W+jets as a background to top physics

The quest for many jets

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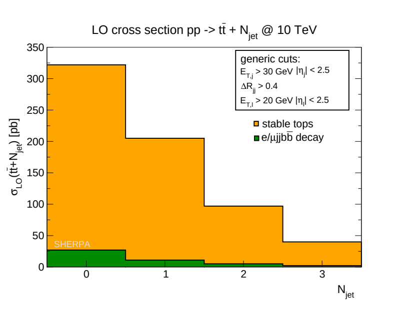
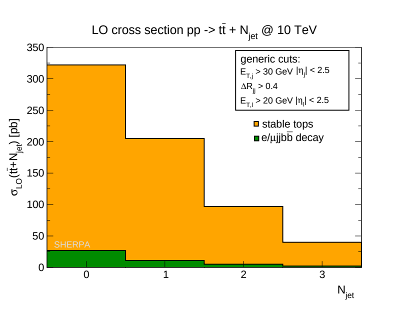
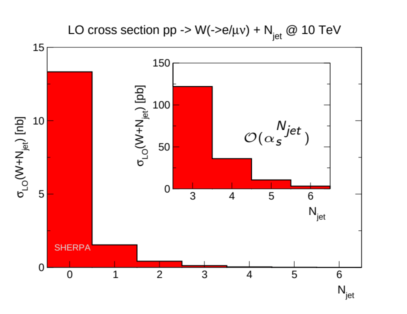
W+jets as a background to top physics: $l^{\pm} + \not{E}_T + \#\text{jets}$

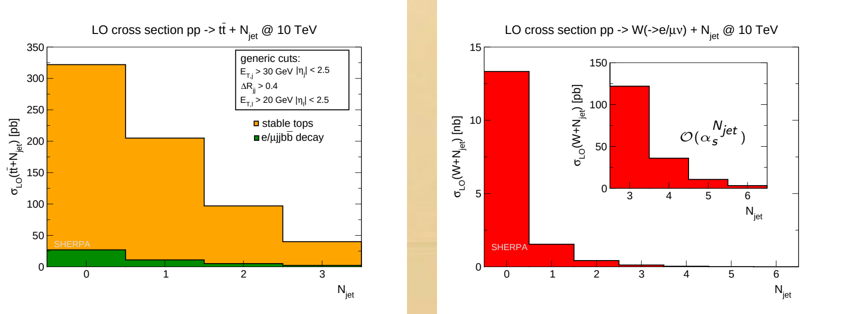


W+jets as a background to top physics: $l^\pm + \not{E}_T + \#$jets





W+jets as a background to top physics: $l^{\pm} + \not{E}_T + \#jets$



- need for higher-order calculations: high jet multiplicities & heavy flavours
  - $\Rightarrow$ stabilized total cross-sections
  - $\Rightarrow$ reliable differential distributions [partonic]
- improved Monte-Carlo simulations: parton showers matched to fixed order
  - $\Rightarrow$ account for high-p_T emissions
  - $\Rightarrow$ realistic jet profiles incl. hadronisation & UE

Outline

- **Fixed-Order calculations**
  - $W + 3$jets @ NLO
  - Wb @ NLO
- **Monte Carlo generators: Showers matched to Fixed Order**
  - Truncated Shower concept
  - inherent merging systematics

Fixed-Order calculations

NLO QCD calculations: Overview

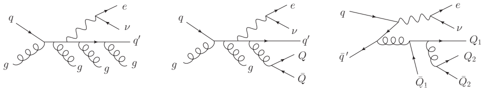
	final state	$m_b \neq 0$	groups
	Wj	no	Campbell, Ellis '02 [1]
	Wjj	no	Campbell, Ellis '02 [1]
NEW $\Rightarrow$	$Wjjj$	no	Berger et al. '09 & Ellis et al. '09
	Zj	no	Campbell, Ellis '02 [1]
	Zjj	no	Campbell, Ellis '02 [1]
NEW $\Rightarrow$	$Zjjj$	no	Berger et al. '10
NEW $\Rightarrow$	Wb	yes	Cordero et al. '09
	Wbj	no	Campbell et al. '07
	$Wb\bar{b}$	no	Campbell, Ellis '02 [1]
	$Wb\bar{b}$	yes	Cordero, Reina, Wackeroth '07
	Zb	no	Campbell et al. '03 [1]
	Zbj	no	Campbell et al.'06 [1]
	$Zb\bar{b}$	no	Campbell, Ellis '00 [1]
	$Zb\bar{b}$	yes	Cordero, Reina, Wackeroth '08

[1] available in MCFM

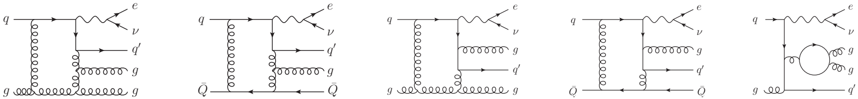
NLO QCD calculations: $W + 3$jets

$W + 3$j @ NLO: The challenge

- real emission corrections:



- one-loop corrections:



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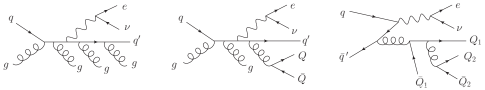

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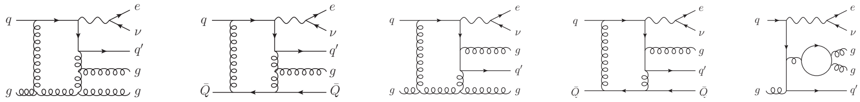


recently calculated by two groups $[m_q = 0]$

- ROCKET+MCFM: Ellis, Melnikov & Zanderighi [Phys. Rev. D **80** (2009) 094002]
  - generalized D-dim unitarity for one-loop amplitudes [JHEP **0901** (2009) 012]
  - leading colour approximation
- BLACKHAT+SHERPA: Berger et al. [Phys. Rev. Lett. **102** (2009) 222001, Phys. Rev. D **80** (2009) 074036]
  - on-shell methods for one-loop amplitudes [arXiv:0808.0941]
  - all subprocesses, full colour

⇒ $Z/\gamma^* + 3$j completed [arXiv:1004.1659]

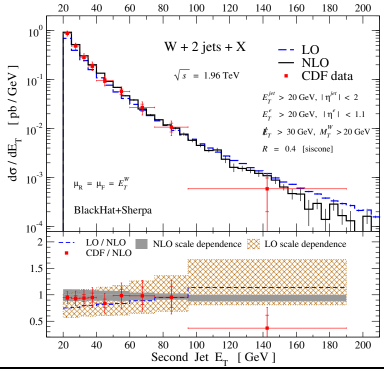
⇒ currently working on $W+4$jets [arXiv:1005.3728]

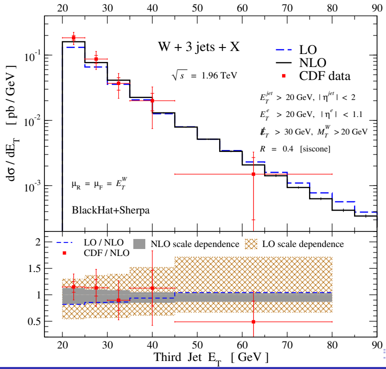
NLO QCD calculations: $W + 3$jets

BLACKHAT+SHERPA: Tevatron results [Phys. Rev. D **80** (2009) 074036]

- consider $W \to e\nu$ and SISCONE jets with $E_T^{n\text{th-jet}} > 25$ GeV & R=0.4

# of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

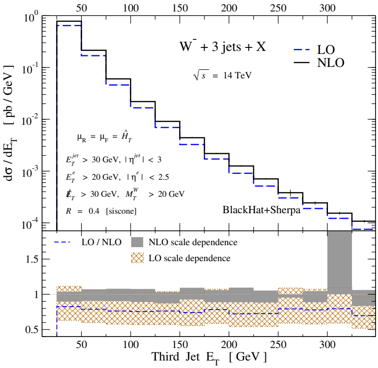


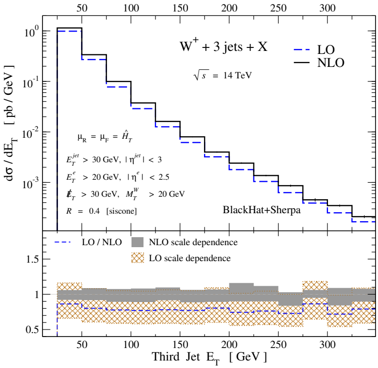


BlackHat+Sherpa: LHC predictions [Phys. Rev. D **80** (2009) 074036]

- consider SISCone jets with $E_T^{n\text{th-jet}} > 30$ GeV & R=0.4

# of jets	W^- – LO	W^- – NLO	W^+ – LO	W^+ – NLO
1	$343.29(0.18)^{+15.65}_{-15.43}$	$456.60(1.43)^{+16.61}_{-10.10}$	$469.37(0.32)^{+21.86}_{-21.26}$	$615.77(2.04)^{+23.76}_{-14.39}$
2	$99.78(0.09)^{+20.81}_{-15.60}$	$122.71(0.92)^{+5.88}_{-7.41}$	$143.91(0.18)^{+29.92}_{-22.43}$	$174.28(0.48)^{+6.56}_{-10.37}$
3	$22.28(0.04)^{+7.80}_{-5.34}$	$27.52(0.14)^{+1.34}_{-2.81}$	$34.75(0.05)^{+12.06}_{-8.31}$	$41.47(0.27)^{+2.81}_{-3.50}$

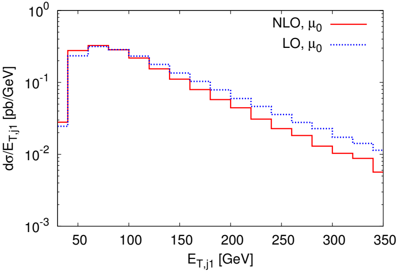


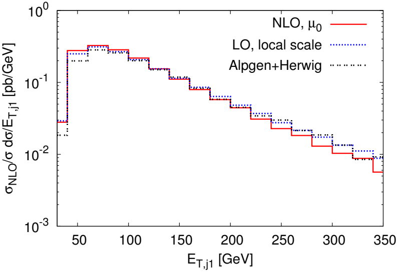


NLO QCD calculations: $W + 3$jets

ROCKET+MCFM: scale setting discussion [Melnikov, Zanderighi Phys. Rev. D **81** (2010) 074025]

- consider $W^+ + \geq 3j$ @ 10 TeV LHC





- $\mu_0 = \sqrt{p_{T,W}^2 + m_W^2} \rightsquigarrow \sigma^{LO}_{W^+ + \geq 3j} = 37.6$ pb vs. $\sigma^{NLO,aLC}_{W^+ + \geq 3j} = 34.2$ pb
- shape difference overcome when using local k_T scales for α_S in LO calc.

$\Rightarrow$ default in all ME$\oplus$PS matching schemes [see e.g. Krauss et al. Phys. Rev. D **70** (2004) 114009]

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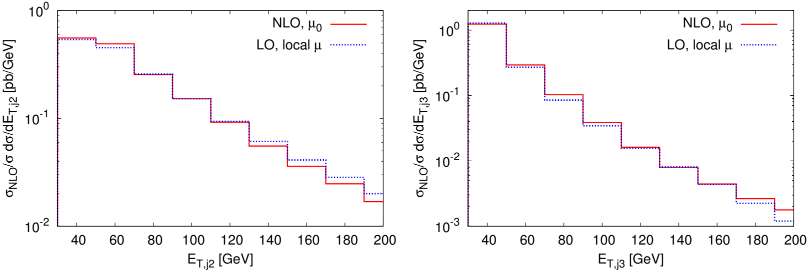

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NLO QCD calculations: Wb

Associated $Wb(b)$ production @ Tevatron: Data vs. Theory

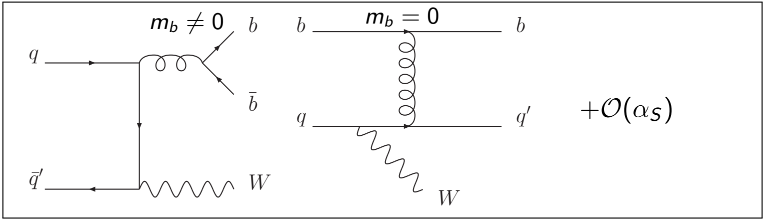
CDF measurement [Phys. Rev. Lett. **104** (2010) 131801]

$$\sigma^{CDF}_{Wb(b)}(W \to l\nu) = 2.74^{+0.50}_{-0.50}\ \mathrm{pb}$$

Fixed-Order QCD [Campbell et al. Phys. Rev. D **79** (2009) 034023 & Cordero et al. arXiv:1001.3362]

$$\sigma^{LO}_{Wb(b)}(W \to l\nu) = 0.91^{+0.29}_{-0.20}\ \mathrm{pb} \qquad \sigma^{NLO}_{Wb(b)}(W \to l\nu) = 1.22^{+0.14}_{-0.14}\ \mathrm{pb}$$

$\Rightarrow$ consistently combines 4FNS $Wb\bar{b}$ $[m_b \neq 0]$ and 5FNS Wbj $[m_b = 0]$ @ NLO



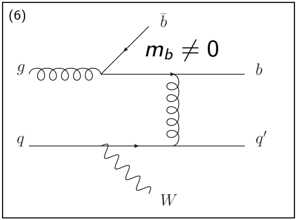
NLO QCD calculations: $Wb(b)$

$Wb(b)$ production @ Tevatron: NLO calculation [Campbell et al. Phys. Rev. D **79** (2009) 034023]

1. $q\bar{q}' \to Wb\bar{b}$ tree & one-loop $[m_b \neq 0]$
2. $q\bar{q}' \to Wb\bar{b}g$ tree level $[m_b \neq 0]$
3. $bq \to Wbq'$ tree & one-loop $[m_b = 0]$
4. $bq \to Wbq'g$ tree level $[m_b = 0]$
5. $bg \to Wbq'\bar{q}$ tree level $[m_b = 0]$
6. $gq \to Wb\bar{b}q'$ tree level $[m_b \neq 0]$

$\Rightarrow$ redefined b-PDF to avoid double counting

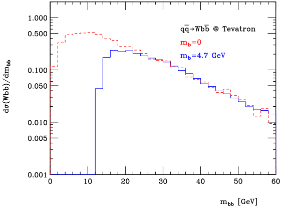
$\Rightarrow$ fully consistent 5FNS with $m_b \neq 0$



combined calculation can now account for

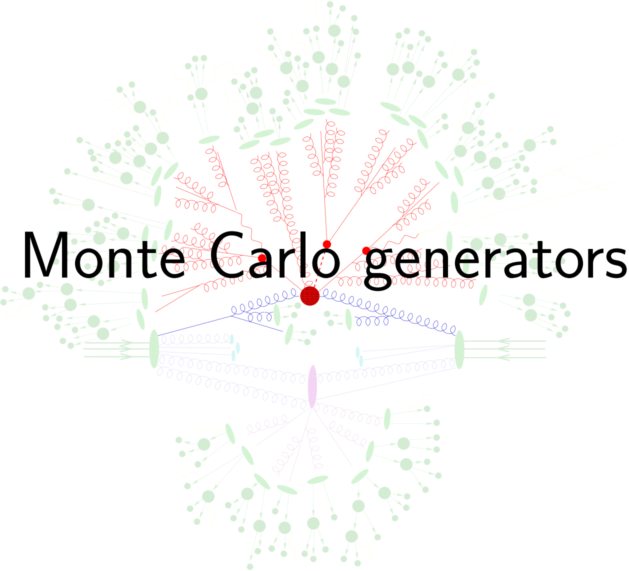
- Wb and $W(b\bar{b})$ exclusive
- Wb and Wbj inclusive
- $W(b\bar{b})$ and $W(b\bar{b})j$ inclusive

$\Rightarrow$ further insight from differential distributions



$\Rightarrow$ one b might escape detection

Monte Carlo generators



Monte Carlo Tools: Matrix Elements and Parton Showers

Parton Shower Monte Carlos [a.k.a. PYTHIA, HERWIG]

- account for intra-jet radiation (plus hadronisation, underlying event, ...)
- based on soft- & collinear factorisation
- leading-order – leading-log accuracy

ways to improve

- match parton shower to full one-loop process [MC@NLO, POWHEG]
- use tree-level matrix elements for first few emissions [CKKW, MLM]
  - ALPGEN+HERWIG/PYTHIA: original MLM [Mangano et al. JHEP **0701** (2007) 013]
  - MADGRAPH+HERWIG/PYTHIA: modified MLM [Alwall et al. Eur. Phys. J. C **53** (2008) 473]
  - SHERPA: $<$ v1.2.0 CKKW [Catani et al. '01]

    $\Rightarrow$ extensive comparison for W+jets [Alwall et al. Eur. Phys. J. C **53** (2008) 473]

    $\geq$ v1.2.0 Truncated Shower (ME$\oplus$TS) [Höche et al. JHEP **0905** (2009) 053]

ME+PS common features

- emission phase space sliced / 'jet' measure $Q_{\rm cut}$ regulates matrix elements
- attach (vetoed) shower to multi-parton matrix elements
- inclusive samples with up to $N_{\rm max}$ ME initiated jets [excl. $0, \ldots, N_{\rm max} - 1$, incl. $N_{\rm max}$]

Matrix Elements and Truncated Showers: ME⊕TS

How to attach shower to an N-parton ME?

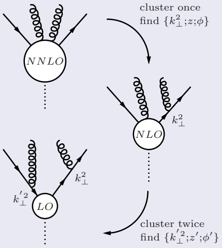
A new merging algorithm [Höche, Krauss, S., Siegert JHEP **0905** (2009) 053]

- ME legs pre-determined shower emissions determined by clustering inverse to the shower
  $\rightarrow$ **pseudo shower history for MEs**
- PS starts off a reconstructed $2 \rightarrow 2$ core can radiate gluons off "intermediate" lines
  $\rightarrow$ **Truncated Shower**
- ME branchings must be respected
  evolution-, splitting- & angular variables $\{k_\perp^2, z, \phi\}$ preserved
- veto event if shower emission above Q_{cut}
  $\rightsquigarrow$ preserves the log-accuracy of the shower

implemented in SHERPA-1.2

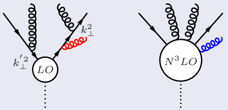
- Catani-Seymour dipole shower [S., Krauss JHEP **0803** (2008) 038]
- MEs from COMIX [Gleisberg, Höche JHEP **0812** (2008) 039]

pseudo shower history



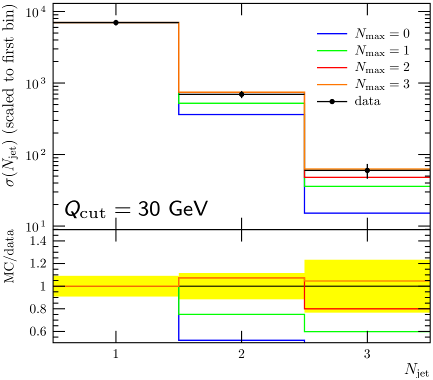
Truncated Shower

$Q < Q_{\text{cut}}$ $\qquad$ $Q > Q_{\text{cut}}$



Jet rates and -spectra improved compared to pure PS simulation
due to exact real emission ME's

Example: DY-pair production $\sigma_{\mathrm{e^+e^-+N_{jet}}}$ CDF Data: PRL **100** (2008) 102001
[SHERPA normalized to $\sigma_{\mathrm{e^+e^-+1_{jet}}}$]



ME⊕TS: Z^0+jets at Tevatron – jet spectra

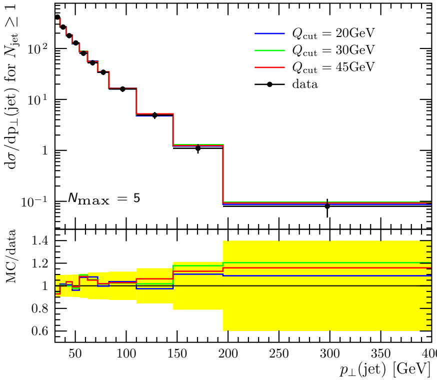
Variation of Q_{cut} should affect distributions only beyond (N)LL

But Q_{cut} must be in range where PS approximation is valid!

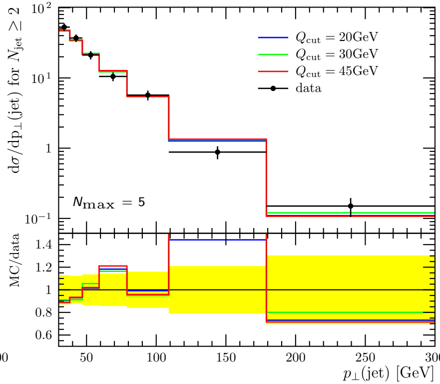
Example: All-jets p_T's in DY-pair production CDF Data: PRL **100** (2008) 102001

[SHERPA normalized to $\sigma_{e^+e^-+1_{jet}}$]

p_T(jet) for $N_{jet} \geq 1$



p_T(jet) for $N_{jet} \geq 2$



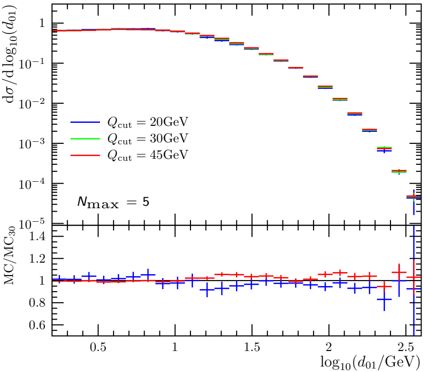
ME⊕TS: Z^0+jets at Tevatron – jet spectra

Variation of Q_{cut} should affect distributions only beyond (N)LL

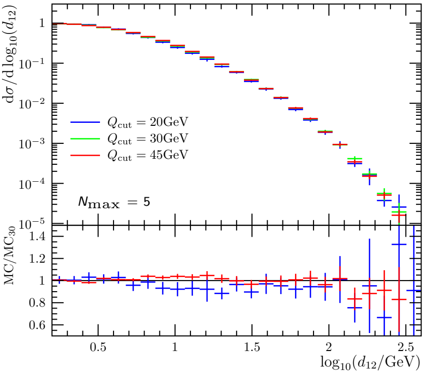
But Q_{cut} must be in range where PS approximation is valid!

Example: Differential $\mathbf{k_T}$ jet rates

1 → 0



2 → 1



⇝ **Q_{cut} variations within ±10%**

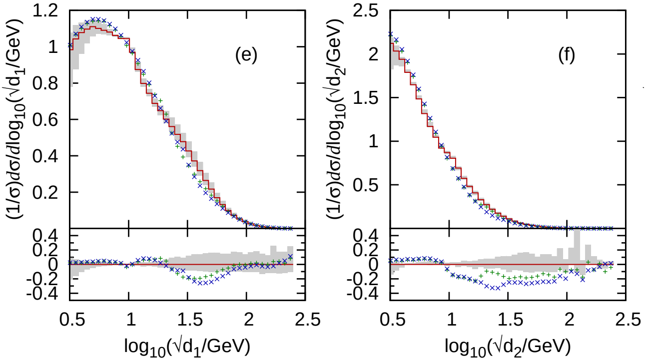
ME⊕TS: Z^0+jets at Tevatron – jet spectra

Variation of Q_{cut} should affect distributions only beyond (N)LL

But Q_{cut} must be in range where PS approximation is valid!

Example: Differential $\mathbf{k_T}$ jet rates

⇒ 'old' SHERPA CKKW for W+jets [Alwall et al. Eur. Phys. J. C **53** (2008) 473]



Summary/Outlook

Summary

- new NLO results for $W/Z + 3$jets
  - largely reduced dependence on unphysical scales
  - good agreement with data from Tevatron
- NLO calculation for Wb combining 4FNS $Wb\bar{b}$ and 5FNS Wbj
- ME-PS merging sustainable approach to describe multijet events
  - hard emissions through exact tree-level matrix elements
  - intra jet evolution through (truncated) QCD parton showers
  - reduced inherent "merging" systematics
- ongoing validation against Tevatron data [light & heavy flavours]

Outlook

- $W/Z + 4$jets @ NLO from BlackHat
- $W/Zb\bar{b}+ \leq 3$jets @ NLO from Helac-NLO $\Rightarrow$ see Malgorzata's talk
- MENLOPS [Hamilton, Nason arXiv:1004.1764] $\Rightarrow$ see Paolo's talk