Inclusive $W$, $Z$ and $W/Z$+jets Production at the LHC

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On behalf of the ATLAS and CMS collaborations

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Introduction

- Studies of Vector boson production play several important roles in the physics program of the LHC:
  - Provide important tests of QCD calculations.
  - Constrain parton distribution functions.
  - Non-negligible backgrounds for many searches.
  - Valuable control samples.
- First time probing:
  - Jet multiplicities up to 7.
  - Jet $p_T$ in TeV range.
- V+jets cross sections span 5 orders of magnitude.
- Will summarize a selection of recent results.
Introduction

- Recent advances in predictions:
  - New higher-multiplicity calculations at NLO available in recent years
  - Many aspects need data to validate and tune, e.g. choice of scale, matrix element/parton shower matching, flavor schemes
  - Overall good agreement over many measurements and jet multiplicities
Z \ pT

- Sensitive to ISR, intrinsic $p_T$ of partons at low $p_T$, and pQCD at high $p_T$
- Useful to constrain parton shower parameters
- Needed for W mass measurement
- After background subtraction, data unfolded in $|y|<1$, $1<|y|<2$, & $2<|y|<2.4$ regions
- Uncertainties $\sim 1\%$ for $p_T < 100$ GeV
- Used to tune parton shower model in generators

JHEP09(2014)145
Prediction/Data

- Overall good agreement with predictions; see a few known features of predictions
- Unfolded results used to tune Pythia8 and Powheg+Pythia8 parton shower
- Tuned predictions agree to within 2% in range used for tuning
(Z+γ*)/γ Ratio

- Ratio expected to be constant in limit of high $p_T$ where Z mass term can be neglected - plateau at high $p_T$
- Provides information useful to inform about possible log contributions in calculations at higher $p_T$
- Analysis performed for $p_T(Z/\gamma) > 100$ GeV and then four kinematic regimes considered: nJets ≥ 1, 2, 3, and $H_T > 100$ GeV
- Result compared to LO MadGraph+Pythia6 prediction
- Observe ~20% normalization difference in ratio. Higher-order corrections expected to be smaller than experimental uncertainties
Drell-Yan $A_{FB}$

$$\frac{d\sigma}{d(\cos\theta)} = A(1 + \cos^2 \theta) + B \cos \theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- Sensitive to $\sin^2 \theta_W$
- “Forward” direction most likely to be along direction of $Z$ boson $z$-momentum direction (quark vs. gluon PDF)
- Collins-Soper frame used to reduce effects of $p_T$ of incoming quarks
- Weak-EM interference — Expect:
  - $A_{FB} < 0$ below $Z$ pole
  - $A_{FB} > 0$ above $Z$ pole
- Interference from NP would alter the expected asymmetry

CMS-PAS-SMP-14-004
Z Angular Coefficients

\[
\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \left[ (1 + \cos^2\theta^*) + A_0 \frac{1}{2} (1 - 3\cos^2\theta^*) + A_1 \sin(2\theta^*) \cos\phi^* + A_2 \frac{1}{2} \sin^2\theta^* \cos(2\phi^*) \\
+ A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin^2\theta^* \sin(2\phi^*) + A_6 \sin(2\theta^*) \sin\phi^* + A_7 \sin\theta^* \sin\phi^* \right].
\]

- First measurement at LHC
- Play important role in future measurements of W mass and weak mixing angle
- \(A_i(q_T)\) are related to Z polarization, V-A structure of fermion-boson couplings, and electroweak parity violation
- Template fits for \(A_0 - A_4\) performed in Collins-Soper frame
- Performed as a function of boson transverse momentum \(q_T\) and rapidity \(y\)
- \(A_0(q_T)\) and \(A_2(q_T)\) larger than in ppbar collisions due to qg process at LHC
- Results compared to a variety of calculations and used to improve predictions

W Asymmetry

\[ A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+\nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+\nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^-\bar{\nu})} \]

- W\(^+\) produced more than W\(^-\) in pp collisions
- Sensitive to both valence and sea quark Parton Distribution Functions
- Measured as a function of \(\eta_\mu\)
- Asymmetry corrected for different efficiencies for \(\mu^+\) and \(\mu^-\)
- Result used along with HERA data to improve valence quark PDFs

CMS-PAS-SMP-14-022
W+Jets

- Useful to validate pQCD calculations over large kinematic range
- Dominant background for many SM measurements and Exotica searches
- Unfolded to particle level up to 7 jets
- Differential distributions studied for approximately 40 observables
- Data are compared with variety of NLO predictions
- Signal and Background modeled with MC, except for data-driven ttbar and multijet estimates
- Electron and Muon channels show agreement and are combined

W+Jets

- Large statistics sample allows thorough exploration of many distributions
- Jet $p_T$ explored to 1 TeV
- Various predictions show better agreement in different kinematic observables
- Valuable comparison between data and predictions for Monte Carlo developers
- Level of agreement varies somewhat across observables and predictions
Z+jets

- Useful to validate pQCD calculations over large kinematic range
- Background for many SM measurements and Exotica searches
- Full 8 TeV 20/fb dataset allows comparison over 20+ observables
- Predictions from MadGraph + Pythia normalized to NNLO from FEWZ and Sherpa2+Blackhat for 1-loop corrections
- Unfolded differential distributions in inclusive and exclusive jet multiplicities, $p_T$, $H_T$, $\eta$, for nJets up to 5

CMS-PAS-SMP-13-007
ATLAS 7 TeV: JHEP07(2013)032
Z+jets Double-differential $\sigma$

\[
\frac{d^2\sigma}{dp_T^j dy^j} = \frac{1}{\mathcal{L} \times \epsilon} \times \frac{N}{2 \times \Delta |y^j| \times \Delta p_T^j}
\]

- Muon channel unfolded double-differential distribution in $p_T$ and $y$ to 4.7
- Overall good agreement of MC predictions with data
- Discrepancies (10%) of MadGraph with measurement at higher $p_T$ (> 100 GeV)
- Overall agreement with Sherpa except in a few $p_T$ and $y$ ranges
- Discrepancy seen in 7 TeV data (both CMS and ATLAS) in 1-jet bin from 100-450 GeV remains

CMS-PAS-SMP-14-009
W+jets/Z+jets (R-jets)

- Systematics significantly reduced in ratio, esp. in dominant jet uncertainties, compared to individual V+jets measurements
- Precision test of pQCD
- Generic sensitivity to New Physics coupling to W or Z
- Updated result using 5/fb allows measurement of many kinematic distributions including $p_T$, $S_T$, $H_T$, $y$, $\Delta R$, $\Delta \Phi$, $m_{12}$, for $n_{Jets} = 0-3$.
- Signal and Background modeled with MC, except for data-driven ttbar and multijet estimates
- Electron and Muon channels show agreement and are combined

W+jets/Z+jets (R-jets)

- All observables studied both exclusively and inclusively to nJets=3
- Many distributions studied; overall predictions show good agreement with data
**Z+b(b)**

- Z+b probes b-quark content of proton
- Z+bb background for Higgs associated production and BSM searches
- Jets are tagged with Neural Net b-tagging using jet kinematics and impact parameter information
- Differential cross sections in 12 observables compared to NLO JHEP10(2014)141
- Iterative Bayesian (1-tag) and fiducial/efficiency (2-tag) unfolding to particle-level
- Fixed-order MCFM discrepant at $\Delta \Phi = \pi$. Likely because it includes at most 2 outgoing partons in association with Z

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Conclusions

• Vector Boson production is one of the most important benchmark channels at the LHC.

• Background for Higgs and many other measurements and searches — important to model well.

• Most measurements show good agreement over many observables; a few show some tension in some corners of phase space.

• Many precise measurements enable checks of predictions against many observables - should help improve predictions.

• Looking forward to studying V+jets in new energy regime at 13 TeV.
Backup
Particle-Level Final State Kinematics: Born, Bare, Dressed, Unfolded

- Born: Lepton Kinematics before FSR
- Bare: After FSR
- Dressed: Bare + Photons within cone of $\Delta R < 0.1$
- Unfolding: Correcting data for detector resolution, QED FSR, fiducial acceptance back to Born-level in order to facilitate comparison with predictions