W/Z + jets and W/Z + heavy flavor production at the LHC

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on behalf of the ATLAS and CMS collaborations

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Motivation for studies of jets produced with a $W$ or $Z$ boson

- “Standard Model Candle”; well-understood control region to test pQCD calculations; validation of detector performance
- An irreducible background to SM measurements ($\bar{t}t$, single top, VBF, WW-scattering) and new physics (Higgs, SUSY, etc)
- Foundation for development of novel pQCD calculations; choices of scales, jet-parton matching schemes, and parton showering
  - Alpgen, Sherpa, MCFM, BlackHat-Sherpa, Madgraph, etc.
Motivation for studies of associated production of heavy flavor ($b$- and $c$-) jets and a gauge boson

- Constraints on PDFs of the heavy quarks
- The final states are tricky to calculate $\rightarrow$ the experimental input is key for future theory developments
- The LHC gives sensitivity to a different phase-space than the Tevatron:
  - $pp$ instead of $p\bar{p}$ (better probe of sea quark and gluons)
  - 7 TeV instead of 1.96 TeV (wider reach in transferred momenta)
Observables

- Cross sections and their ratios
  - Inclusive $\sigma(V + \geq N \text{ jets})$
  - Differential: e.g. $d\sigma/dp_T(N^{\text{th}} \text{ jet})$
  - Ratios of cross sections: $\sigma(V + \geq N \text{ jets})/\sigma(V + \geq N-1 \text{ jets})$ → Cancelation of uncertainties

- Those are often calculated for phase-space resembling the detector acceptance
  - $W$’s and $Z$’s are identified using central electrons and muons
  - Anti-$k_T$ jets with $R=0.4$; $p_T^{\text{jet}} > 20, 25, \text{ or } 30 \text{ GeV}; |y^{\text{jet}}| < 2.1 .. 4.4$
  - Identification of heavy quarks ($b$- and $c$-) utilizes secondary vertices (lifetime and mass)
  - Understanding of backgrounds is the key issue
Backgrounds to $Z+\text{jets}$ ($Z\to\text{ee}$ or $Z\to\mu\mu$)

- Irreducible backgrounds ($tt$, $Wt$, $WZ$, $ZZ$, $WW$, and $Z+\gamma$) are small and estimated using simulations.
- "fake" (non-prompt) leptons are from multi-jet and $W+$jet production and are obtained using data.
- $b$-tagging enhances the fraction of $tt$ and diboson events (backgrounds with fake leptons become negligible) by $\sim 2$. 

![Graph showing event distribution]
Backgrounds to $W+$jets

- Nicely complements the $Z+$jets processes with higher statistics, different background composition, and sensitivity to different PDFs
- Multi-jet events is a significant background at low jet multiplicities $\rightarrow$ **Important to do electron and muon channels simultaneously**
- The top quark pair production becomes the dominant background at high jet multiplicity (at 3-4) $\rightarrow$ One of the limiting factors

![Graph showing number of events vs exclusive jet multiplicity](image)

![Graph showing events vs inclusive jet multiplicity](image)
The message on backgrounds to V+jets events

- Background in Z+jets production is low
- The top pair production and multijet events are the most significant backgrounds to W+jets:
  - $t\bar{t}$ events are dominant when the jet multiplicity is high ($\geq 4$ jets)
  - Multi-jet backgrounds are dominant at lower jet multiplicities.
- Top pair production becomes the dominant background to W+b-jets (when a b-tagged jet is required)
  - Limits our ability to measure cross-section for $W+bb$⁻
  - Require exclusively a b-tagged jet to measure the $W+b$ cross section
- Beneficial to study Z+jets and W+jets production in parallel:
  - Sensitive to similar physics processes
  - Sensitive to different detector effects and backgrounds
Systematic Uncertainties

- Dominated by the uncertainty on the jet response (JES)
  - Increases for forward jets and decreased with jet $p_T$
  - $b$-tagging efficiency is important for the corresponding channels ($W+b$, $Z+b$, $Z+bb$)
W+jets: Jet multiplicity

- Accurate predictions require ME+PS approach (Alpgen, MadGraph, & Sherpa); PS-only simulations (Pythia) fail at high jet multiplicity, >1 jet
- Crucial for multiple measurements and searches (e.g. separation between WW and tt; BSM searches using high jet multiplicities)
- NLO calculation (BlackHat-Sherpa) are superbly accurate.
Z+jets: Multiplicity

- Complements the W+jets results; different backgrounds and colliding partons
- Good agreement with NLO and ME+PS predictions (within statistics)
Ratios of cross sections: $\sigma(\text{V+ N}_{\text{jet}})/\sigma(\text{V+N}_{\text{jet}}-1)$

- Cancelation of systematic and theory uncertainties $\rightarrow$ Robust way to compare data and theory

- CMS results in the two previous slides.

ATLAS: $Z \rightarrow \ell\ell$
W+charm

- Constraints the strange quarks density function (PDF)
- Utilized decay length from “simple secondary vertex high-efficiency” algorithm (SSVHE)
Measurement of W+b, Z+b and Z+bb production

- Test of perturbative QCD and heavy-flavor quark PDF’s
- \( t\bar{t} \) background is the limiting factor to measure \( W+b\bar{b} \) (2 b-jets)
- Background to the associated Higgs (WH, \( H\rightarrow b\bar{b} \)) and top production

<table>
<thead>
<tr>
<th>Final state</th>
<th>( \sigma ) Measured [pb]</th>
<th>( \sigma ) Expected [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z + \geq 1 ) b-jet + jets</td>
<td>3.78±0.05(stat) ±0.31(syst) ±0.11(theory)</td>
<td></td>
</tr>
<tr>
<td>( Z + \geq 2 ) b-jet + jets</td>
<td>0.37±0.02(stat)±0.07(syst)±0.02(theory)</td>
<td>LO: 0.33±0.01(stat)</td>
</tr>
</tbody>
</table>

At CDF the measured cross section is higher than the theory prediction

**ATLAS: Z+b+jets**

<table>
<thead>
<tr>
<th></th>
<th>( \sigma ) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>3.55±0.82(stat)±0.73(syst)±0.12(lumi)</td>
</tr>
<tr>
<td>MCFM</td>
<td>3.88±0.58 pb</td>
</tr>
<tr>
<td>ALPGEN</td>
<td>2.23±0.01 (stat only) pb</td>
</tr>
<tr>
<td>SHERPA</td>
<td>3.29±0.04 (stat only) pb</td>
</tr>
</tbody>
</table>
Z+bb $\rightarrow$ Angular separation

- $Z\rightarrow$ee and $Z\rightarrow$\(\mu\mu\)
- Jets are not used; reconstructed B-hadrons, $B\rightarrow D+X$, using secondary vertices
  - $p_T(B) > 15$ GeV $\&\& |\eta(B)| < 2.0$

![Graphs showing angular distribution for $Z+1p$ and $Z+2p$ events.](image)
Kinematic properties of jet production: $p_T$

- Well reproduced by NLO and LO (ME+PS) predictions

**ATLAS: $Z \rightarrow \ell \ell$**

\[
\int L \, dt = 36 \, \text{pb}^{-1}
\]

- anti-$k_T$ jets, $R = 0.4$, $p_T^{\text{jet}} > 30$ GeV, $|y^{\text{jet}}| < 4.4$

**ATLAS: $W \rightarrow \ell v$**

- $W \rightarrow \ell v +$ jets
- $W \rightarrow \nu v +$ jets
- $W \rightarrow$ jets
- $W \rightarrow \nu v$
\( \frac{d\sigma(W+1\text{jet})/dp_T}{d\sigma(Z+1\text{jet})/dp_T} \)

- Ratio of differential cross sections
- Cancelation of uncertainties → Precision measurement
- Well reproduced by NLO and LO (ME+PS) predictions as well
Searches for heavy particles use $H_T$ (scalar sum of $p_T$ of all reconstructed objects) or $M$(jets); the discrepancy is by definition.

They are often used as a scale in NLO calculations:

- The choice of scales evolved $M(W) \rightarrow M(W)+p_T(W) \rightarrow H_T$ (or $M$(jets))
Jets in the future measurements (VBF and WW-scattering)

- Future observations of VBF and WW-scattering will rely on our understanding of forward jets and rapidity gaps between jets.
  - W, Z, and H bosons via VBF
Conclusions and Outlook

- Mostly good agreement between NLO and ME+PS predictions and data
- Accuracy of the measurement is already systematically limited by uncertainties on the JES and b-/c- tagging efficiencies
- Novel NLO calculations (BlackHat-Sherpa) prediction work well up to V+4 jets!
- The comprehensive set of measurements enable development of future ME+PS simulations (Alpgen, Sherpa, etc)
  - Currently we have up to W+5p and Z+5p → will be up to V+8p or V+10p
- Precise understanding of the kinematic variables is crucial for the future measurements. (WW-scattering, searches for BSM, etc)
References

- “Measurement of the Z/γ* +bb-jet cross section in pp collisions at √s=7 TeV with the CMS detector”, (The CMS collaboration), CMS-PAS-SMP-12-003
- “A measurement of the ratio of the W and Z cross section with exactly one associated jet in pp collisions at √s = 7 TeV with ATLAS”, PLB 708 (2012) 221-240
- “Jet Production Rates in Association with W and Z Bosons in pp Collisions at √s = 7 TeV”, (The CMS Collaboration), arXiv:1110.3226
- “Observation of Z+b, Z→ee, μμ with CMS at √s = 7 TeV”, CMS-PAS-EWK-10-015
- “Measurement of associated charm production in W final states at √s = 7 TeV”, (The CMS Collaboration), CMS-PAS-EWK-11-013
NLO calculation for $H_T$

- Each NLO sample contains one additional emission beyond the base number of parton emission
- Events with high HT contain multiple jets → The conventional NLO calculations does not access the phase space
- Exclusive (matched) some of NLO calculations describes the high-$H_T$ tail well
Charge asymmetry in multi-jet events

- Well predicted with ME+PS simulations
- Many uncertainties cancel out
- Sensitive to new physics
Rapidity of jets; di-jet separation

- ATLAS provides great coverage for rapidity of jets.  \( \Delta R(\text{First Jet, Second Jet}) \)
- Required for development of ME-PS simulations
- Jet kinematic distributions are key for WW-scattering and VBF
Backgrounds to $Z^+$ heavy-flavor jets

- Require a b-tagged jet with $p_T > 20$ (CMS): 25 (ATLAS) GeV

- b-tagging enhances the fraction of $t\bar{t}$ and diboson events (backgrounds with fake leptons become negligible) by $\sim 2$

- $Z^+$ light-flavor jets is still the major background
Evaluation of the multi-jet and top pair backgrounds in the $W+\text{jets}$ sample

- Data-driven: Fit observed distributions using templates for signal and backgrounds
  - ATLAS analysis: 1D fit using distributions in missing-$p_T$
  - CMS analysis: 2D fit in $m_T(W)$ vs. number of $b$-tagged jets (to constrain $t\bar{t}$)

- The evaluation was done separately for each jet multiplicity sample
Backgrounds to $W^+$ heavy flavor jets

- Require a b-tagged jet (or with a secondary vertex to ID charm)
  - The $t\bar{t}$ background is too high when two b-jets are required
- Use the secondary vertex mass to distinguish between light-flavor, charm-, and b-jets.
- Use the decay length to identify charm jets

**ATLAS**

- Muon + 1 or 2 Jets
  - $\int L dt = 35 \text{ pb}^{-1}$

**CMS preliminary**

- 36 pb$^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$

- Data
  - $W^+$+charm
  - $W^+$+light
  - top
  - Other bkgd.