PRODUCTION OF VECTOR BOSONS AND JETS AT CMS

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On behalf of the CMS Collaboration

ICHEP 2014 – Valencia, 4/7/2014
CMS $V(W,Z)+$jets recent results

- Several motivations of interest:
  - Important test of perturbative QCD
  - Constraint for PDF determination
  - Characterization of backgrounds for Higgs studies/new physics searches

- $W$
  - $W+$jets, 7 TeV: CMS-SMP-12-023, arXiv.1406.7533 (submitted to PLB)
  - $W+b$, 7 TeV: CMS-SMP-12-026, arXiv.1312.6608 (accepted by PLB)

- $Z$
  - $Z+$jets, 7 TeV: CMS-PAS-SMP-12-017
  - $Z+$jets, 8 TeV: CMS-PAS-SMP-13-007
  - $Z+$jets, 8 TeV: CMS-PAS-SMP-14-009
  - $Z+$jets, $\gamma+$jets, 8 TeV: CMS-PAS-SMP-14-005
  - $Z+$jets, 7 TeV: CMS-SMP-12-004, PRD 88 (2013) 112009
  - $Z+b$, 7 TeV: CMS-SMP-13-004, arXiv.1402.1521 (accepted by JHEP)
  - $Z+b$, 7 TeV: CMS-EWK-11-015, JHEP 12 (2013) 039

- $VZ$ with $V$ hadronic decays
  - $WZ/ZZ$ with $b$, 8 TeV: CMS-SMP-13-011, arXiv.1403.3047 (submitted to PRL)
Z+bb process, where collinear b-hadron production is expected to be enhanced compared to the b hadrons. This fact may be particularly important in the simulation of the Wb and new physics searches as well as SM studies. The results reported here indicate that grounds from associated production of vector bosons and heavy quarks for Higgs boson and the measurements is also shown, with the total experimental uncertainty indicated by the uncertainties. Statistical uncertainties are shown separately as solid bands. The measurements black points. The dotted bands correspond to the quadratic sum of statistical and systematic uncertainties.

**Figure 5**

CMS - L = 5.2 fb^{-1} √s = 7 TeV

- **Z+bb production cross-section (pb)**
- **Z+b production cross-section (pb)**
- **W+bb production cross-section (pb)**

**CMS-SMP-13-004 arXiv.1402.1521**

**CMS-EWK-11-015 JHEP 12 (2013) 039**

**CMS-SMP-12-026 arXiv.1312.6608**
V(W,Z)+b

• Agreement dependent on flavour scheme
• b quarks collinear production not well described
V(W,Z)Z with Z→bb

- Key background for VH, same final state as Z+b jets
- 0,1,2 charged leptons decays from V
- 2012 data, 18.9 fb⁻¹, √s=8 TeV
- Measured for p_T^V > 100 GeV in channel dependent p_T^V bins
  - 60 < M_{bb} < 120 GeV
- corrected to full acceptance with MCFM

Cross sections in the p_T^V/M_{bb} measurement phase space:
- \( \sigma(pp\rightarrow WZ) = 4.8\pm1.4\text{(stat)}\pm1.1\text{(syst)} \text{ pb} \)
  - MCFM: 3.39±0.17 pb
- \( \sigma(pp\rightarrow ZZ) = 0.90\pm0.23\text{(stat)}\pm0.16\text{(syst)} \text{ pb} \)
  - MCFM: 1.03±0.05 pb

See P. Eller’s talk in TOP/EWK session
• $W \to \mu\nu$ decays
• 2011 data, 5 fb$^{-1}$, $\sqrt{s}=7$ TeV
• Unfolded at particle level

• Phase space:
  • Muon: $p_T > 25$ GeV, $|\eta| < 2.1$
  • $M_T(\mu, E_T^{\text{miss}}) > 50$ GeV
  • Jets: anti-$k_T$ $\Delta R=0.5$,
    $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R(\text{jet},\mu) > 0.5$

• Parton-level comparison with NLO ME
  • BlackHat+Sherpa for $W +1,2,3,4$ partons
  • Particle-level comparison with LO ME $W + \leq 4$ jets
    • MadGraph+Pythia6, Sherpa 1.4.0
W+jets: jet $p_T$

NLO: reasonable agreement, LO: overestimate at high $p_T$ (overall normalization at NNLO)
W+jets: scalar sum of jets $p_T$

NLO: fixed order $W+1$ jet cannot reproduce the effect of higher multiplicities
**W+jets: lepton-jet azimuthal angle**

All calculations fail to describe the $\Delta\phi \sim 0$ region for the 1st jet.
Z+jets, 7 and 8 TeV

- $Z \rightarrow l(e, \mu)\nu$ decays
- 2011 data, 4.9 fb$^{-1}$, $\sqrt{s}=7$ TeV
- 2012 data, 19.6 fb$^{-1}$, $\sqrt{s}=8$ TeV
- Unfolded at particle level

- Phase space:
  - Leptons: $p_T > 20$ GeV, $|\eta| < 2.4$
  - $71 < M_{ll} < 111$ GeV
  - Jets: anti-$k_T$ $\Delta R=0.5$, $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R($jet,l$) > 0.5$

- 7 TeV particle-level comparisons:
  - Sherpa2$b^2$, NLO ME Z+0/1 + LO ME $\leq 4$ jets
  - POWHEG+Pythia6, NLO ME Z+1 jets
  - Madgraph+Pythia6, LO ME Z+$\leq 4$ jets

- 8 TeV particle-level comparisons
  - Sherpa2, NLO ME Z+0/1/2 + LO ME $\leq 4$ jets
  - Madgraph+Pythia6, LO ME Z+$\leq 4$ jets

CMS-PAS-SMP-12-017
CMS-PAS-SMP-13-007

See B. Bilin’s poster
**Z+jets, 7 and 8 TeV**

**Overall good description of inclusive multiplicity**

CMS Preliminary

$\sqrt{s} = 7$ TeV $L_{\text{int}} = 4.9$ fb

- $\sigma_{\text{dN}}$ [pb]
- $\sigma$ [pb]

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

7 TeV

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

8 TeV

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

Inclusive jet multiplicity

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Statistical un. (gen)
Z+jets, 7 TeV: jet $p_T$
Z+jets, 8 TeV: jets $p_T$

1st jet spectrum: data/MC ratio similar to 7 TeV Sherpa2: 2nd jet spectrum in better agreement (addition of Z+2 jets NLO compared to 7 TeV)
**Z+jets, 7 and 8 TeV: scalar sum of jets \( p_T \)**

- **7 TeV**
  - CMS Preliminary
  - \( H_T, N_{jets} \geq 1 \) [GeV]
  - \( d\sigma/dH_T \) [pb/GeV]
  - Data
  - Sherpa2 (0.1@NLO ≤ 4@LO + PS)
  - Powheg+Pythia6 (Z+1@NLO + PS)
  - MadGraph+Pythia6 (≤ 4@LO + PS)

- **8 TeV**
  - CMS Preliminary
  - \( H_T, N_{jets} \geq 1 \) [GeV]
  - \( d\sigma/dH_T \) [pb/GeV]
  - Data
  - Sherpa2 (0.1@NLO ≤ 4@LO + PS)
  - MadGraph + Pythia6 (≤ 4@LO + PS)

**Statistical uncertainties:**
- Theory/Data
  - 0.5
  - 1
  - 1.5

**H_\( 1 \) distributions show a similar trend to \( p_T \)**

Different PDFs (CT10, MSTW2008, NNPDF2.1) produces very similar results.
Z+jets, 8 TeV, leading jet double differential cross section

- Analysis similar as SMP-13-007
- Use only decays into muons
- Extend jets acceptance in the forward region

- Phase space:
  - Jets: anti-$k_T$ $\Delta R=0.5$
  - $p_T > 30 \text{ GeV}, |\eta| < 2.5$
  - $p_T > 50 \text{ GeV}, 2.5 < |\eta| < 4.7$
  - $\Delta R(\text{jet, l}) > 0.5$

CMS-PAS-SMP-14-009
See B. Bilin’s poster
Madgraph overestimates by $\geq 10\%$ the 1$\text{st}$ jet $p_T > 100$ GeV tail at all $|\eta| < 3.2$
Z+jets, 8 TeV: \( Z \ p_T \) vs \( N_{jet} \)

- Same dataset and phase space selection as CMS-PAS-SMP-13-007
- But restrict ratio to \( \gamma+jets \) to \( p_T^Z > 100 \) GeV
  - \( N_{jet} \geq 1,2,3 \)
  - Scalar sum of jet \( p_T > 300 \) GeV
    - \( p_T^{jet} > 30 \) GeV

- Study of phase space selected in searches with missing \( E_T \)
- Meant for comparisons with \( \gamma+jets \) spectrum

- See A. Marini’s talk in QCD session
- See E. Takasugi’s poster

- Parton-level comparison with NLO ME
  - BlackHat+Sherpa for \( Z +1,2,3 \) partons
- Particle-level comparison with LO ME \( Z + \leq 4 \) jets
  - Magraph+Pythia6, Sherpa 1.4.2
Z+jets, 8 TeV: Z $p_T$ vs $N_{\text{jet}}$

- NLO: 10% differences for 1$^{\text{st}}$ jet
- LO ME overestimates the Z $p_T$ tail
Where higher multiplicities become dominant, fixed order NLO predictions becomes effectively LO.

Test limit of NLO calculation where $p_T^Z > H_T$, $p_T^Z > p_T^{j1}$
Summary

- Several (W,Z)+jets results produced by CMS during last year
  - First public presentation of Z+jets results on 2012 data at $\sqrt{s}=8$ TeV
- Comparisons with LO and NLO predictions are presented
  - Merged NLO multi-body calculations matched with parton showers start to be tested
- The theoretical description is overall good but shows some discrepancies
  - $b$ quarks collinear production not well described
  - Jet $p_T$ spectra associated to W,Z not very well reproduced by Madgraph+Pythia6 at high $p_T$
    - Effect visible on Z $p_T$ spectrum tail
  - NLO fixed order calculations have limitations in describing the inclusive jet spectra
BACKUP
Z+jets, 7 and 8 TeV: scalar sum of jets $p_T$

$H_T$ theory/data for $N_{\text{jet}} \geq 2$ has a similar behaviour to $N_{\text{jet}} \geq 1$
Z+jets, 8 TeV: Z $p_T$ at high $H_T$

- Z+1 jet NLO prediction breaks at $p_T^Z < H_T$ cut as expected
- LO predictions overestimate the high $p_T$ tail
  - Sherpa fails to reproduce most of the spectrum
Z+jets event shapes

- particle level comparison, normalized cross sections
- Madgraph +Pythia6, Sherpa 1.3.1 ME@LO
- POWHEG Z+1 jet ME@NLO
- Pythia6 PS

- $Z \rightarrow l(e, \mu)\nu$ decays
- 2011 data, 5 fb$^{-1}$, $\sqrt{s}=7$ TeV
- Unfolded at particle level

- 76 < $M_{ll}$ < 106 GeV
- Jets: anti-$k_T$ $\Delta R=0.5$, $p_T > 50$ GeV, $|\eta| < 2.5$, $\Delta R(jet,l) > 0.4$

- Phase space selected:
  - Leptons: $p_T > 20$ GeV, $|\eta| < 2.4$
### Z+jets event shapes

- **Boosted events:** $p_T^{Z} > 150$ GeV
- **Topology** important as background for searches with missing $E_T$

- Madgraph ~ ok apart low $\tau$
- POWHEG and Sherpa within ~ 10% on most of the ranges

- Pure Pythia6 PS works better at high $p_T^{Z}$
- Large phase space for parton emission

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**04/07/2014**

F. Cossutti

25
Z+1 jet rapidity

CMS-SMP-12-004
PRD 88 (2013) 112009

- Z/jet level comparison
- MCFM, Sherpa 1.3.1, Madgraph+Pythia6 using CTEQ6.6M PDF
- Z, jet rapidities well reproduced

- $Z \rightarrow l(e, \mu)\nu$ decays
- 2011 data, 5 fb$^{-1}$, $\sqrt{s}=7$ TeV
- Unfolded at Z/jet level

- Phase space selected:
  - Leptons: $p_T > 20$ GeV, $|\eta| < 2.1$
  - 76 < $M_{ll}$ < 106 GeV, $p_T^{ll} > 40$ GeV
  - Jets: anti-$k_T$ $\Delta R=0.5$, $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R(\text{jet}, l) > 0.5$
Z+b/bb jets

- Z → l(e,μ)ν decays
- 2011 data, 5 fb⁻¹, √s=7 TeV
- Only one or at least 2 b jets
- Cross sections at particle level

Phase space selected:
- Leptons: p_T > 20 GeV, |η| < 2.4
- 76 < M_{ll} < 106 GeV
- b jets: anti-k_T ΔR=0.5, p_T > 25 GeV, |η| < 2.1, ΔR(jet,l) > 0.5

Madgraph/aMC@NLO 5F in good agreement, MCFM ~2σ lower
Z+b/ bb jets kinematics

- Most kinematic observables well reproduced by Madgraph 5F
- $p_T^Z$ has a harder spectrum in data
Z+BB hadrons angular correlations

- $Z \rightarrow l(e,\mu)\nu$ decays
- 2011 data, 5.2 fb$^{-1}$, $\sqrt{s} = 7$ TeV
- Exactly 2 B hadrons
- Cross sections at particle level
- Both $p_T^Z = 0$ and > 50 GeV

- Phase space selected:
  - Leptons: $p_T > 20$ GeV, $|\eta| < 2.4$
  - $81 < M_{ll} < 101$ GeV
  - B hadrons: $p_T > 15$ GeV, $|\eta| < 2$

- Alpgen 4F provides best agreement
- Madgraph 5F not optimal in the collinear region
- Z boost improves cross section agreement

**CMS-EWK-11-015**
**JHEP 12 (2013) 039**
$W \rightarrow \mu \nu$ decays
2011 data, 5 fb$^{-1}$, $\sqrt{s}=7$ TeV
Exactly and only 2 b-tagged jets

Phase space selected:
- Muon: $p_T > 25$ GeV, $|\eta| < 2.1$
- $M_T(\mu,E_{T}^{miss}) > 45$ GeV
- b jets: anti-$k_T$ $\Delta R=0.5$, $p_T > 25$ GeV, $|\eta| < 2.4$

$\sigma(W\bar{b}b) \times BR(W \rightarrow \mu \nu) = 0.53\pm0.05(\text{stat})\pm0.09(\text{syst})\pm0.06(\text{th})\pm0.01(\text{lum}) \text{ pb}$
Corrected MCFM = $0.55\pm0.03(\text{MCFM})\pm0.01(\text{had})\pm0.05(\text{DPS})$