Vector-Boson + Multi-Jet Production with BlackHat

David A. Kosower
Institut de Physique Théorique, CEA–Saclay
on behalf of the BlackHat Collaboration
Carola Berger, Z. Bern, L. Dixon, Fernando Febres Cordero, Darren Forde, Harald Ita, DAK, Daniel Maître, Tanju Gleisberg
High Precision for Hard Processes (HP2.3), Florence
September 14–17, 2010
Why NLO?

QCD at LO is not quantitative: large dependence on unphysical renormalization scale
NLO: reduced dependence, first quantitative prediction
…want this for $W+$more jets too
Ingredients for NLO Calculations

- Tree-level matrix elements for LO and real-emission terms known since ’80s

- Singular (soft & collinear) behavior of tree-level amplitudes, integrals, initial-state collinear behavior known since ’90s

- NLO parton distributions known since ’90s

- General framework for numerical programs known since ’90s

  Catani, Seymour (1996); Giele, Glover, DAK (1993); Frixione, Kunszt, Signer (1995)

- Automating it for general processes

  Gleisberg, Krauss; Seymour, Tevlin; Hasegawa, Moch, Uwer; Frederix, Gehrmann, Greiner (2008);
  Frederix, Frixione, Maltoni, Stelzer (2009)

- Bottleneck: one-loop amplitudes

  W+2 jets (MCFM) W+3 jets

BlackHat

• New technologies for one-loop computations: numerical implementation of on-shell methods
• Automated implementation → industrialization

• **SHERPA** for real subtraction, real emission, phase-space integration, and analysis
• Other groups using on-shell methods numerically: **CUTTOOLS** [HELC (Ossola, Papadopoulos, Pittau, Actis, Bevilacqua, Czakon, Draggiotis, Garzelli, van Hameren, Mastrolia, Worek); **ROCKET** (Ellis, Giele, Kunszt, Lazopoulos, Melnikov, Zanderighi); **GKW** (Giele, Kunszt, Winter); **SAMURAI** (Mastrolia, Ossola, Reiter, Tramontano);
• On-going analytic computations
  Anastasiou, Britto, Feng, Mastrolia; Britto, Feng, Mirabella

Vector-Boson + Multi-Jet Production with BlackHat, HP2.3, Florence.
New Technologies: On-Shell Methods

• Use only information from physical states
• Use properties of amplitudes as calculational tools
  – Factorization → on-shell recursion relations
  – Unitarity → unitarity method
  – Underlying field theory → integral basis

• Formalism

\[ \text{Ampl} = \sum_{j \in \text{Basis}} c_j \text{Int}_j + \text{Rational} \]

Known integral basis:

On-shell Recursion; 
\( D \)-dimensional unitarity via \( \int \) mass

Unitarity
Recent Developments in BlackHat

• Generation of ROOT tuples
• Re-analysis possible
• Distribution to experimenters

• Flexibility for studying scale variations
• Flexibility for computing error estimates associated with parton distributions

• More processes
The Tevatron is Still Producing Ws...

- Third jet in W+3 jets [0907.1984]
- Reduced scale dependence at NLO
- Good agreement with CDF data [0711.4044]
- Shape change small compared to LO scale variation
- SISCones (Salam & Soyez) vs JETCLU — LHC experiments will use anti-\(kT\)
Reduced Scale Dependence

- Anti-$k_T$ @ LHC 7 TeV
- Reduction of scale dependence
- NLO importance grows with increasing number of jets
Scale Choices in $V+\text{Jets}$

- Need to choose scales event-by-event
- Functional form of scale choice is also important
- $E_T^\text{W}$ is not suitable; $\hat{H}_T$ is
- NLO calculation is self-diagnosing, LO isn't

In the absence of an NLO calculation, should use a scale like $\hat{H}_T$

Vector-Boson + Multi-Jet Production with BlackHat, HP2.3, Florence.
Scale Variation

• How should we assess uncertainty due to scale variation?
• Varying up & down by a factor of two is “traditional” but arbitrary
• For events with many jets, there are many scales
• Can use shower-inspired scales
  \[ \alpha_s^{-1} \left( [\alpha_s(p_{T1})\alpha_s(p_{T2})\alpha_s(p_{T3})]^{1/3} \right) \]
• Standard “recipe” allows comparing different calculations across time
• We use \( \hat{H}T/2 \) (sum of partonic \( ET \), including leptons) or \( \hat{H}'T/2 \) (sum of QCD partonic \( ET \) & \( ETW \)
Z+3 Jets at the LHC

- Z+3 jets: new
- NLO scale uncertainty smaller than LO (band accidently narrow given central choice — but would in any case be much improved)
- Shape change mild
- Scale choice $\hat{H}_T/2$ (half total partonic $E_T$)
- Anti-$k_T$
W$^- + 4$ Jets

- Background to top quark studies
- Background to new physics searches
- High-multiplicity frontier
- SISConet, $R = 0.4$
Total Transverse Energy

\[ H_T = \sum_{\text{jets } j} E_T^j + E_T^e + E_T^\nu \]

- Useful distribution in new-physics searches
- Normalization corrected but shape is stable at NLO
• All four jets — leading three show shape changes from LO to NLO
Also seen in W+3 jet production at 14 TeV (SIS Cone): leading two jets have shape corrections to $E_T$ distributions

- Cannot always choose scales to make all LO/NLO ratios flat simultaneously!
- □ R(1st,2nd) jet
- Shapes can change!
- Physics of leading jets not modeled well at LO: additional radiation allows jets to move closer
- Cf Les Houches study [in 1003.1241] (Hoche, Huston, Maitre, Winter, Zanderighi) comparing to SHERPA w/ME matching & showering
- W+4 shows similar but milder effect at parton level
Tools for New Physics Searches

• Look for quantities which have different behavior for Standard-Model physics and new physics

• Look for quantities in which experimental systematics are reduced or cancel □ think about ratios
**W+ vs W− Production**

- Standard-Model production of W+ and W− differ because of different u and d quark distributions.
- See that in charged-lepton distributions — hemispheres are the same in each distribution, distributions differ.
- In heavy-particle pair production, typically no asymmetry (for example, top quark).
W+3 jets at the LHC

- Dominant initial state at the LHC $\Rightarrow$ $E_T$-dependent rate difference because of $u(x)/d(x)$ distribution difference
- But that's not the whole story

$W + 3$ jets + $X$

$\sqrt{s} = 7$ TeV

Preliminary

$W^+ / W^-$ ratio

BlackHat+Sherpa

V+Jets at Next-to-Leading-Jet Physics with BlackHat, MC4LHC, CERN.
High-ET W Polarization

- Polarization of low-\( p_T \), longitudinal, \( W \)s is textbook material (Ellis, Stirling & Webber)  dilution in charged-lepton rapidity distribution at Tevatron
- This is a different effect! \( W \)s are also polarized at high \( p_T \)  \( E_{T} \) dependence of \( e^+ \)/\( e^- \) ratio and missing \( E_{T} \) in \( W^+ \)/\( W^- \) at LHC
  - Present at LO
  - Present for fewer jets too: universality
- Useful for distinguishing “prompt” \( W \)s from daughter \( W \)s in top decay (or new heavy-particle decays)!

Vector-Boson + Multi-Jet Production with BlackHat, HP2.3, Florence, September 14–17, 2010
$W^+/W^-$ Ratio

- Ratio of cross sections should be less sensitive to experimental systematics and theoretical uncertainties too

\[ R^\pm(n) = \frac{\sigma(W^+ + n \text{ jets})}{\sigma(W^- + n \text{ jets})} \]

- PDF uncertainties should be small, jet measurement uncertainties too

- Example: top-quark production at 14 TeV reduces $R_{\oplus}(4)$ from 1.44 to 1.22 (LO)
Correlated scale variation cancels

Ratio $\frac{W}{W^+}$ with $n$ as higher $x$ is probed

<table>
<thead>
<tr>
<th>Jets</th>
<th>$W$ LO</th>
<th>$W$ NLO</th>
<th>$W^+/W^-$ LO</th>
<th>$W^+/W^-$ NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$1614.0(0.5)$</td>
<td>$2077(2)$</td>
<td>$1.507(0.002)$</td>
<td>$1.498(0.009)$</td>
</tr>
<tr>
<td></td>
<td>$264.4(0.2)$</td>
<td>$331(1)$</td>
<td>$1.596(0.003)$</td>
<td>$1.57(0.02)$</td>
</tr>
<tr>
<td>1</td>
<td>$73.14(0.09)$</td>
<td>$78.1(0.5)$</td>
<td>$1.596(0.003)$</td>
<td>$1.57(0.02)$</td>
</tr>
<tr>
<td>2</td>
<td>$17.22(0.03)$</td>
<td>$16.9(0.1)$</td>
<td>$1.694(0.005)$</td>
<td>$1.66(0.02)$</td>
</tr>
<tr>
<td>3</td>
<td>$3.81(0.01)$.</td>
<td>$3.56(0.03)$</td>
<td>$1.817(0.003)$</td>
<td>$1.817(0.003)$</td>
</tr>
</tbody>
</table>

LHC, 7 TeV, anti-$k_T$ ($R = 0.5$), $pT_{jet} > 25$ GeV
Jet-Production Ratio in $W$+Jets

- Lore: ratio $\sim (W+n)/(W+n-1)$ should be independent of $n$
- More dependence on jet systematics than $W^+/W^-$, but much less than $W+n$ jets

<table>
<thead>
<tr>
<th>Jets</th>
<th>$W^- n/(n-1)$ LO</th>
<th>$W^- n/(n-1)$ NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1638(0.0001)$^{+0.044}_{-0.031}$</td>
<td>0.159(0.001)</td>
</tr>
<tr>
<td>2</td>
<td>0.2766(0.0004)$^{+0.051}_{-0.037}$</td>
<td>0.236(0.002)</td>
</tr>
<tr>
<td>3</td>
<td>0.2354(0.0005)$^{+0.034}_{-0.025}$</td>
<td>0.216(0.002)</td>
</tr>
<tr>
<td>4</td>
<td>0.2212(0.0004)$^{+0.026}_{-0.020}$</td>
<td>0.211(0.003)</td>
</tr>
</tbody>
</table>

- LHC, 7 TeV, anti-$k_T$ ($R = 0.5$), $p_T$jet > 25 GeV
Jet-Production Ratio in Z+Jets

Ratios of jet cross sections should be less sensitive to systematics.

Ratios are stable LO\rightarrow NLO.

But hide a lot of structure in differential distributions!

- Kinematic constraints at low $p_T$
- Factorization & IR $\ln(p_T/p_T\text{ min})$ at intermediate $p_T$
- Phase-space & pdf suppression at higher $p_T$

$\sqrt{s} = 7$ TeV

More Ratios

- W/Z ratios should also be interesting to study
- Can now be done with up to three accompanying jets
Summary

• NLO calculations required for reliable QCD predictions at the Tevatron and LHC
• On-shell methods are maturing into the method of choice for these QCD calculations

• BlackHat: automated seminumerical one-loop calculations
• Phenomenologically useful NLO parton-level calculations:
  - $W+3$ jets at Tevatron and LHC
  - $Z+3$ jets at Tevatron and LHC
  - First results for $W+4$ jets at LHC
  - Broad variety of kinematical configurations probed

• Detailed tools for new-physics searches
Vector-Boson + Multi-Jet Production with BlackHat, HP2.3, Florence, September 14–17, 2010
<table>
<thead>
<tr>
<th>Jets</th>
<th>$W^-\ LO$</th>
<th>$W^-\ NLO$</th>
<th>$W^+/W^-\ LO$</th>
<th>$W^+/W^-\ NLO$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1614.0(0.5)$^{+208.5}_{-235.2}$</td>
<td>2077(2)$^{+40}_{-31}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>264.4(0.2)$^{+22.6}_{-21.4}$</td>
<td>331(1)$^{+15}_{-12}$</td>
<td>1.507(0.002)</td>
<td>1.498(0.009)</td>
</tr>
<tr>
<td>2</td>
<td>73.14(0.09)$^{+20.81}_{-14.92}$</td>
<td>78.1(0.5)$^{+1.5}_{-4.1}$</td>
<td>1.596(0.003)</td>
<td>1.57(0.02)</td>
</tr>
<tr>
<td>3</td>
<td>17.22(0.03)$^{+8.07}_{-4.95}$</td>
<td>Watch this!</td>
<td>1.694(0.005)</td>
<td>Watch this!</td>
</tr>
<tr>
<td>4</td>
<td>3.81(0.01)$^{+2.44}_{-1.34}$</td>
<td>Watch this!</td>
<td>1.817(0.003)</td>
<td>Watch this!</td>
</tr>
<tr>
<td>0</td>
<td>1614.0(0.5)$^{+208.5}_{-235.2}$</td>
<td>2077(2)$^{+40}_{-31}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>264.4(0.2)$^{+22.6}_{-21.4}$</td>
<td>331(1)$^{+15}_{-12}$</td>
<td>1.507(0.002)</td>
<td>1.498(0.009)</td>
</tr>
<tr>
<td>2</td>
<td>73.14(0.09)$^{+20.81}_{-14.92}$</td>
<td>78.1(0.5)$^{+1.5}_{-4.1}$</td>
<td>1.596(0.003)</td>
<td>1.57(0.02)</td>
</tr>
<tr>
<td>3</td>
<td>17.22(0.03)$^{+8.07}_{-4.95}$</td>
<td>Watch this!</td>
<td>1.694(0.005)</td>
<td>Watch this!</td>
</tr>
<tr>
<td>4</td>
<td>3.81(0.01)$^{+2.44}_{-1.34}$</td>
<td>Watch this!</td>
<td>1.817(0.003)</td>
<td>Watch this!</td>
</tr>
<tr>
<td>Jets</td>
<td>$W^{-}$ LO</td>
<td>$W^{-}$ NLO</td>
<td>$W^{+}/W^{-}$ LO</td>
<td>$W^{+}/W^{-}$ NLO</td>
</tr>
<tr>
<td>------</td>
<td>-------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>0</td>
<td>1614.0(0.5)$^{+208.5}_{-235.2}$</td>
<td>2077(2)$^{+40}_{-31}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>264.4(0.2)$^{+22.6}_{-21.4}$</td>
<td>331(1)$^{+15}_{-12}$</td>
<td>1.507(0.002)</td>
<td>1.498(0.009)</td>
</tr>
<tr>
<td>2</td>
<td>73.14(0.09)$^{+20.81}_{-14.92}$</td>
<td>78.1(0.5)$^{+1.5}_{-4.1}$</td>
<td>1.596(0.003)</td>
<td>1.57(0.02)</td>
</tr>
<tr>
<td>3</td>
<td>17.22(0.03)$^{+8.07}_{-4.95}$</td>
<td>16.9(0.1)$^{+0.2}_{-1.3}$</td>
<td>1.694(0.005)</td>
<td>1.66(0.02)</td>
</tr>
<tr>
<td>4</td>
<td>3.81(0.01)$^{+2.44}_{-1.34}$</td>
<td>3.56(0.03)$^{+0.08}_{-0.30}$</td>
<td>1.817(0.003)</td>
<td>Stay tuned!</td>
</tr>
</tbody>
</table>