Measurements of $V+\text{jets}$ production in CMS

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**Introduction**

- Electroweak vector boson (V=W, Z, and γ) plus jets at the LHC has several motivations:
  - copious production in pp collisions enables precision tests of the SM
  - stringent tests for MC event generators and perturbative QCD calculations
  - prominent backgrounds for SM processes and new physics searches
  - good probes for the quark and gluon PDFs in the proton
  - inputs for calibrating detector response (lepton, jet, and missing energy performances)

- W and Z boson are reconstructed via leptonic final states: Z/γ*→l⁺l⁻ and W→lν (l=e, μ)
- Prompt photons are reconstructed from isolated energy deposits in the electromagnetic calorimeter (ECAL)
- Their measurements are corrected for detector effects to fiducial phase space and compared with predictions from several MC event generators and theoretical calculations, where available

- **Presented here only the more recent V+jets results mostly based on 13 TeV pp collisions**

- **A complete set of CMS V+jets (and more SM) measurements can be found at:**
Summary of V+jets measurements

- CMS V+jets measurements at 7, 8, and 13 TeV span several orders of magnitude in cross section
- See M. Meena’s dedicated talk on V+HF measurements, presented in Monday’s Flavor II session!

- Differential cross section (xsec) measurements of several kinematical/angular variables at 13 TeV
  - W+jets: $p_T(\mu)>25$ GeV, $|\eta(\mu)|<2.4$, $p_T(j)>30$ GeV, $|y(j)|<2.4$, and $m_T(W)>50$ GeV
  - Z+jets: $p_T(l)>20$ GeV, $|\eta(l)|<2.4$, $p_T(j)>30$ GeV, $|y(j)|<2.4$, $71<m_{ll}<111$ GeV
- Comparison with (N)LO ME+PS, fixed-order NNLO, and NNLO+NNLL+PS predictions
- Generally, better agreement of the data with the (N)NLO predictions
- Probing W collinear emission off a jet with $\Delta R(\mu, j)$ and Z+jets imbalance with $p_T^{\text{bal}}$

\[
p_T^{\text{bal}} = |\vec{p}_T(Z) + \sum_{\text{jets}} \vec{p}_T(j_i) |
\]

- Triple differential xsecs as functions of $p_T(\gamma)$, $|\eta(\gamma)|$, and $|\eta(j)|$
  - γ isolation based on sum $p_T$ of all particles in a cone of radius $\Delta R=0.3$ is less than 5 GeV
  - $p_T(\gamma)=40$-1000 GeV, $|\eta(\gamma)|<2.5$, $p_T(j)>25$ GeV, and $|\eta(j)|<2.5$
  - 16 different combinations of $|\eta(\gamma)|$ and $|\eta(j)|$ regions

- Good agreement between data and GamJet NLO (using CJ15 PDF set and set II BFG fragmentation functions)

- Probing a wide range of $Q^2$ and $x_T$ with smaller experimental uncertainties compared to theory

- γ+jet measurements are potentially sensitive to gluon PDF in the proton

- Triple differential xsecs for γ+jet events, with γ isolation in a cone of ΔR=0.4
  - several shower shape and isolation variables used in an MVA (BDT)
  - fiducial selection: $E_T(γ)>190$ GeV, $|γ(y)|<2.5$, $|γ(j)|<2.4$, and $p_T(j)>30$ GeV
  - in the extended $E_T(γ)$ range up to 1 TeV for two photon and two jet rapidity ranges
- Compared with JETPHOX 1.3.1 NLO (using NNPDF3.0 PDF and set II BFG frag. functions)
  - reasonable agreement between data and predictions within uncertainties
  - the differences between predictions using different PDF sets are not sizable

for $|γ(y)|<1.44$ and $|γ(j)|<1.5$
• Differential xsec measurements for Z+jets, γ+jets, and their ratio
  – $p_T(V)>200$ GeV and $|y(V)|<1.4$
  – at least one jet with $p_T>100$ GeV and $|\eta|<2.4$
• First direct measurement of collinear emission of a Z boson with a jet based on the $\Delta R_{Z,j}$
  – require harder leading jet $p_T$ thresholds (>300 and 500 GeV) to enhance collinear emission
• Predictions by MG5_aMC at (N)LO, Sherpa+OpenLoops NLO QCD+EW, JETPHOX NLO (for γ)
• Predictions are generally in agreement with the data except some deviations in a few ranges of the distributions
• $Z/\gamma$ ratio provides input to help reduce uncertainties related to the $Z\rightarrow \nu\bar{\nu}$ bkg. estimation in new physics searches

The $Z/\gamma$ ratio is sensitive to higher order QCD and EW corrections at high $p_T$ range

$\Delta R_{Z,j}<2.5$ ($\Delta R_{Z,j}>2.5$) dominated by collinear (back-to-back) production

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Measurements of fiducial and differential xsec of $Z \rightarrow \nu\bar{\nu} + \text{jets}$ at 13 TeV

- Important background to searches with invisible decays (SUSY, dark matter, etc.)
- Neutrinos reconstructed indirectly through the $p_T$ imbalance in the event
- $p_T^{\text{miss}}>250$ GeV, and the leading jet $p_T>100$ GeV and $|\eta|<2.4$

- Measured fiducial xsec for $p_T(Z)$ 200-1500 GeV: $3000^{+180}_{-170}$ fb
- Prediction by MG5_aMC (NLO QCD+NLO EW): $2700\pm440$ fb

- Agreement within uncertainties with MG5_aMC, FEWZ, and NNLOJET at (N)NLO w/o NLO EW corrections
- Better description of data with MG5_aMC at NLO QCD+EW for $p_T(Z)>500$ GeV

- Combination with the $Z \rightarrow ll$ channel, results in improved precision for the measured differential $p_T(Z)$ xsec

Signal extracted from fits in signal region (to $p_T^{\text{miss}}$ distribution) and in two $W \rightarrow lv$ control regions
DPS with Z+jets *(CMS-PAS-SMP-20-009)*

- **Measurement of observables sensitive to the presence of DPS with Z+≥1-jet and Z+≥2-jet events**
  - Double parton scattering (DPS): two hard parton-parton interactions in a single pp collision
  - $p_T(\mu)>27$ GeV, $|\eta(\mu)|<2.4$, $p_T(j)>20$ GeV, $|\eta(j)|<2.4$, $70<m_{\mu\mu}<110$ GeV
- **Use $\Delta \Phi(Z,j)$ and $p_T$ imbalance $\Delta p_T^{\text{rel}}$ among the Z boson and jets**

\[
\Delta p_T^{\text{rel}}(A,B) = \frac{\hat{p}_T(A) + \hat{p}_T(B)}{|\hat{p}_T(A)| + |\hat{p}_T(B)|}
\]

$\Delta \Phi(Z,j_1)$ is expected to be flat (around $\pi$) in DPS (SPS)

$\Delta p_T^{\text{rel}}(Z,dijet)$ is expected to be at higher values (zero) in DPS (SPS)

- Jets balance each other in DPS production, whereas not in SPS

- **Predictions with MPI off are significantly lower than data in the DPS-sensitive regions**
- Other predictions are overall consistent with data except for CDPSTP8S1-WJ tune which overshoots data by ~10-20%
- Results are important to further improve DPS modeling in MC
Collinear, large-angle, soft, and hard radiations in $Z+2$-jet (also 3-jet) events

- Select events with $p_T > 25$ (5) GeV and $|\eta| < 2.1$ (2.4) for the lead (sublead) muon, $p_T(\mu^+\mu^-) > 80$ GeV and $|\eta(\mu^+\mu^-)| < 2$, $70 < m_{\mu\mu} < 110$ GeV, and $p_T > 80$ (20) GeV and $|\eta| < 1$ (2.4) for the lead (sublead) jet

- Measure $p_{T3}/p_{T2}$ ratio and angular distance $\Delta R_{23}$ from subleading jets

$$\Delta R_{23} = \sqrt{(y_3 - y_2)^2 + (\phi_3 - \phi_2)^2}$$

- Split events into categories using the classification scheme:

  - Soft radiation ($p_{T3}/p_{T2} < 0.3$)
  - Hard radiation ($p_{T3}/p_{T2} > 0.6$)

  - Collinear radiation (small-angle, $\Delta R_{23} < 1.0$)
  - Large-angle radiation ($\Delta R_{23} > 1.0$)

- Expect good description by PS
- Expect good description by ME

- Overall, good data description by all the MCs
- Predictions tend to underestimate $\Delta R_{23}$ at large $p_{T3}/p_{T2}$ in small- and large-angle regions
EW V+2 jets production

• Characterized by the presence of two high-$p_T$ jets with large separation in $\eta$ and low hadronic activity in-between

• Tests of the gauge structure of the EW sector (i.e., gauge boson self interactions) $\rightarrow$ sensitive to anomalous trilinear gauge coupling (aTGC) searches

• Modeling of VBF processes for Higgs measurements

• Tests of soft QCD rapidity gap modeling

• Main background from QCD $W/Z$+jets production

• Roughly ten times lower cross sections than QCD production
Signal defined as $m_{jj} > 120$ GeV, $p_T(j) > 25$ GeV, and $m_{ll} > 50$ GeV:
- measured $\sigma(EW\ Z \rightarrow lljj) = 534 \pm 20$(stat) $\pm 57$(syst) fb
- good agreement with the SM prediction $\sigma_{LO}(EW\ Z \rightarrow lljj) = 543 \pm 24$ fb by MG5_aMC+PYTHIA 8

Event selection: two OS $e(\mu)$: $p_T > 30\ (20)$ GeV, $|\eta| < 2.4$, $m_{ll} - m(Z) < 15$ GeV, at least two jets with $p_T > 50\ (30)$ GeV, $|\eta| < 4.7$, $m_{jj} > 200$ GeV

Several discriminating variables used to achieve the best separation between signal and DY+2 jets strong process → signal extracted from the fit to the BDT

Additional hadronic activity in signal-enriched region (BDT > 0.92) is studied
- consider additional jets with $p_T > 15$ GeV jets in the gap
- Herwig (Pythia 8) PS models data better for low and moderate (higher) gap activity
• Signal region defined with $m_{jj}>120$ GeV, $p_T(j)>25$ GeV:
  – measured $\sigma(EW \rightarrow l\nu jj) = 6.23 \pm 0.12$ (stat) $\pm 0.61$ (syst) pb
  – consistent with LO SM prediction by MG5_aMC $\sigma_{LO}(EW \rightarrow l\nu jj)=6.81^{+0.03}_{-0.06}$ (scale)$\pm0.26$ (PDF) pb
• Event selection: e ($\mu$) channel: $p_T>30$ (25) GeV, $|\eta| < 2.4$, $p_T^{miss}>40$ (20 GeV) GeV, $m_T(W)>40$ GeV, at least two jets with $p_T > 50$ (30) GeV, $|\eta| < 4.7$, $m_{jj} > 200$ GeV, and $R(p_T) < 0.2$

• Several discriminating variables ($m_{jj}$, $\Delta\eta_{jj}$, etc.) used to differentiate signal from $W$+jets strong process (DY $W$+2 jets)
• Extraction of signal via fit to BDT $\rightarrow$ QCD $W$+jets dominant background, but significant contributions as well from top and QCD multijet

• Additional hadronic activity and gap veto efficiencies in the signal-enriched region (BDT>0.95)
• Good agreement between data and Herwig, while Pythia 8 shows greater activity in the rapidity gap between the two tagging jets
EW V+2 jets – constraints on aTGCs

- Both the EW Zjj and EW Wjj measurements are sensitive to aTGC EFT parameters: $c_{WWW}/\Lambda^2$, $c_W/\Lambda^2$, and $c_B/\Lambda^2$
- Exploit combined fit of experimentally clean $p_T(Z)$ (from VBF Z) and $p_T(l)$ (from VBF W) distributions to limit systematic uncertainties
- Constraint in VBF W channel improved by 20-25% by requiring BDT>0.5 in pre-selection
- No evidence found for aTGCs from the combined 13 TeV Wjj and Zjj results
- Suggest limits on aTGCs -> stringent limit on $c_{WWW}/\Lambda^2$: $-1.8 < c_{WWW}/\Lambda^2 < 2.0$ TeV$^{-2}$

One-dimensional limits on the aTGC EFT parameters from the combination of EW Wjj and EW Zjj analyses
V+jets measurements are an integral part of the CMS SM physics program at the LHC, deeping our understanding of QCD and EW processes and their theoretical modeling

- Precise measurements compared with various MC-based and theoretical predictions, exploiting different PDF models → overall good agreement with the data on several angular and kinematical observables
- Valuable inputs provided for improving existing constraints on the proton PDFs → $b$, $c$, and $s$ quark PDFs from V+HF jets and gluon PDF from $\gamma$+jet
- Provided wealth of results on many fronts → background modeling for Higgs and new physics, perturbative and soft QCD effects, DPS modeling, collinear and large-angle radiation, QCD HF sector, EW tests including aTGCs, etc.

Stay tuned for more V+jets results with Run 2 data at 13 TeV towards Run 3!

Thank you!
Back-up slides
W/Z+jets at 13 TeV (more distributions)
Charm jets identified through:
- a semileptonic decay of a c hadron leading to a well identified μ inside a jet (SL)
- a reconstructed displaced secondary vertex inside a jet (SV)

Selection: \( p_T(l) > 30 \text{ GeV}, \ |\eta(l)| < 2.1 \), and \( m_T(W) > 55 \text{ GeV}, \ p_T(j) > 25 \text{ GeV}, \ |\eta(j)| < 2.5 \)

Measured \( W+c \) cross section and \( W^++c/W^-+c \) ratio inclusively
- good agreement with MCFM NLO predictions with various PDFs

Measured \( W+c \) cross section and \( W^++c/W^-+c \) ratio differentially for \( p_T(l) \) and \( |\eta(l)| \)
- slight discrepancies with MCFM NLO at low-\( p_T(l) \) region

- W+c-jet can test s quark PDF
- Fiducial acceptance: \(p_T(c) > 5 \text{ GeV}, \ |\eta(c)| < 2.4, \ p_T(\mu) > 26 \text{ GeV}, \ |\eta(\mu)| < 2.4, \text{ and } m_T(W) > 50 \text{ GeV}
- Charm quarks are tagged via full reconstruction chain of \(D^*(2010) \pm \rightarrow D^0 + \pi^\pm_{\text{slow}} \rightarrow K^\mp + \pi^\pm + \pi^\pm_{\text{slow}}\)

\[\sigma(W+c) \text{ and } \sigma(W^+c)/\sigma(W^-c) \text{ inclusive measurements compared to MCFM NLO} \]
\[\text{good agreement with various predictions except for the ATLASSepWZ16nnlo PDF set for } \sigma(W+c)\]

- measurements used in a QCD analysis at NLO studying s quark distribution and the strangeness suppression factor \(r_s(x,\mu_f^2) = (s + \bar{s})/(\bar{u} + \bar{d})\)
- analysis probes s quark distribution at \(x \leq 0.01\) depending on the scale
- agreement with earlier results from neutrino scattering experiments

- \(Z(ll)+\geq 1c(1b)\) event selection for isolated leptons with \(p_T(l)>20\) GeV, \(|\eta(l)|<2.1\), \(71 < m_{ll} < 111\) GeV and at least one c or b jet with \(p_T(j)>25\) GeV, \(|\eta(j)|<2.5\).
- HF jets identified through (1) the semileptonic decay of c or b flavoured hadrons with a muon in the final state, and (2) using exclusive decay channels of charm hadrons through \(D\pm\) and \(D^\ast(2010)\pm\) mesons.
- Inclusive and differential \(Z+c\) cross section and \((Z+c)/(Z+b)\) cross section ratio measurements:
  \[
  \sigma(pp \to Z+c+X)B(Z \to l+l^-) = 8.8\pm0.5 \text{ (stat)}\pm0.6 \text{ (syst)} \text{ pb and } \sigma(pp \to Z+c+ X)/\sigma(pp \to Z+b+X) = 2.0 \pm 0.2 \text{ (stat)} \pm 0.2 \text{ (syst)}. 
  \]
- Differential results are presented using only semileptonic selection.
- MCFM underestimates data due to absence of inclusion of parton shower development and nonperturbative effects.

- MG5\_aMC LO(NLO)+PYTHIA describe well the measurement. MCFM fixed order NLO (using different PDF sets) predicts smaller cross section both inclusively and differentially.
- All predictions reproduce the data in \(Z+c/Z+b\) cross section ratio better.

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• Inclusive and differential measurements of $\sigma(Z+c)/\sigma(Z+j)$, $\sigma(Z+b)/\sigma(Z+j)$, and $\sigma(Z+c)/\sigma(Z+b)$ in the associated production of a $Z$ boson with at least one $c$ or $b$ quark jet
  
  – differentially as functions of $p_T(j)$ and $p_T(Z)$ in both $e^+e^-$ and $\mu^+\mu^-$ channels
  
  – $p_T(j)>30$ GeV and $|\eta(j)|<2.4$, $p_T(l)>25$ GeV and $|\eta(l)|<2.4$, $71<m_{ll}<111$ GeV

• Measured ratios: $\sigma(Z+c)/\sigma(Z+j)=0.102\pm0.002$ (stat)$\pm0.009$ (syst), $\sigma(Z+b)/\sigma(Z+j)=0.0633\pm0.0004$ (stat)$\pm0.0015$ (syst), and $\sigma(Z+c)/\sigma(Z+b)=1.62\pm0.03 \pm0.15$

• Compared to MG5_aMC and MCFM both at LO and NLO
  
  – MG5_aMC (N)LO predictions are higher but compatible with data within uncertainties
Z+c-jets at 13 TeV (JHEP 04 (2021) 109)

- Both incl. and diff. x-secs of Z boson production with at least one c-jet
  - differentially as functions of $p_T(j)$ and $p_T(Z)$ in the combined ($e^+e^-$ and $\mu^+\mu^-$) channel
  - $p_T(l)>10$ GeV (at least one $e$ ($\mu$) with $p_T(l)>29\,(26)$ GeV), $|\eta(l)|<2.4$, $71 < m_{ll} < 111$ GeV, $p_T(j)>30$ GeV, $|\eta(j)|<2.4$,

- Comparisons with MG5_aMC and Sherpa (N)LO interfaced with PS
  - Predictions normalized to FEWZ NNLO
  - MG5_aMC LO is in good agreement with the data
  - NLO predictions tend to overestimate the data
**γ+jets production**

- Prompt photons are produced via three main mechanisms: a) quark-gluon Compton scattering, b) quark-anti-quark annihilation, and c) bremsstrahlung radiation from an outgoing quark.

- Non-prompt photons (main background) are π⁰ and η from hadronic jets, discriminated from signal photons based on isolation and shower shape properties.

- Measurements are sensitive to gluon PDF over a wide range of $Q^2-x$.
- Main background to SM processes such as $H\rightarrow\gamma\gamma$ and new physics searches.
- Provides means for testing pQCD predictions.
- Valuable for jet energy calibration and modeling of missing energy.
**EW V+2 jets production** (representative Feynman diagrams)

Pure EW $W \rightarrow l\bar{v}jj$ production: VBF (left), bremsstrahlung-like (middle), and multiperipheral (right)

Main background QCD Drell-Yan $W \rightarrow l\bar{v}jj$ production

Pure EW $Z \rightarrow lljj$ production: VBF (left), bremsstrahlung-like (middle), and multiperipheral (right)

Main background QCD Drell-Yan $Z \rightarrow lljj$ production