NLO Assistance to LHC Searches with Complex Final States using BlackHat and Sherpa

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Classic SUSY dark matter signature

→ Multiple jets + missing energy (+ lepton(s)?)

In models such as supersymmetry, heavy produced particles (colored) decay rapidly to stable Weakly Interacting Massive Particle (WIMP) plus jets

→ Missing transverse energy
MET + 4 jets
Irreducible Standard Model Background

- MET + 4 jets from
  \[ pp \rightarrow Z + 4 \text{ jets}, \]
  \[ Z \rightarrow \nu\nu \]
- Neutrinos also weakly interacting, escape detector.
- Also large background from
  \[ pp \rightarrow W + 4 \text{ jets}, \]
  \[ W \rightarrow l\nu \]
  \( (~10x \ Z \rightarrow \nu\nu \text{ rate}) \)
  - if you lose the charged lepton
  ( - or if you want a lepton )

- Motivates theoretical and experimental study of \( V + n \) jets at Tevatron and LHC.
- Talks in this session by Strauss, Mesropian, Beauchemin, Lenzi, Ganguli, Kosower, Schönherr
Recent progress on $V + \text{jets}$ at NLO

**MCFM:** $V + 0,1,2 \text{jets}$ Campbell, Ellis, hep-ph/0202176

**Rocket:** $W + 3 \text{jets}$ Ellis, Melnikov, Zanderighi, 0901.4101, 0906.1445

**Blackhat+Sherpa:** Berger, Bern, LD, Diana, Febres Cordero, Forde, Gleisberg, Höche, Ita, Kosower, Maître, Ozeren

$W + 3 \text{jets}$ 0902.2760, 0907.1984
$Z + 3 \text{jets}$ 1004.1659
$W + 4 \text{jets}$ 1009.2338
$Z + 4 \text{jets}$ 1108.2229
$W + 5 \text{jets}$ 12mm.nnnn

- Could try to use such predictions **directly** for backgrounds to experimental searches.
- However, it is generally safer to use **data-driven techniques**
Data Driven Techniques

• Measure process “close” to the one you want to estimate. (Possibly the same process in a different kinematic region.)
• Rely on theory only for ratio of desired process to measured one.
• Ratios can be considerably less sensitive to:
  - perturbative uncertainties
  - shower + nonperturbative effects
  - jet energy scale
  - pdf uncertainties
• Nevertheless, useful to have at NLO as well as LO+shower.
• Examples of $V + j$ets ratios:
  • $[W + n \text{jets}]/[Z + n \text{jets}]$
  • $[W^+ + n \text{jets}]/[W^- + n \text{jets}]$
  • $[\gamma + n \text{jets}]/[Z + n \text{jets}]$
  • $W$ polarization fractions
  • $[V + n \text{jets}]/[V + (n-1) \text{jets}]$
\[ \gamma + \text{jets} \quad \text{for} \quad Z(\rightarrow \nu\nu) + n \text{ jets} \]

- CMS [CMS PAS SUS-08-002, SUS-10-005, 1106.4503] and ATLAS [1107.2803, 1109.6572] both use \( \gamma + \text{jets} \) to “calibrate” \( Z(\rightarrow \nu\nu) + \text{jets} \) SUSY background.
- High rate compared to \( Z(\rightarrow l^+l^-) \), relatively clean.
- But: How much does a \( \gamma \) behave like a \( Z \)?
- \( E.g. \), photon-quark collinear pole is cut off by \( Z \) mass in the \( Z \) case. Does this make much difference?
NLO \((Z + 2 \text{ jets})/ (\gamma + 2 \text{ jets})\)

- Computed \((Z + 2 \text{ jets})/ (\gamma + 2 \text{ jets})\) as a function of various kinematic variables, 3 different ways:
  - LO (just for reference)
  - NLO (probably the most reliable)
  - LO+shower (ME+PS) – to estimate NLO error, and because it is similar to what CMS/ATLAS rely on.
- Traditional method of varying renormalization and factorization scales does not provide useful uncertainty estimate for ratios of similar quantities
- We used a “Frixione” photon isolation to simplify the NLO theory, but checked that it’s within \(\sim 1\%\) of CMS’s isolation cone.
(Z + 2 jets)/ (γ + 2 jets) distributions

- Azimuthal angle distribution, between MET vector and \( p_T \) vector of 1\(^{\text{st}} \), 2\(^{\text{nd}} \) jets

- LO distribution wrong – kinematics too restrictive.
NLO and ME+PS agree to within about 10% in \( Z/\gamma \) ratio.
NLO \((Z + 3 \text{ jets})/ (\gamma + 3 \text{ jets})\)

- Most events in CMS samples have at least 3 jets
- For 2011 data, new (tighter) kinematic cuts

### 2010 data

**Set 1:** \(H_T^{\text{jet}} > 300 \text{ GeV}, |\text{MET}| > 250 \text{ GeV}\)

**Set 2:** \(H_T^{\text{jet}} > 500 \text{ GeV}, |\text{MET}| > 150 \text{ GeV}\)

**Set 3:** \(H_T^{\text{jet}} > 300 \text{ GeV}, |\text{MET}| > 150 \text{ GeV}\)

**Set 4:** \(H_T^{\text{jet}} > 350 \text{ GeV}, |\text{MET}| > 200 \text{ GeV}\)

### 2011 data

**Set 5:** \(H_T^{\text{jet}} > 500 \text{ GeV}, |\text{MET}| > 350 \text{ GeV}\)

**Set 6:** \(H_T^{\text{jet}} > 800 \text{ GeV}, |\text{MET}| > 200 \text{ GeV}\)

**Set 7:** \(H_T^{\text{jet}} > 800 \text{ GeV}, |\text{MET}| > 500 \text{ GeV}\)
NLO \((\gamma + 3 \text{ jets})/ (Z + 3 \text{ jets})\) results

<table>
<thead>
<tr>
<th>Set</th>
<th>Prediction</th>
<th>(Z + 3)-jet/(\gamma + 3)-jet</th>
<th>(Z + 2)-jet/(\gamma + 2)-jet</th>
<th>ratio</th>
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<tbody>
<tr>
<td>4</td>
<td>LO</td>
<td>0.215(0.001)</td>
<td>0.2336(0.0003)</td>
<td>0.922(0.003)</td>
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<tr>
<td></td>
<td>ME+PS</td>
<td>0.194(0.003)</td>
<td>0.213(0.002)</td>
<td>0.908(0.01)</td>
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<td>NLO</td>
<td>0.209(0.003)</td>
<td>0.215(0.001)</td>
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<td>LO</td>
<td>0.245(0.001)</td>
<td>0.257(0.001)</td>
<td>0.952(0.01)</td>
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<tr>
<td></td>
<td>ME+PS</td>
<td>0.230(0.004)</td>
<td>0.239(0.004)</td>
<td>0.961(0.02)</td>
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<tr>
<td></td>
<td>NLO</td>
<td>0.242(0.01)</td>
<td>0.246(0.002)</td>
<td>0.981(0.02)</td>
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<td>0.220(0.002)</td>
<td>0.232(0.001)</td>
<td>0.948(0.01)</td>
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<tr>
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<td>0.218(0.004)</td>
<td>0.232(0.003)</td>
<td>0.940(0.02)</td>
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<td></td>
<td>NLO</td>
<td>0.222(0.01)</td>
<td>0.224(0.002)</td>
<td>0.988(0.03)</td>
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<td>7</td>
<td>LO</td>
<td>0.257(0.003)</td>
<td>0.259(0.001)</td>
<td>0.992(0.01)</td>
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<tr>
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<td>ME+PS</td>
<td>0.244(0.01)</td>
<td>0.261(0.003)</td>
<td>0.935(0.02)</td>
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<tr>
<td></td>
<td>NLO</td>
<td>0.254(0.01)</td>
<td>0.255(0.003)</td>
<td>0.993(0.03)</td>
</tr>
</tbody>
</table>

BH+S, 1206.nnnn

ME+PS, NLO always within 10%

pdf and other uncertainties 5% or less

Validates this method of estimating background
$W^+$ and $W^-$ “differ” at LHC: polarized same way [left-handed]

$$\frac{1}{\sigma d \cos \theta^*} \frac{d\sigma}{d\cos \theta^*} = \frac{3}{8} (1 \pm \cos \theta^*)^2 f_L + \frac{3}{8} (1 \pm \cos \theta^*)^2 f_R + \frac{3}{4} \sin^2 \theta^* f_0$$

Helicity frame:
Leptonic $E_T$ in $W^\pm + 3$ jets

$W^+/W^-$ transverse lepton ratios are skewed because they are analyzing a large left-handed $W$ polarization at large $p_T(W)$.
Origin of $W$ polarization at LHC at large $p_T(W)$

$ug \rightarrow W^+ d$ dominates due to pdfs at a pp machine. Only 2 relevant helicity configurations:

100% left-handed (in partonic CM frame)

Mixture of polarizations $\rightarrow$ 100% right-handed, but only $\frac{1}{4}$ the size
Stable $W$ polarization: $W + 2$ jets, vs. Jet $p_T$ cut

![Graph showing $f_L$, $f_R$, and $f_0$ vs. $p_{T,W^+}$ for different $p_{T,jet}$ cuts.]

- $p_{T,jet} > 10$ GeV
- $p_{T,jet} > 20$ GeV
- $p_{T,jet} > 30$ GeV
- $p_{T,jet} > 50$ GeV
- $p_{T,jet} > 100$ GeV

Also stable vs. number of jets

$\sqrt{s} = 14$ TeV

$R=0.4$ [siscone]
CMS measurement – no explicit jet cuts

\[ p_T(W) > 50 \text{ GeV} \]

\[ L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2} \]

Also ATLAS measurement (smaller uncertainties) using

\[ \cos \theta_{2D} = \frac{\vec{p}_T^{\ell^*} \cdot \vec{p}_T^W}{|\vec{p}_T^{\ell^*}| \cdot |\vec{p}_T^W|} \]

1104.3829

1203.2165
Conclusions

- We compared $\gamma + 2,3 \text{ jets}$ to $Z + 2,3 \text{ jets}$ for cuts relevant for CMS SUSY searches with 2010 and 2011 data.
- We found very similar results for the ratio, between NLO and ME+PS approximations,
- This validates the data-driven method of using $\gamma + \text{ jets}$ to calibrate the $Z + \text{ jets}$ background to the MET + jets SUSY searches.

- Left-handed $W$ polarization can provide another handle on $W + \text{ jets}$ backgrounds, due to the charge asymmetries it induces.
- In fact, CMS [1107.1870] has used the measured lepton $p_T$ spectrum in $W + \text{ jets}$, plus the predicted $W$ polarization to infer the MET distribution in $W + \text{ jets}$ backgrounds to SUSY.

- Many other ratios out there to study and exploit!
Extra slides
ATLAS measurement – no explicit jet cuts

\[ p_T(W) > 50 \text{ GeV} \]

\[ \cos \theta_{2D} = \frac{\mathbf{p}_T^{\ell^*} \cdot \mathbf{p}_T^{W}}{\left| \mathbf{p}_T^{\ell^*} \right| \left| \mathbf{p}_T^{W} \right|} \]
Different dynamics for $W/Z + \text{jets}$ ratios for 1 jet, versus more jets

Recent ATLAS measurement of $W/Z + \text{exactly 1 jet ratio}$ $1108.4908$

- strong dependence on jet $p_T$

First jet in $W/Z + 4 \text{ jet ratio}$: 

\[ p_T^V \approx p_T^{\text{jet}} \]

\[ p_T^V \neq p_T^{\text{jet}} \]

- Would be nice to measure with 2,3,4 jets!
- Also, why not separate $W^+$ from $W^-$?
NLO $pp \rightarrow Z + 4\text{ jets}$, and ratio to $W^{\pm}$

Ita et al.
1108.2229
Ratio of $W^+$ to $W^-$ rates with jets

$$R^\pm(n) \equiv \frac{\sigma(W^+ + n \text{ jets})}{\sigma(W^- + n \text{ jets})}$$

- Very small experimental systematics
- NLO QCD corrections quite small, 2% or less
- $\rightarrow$ Intrinsic theoretical uncertainty very small.
- PDF uncertainty also $\sim$1-2%. Driven by PDF ratio $u(x)/d(x)$
  in well-measured valence region of moderate $x$.
- Sensitive to new physics (or Higgs, or top quark pairs) that produces $W^\pm$ symmetrically
- Fraction of new physics in sample is:

$$f_{NP} = \frac{2(R_{SM}^\pm - R_{exp.}^\pm)}{(R_{SM}^\pm + 1)(R_{exp.}^\pm - 1)}$$

Kom, Stirling, 1004.3404

<table>
<thead>
<tr>
<th>$n$</th>
<th>$QQ$</th>
<th>$Qg$</th>
<th>$gg$</th>
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<tr>
<td>4</td>
<td>25</td>
<td>67</td>
<td>8</td>
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</tbody>
</table>
### $W^+ \text{ to } W^-$ ratios at NLO

<table>
<thead>
<tr>
<th>no. jets</th>
<th>$W^- \text{ LO}$</th>
<th>$W^- \text{ NLO}$</th>
<th>$W^+/W^- \text{ LO}$</th>
<th>$W^+/W^- \text{ NLO}$</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>$1.656(0.001)$</td>
<td>$1.580(0.004)$</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>$3.55(0.04)^{+0.08}_{-0.30}$</td>
<td>$1.812(0.001)$</td>
<td>$1.73(0.03)$</td>
</tr>
</tbody>
</table>

- $p_T^{\text{jet}} > 25 \text{ GeV, } |\eta^{\text{jet}}| < 3$
- $E_T^e > 20 \text{ GeV, } |\eta^e| < 2.5$
- $E_T^V > 20 \text{ GeV, } M_T^{W'} > 20 \text{ GeV}$
- $R = 0.5 \text{ [anti-}k_T\text{]}$

- Huge scale dependence at LO cancels in ratio
- Small corrections from LO $\rightarrow$ NLO
- Increases with $n$ due to increasing $x$