CMS: Vector-boson production plus N-jets

Eric Takasugi, University of California, Los Angeles (UCLA) on behalf of CMS

Jet Vetoes and Multiplicity Observables

University of California, Los Angeles (UCLA)
Introduction

• Precise knowledge of W+jets and Z+jets is crucial as important backgrounds to BSM searches
• Both processes have large cross-sections, controllable background which enables precision measurement
  – Can confront predictions from theory in high end tails
• High statistics allows access to phase spaces not tested before
Overview:

1. $W + \text{Jets}$
2. $Z + \text{Jets}$
3. $\gamma + \text{Jets}$
4. $Z/\gamma$ Ratio
W+jets, √s=7 TeV

• $W \rightarrow \mu \nu$ decays
• Muon $p_T>25$ GeV, $|\eta|<2.1$
• Jets are anti-$k_T$, $\Delta R=0.5$, $p_T>30$ GeV, $|\eta|<2.4$, $\Delta R($Jet,\(\mu$)$)>0.5$
Jet multiplicity at 7 TeV

- Agreement up to 4 jets for BlackHat+Sherpa, 6 jets for Sherpa 1.4 and Madgraph
- Can test quantities with high accuracy up to 6 jets
  - Uncertainty at highest jet multiplicity is 30%, below 15% up to 4 jet multiplicity

arXiv:1406.7533

Takasugi (UCLA)
Jet $p_T$ at 7 TeV

- Upward trend in all cases
- BlackHat agrees through the entire $p_T$ range
- MadGraph and Sherpa overestimate the rate in the leading jet
- MadGraph overestimates in second leading jet.

arXiv:1406.7533

Takasugi (UCLA)
Z+jets, √s=7 TeV and 8 TeV

- Z→ll decays
- Leptons $p_T>20\text{GeV}$, $|\eta|<2.4$
- $71<M_{ll}<111\text{GeV}$
- Jets are anti-$k_T$, $\Delta R=0.5$, $p_T>30\text{GeV}$, $|\eta|<2.4$, $\Delta R(\text{Jet},l)>0.5$
Leading jet $p_T$

N.B these analyses are with Sherpa2

Same disagreement in both cases!

W and Z show similar trends, but worse in W case

CMS-SMP-12-017

Takasugi (UCLA)

CMS-SMP-13-007
Can measure 4th and even 5th jet $p_T$ with the available data
Exclusive jet multiplicity

CMS Preliminary
\( \mathcal{L} = 7 \text{ TeV} \) \( \mathcal{L}_{\text{int}} = 4.9 \text{ fb}^{-1} \)

- Data
- Sherpa2 \((0,1)\@NLO \leq 4j@LO +PS\)
- Powheg+Pythia6 \((Z+1)\@NLO +PS\)
- MadGraph+Pythia6 \((\leq 4j)@LO +PS\)

\( \frac{d\sigma}{dN} \) \( [\text{pb}] \)

| \( N_{\text{jets}} \) | Data
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \times 10^{-1} )</td>
</tr>
<tr>
<td>2</td>
<td>( \times 10^{-2} )</td>
</tr>
<tr>
<td>3</td>
<td>( \times 10^{-3} )</td>
</tr>
<tr>
<td>4</td>
<td>( \times 10^{-4} )</td>
</tr>
<tr>
<td>5</td>
<td>( \times 10^{-5} )</td>
</tr>
<tr>
<td>6</td>
<td>( \times 10^{-6} )</td>
</tr>
<tr>
<td>7</td>
<td>( \times 10^{-7} )</td>
</tr>
</tbody>
</table>

We have up to 7 jets measured at 8 TeV!

CMS-SMP-12-017

Takasugi (UCLA)

CMS-SMP-13-007
$p_T^Z$ Spectrum, $N_{\text{Jets}} \geq 1$ at 8 TeV

- Error band is statistics and systematics combined
- Black bar is statistics only
- MadGraph, Sherpa1.4 overestimate the high end tail by 15-30%
- Very good agreement between MadGraph and data in shape and rate at low end
- BlackHat+Sherpa is 10% lower in rate but flat in shape

CMS-SMP-14-005
$p_T^Z$ Spectrum, $N_{\text{Jets}} \geq 2$ at 8 TeV

- MadGraph, Sherpa overestimate the high end tail by approx. 30%
- Sherpa1.4 underestimates the low end
- Very good agreement between MadGraph and data in shape and rate at low end
- BlackHat is flat in shape and rate
- Overall conclusions from before still hold

\[ \text{Takasugi (UCLA)} \]
\( p_T^Z \) Cross Section Ratios at 8 TeV

- \( N_{\text{Jets}} = 2 / N_{\text{Jets}} = 1 \)
  - Syst error are taken to be fully correlated (leads to cancellation, e.g. Jet and lepton scale and resolution uncertainties, etc.)
- BlackHat overestimates by approx. 10%
  - Recall: BlackHat underestimated rate in 1-jet case
- Sherpa 1.4 underestimates in the low end
- MadGraph performs well through the entire range

\[ \text{CMS-SMP-14-005} \]
$p_T^Z$ Cross Section Ratios at 8 TeV

- $N_{\text{Jets}} = 3/N_{\text{Jets}} = 2$
- BlackHat is more accurate than before
- Sherpa1.4 underestimates in the low end as before
- MadGraph performs well

CMS-SMP-14-005
$p_T^{Z}/H_T, \ N_{\text{jets}} \geq 2$ at 8 TeV

- Data well reproduced in MadGraph
- Sherpa1.4 underestimates in the low end
- BlackHat has a drop at 1.2 where BlackHat changes from NLO to LO

Takasugi (UCLA)

CMS-SMP-14-005
\[ \log_{10}(p_T^Z/p_T^1), \text{N}_{\text{Jets}} \geq 2 \text{ at 8 TeV} \]

- Ratio works well in MadGraph
- Sherpa1.4 underestimates in the central area
- BlackHat has a drop at 0.3 where BlackHat changes from NLO to LO

CMS-SMP-14-005
$\gamma+$jets, $\sqrt{s}=7$ TeV

- Photons $|\eta^\gamma| < 2.5$
- Jets are anti-$k_T$, $\Delta R=0.5$, $p_T>30\text{GeV}$, $|\eta|<2.5$
- $\Delta R(\text{Jet,}\gamma)>0.4$
\( p_T^{\gamma} \) Spectrum, 7 TeV

- The different canvases represent different jet eta selections
  - \(|\eta^{\text{jet}}|<1.5\) on left, \(1.5<|\eta^{\text{jet}}|<2.5\) on right
- The different distributions on each canvas represent different \( \eta^{\gamma} \) selections.
- Good agreement over several orders of magnitude!
  - Forward photons at high \( p_T \) are off by 10-20%

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)

---

\[
\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{\text{jet}}} \text{ (pb/GeV)}
\]

- CMS \( L = 2.14 \text{ fb}^{-1} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- JETPHOX
- SHERPA
- \( |\eta^{\text{jet}}| < 0.9 \) (X8000)
- \( 0.9 < |\eta^{\text{jet}}| < 1.4442 \) (X400)
- \( 1.566 < |\eta^{\text{jet}}| < 2.1 \) (X20)
- \( 2.1 < |\eta^{\text{jet}}| < 2.5 \)
• Ratio plots for the previous distributions
• We again see good agreement over orders of magnitude
  – Forward photons at high $p_T$ are off by 10-20%
γ+jets, 8 TeV

- Photons $|\eta^\gamma| < 1.4$
- Jets are anti-$k_T$, $\Delta R=0.5$, $p_T>30$GeV, $|\eta|<2.4$
- $\Delta R$(Jet,γ)>0.4
$p_T^\gamma$ Spectrum, $N_{\text{Jets}} \geq 1$ at 8 TeV

- No k-factor applied
- Qualitatively flat up to 200 GeV
  - Lower by approx. 20%
- Upward trend in ratio analogous to Z
- Largest uncertainty is template systematics (10%)

CMS-SMP-14-005
\( p_T^\gamma \) Spectrum, \( N_{\text{jets}} \geq 2 \) at 8 TeV

- Similar trends as before
- MadGraph underestimates in the low end
- Similar trend to the Z case as well

CMS-SMP-14-005
$p_T^\gamma$ Spectrum Cross Section Ratios at 8 TeV

- $N_{\text{Jets}} = 2/N_{\text{Jets}} = 1$
  - Syst error are taken to be fully correlated (leads to cancellation, e.g. jet and photon scale and resolution uncertainties, etc.)

- MadGraph performs well through the entire range

CMS-SMP-14-005
\( p_T^\gamma \) Spectrum Cross Section Ratios at 8 TeV

- \( N_{Jets} = 3 / N_{Jets} = 2 \)
- MadGraph performs well through the entire range

**CMS-SMP-14-005**
Z/\gamma \text{ RATIO}
Systematics Correlation

- Systematics from the same source are treated as fully correlated as in previous cross section ratios
  - JES, JER and luminosity uncertainty are treated as fully correlated
- Systematics are added quadratically
- Statistics are propagated assuming gaussian-independent error propagation with the diagonal element of the covariance matrix
- We removed the NNLO k-factor on the Z distribution
  - we compare the LO cross section ratio for MC
$Z/\gamma$ ratio: $N_{\text{Jets}} \geq 1$ at 8 TeV

- $R$ is the ratio between the cross section of $Z$ over gamma
- Measured for average dilepton, $R_{\text{lep}} = 0.0322 \pm 0.0007 \text{(stat)} \pm 0.0023 \text{(stat+sys)}$
- Rate overestimated by MadGraph by 20%, $R_{\text{lep,MC}} = 0.0370$
- $R_{\text{lep}}/(\text{B.R. } Z \rightarrow l^+l^-) = 0.957 \pm 0.068$
- Agreement in shape
\(Z/\gamma\) ratio: \(N_{\text{Jets}} \geq 2\) at 8 TeV

- Similar to \(N_{\text{Jets}} > 1\)

\[
\frac{d\sigma}{dP_T^{Z/\gamma}} / \frac{d\sigma}{dP_T^{\gamma}}
\]

19.7 fb\(^{-1}\) (8 TeV)

\(N_{\text{Jets}} \geq 2\)

data

\(\text{stat+syst}\)

MadGraph

MadGraph Stat. Err.

CMS Preliminary

CMS-SMP-14-005

Takasugi (UCLA)
Conclusions

• Measured
  – Z and $\gamma p_T$ spectra
  – Jet $p_T$ spectra in W, Z and $\gamma$
  – Ratios in Z and $\gamma p_T$ spectra
  – Jet multiplicities
• Observe similar trends in Z and $\gamma p_T$ spectra
• Differential jet multiplicity ratios agree between data and MadGraph
• Plateau is observed in both Madgraph and data in ratio between Z and $\gamma$
  – Slight disagreement in scale but agreement in shape
• Dominated by statistical errors in tails
• Dominated by systematics at low $p_T$
References

• W [7TeV]
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12023
  – http://cds.cern.ch/record/1712497

• Z [8TeV]
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13007
  – http://cds.cern.ch/record/1728322
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP14005
  – http://cds.cern.ch/record/1740969?ln=en

• Z [7TeV]
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12017
  – http://cds.cern.ch/record/1667906?ln=en

• Photon [7TeV]
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsQCD11005
  – JHEP 06 (2014) 009

• Photon [8 TeV]
  – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP14005
  – http://cds.cern.ch/record/1740969?ln=en
BACKUP
Templates and Purity

- Fit Variable: photon isolation with footprint removal
  - Rho corrections computed to minimize pileup dependencies
- Fit templates:
  - $\sigma_{\eta\eta} < 0.011$
- Background template:
  - $\sigma_{\eta\eta} \geq 0.011$
- Signal template is taken from RandomCone (RC) as in 7TeV PAS-SMP-13-001
- A purity fit is performed in each analysis bin
  - Signal and Background templates are taken with coarser bins
- Agreement in different order of magnitude
$p_T^Z$ Spectrum, $N_{Jets} \geq 3$ at 8 TeV

- MadGraph, Sherpa overestimate the high end tail by 10%
- Very good agreement between MadGraph and data in shape and rate at low end
- BlackHat accurate in rate and shape but suffers from statistics
$p_T^Z$ Spectrum, $H_T \geq 300$ at 8 TeV

CMS Unpublished

$Z/\gamma \rightarrow l^+l^-, H_T \geq 300$ GeV

- data
- stat+syst
- BlackHat\((Z+1\text{jet})\)
- Sherpa $k_{\text{NNLO}}$
- MadGraph $k_{\text{NNLO}}$

$\frac{d\sigma}{dp_T}$ [fb GeV$^{-1}$]

10
1

100 200 300 400 500 600 700 800

$p_T^Z$ [GeV]$^2$

CMS Unpublished

$Z/\gamma \rightarrow l^+l^-, H_T \geq 300$ GeV

- data
- stat+syst
- BlackHat\((Z+1\text{jet})\)
- Sherpa $k_{\text{NNLO}}$
- MadGraph $k_{\text{NNLO}}$

PDF Scale

Unpublished CMS

$19.7 \text{fb}^{-1}$ (8TeV)

Takasugi (UCLA)
$H_T$ for $Z + $ Jets

7 TeV

- anti-$k_T$ (R = 0.5) Jets
- $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$
- $Z/\gamma^* \rightarrow \ell\ell$ channel

8 TeV

- anti-$k_T$ (R = 0.5) Jets
- $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$
- $Z/\gamma^* \rightarrow \ell\ell$ channel
Leading Jet $|\eta|$ for $Z + \text{Jets}$

- **7 TeV**
  - Anti-$k_T$ ($R = 0.5$) Jets
  - $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 2.4$
  - $Z/\gamma^* \to ll$ channel

- **8 TeV**
  - Anti-$k_T$ ($R = 0.5$) Jets
  - $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 2.4$
  - $Z/\gamma^* \to ll$ channel

CMS Preliminary

- 7 TeV: $\sqrt{s} = 7$ TeV $L_{int} = 4.9$ fb$^{-1}$
  - Data
  - Sherpa2 (0,1@NLO ≤4@LO +PS)
  - Powheg+Pythia6 (Z+1j@NLO +PS)
  - MadGraph+Pythia6 (≤4@LO +PS)

- 8 TeV: $\sqrt{s} = 8$ TeV $L_{int} = 19.6$ fb$^{-1}$
  - Data
  - Sherpa2 (≤2j@NLO 3,4j@LO + PS)
  - Madgraph + Pythia6 (≤4@LO + PS)

- Theory/Data
  - Sherpa2/Data
  - Powheg+Pythia6 (Z+1j@NLO +PS)
  - MadGraph+Pythia6 (≤4@LO +PS)

Statistical unc. (gen)

Takasugi (UCLA)
4th Jet | $\eta$ | for Z + Jets

CMS Preliminary
$\sqrt{s} = 7$ TeV $L_{int} = 4.9$ fb$^{-1}$

7 TeV

- Sherpa2 (0,1j@NLO ≤4j@LO +PS)
- Powheg+Pythia6 (Z+1j@NLO +PS)
- MadGraph+Pythia6 (≤4j@LO +PS)

Theory/Data

- Statistical unc. (gen)
- Theory unc. (gen)

Fourth jet $|\eta|$ for Z + Jets

- $p_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2.4$
- $Z/\gamma^* \rightarrow ll$ channel

8 TeV

- Sherpa2 (≤2j@NLO 3,4j@LO + PS)
- Madgraph + Pythia6 (≤4j@LO + PS)

Theory/Data

- Statistical unc. (gen)
- Theory unc. (gen)

Takasugi (UCLA)

CMS Preliminary
$19.6$ fb$^{-1}$ (8 TeV)
5\textsuperscript{th} Jet $|\eta|$ for $Z + \text{Jets}$ at 8 TeV

CMS Preliminary
19.6 fb$^{-1}$ (8 TeV)

anti-$k_T$ (R = 0.5) Jets
$p_T^{\text{jet}} > 30$ GeV, $|\eta|^{\text{jet}} < 2.4$

$Z/\gamma^* \rightarrow \mu\mu$ channel

Sherpa2/Data
MadGraph/Data

Stat. unc. (gen)
Inclusive jet multiplicity, Z + jets

CMS Preliminary
$\sqrt{s} = 7$ TeV $L_{\text{int}} = 4.9$ fb$^{-1}$

$\frac{\text{d}N}{\text{d}p_{\text{T}}}$ [pb]

7 TeV

anti-$k_T$ (R = 0.5) Jets
$p_{\text{T}}^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 2.4$

$Z/\gamma^* \rightarrow ll$ channel

Sherpa2 (0,1@NLO ≤4@LO +PS)
Powheg+Pythia6 (Z+1@NLO +PS)
MadGraph+Pythia6 (≤4@LO +PS)

Data

CMS Preliminary
$\sqrt{s} = 8$ TeV $L_{\text{int}} = 19.6$ fb$^{-1}$

$\frac{\text{d}N}{\text{d}p_{\text{T}}}$ [pb]

8 TeV

anti-$k_T$ (R = 0.5) Jets
$p_{\text{T}}^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 2.4$

$Z/\gamma^* \rightarrow ll$ channel

Sherpa2 (∼2j@NLO 3,4j@LO + PS)
MadGraph + Pythia6 (∼4j@LO + PS)

Data

Takasugi (UCLA)
$p_T^{Z}/H_T$, $N_{\text{jets}} \geq 3$ at 8 TeV

- As before:
  - Ratio works well in MadGraph
  - Sherpa underestimates in the lower end
  - BlackHat has a drop at 1.1 where BlackHat changes from NLO to LO
\( \log_{10}(p_T^Z/p_T^1), N_{\text{Jets}} \geq 3 \) at 8 TeV

- Ratio works well in MadGraph
- Sherpa underestimates in the central area
- BlackHat has a drop at 0.3 where BlackHat changes from NLO to LO
$p_T^\gamma$ Spectrum, $N_{\text{Jets}} \geq 3$ at 8 TeV

- Similar to $N_{\text{Jets}} \geq 2$
$p_T^\gamma$ Spectrum, $H_T > 300$ GeV at 8 TeV
Z/γ ratio: $N_{\text{Jets}} \geq 3$ at 8 TeV

- Similar to $N_{\text{Jets}} \geq 1$ and $N_{\text{Jets}} \geq 2$

Takasugi (UCLA)
Z/\gamma ratio: H_T > 300 GeV at 8 TeV

- Due to a mixture of statistics and the high uncertainty on the photon purity measurement, shown for p_T > 100 GeV