# Z/W + jets production at 8/13 TeV in CMS

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#### Outline

- Introduction
- V + jets analysis strategy
- Z + jets @ 8 TeV, <u>CMS PAS SMP-13-007</u>, <u>CMS-PAS-SMP-14-009</u>
- W + jets @ 8 TeV, <u>CMS-PAS-SMP-14-023</u>
- Z + jets @ 13 TeV, <u>CMS-PAS-SMP-15-010</u>
- W + 2b jets @ 8 TeV, <u>CMS-PAS-SMP-14-020</u>
- Z + b jets @ 8 TeV, <u>CMS-PAS-SMP-14-010</u>
- Conclusions
- Back-up slides
- Most recent results of Z/W + jets measurements based on 8 TeV (2012, L ≤ 19.8 fb<sup>-1</sup>) and 13 TeV (2015, L = 2.5 fb<sup>-1</sup>) pp collision data will be presented
- Complete set of SM results can be found at
  - <u>http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html</u>

#### Introduction

- Production of vector boson in association with jets is an important SM benchmark
  - provides precision tests for pQCD calculations
  - helps to improve PDFs
- Constitute prominent background for several SM processes and BSM searches
  - Higgs production VH ( $H \rightarrow b\bar{b}$ ), single top, t $\bar{t}$ , VBF, ...
  - SUSY, dark matter, extra dimensions, ...
- Needed for detector calibration, testing MC based event generators, etc.

### V + jets analysis strategy

- Z and W bosons are reconstructed via their leptonic decays  $(Z/\gamma^* \rightarrow l^+l^-, W \rightarrow l\nu)$
- Lepton and jet candidates are reconstructed using Particle Flow (PF) algorithm based on information from all detector subsystems
- Anti-kt clustering algorithm for jets with R= 0.5 (0.4) at 8 TeV (13 TeV)
- Events containing isolated lepton(s) and hadronic jets are
  - restricted to a limited phase space where they are efficiently selected
  - corrected for data-to-simulation discrepancies in lepton selection, jet energy scale (JES) and resolution (JER) calibration, pileup, flavor tagging, etc.
- V+jets productions are characterized by measuring differential cross sections as a function of various observables (jet multiplicity, kinematics, angular correlations, ...)
- Measured cross sections are unfolded to particle level for detector effects and confronted by LO, NLO (+PS) predictions and NLO, NNLO fixed-order calculations

List of theoretical predictions in <u>back-ups</u>

### Z + jets at 8 TeV

- $Z(\rightarrow l^+l^-, l = \mu, e)$  + jets production, up to 7 jets and inclusive 5 jets on kinematics
- Phase space: p<sub>T</sub>(*I*)>20 GeV, p<sub>T</sub>(jet)>30 GeV and |η(*I*,jet)|<2.4 and <4.7</li>
- Predictions: MADGRAPH5+PYTHIA6, SHERPA2+BLACKHAT (NLO up to 2 partons)



Total cross section for MADGRAPH5 is normalized to the NNLO computed with FEWZ

Overall good data/theory agreement, MADGRAPH is harder for  $p_T(j_1)=150-450$  GeV

### W + jets at 8 TeV

- Production of W( $\rightarrow \mu v$ ) + jets,  $p_T(\mu) > 25$  GeV and  $|\eta(\mu)| < 2.1$ ,  $p_T(jet) > 30$  GeV and  $|\eta(jet)| < 2.4$ ,  $M_T(W) > 50$  GeV, up to 7 jets and inclusive 4 jets on observables
- Several predictions by (N)LO + PS, fixed-order NLO, NNLO for W + 1 jet in pQCD



MADGRAP5 LO tot. cross section is normalized to FEWZ NNLO

#### more in **back-ups**

MADGRAPH5\_AMC@NLO and NNLO describe data well on jet  $p_T$  and  $H_T$  (scalar sum of jets  $p_T$ )

## W + jets at 8 TeV

• Differential cross sections as a function of azimuthal correlations and rapidity separation among jets (and muon)



MADGRAP5 LO tot. cross section is normalized to FEWZ NNLO

Predictions describe data reasonably well, BLACKHAT+SHERPA fixed-order shows some tensions

## Z + jets at 13 TeV

- First measurement of Z + jets production using 13 TeV collision data (L = 2.5 fb<sup>-1</sup>)
- Require isolated muon pairs with  $p_T(\mu) > 20$  GeV and jets with  $p_T(jet) > 30$  GeV,  $|\eta| < 2.4$
- Comparisons by MADGRAPH 5\_AMC@NLO + PYTHIA 8 (NLO accuracy up to 2 additional partons merged using FxFx scheme) and NNLO prediction for Z + 1 jet



Good data description by MG5\_AMC@NLO and NNLO predictions

## W + 2b jets at 8 TeV

- Production of W( $\rightarrow lv$ ,  $l = \mu$ , e) +  $b\bar{b}$
- Signal region:  $p_T(I) > 30$  GeV and  $|\eta(I)| < 2.1$ ,  $p_T(b) > 25$  GeV and  $|\eta(b)| < 2.4$
- Likelihood fit to M<sub>T</sub>(W) in two tt control regions: fit in tt-multijet to estimate btagging efficiency scale factors and in tt-multilepton to adjust for JES in simulation
- Then, extract W+bb event yield by fitting in the signal region



## W + 2b jets at 8 TeV

• Measured cross sections in the muon, electron, and combined lepton channels

 $\sigma(pp \rightarrow W(lv) + b\overline{b})(\text{combined}) = 0.69 \pm 0.02(\text{stat}) \pm 0.11(\text{syst}) \pm 0.07(\text{theo}) \pm 0.02(\text{lumi}) \text{ pb}$ 

- Theory predictions: MCFM NLO, MADGRAPH 5 + PYTHIA 6 / PYTHIA 8 in 4FS / 5FS approach
  - MCFM is corrected for hadronization with a correction obtained from MADGRAPH 5 + PYTHIA 6
  - MCFM and MADGRAPH + PYTHIA 6 / 8 using 4FS do not account for the bb̄ system coming from DPS and for these generators the DPS contribution is estimated with MADGRAPH 5 + PYTHIA 8



Predictions agree with each other and are consistent with CMS data within their uncertainties

## Z + b jets at 8 TeV

- $Z(\rightarrow l^+l^-, l = \mu, e) + \ge 1$  b,  $\ge 2b$  productions, shortened as Z(1b) and Z(2b)
- Phase space:  $p_T(e) > 20$  GeV and  $|\eta(e)| < 1.44$  and  $1.57 < |\eta(e)| < 2.4$ ,  $p_T(\mu) > 20$  GeV and  $|\eta(\mu)| < 2.4$ ,  $p_T(b) > 30$  GeV and  $|\eta(b)| < 2.4$
- Measured fiducial cross sections for Z(1b), Z(2b), and their ratio in combined lepton channel:  $\sigma(Z(1b))(\text{combined}) = 3.55 \pm 0.12(\text{stat.}) \pm 0.21(\text{syst.}) \text{ pb}$

 $\sigma(Z(2b))$ (combined) = 0.331±0.011(stat.)±0.035(syst)pb

 $\sigma(Z(2b))/\sigma(Z(1b)) = (9.3 \pm 0.4(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-2}$ 

MADGRAPH 5 (4FS & 5FS) + PYTHIA 6 and POWHEG NLO (5FS) + PYTHIA 6 predictions



## Z + b jets at 8 TeV

- Ratios of cross sections between Z(1b) and Z+jets events are also measured
- Several systematic uncertainties cancel in ratios allowing improved precision



Ratios are generally better reproduced in 5FS (more in back-ups)

#### Conclusions

- CMS has an active physics program to measure vector boson production in association with jets including heavy flavor jets, providing unique precision tests for pQCD
- Measured W/Z + jets cross sections differential in various observables have been confronted by several predictions
  - Good agreement with NLO (ME + PS) predictions and with NNLO fixed-order
  - LO (ME + PS) shows some discrepancies
- Measured fiducial cross sections in combined lepton channel for W/Z + b jets production
  - Overall, differential distributions are reproduced consistently by the predictions
  - Encourages analyses of V + charm jets for the constraints on strange quark PDF
- Expect more V+jets results to come with 8 TeV and 13 TeV data!

## Thank you

## Back-ups

#### **CMS detector**

J. Phys.: Conf. Ser. 513 022032



## **Summary of theoretical predictions**

#### • Z+jets at 8 TeV

- MADGRAPH 5 + PYTHIA 6 using CTEQ6L1 PDF, ME + PS merged with kt-MLM
- SHERPA 2 + BLACKHAT (NLO up to 2 partons) using CT10 PDF, ME + PS merged with MEPS@NLO

#### W+jets at 8 TeV

- MADGRAPH 5 + PYTHIA 6 using CTEQ6L1 PDF, ME + PS merged with kt-MLM
- MADGRAPH 5\_AMC@NLO (ME using NNPDF3.0 and NLO accuracy up to 2 jets) + PYTHIA 8 (using NNPDF2.3)
- SHERPA 2 + BLACKHAT (NLO up to 2 partons) using CT10 PDF, ME + PS merged with MEPS@NLO
- BLACKHAT + SHERPA (fixed-order NLO up to 4 jets) using CT10 PDF
- NNLO prediction for W + 1 jet (<u>Phys. Rev. Lett. 115, 062002</u>) using CT14 NNLO PDF

#### • Z+jets at 13 TeV

- MADGRAPH 5\_AMC@NLO + PYTHIA 8 (NLO up to 2 partons merged using FxFx scheme) using NNPDF 3.0 PDF
- NNLO prediction for Z + 1 jet (see for example <u>arXiv:1602.08140</u>) using CT14 NNLO PDF

#### • W+bb at 8 TeV

- MADGRAPH 5 + PYTHIA 6 in 5FS using CTEQ6L PDF
- MADGRAPH 5 + PYTHIA 6 / PYTHIA 8 in 4FS using NNLO PDF, corrected for DPS
- MCFM NLO using MSTW2008 PDF, corrected for hadronization and DPS effects

#### • Z+b jets at 8 TeV

- MADGRAPH 5 + PYTHIA 6 in 5FS using CTEQ6L1 PDF
- MADGRAPH 5 + PYTHIA 6 in 4FS using MSTW2008 PDF
- POWHEG (NLO) + PYTHIA 6 in 5FS using CT10 PDF

Z2\* (CUETP8M1) tune is used in PYTHIA 6 (PYTHIA 8) consistently in analyses

## Z + jets production at 8 TeV

Double differential cross section for the same measurement (<u>CMS PAS SMP-13-007</u>), but in dimuon channel with an extended acceptance in jet rapidity, |y| < 4.7 (<u>CMS-PAS-SMP-14-009</u>)



#### **Consistent data/predictions for the forward jets**

#### W + jets (dijet $p_T$ and $\Delta R$ )





<u>back</u>

## V + heavy flavor jets

- Sensitivity to probe heavy quark content in the proton
- Important background processes to Higgs and searches
- Apply heavy flavor tagging to jets
- CMS Combined Secondary Vertex (CSV) b-tagging algorithm
  - Combines discriminating power of secondary vertex, impact parameter significance, and jet kinematics using multivariate analysis techniques
- CMS tests different flavor number schemes along with predictions
  - 4FS: no b quark PDF used, b-quark is massive produced explicitly through gluon splitting
  - 5FS: b-quark is treated massless and generated in the initial state, gluon splitting is included through a b quark PDF

#### Z + b jets additional





#### Z + 2b jets - asymmetry

- Asymmetry between the min. and max. distances for the Z boson and a b jet in Z(2b)
- Provide an indirect test of pQCD validity at higher orders



$A_{Zbb} =$	$(\Delta R_{Zb}^{max} -$	$\Delta R_{Zb}^{min}$ )
	$\overline{(\Delta R_{Zb}^{max} + $	$\Delta R_{Zb}^{min})$