NLO Assistance to LHCsearches
with Complex Final Statés
uising BlackHat aná Shérpa

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## Classic SUSY dark matter signature $\rightarrow$ 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
$\rightarrow$ Missing transverse energy MET + 4 jets


## Irreducible Standard Model Background

- MET + 4 jets from

$$
\begin{gathered}
\mathrm{pp} \rightarrow Z+4 \text { jets, } \\
Z \rightarrow v v
\end{gathered}
$$

- Neutrinos also weakly interacting, escape detector.
- Also large background from $\mathrm{pp} \rightarrow W+4$ jets,

$$
W \rightarrow l v
$$


( $\sim 10 \mathrm{x} Z \rightarrow \nu v$ 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 + jets at NLO

MCFM: $V+0,1,2$ jets Campbell, Ellis, hep-ph/0202176
Rocket: $W+3$ jets Ellis, Melnikov, Zanderighi, 0901.4101, 0906.1445

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Blackhat+Sherpa: Berger, Bern, LD, Diana, Febres Cordero, Forde,
Gleisberg, Höche, Ita, Kosower, Maître, Ozeren
W+3 jets 0902.2760,0907.1984
Z + 3 jets 1004.1659
W+4 jets 1009.2338
Z + 4 jets 1108.2229
W+5 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 $V+$ jets ratios:
- [W $+n$ jets]/[ $Z+n$ jets]
- $\quad\left[W^{+}+\mathrm{n} j e t s\right] /\left[W^{-}+\mathrm{n} j e t s\right]$
- $[\gamma+n$ jets $] /[Z+n$ jets]
- $W$ polarization fractions
- [V + $n$ jets]/[ $V+(n-1)$ jets]


## $\gamma+$ jets for $\quad Z(\rightarrow v v)+n$ jets



- CMS [CMS PAS SUS-08-002, SUS-10-005, 1106.4503] and ATLAS [1107.2803, 1109.6572] both use $\gamma+$ jets to "calibrate" $Z(\rightarrow \nu v)+$ jets SUSY background.
- High rate compared to $Z\left(\rightarrow^{+} l^{-}\right)$, 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 $(Z+2$ jets $) /(\gamma+2$ jets $)$



- Computed $(Z+2$ jets) $/(\gamma+2$ 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)/ $(\gamma+2$ 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.


## $\mathrm{NLO}(Z+3$ jets $) /(\gamma+3$ jets $)$

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



## NLO ( $\gamma+3$ jets $) /(Z+3$ jets $)$ results

| Set | Prediction | $Z+3$-jet $/ \gamma+3$-jet | $Z+2$-jet $/ \gamma+2$-jet | ratio |
| :---: | :---: | :---: | :---: | :---: |
| 4 | LO | $0.215(0.001)$ | $0.2336(0.0003)$ | $0.922(0.003)$ |
|  | $\mathrm{ME}+\mathrm{PS}$ | $0.194(0.003)$ | $0.213(0.002)$ | $0.908(0.01)$ |
|  | NLO | $0.209(0.003)$ | $0.215(0.001)$ | $0.973(0.01)$ |
| 5 | LO | $0.245(0.001)$ | $0.257(0.001)$ | $0.952(0.01)$ |
|  | $\mathrm{ME}+\mathrm{PS}$ | $0.230(0.004)$ | $0.239(0.004)$ | $0.961(0.02)$ |
|  | NLO | $0.242(0.01)$ | $0.246(0.002)$ | $0.981(0.02)$ |
| 6 | LO | $0.220(0.002)$ | $0.232(0.001)$ | $0.948(0.01)$ |
|  | $\mathrm{ME}+\mathrm{PS}$ | $0.218(0.004)$ | $0.232(0.003)$ | $0.940(0.02)$ |
|  | NLO | $0.222(0.01)$ | $0.224(0.002)$ | $0.988(0.03)$ |
| 7 | LO | $0.257(0.003)$ | $0.259(0.001)$ | $0.992(0.01)$ |
|  | $\mathrm{ME}+\mathrm{PS}$ | $0.244(0.01)$ | $0.261(0.003)$ | $0.935(0.02)$ |
|  | NLO | $0.254(0.01)$ | $0.255(0.003)$ | $0.993(0.03)$ |

BH+S, 1206.nnnn

ME+PS, NLO always within 10\%
pdf and other uncertainties 5\% or less

Validates this method of estimating background
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## $W^{+}$and $W^{-}$"differ" at LHC: polarized same way [left-handed]



Helicity frame:

$$
\begin{aligned}
\frac{1}{\sigma} \frac{d \sigma}{d \cos \theta^{*}} & =\frac{3}{8}\left(1 \mp \cos \theta^{*}\right)^{2} f_{L} \\
& +\frac{3}{8}\left(1 \pm \cos \theta^{*}\right)^{2} f_{R} \\
& +\frac{3}{4} \sin ^{2} \theta^{*} f_{0}
\end{aligned}
$$


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## Leptonic $E_{T}$ in $W^{ \pm}+3$ jets

0907.1984


$W^{+} / W^{-}$transverse lepton ratios are skewed because they are analyzing a large left-handed $W$ polarization at large $\mathrm{p}_{\mathrm{T}}(W)$

## Origin of $W$ polarization at LHC at large $\mathrm{p}_{\mathrm{T}}(W)$

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

$A^{\text {tree }} \propto \frac{\langle d \nu\rangle^{2}}{\langle u g\rangle\langle g d\rangle}$
$d \sigma \propto\left(k_{d} \cdot k_{\nu}\right)^{2}$

## 100\% left-handed

(in partonic CM frame)

$A^{\text {tree }} \propto \frac{[u e]^{2}}{[u g][g d]}$
$d \sigma \propto\left(k_{u} \cdot k_{e}\right)^{2}$
Mixture of polarizations
$\rightarrow 100 \%$ right-handed, but only $1 / 4$ the size
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## Stable $W$ polarization: $W+2$ jets, vs. Jet $p_{T}$ cut



## CMS measurement - no explicit jet cuts



1104.3829 $\mathrm{p}_{\mathrm{T}}(W)>50 \mathrm{GeV}$
$L_{P}=\frac{\vec{p}_{T}(\ell) \cdot \vec{p}_{T}(\mathrm{~W})}{\left|\vec{p}_{T}(\mathrm{~W})\right|^{2}}$



## Also ATLAS measurement (smaller uncertainties) using


1203.2165

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## Conclusions

- We compared $\gamma+2,3$ jets to $Z+2,3$ 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 $\gamma+$ jets to calibrate the $Z+$ jets background to the MET + jets SUSY searches.
- Left-handed $W$ polarization can provide another handle on $W+$ jets backgrounds, due to the charge asymmetries it induces.
- In fact, CMS [1107.1870] has used the measured lepton $\mathrm{p}_{\mathrm{T}}$ spectrum in $W+$ jets, plus the predicted $W$ polarization to infer the MET distribution in $W+$ jets backgrounds to SUSY.
- Many other ratios out there to study and exploit!


## Extra slides

## ATLAS measurement - no explicit jet cuts



1203.2165
$\mathrm{p}_{\mathrm{T}}(W)>50 \mathrm{GeV}$
$\cos \theta_{2 \mathrm{D}}=\frac{\vec{p}_{\mathrm{T}}^{\ell *} \cdot \vec{p}_{\mathrm{T}}^{W}}{\left|\vec{p}_{\mathrm{T}}^{\ell *}\right|\left|\vec{p}_{\mathrm{T}}^{W}\right|}$


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# Different dynamics for $W / Z+$ jets ratios for 1 jet, versus more jets 

Recent ATLAS measurement of $W / Z$ + exactly 1 jet ratio 1108.4908 - strong dependence on jet $p_{T}$

First jet in W/Z + 4 jet ratio:
flat in jet $p_{T}$


- Would be nice to measure with $2,3,4$ jets!
- Also, why not separate $W^{+}$from $W^{-}$?


## NLO $p p \rightarrow Z+4$ jets, and ratio to $W^{ \pm}$



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

Kom, Stirling, 1004.3404

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

- 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:

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


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## $W^{+}$to $W^{-}$ratios at NLO

$B H+S, 1009.2338$

| no. jets | $W^{-} \mathrm{LO}$ | $W^{-} \mathrm{NLO}$ | $W^{+} / W^{-} \mathrm{LO}$ | $W^{+} / W^{-} \mathrm{NLO}$ |
| :---: | :---: | :---: | :---: | :---: |
| 0 | $1614.0(0.5)_{-235.2}^{+208.5}$ | $2077(2)_{-31}^{+40}$ | $1.656(0.001)$ | $1.580(0.004)$ |
| 1 | $264.4(0.2)_{-21.4}^{+22.6}$ | $331(1)_{-12}^{+15}$ | $1.507(0.002)$ | $1.498(0.009)$ |
| 2 | $73.14(0.09)_{-14.92}^{+20.81}$ | $78.1(0.5)_{-4.1}^{+1.5}$ | $1.596(0.003)$ | $1.57(0.02)$ |
| 3 | $17.22(0.03)_{-4.95}^{+8.07}$ | $16.9(0.1)_{-1.3}^{+0.2}$ | $1.694(0.005)$ | $1.66(0.02)$ |
| 4 | $3.81(0.01)_{-1.34}^{+2.44}$ | $3.55(0.04)_{-0.30}^{+0.08}$ | $1.812(0.001)$ | $1.73(0.03)$ |

$p_{T}^{\text {jet }}>25 \mathrm{GeV},\left|\eta^{\text {jet }}\right|<3$
$E_{T}^{e}>20 \mathrm{GeV},\left|\eta^{e}\right|<2.5$
$E_{T}^{v}>20 \mathrm{GeV}, M_{T}^{W}>20 \mathrm{GeV}$
$R=0.5\left[\right.$ anti- $\left.k_{T}\right]$

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

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