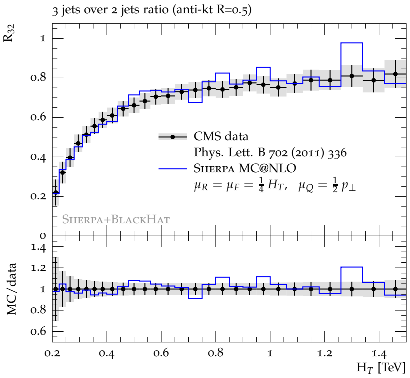
- complexity not a problem
- speed limited by the virtual amplitude in $W + 3$jet
- scales:

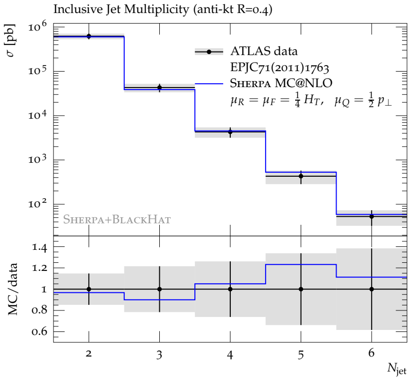
$$\mu_R = \mu_F = \tfrac{1}{2}\,\hat{H}_T'$$

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

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

Results – pp → jet jet + X (preliminary)





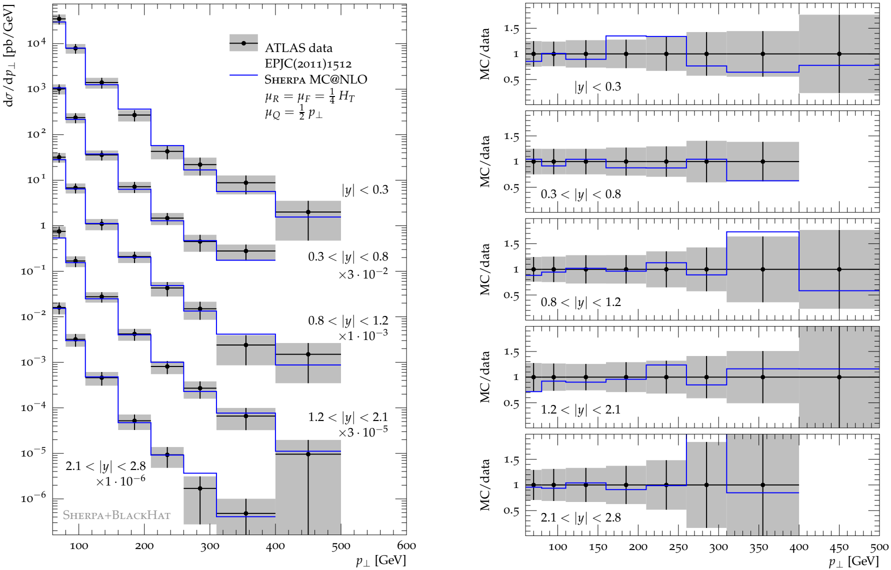
- scales:

$$\mu_R = \mu_F = \frac{1}{4} H_T = \frac{1}{2} p_\perp \qquad \mu_R^{\text{exp}} = \min\{p_\perp, \mu_R\}$$

$$\mu_Q^2 = \frac{1}{2} p_\perp$$

Results – pp → jet jet + X (preliminary)

Inclusive jet transverse momenta in different rapidity ranges



Associated uncertainties

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 $\mu_Q = \mathbf{k}_\perp^{\text{max}}$
- renormalisation scale $\mu_R = m_h$, $\mu_R^{\text{exp}} = \min\{p_\perp, \mu_R\} \xrightarrow{p_\perp \to \infty} \mu_R$
  ($\mu_R^{\text{exp}} = \sqrt{\frac{1}{1/p_\perp^2 + 1/\mu_R^2}}$ gives similar results)
- vary resummation scale $\mu_Q = \mathbf{k}_\perp^{\text{max}}$, i.e. starting conditions of MC@NLO-PS
- 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

Associated uncertainties

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 $\mu_Q = \mathbf{k}_\perp^{\text{max}}$
- renormalisation scale $\mu_R = m_h$, $\mu_R^{\text{exp}} = \min\{p_\perp, \mu_R\} \xrightarrow{p_\perp \to \infty} \mu_R$
  ($\mu_R^{\text{exp}} = \sqrt{\frac{1}{1/p_\perp^2 + 1/\mu_R^2}}$ gives similar results)
- vary resummation scale $\mu_Q = \mathbf{k}_\perp^{\text{max}}$, i.e. starting conditions of MC@NLO-PS
- 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

Associated uncertainties

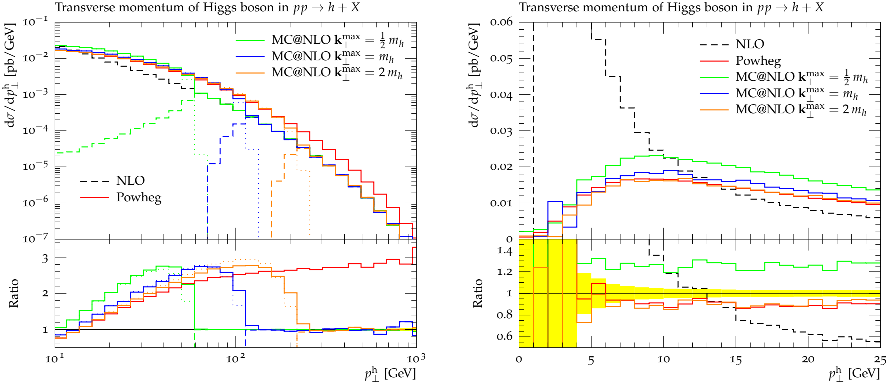
Assessment of uncertainties

- 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 $\mu_Q = \mathbf{k}_\perp^{\text{max}}$
- renormalisation scale $\mu_R = m_h$, $\mu_R^{\text{exp}} = \min\{p_\perp, \mu_R\} \xrightarrow{p_\perp \to \infty} \mu_R$
  ($\mu_R^{\text{exp}} = \sqrt{\frac{1}{1/p_\perp^2 + 1/\mu_R^2}}$ gives similar results)
- vary resummation scale $\mu_Q = \mathbf{k}_\perp^{\text{max}}$, i.e. starting conditions of MC@NLO-PS
- 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

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

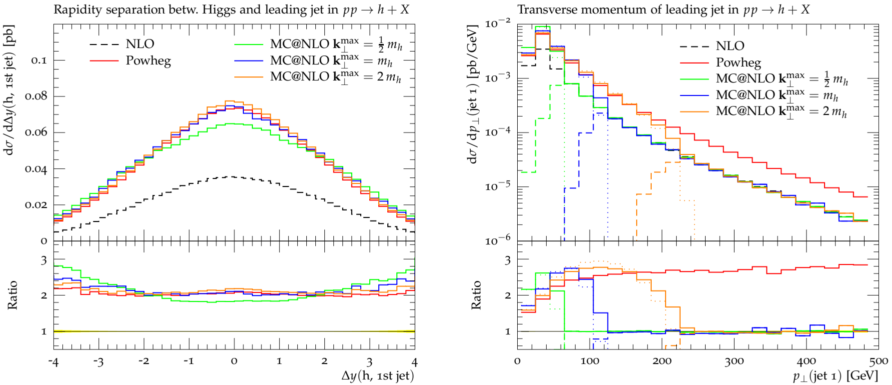
traditional MC@NLO and POWHEG choices of splitting kernels



- large uncertainties when varying $\mathbf{k}_\perp^{\text{max}}$
- 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 – $\mathrm{D}^{(\mathbf{A})}/\mathrm{B}$

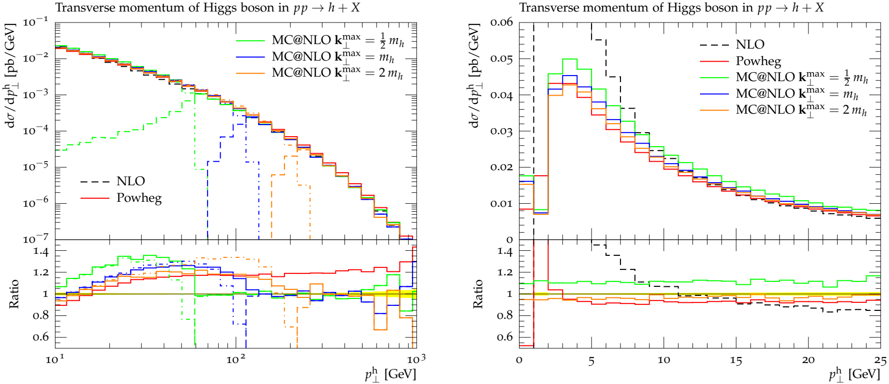
traditional MC@NLO and POWHEG choices of splitting kernels



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

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

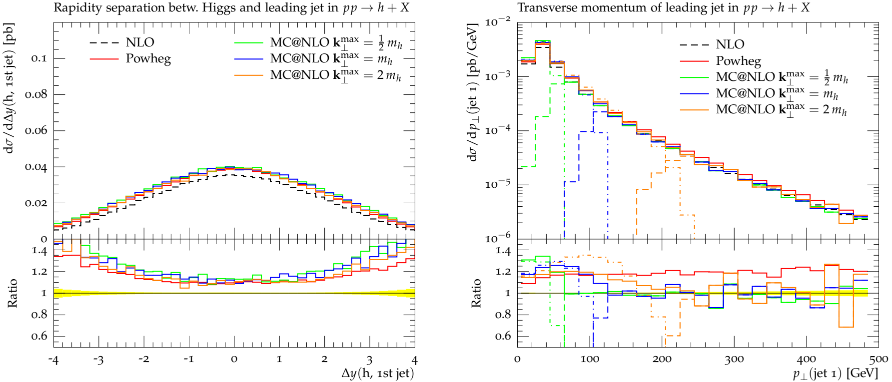
here: change splitting kernels $\mathrm{K} \longrightarrow (1 + \alpha_s \cdot \text{const.})\,\mathrm{K}$



- 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

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

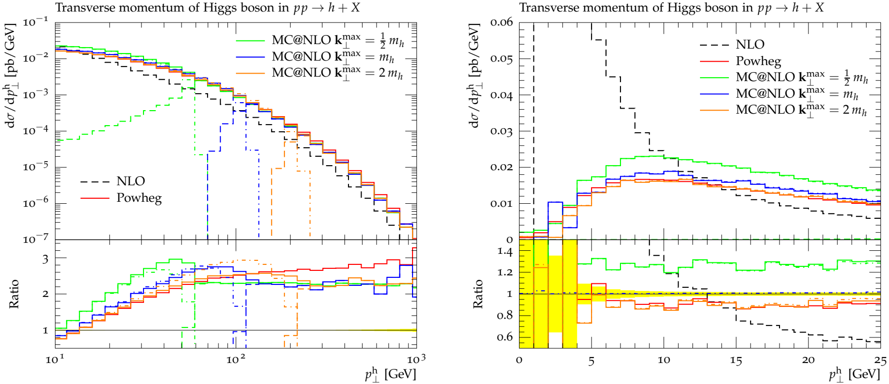
here: change splitting kernels $\mathrm{K} \longrightarrow (1 + \alpha_s \cdot \text{const.})\,\mathrm{K}$



- 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

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

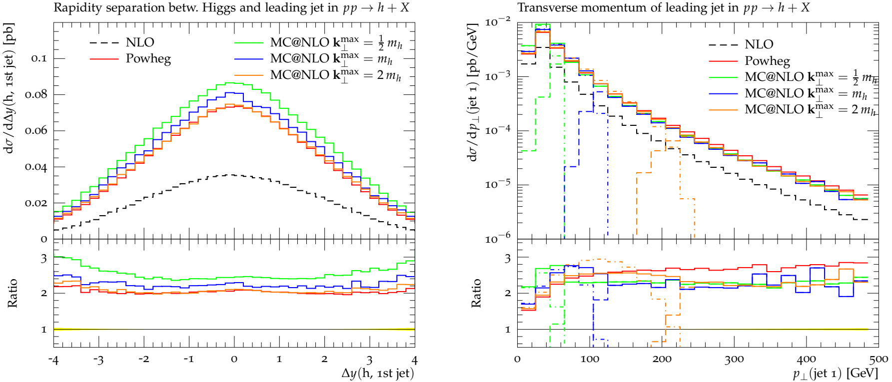
here: modify $\mathbb{H}$-term with arbitrary higher order corrections $\mathbb{H} \to \frac{\bar{\mathrm{B}}^{(\mathrm{A})}}{\mathrm{B}}\,\mathbb{H}$



- 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 – $\bar{\mathrm{B}}^{(\mathsf{A})}/\mathrm{B}\cdot\mathbb{H}$

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

Conclusions

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

Conclusions

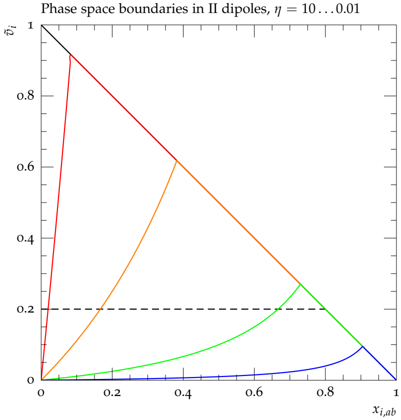
- MC@NLO in $D_i^{(A)} = D_i^{(S)}$ scheme with resummation phase space restriction in α_{cut} included in release SHERPA-1.4.0
- MC@NLO in $D_i^{(A)} = D_i^{(S)}$ scheme with resummation phase space restriction in $\mathbf{k}_\perp^{\text{max}}$ in upcoming release SHERPA-1.4.1
  $\rightarrow$ first NLO+PS implementation to study dependence on resummation scale

http://www.sherpa-mc.de

- new Minimum Bias model (Khoze, Martin, Ryskin) also included
- tune will be available with upcoming SHERPA-1.4.1

Thank you for your attention!

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



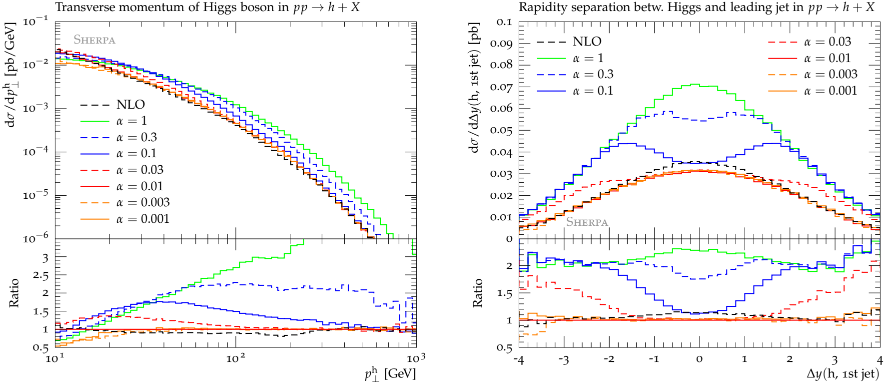
Real emission phase space

$$\tilde{v}_i = \frac{p_a \cdot k}{p_a \cdot p_b} \qquad x_{i,ab} = 1 - \frac{(p_a + p_b) \cdot k}{p_a \cdot p_b}$$

- restriction in α permits very hard ($x_{i,ab} \to 0$), not too collinear radiation at larger $\tilde{v}_i$
- restriction in $\mathbf{k}_\perp^2 = Q^2\, \tilde{v}_i\, \frac{1-x_{i,ab}}{x_{i,ab}}$ permits only very soft ($x_{i,ab} \to 1$) radiation at larger $\tilde{v}_i$

Results – $pp \to h + X$ in gl. fusion

limit phase space for exponentiation by α_{cut}

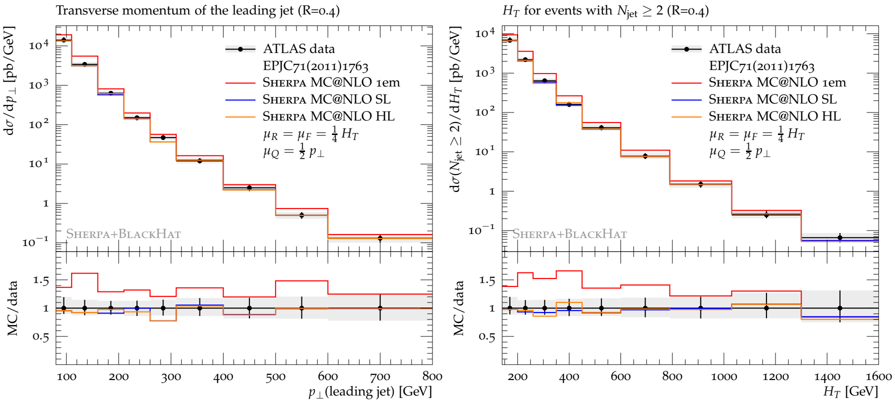


however, α_{cut} no sensible parameter w.r.t. exponentiation region

$\rightarrow$ restricts emissions to small opening angle wrt. beam

$\rightarrow$ bias towards hard collinear emissions

Different levels of MC@NLO simulation



1em MC@NLO emission only

SL MC@NLO and parton shower

HL MC@NLO, parton shower, hadronisation and multiple interactions