

(W/h+) jet production at NLO matched with a parton shower

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arXiv:1111.1220 [hep-ph], arXiv:1201.5882 [hep-ph]



LoopFest XI

Pittsburgh, 12/5/2012



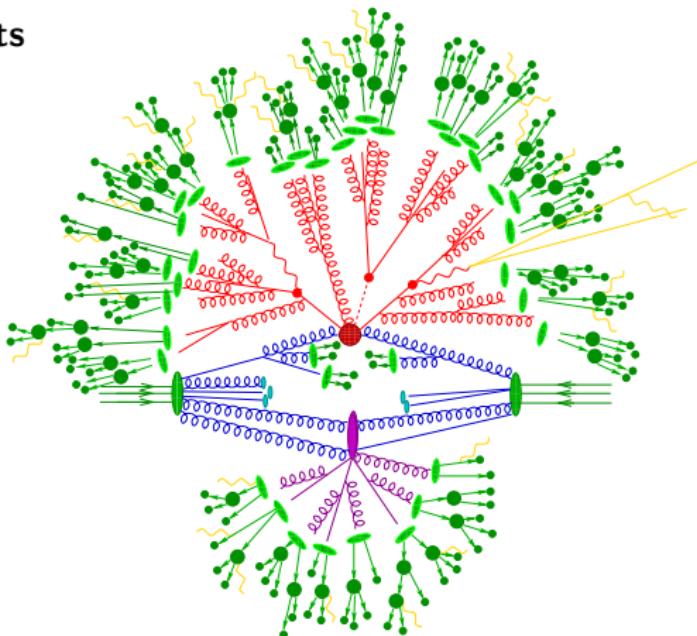
Event generation for the LHC



Structure of simulated LHC events

- Hard interaction
- QCD evolution
- Secondary hard interactions
- Jet fragmentation
- Hadron decays
- Higher-order QED corrections

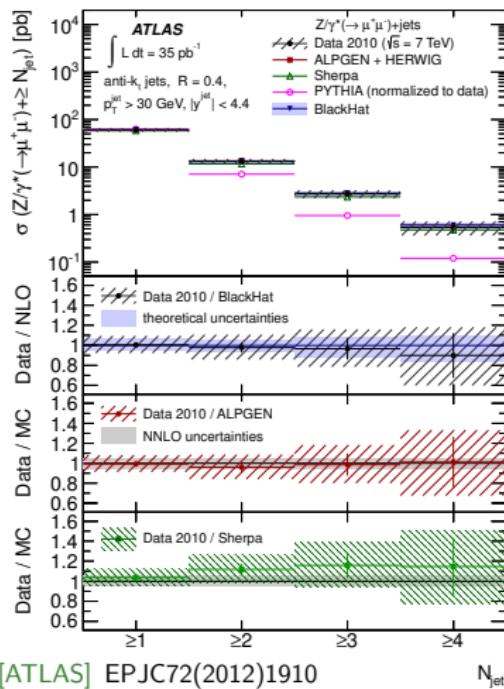
Much recent progress on hard QCD
Benefits from “NLO (r)evolution”



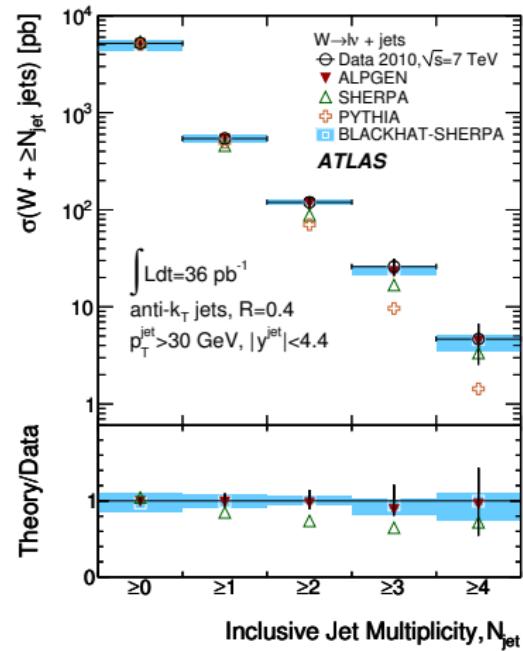
The quest for precision



Often good description of data with NLO, but not so good with LO+PS
Uncertainties should be reduced by matching PS to NLO instead of LO



[ATLAS] EPJC72(2012)1910



[ATLAS] arXiv:1201.1276 [hep-ex]

Basics of POWHEG



Assume parton shower (PS) with splitting kernels $K \rightarrow$
Expectation value of observable O to $\mathcal{O}(\alpha_s)$ in parton-shower approximation:

$$\langle O \rangle = \sum \int d\Phi_B B \left[\Delta^{(PS)}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B}^{ij,k} K_{ij,k} \Delta^{(PS)}(t(\Phi_{R|B})) O(\Phi_R) \right]$$

where $\Delta^{(PS)}(t) = \exp \left\{ - \int_t d\Phi_{R|B}^{ij,k} K_{ij,k} \right\}$

Make this NLO-correct:

- Radiation pattern of R from ME correction ($D_{ij,k}^{(S)} \rightarrow$ subtraction term)
 $w = R_{ij,k} / B K_{ij,k}$, where $R_{ij,k} = \rho_{ij,k} R$ and $\rho_{ij,k} = D_{ij,k}^{(S)} / \sum D_{mn,l}^{(S)}$
- Replace “seed cross section” by ($I^{(S)} \rightarrow$ integrated subtraction terms)

$$\bar{B} = B + \tilde{V} + I^{(S)} + \sum \int d\Phi_{R|B}^{ij,k} \left[R_{ij,k} - D_{ij,k}^{(S)} \right]$$

Combine ME-correction and local K-factor \rightarrow POWHEG

[Nason] JHEP11(2004)040 [Frixione, Nason, Oleari] JHEP11(2007)070

$$\langle O \rangle = \sum \int d\Phi_B \bar{B} \left[\bar{\Delta}^{(R/B)}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B}^{ij,k} \frac{R_{ij,k}}{B} \bar{\Delta}^{(R/B)}(t(\Phi_{R|B})) O(\Phi_R) \right]$$



Aimed for:

- Automated, process-independent implementation
- Use of existing code for Catani-Seymour dipole subtraction
[Gleisberg,Krauss] EPJC53(2008)501
- Use of existing dipole-like parton shower
[Krauss,Schumann] JHEP03(2008)038, [Schumann,SH,FS] PRD81(2010)034026

Lessons learned in next-to-simplest scenario ($W/Z+1\text{-jet}$):

- Using dipole subtraction to compute \bar{B} is harder than expected numerical instabilities due to cuts on underlying Born process, which have to be applied separately for every dipole term
- Parton shower would have to be “dipole-term corrected” first NLO-accuracy depends crucially on exact same dipole terms in both the subtracted matrix element and the parton shower

Could have changed to different subtraction scheme,
but decided to stick to Catani-Seymour method

→ MC@NLO came to the rescue

Basics of MC@NLO



Parton-shower perspective → only “soft” part $D_{ij,k}^{(A)}$ of $R_{ij,k}$ exponentiated

Defines MC@NLO algorithm [Frixione,Webber] JHEP06(2002)029

$$\langle O \rangle = \sum \int d\Phi_B \bar{B}^{(A)} \left[\bar{\Delta}^{(A)}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B}^{ij,k} \frac{D_{ij,k}^{(A)}}{B} \bar{\Delta}^{(A)}(t(\Phi_{R|B})) O(\Phi_R) \right] \\ + \sum \int d\Phi_R \left[R_{ij,k} - D_{ij,k}^{(A)} \right] O(\Phi_R)$$

Seed cross sections and Sudakov form factors change accordingly:

$$\bar{B}^{(A)} = B + \tilde{V} + I^{(S)} + \sum \int d\Phi_{R|B}^{ij,k} \left[D_{ij,k}^{(A)} - D_{ij,k}^{(S)} \right]$$

Note that $\bar{\Delta}^{(A)} \neq \Delta^{(PS)}$, as soft-gluon limit not exact in PS

Plain POWHEG recovered as special case of MC@NLO ($D_{ij,k}^{(A)} \rightarrow R_{ij,k}$)

Substantial simplification if $D_{ij,k}^{(A)} \rightarrow D_{ij,k}^{(S)}$ ⇒ integral in $\bar{B}^{(A)}$ can be dropped

Note:

- Varying $D_{ij,k}^{(A)}$ changes properties of resummation
[Alioli,Nason,Oleari,Re] JHEP04(2009)002, [SH,FK,MS,FS] arXiv:1111.1220
- $D_{ij,k}^{(A)}$ may differ from $D_{ij,k}^{(S)}$ or $R_{ij,k}$ by simple cuts
Used to implement resummation scale Q^2 (upper scale of PS evolution)

Implementing MC@NLO in SHERPA



Choose $D^{(A)} = D^{(S)}$ up to phase-space cuts \rightarrow

Need to deal with potentially negative branching probability e.g. subleading color

Use modified Sudakov veto algorithm to correct [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

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

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

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

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

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

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



Initial expectations for POWHEG finally met by Mc@NLO:

- Easy to automate and process-independent
Only finite piece V of virtual correction to be supplied
- Based on Catani-Seymour dipole subtraction
- Using existing dipole-like parton shower

Lessons learned in next-to-simplest scenario ($W/Z+1\text{-jet}$):

- Computing $\bar{B}^{(A)}$ with dipole subtraction is simpler than we thought
no numerical instabilities as we do not project R onto $R_{ij,k}$ for $\bar{B}^{(A)}$
- Parton showers are easy to correct with matrix-elements
Ratio $D_{ij,k}^{(A)}/B$ always non-zero and close to parton-shower result
Deviations in soft-gluon regime limited by shower cutoff

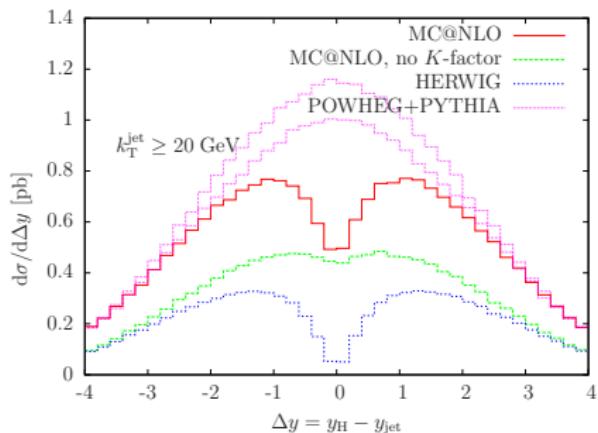
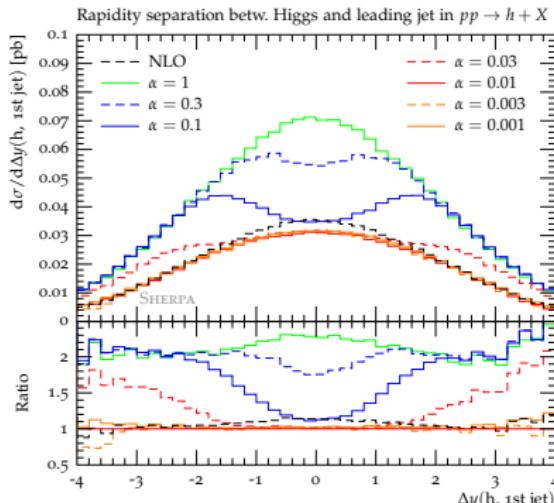
Mc@NLO inherits excellent phase-space mapping from CS dipole terms
Corrections to the parton shower fast and easy to evaluate

Differences between POWHEG and Mc@NLO



Can set resummation scale Q^2 effectively using α_{cut} [Nagy] PRD68(2003)094002

Sub-optimal choice, but provides a handle for checking scale variations



[Nason,Webber] arXiv:1202.1251 [hep-ph]

Essential features of POWHEG analysis JHEP04(2009)002 reproduced:

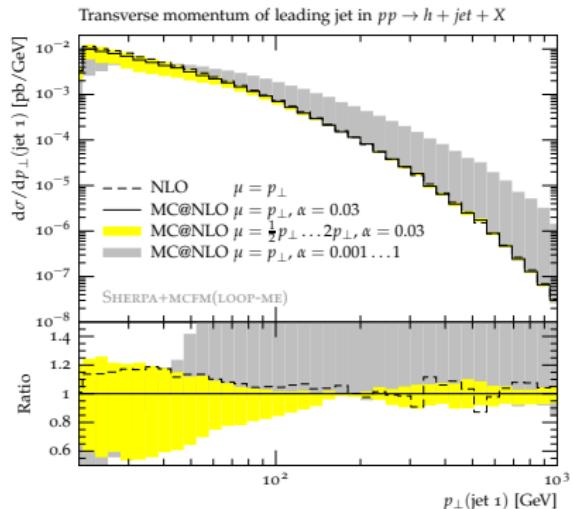
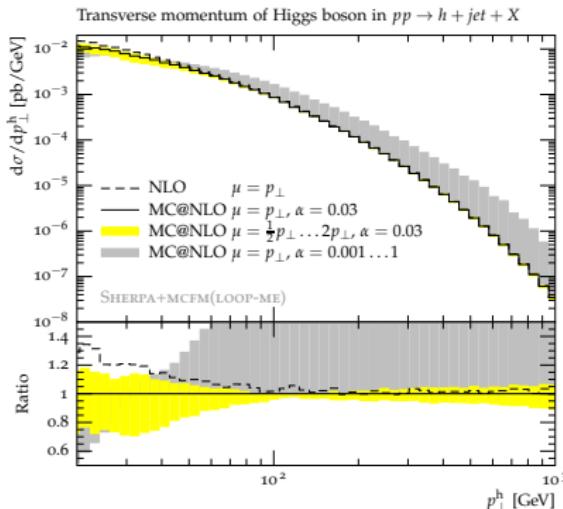
- Hardness of POWHEG p_T spectra for $\alpha_{\text{cut}} \rightarrow 1$
- Dip in Mc@NLO Δy -spectra for intermediate α_{cut}

Need to define $D^{(A)}$ (especially Q^2) properly

Differences between POWHEG and Mc@NLO



Increased parton multiplicity worsens problems → exemplified in $pp \rightarrow h + j$



Lower edge of gray band → Mc@NLO
 Upper edge → plain POWHEG ($R^f = 0$) } Both formally NLO correct!

→ Q^2 should really be $\mathcal{O}(m_{\perp,h})$ to avoid large spurious logs

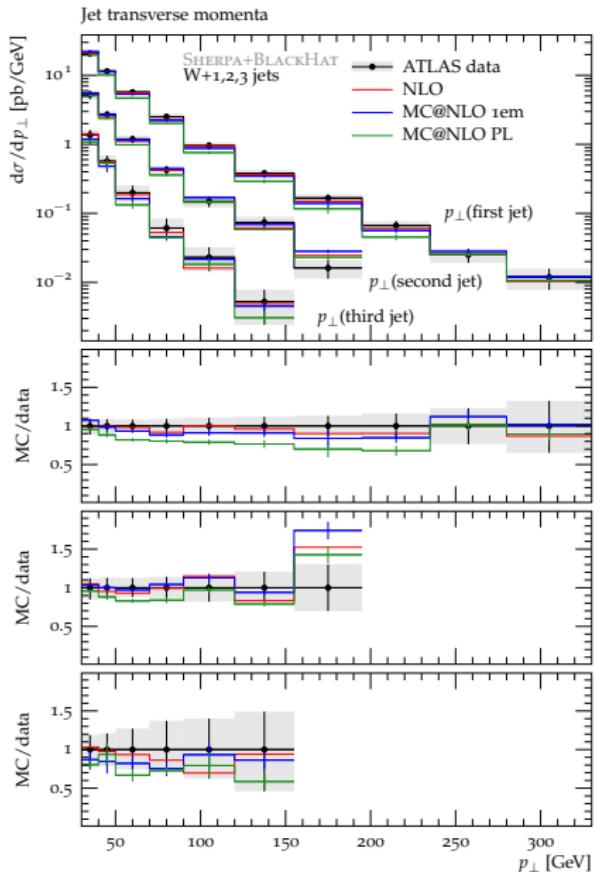
[Banfi, Salam, Zanderighi] JHEP08(2004)062, [Bozzi, Catani, DeFlorian, Grazzini] NPB737(2006)73



**Tested framework in $W+n$ jets,
where $n \leq 3$ at present**

[SH,FK,MS,FS] arXiv:1201.5882

Fully automated for light partons
Finite part of virtual correction
needs to be provided only

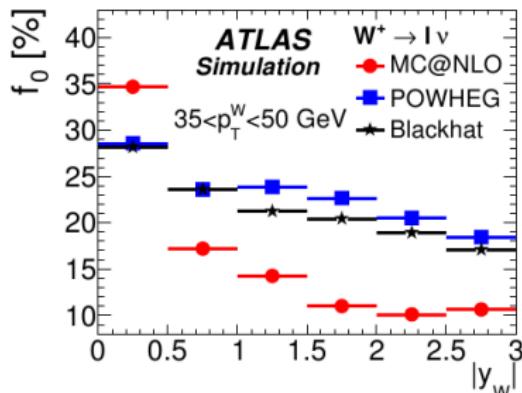
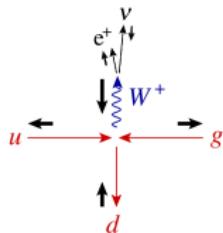




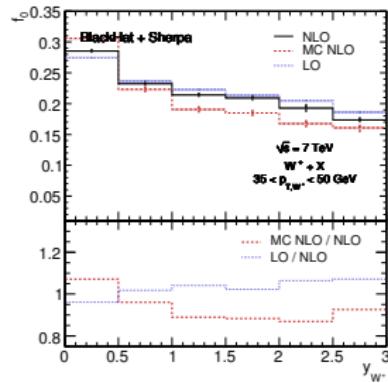
Appropriate predictions, please!

Example: $\text{Mc}@\text{NLO} \leftrightarrow \text{POWHEG}$
in W -polarization measurement

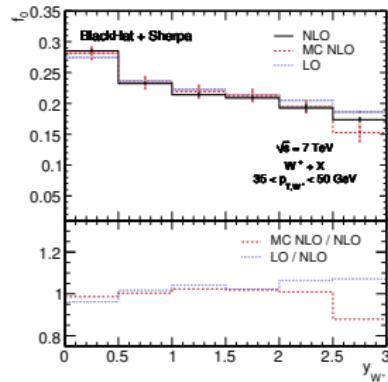
[ATLAS] arXiv:1203.2165



$W+0j$ Mc@NLO X



$W+1j$ Mc@NLO ✓





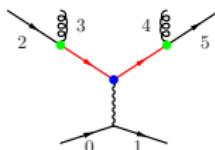
For arbitrary definitions of Q^2 need to determine $\int d\Phi_{R|B}^{ij,k} \left[D_{ij,k}^{(A)} - D_{ij,k}^{(S)} \right]$

Same strategy as in POWHEG implementation [SH,FK,MS,FS] JHEP04(2010)024

Step I: Recycle Born phase space

Standard phase-space generator [Byckling,Kajantie] NPB9(1969)568

VEGAS-refinement [Lepage] JCP27(1978)192 & multi-channel [Kleiss,Pittau] CPC83(1994)141



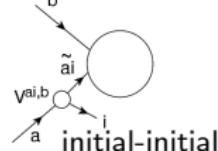
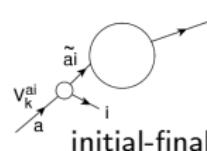
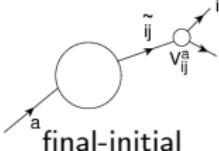
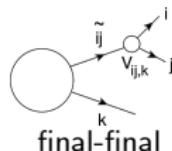
\leftrightarrow

$$D_{iso}(23,45) \otimes P_0(23) \otimes P_0(45) \\ \otimes D_{iso}(2,3) \otimes D_{iso}(4,5)$$

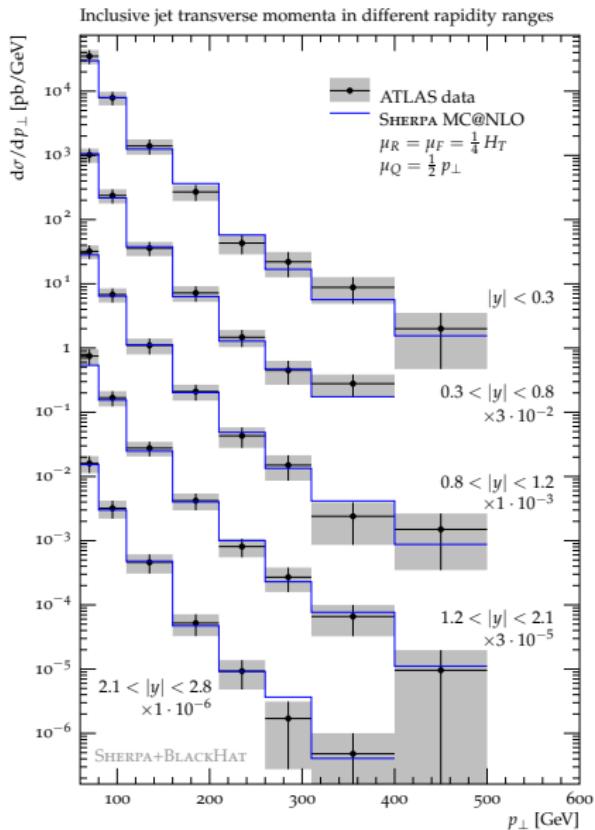
Step II: Generate real-emission point

Produce splitting with kinematics according to CS dipole terms

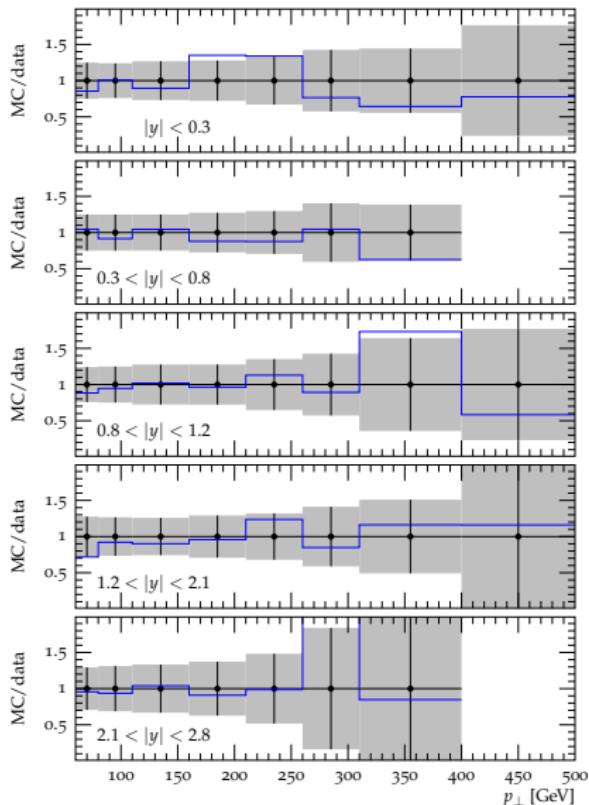
[Catani,Seymour] NPB485(1997)291, [Catani,Dittmaier,Seymour,Trocsanyi] NPB627(2002)189



Mc@NLO at work



Inclusive jet cross sections at 7 TeV



Exp data: [ATLAS] EPJC71(2011)1512

Summary

- Mc@NLO automated for light partons
- No conceptual or practical obstacles for high-multiplicity processes
- Independent check of POWHEG \leftrightarrow Mc@NLO discrepancies
- Baseline for ME+PS merging at NLO

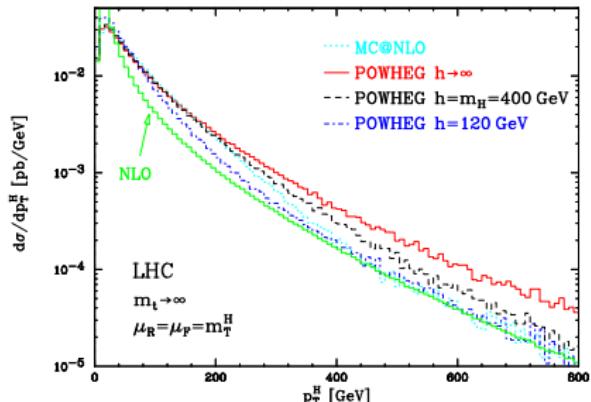
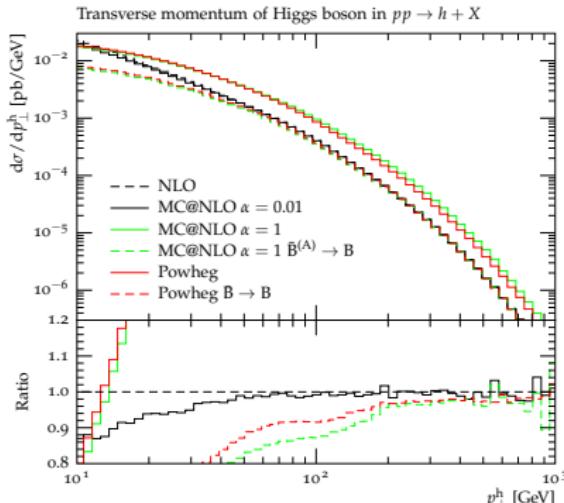


Differences between POWHEG and Mc@NLO



POWHEG \leftrightarrow Mc@NLO analyzed for $gg \rightarrow h$ in JHEP04(2009)002

Differences attributed to shift from B to \bar{B} . Check this carefully:



[Nason,Webber] arXiv:1202.1251 [hep-ph]

Difference $\text{POWHEG}(\bar{B} \rightarrow B) \leftrightarrow \text{NLO}$ still $\geq 10\%$ at $p_{T,h} \sim m_h$

Same for $\text{Mc@NLO}(\bar{B}^{(A)} \rightarrow B)$ if $\alpha \rightarrow 1$, but *no difference* if $\alpha \ll 1$

True discrepancy *not from* $B \rightarrow \bar{B}$, **but from $Q^2 \gg m_h$!**

Was hinted at in JHEP04(2009)002 \rightarrow suppression factor $h/(h + p_\perp)$ proposed