Recent results on vector boson production in association with jets

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On behalf of the ATLAS collaboration

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Outline:

- Motivation and overview
- ATLAS experiment
- $Z + \text{jets}$ – event and scaling factors, based on 2011 data analysis
- $W + \text{jets}$ – event properties, based on 2010 data analysis
- $W/Z$ event ratio
- $Z + \text{jets}$ VBF analysis
- $W + \geq 1$ b-jets cross section
- $W + \text{charm hadron}$ cross section
- Conclusions
Motivation and overview

- Drell-Yan production of W and Z bosons can be used to test perturbative QCD calculations
  - Inclusive analysis, integrated and rapidity dependent cross-sections
  - Test Parton Distribution Functions (PDFs)
  - Boson $P_T$ and $\phi$ measurements, in boosted W/Z analysis
    - Understanding interplay between High Order QCD and re-summation
  - Analysis with jet reconstruction – Z+jets, W+jets, W/Z in association with Heavy Flavor jets
    - Probe High Order QCD and constrain Parton Densities

- Monte-Carlo modeling
  - Parton Shower and Matrix Element approaches need test and tuning

- Measurements
  - Major background to precision SM measurements and searches for new physics
The ATLAS experiment

Excellent level of performance of ATLAS experiment, during years 2010 (36pb⁻¹) and 2011 (4.66fb⁻¹)
- Allowed precise SM measurements

- **Electrons**: EM calorimeter and tracking up to $|\eta|<2.5$
- **Muons**: Muon spectrometer up to $|\eta|<2.7$
- **Jets, MET, forward electrons**: Calorimetric coverage up to $|\eta|<4.9$
Z+jets: jet multiplicity and jet $P_T$

Increased statistics allow an extension of 2010 measurements

- Jet multiplicities up to 7 jets
- Jet $P_T$ up to 700 GeV

Event selection:

- Lepton $P_T > 25$ GeV
- $Z\rightarrow ee$ or $Z\rightarrow \mu\mu$ + jets ($PT > 30$ GeV, $|y| < 4.4$)
- $66$ GeV < $m(ll)$ < 116 GeV

Background:

- $N_{jet} \leq 1$: multi-jet (QCD), di-boson
- $N_{jet} > 1$: top-pair production

Good agreement with BlackHat + Sherpa calculations and with predictions from ALPGEN, SHERPA

The MC@NLO parton shower underestimates observed rate for additional jet emission by a factor of two
Z+jets: scaling properties

Scaling properties are useful in analysis that employ jet vetoes and separate signal from W/Z+jets backgrounds

Ratio of cross sections for successive jet multiplicities

Data compared to NLO pQCD predictions from BlackHat+Sherpa, and ALPGEN and Sherpa event generators

Exclusive ratios: \( R_{(n+1)/n} = \frac{N_{Z+(n+1)}}{N_{Z+n}} \)

Exclusive jet multiplicities with two benchmark patterns, both well reproduced by the theory predictions:

- Staircase scaling: \( R_{(n+1)/n} \) constant, linear fit from \( R_{2/1} \) – \( R_{5/4} \) describes
  \[
  R_{(n+1)/n} = R_0 + \frac{dR}{dn} \times n
  \]

- Poisson scaling, with asymmetric jet PT follows:
  \[
  R_{(n+1)/n} \sim \frac{1}{n}
  \]
Z+jets: $P_T$ of recoiled Z boson

NLO fixed order $Z+\geq 1$ jet underestimate cross section above $P_T \approx 80 \text{GeV}$
- At large $P_T$ 2-jet events contribute
- Use exclusive sum of NLO calculations to have better agreement

Good Theory-Data agreement in exclusive sample (=1jet)
- 2 jet events are vetoed

Both ALPGEN and SHERPA predict harder $Z$ $P_T$ spectrum
Z+jets: Vector Boson Fusion (VBF)

• A veto on a third jet is used to reject Z+jets background in VBF Higgs analysis
• Study of Z+jets events with VBF selection allows to estimate 3rd jet veto efficiency

VBF signature:
• Two forward jets (large $\Delta y(j,j)$ separation)
• High di-jet mass
• Central jet gap

PT distribution of the 3rd jet after VBF-like selection -> Predictions are consistent with data

<- Fraction of events passing veto requirements on 3rd jet in central region, as function of veto scale

The overestimate of $R_{2/3}$ in ALPGEN leads to an underestimation of the efficiency (in the low PT regime), SHERPA prediction agrees better with the data
**W+jets: jet multiplicity and $P_T$**

W+jets complementary to Z+jets

Background to:
- SM processes: ttbar, single-top production
- Higgs searches and searches beyond SM

**Event selection:**
- Lepton PT $> 20$ GeV
- W-$\nu$ or W-$\mu$ + jets (PT$>30$ GeV, $|y| < 4.4$)
- MET$>25$ GeV, MT$>40$ GeV

Good agreement with ALPGEN and BLACKHAT+SHERPA

Worse with SHERPA
**W+jets / Z+jets event ratio**

- Allows to exploit the cancellation of theoretical and experimental uncertainties
  - Common systematic uncertainties, such as JES uncertainty, reduces systematics of the V+jets measurement

- Provides model independent sensitivity to the physics coupling to leptons and jets

- Ratio of W+jets / Z+jets as a function of jet $P_T$ threshold in exclusive 1 jet bin

  \[
  R_{jet}(X) = \frac{W + jets(X)}{Z + jets(X)}
  \]

- Comparison with LO and NLO predictions shows agreement with the data

- With larger data samples from 2011 and 2012 will become very precise measurement
W+jets: double-parton interactions

- Two parton scatterings in the same pp-collision, experimentally measured as W+2jets
- Fraction of DPI events in W+2jets data extracted from template fit to normalized transverse momentum balance of two jets
  - jets $\text{PT}>20\text{GeV}$, $|y|<2.8$
- Rate and kinematics in good agreement with predictions of MC models and with previous measurements at lower energies

\[
d\sigma^{(\text{tot})}_{Y+Z} = d\sigma^{(\text{SPI})}_{Y+Z} + \frac{d\sigma_Y \times d\sigma_Z}{\sigma_{\text{eff}}}
\]
W+b-jets

- Important test for pQCD in presence of HF quarks
  - Modeling HF production in initial state (PDF) and final state (gluon splitting)
- Competing flavor schemes:
  - **Single b final states**, require heavy flavor in initial state, modeled by 5FNS
  - **Two b final states** modeled by 4FNS (u, d, c, s)
- Background to Higgs (WH, ZH), Single-top measurements and to new physics Searches

**Compared with NLO (MCFM and Powheg)**
- MCFM corrected for hadronization and DPI effects
- Powheg corrected for DPI effects

**Compared with LO (Alpgen)**
- Scaled to NNLO inclusive W

**Total uncertainty in prediction (yellow bars)**
- From variations of the normalization and factorization scales, PDF set, DPI model and non-perturbative corrections

Measurements are consistent within 1.5 σ with NLO predictions in 1-jet and 1+2-jet bins
**W+b-jets: b-jet $P_T$**

Large data-sets allowed measurement of differential cross-section as a function of the b-jet PT, for the first time

- Single-top and other backgrounds are subtracted
- Predictions are in agreement with data, within their uncertainties
  - Disagreement larger at high b-jet PT
W + charm hadron cross section

- s-quark is poorly known compared to light quarks, W+c can be used as probe
- Maximum correlation in W+c for s(x) at x ~ 0.02
  - Large sensitivity to s(x) for 0.0001 <= x <= 0.1
D±/D*± decays reconstructed in tracker
Charge correlation between the leptons from W and D(*) used to extract single-charm component: subtracted same-sign contribution (OS – SS)
Yield extracted by fitting the D± mass or D*-D0 mass diff. in OS-SS

Event selection:
W -> eν or μν + charm hadron (D)
D meson reconstructed in D*-→K-π⁺π⁺ and D*+→D0π⁺ with:
- D0→K-π⁺, D0→K-π⁺π⁰ or D0→K-π⁺π⁻π⁺

Measured cross sections compared to a MC@NLO predictions, based on different PDF predictions
- Inner error bar is PDF uncertainty
- Outer error is quadratic sum: PDF +scale+frag
Good agreement with epWZ and NNPDF2.3coll sets
- S-quark enhanced PDFs are favored
- Confirms preference for SU(3) symmetric sea
Summary

• Experimental uncertainties are becoming smaller than theoretical predictions, in large regions of phase space, with 2010-2011 data
  • Higher jet multiplicities and $P_T$ ranges

• Experimental study provides insight on QCD models
  • Construction of PDF: flavor symmetric light quark sea favored ($W+c$ studies)
  • Impact of missing higher jet multiplicity and modification by exclusive summation ($W/Z+jets$)

• Input to Higgs and new physics searches
  • Validation of 3$^{rd}$ jet veto in VBF selection

• More high precision results will come with 2012 ATLAS data
Backup
W+jets: scalar $P_T$ sum (HT)

$H_T = \sum_{\text{leptons, jets}} |p_T|$

- $H_T$ is sensitive to factorization and normalization scales in fixed-order calculations
- Discrepancy at large $H_T$ (higher jet multiplicity) in BLACKHAT due to limited order of calculations
- Agreement improved on $H_T$ with BlackHat by replacing NLO $W+\geq1$ jet with exclusive sum:
  - $W+\geq1 = (W+1) + (W+2) + (W+3) + (W+\geq4)$
  - Confirmed by $Z+$jets analysis
Jet Reconstruction

Calorimeter cells calibrated to electromagnetic (EM) scale

- Input to jet reconstruction
  - 3D topological clusters
    - Uses nearest neighbor energy significance to localize showers in calorimeter
    - Efficient noise suppression
- Jet reconstruction
  - Jets are reconstructed using the anti-Kt algorithm with size parameter R set at 0.4
- Jet Calibration
  - Energy and momentum of a jet measured in the calorimeter are corrected
    - For non-compensation, energy losses in dead material, shower leakage
Jet Energy Scale

- 2010 JES calibration from MC
- Uncertainties from MC, single hadron response and dijet balance validated using in-situ techniques

- 2011 JES calibration from MC with corrections using in situ technique
  - Uncertainties from in-situ techniques
Impact of W, Z data on PDF

- Little is known about s-quark, current information from neutrino-nucleon scattering
- Flavor SU(3) symmetry suggest equal light sea quark distributions
- But strange quarks might be suppressed due to mass effect
- W, Z differential cross section measurements sensitive to s-PDF at Bjorken \( x \approx 0.01 \)
  - Use ATLAS W,Z and HERA ep data in HERAFitter (NNLO) -> epWZfit

\[
r_s(0.023, 1.9\text{GeV}^2) = 1.00^{+0.25}_{-0.28}
\]
Z+jets scaling

- Poisson scaling, well known in FSR QED from e+e- colliders, when large difference between the scale of the process Q and the radiation cut-off scale Q0
  - For Q>>Q0 each emission is independent from previous one
- At hadron colliders, QCD jet radiation of the initial state partons has huge impact.
  - Poisson scaling \((R_{n+1}/n = \langle n \rangle/n+1; P_n = \langle n \rangle^n e^{-\langle n \rangle} / n!)\) – Abelian
    - With large leading jet PT cut, we move to sufficiently high x, such that additional jet ratios are unaffected by the PDF
  - Staircase scaling \((R_{n+1}/n = e^{-b}; \sigma_n = \sigma_0 e^{-bn})\) – non Abelian
    - Appears with democratic jet selection and no major scale separation
    - \(R_{1/0}\) suppressed by PDF (by 60%)
Z+jets: ratio

- Ratio of the cross sections for two successive multiplicities, in events passing the VBF pre-selection
W, Z cross sections

- Uncertainties dominated by lepton reconstruction, identification efficiency and Missing ET for W

<table>
<thead>
<tr>
<th>Electron channels (%)</th>
<th>$W^\pm$</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>$Z$</th>
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<tbody>
<tr>
<td>Trigger</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
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