Associated Production of Vector Bosons and Jets at LHC

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Dr. Federico Sforza (University of Genoa)
on behalf of ATLAS and CMS Collaborations
W or Z plus jets at LHC:

- Abundant QCD production spanning several orders of magnitude of cross-section
- Wide range of measurements now available at different energies and conditions thanks to CMS and ATLAS

Measurements are test of:

- **MC modeling** ⇒ key for Higgs, BSM, EWK etc.
- Perturbative QCD (pQCD) predictions
- **Proton PDFs** ⇒ Thanks to dominant $qg$ interaction
One Slide Overview of V+jets Analyses

**Selection of W(e/µ+ν) or Z(ee/µµ) candidates in fiducial volume:**
- *Isolated* leptons (electron or muon) with $p_T > 20$ or $25$ GeV and $|\eta| < 2.4$ to $2.5$
- **Z**: di-lepton invariant mass around Z peak ⇒ *pure sample*
- **W**: $E_T^{\text{miss}}$ for $\nu$ reconstruction, $l\nu$ transverse mass ⇒ *multi-jet bkg. (data-driven)*

Jet reconstruction and selection in fiducial volume:
- Anti-$k_t$ $\Delta R = 0.4$, $p_T > 30$ GeV,
- $|Y| < 2.5$ (ATLAS), $|\eta| < 2.4$ CMS
- **NB**: also $|Y| < 4.4$ in ATLAS Run 1

**Extract signal as function a variable “x”:**
- Signal $(x)$ = Data $(x)$ - Backgrounds $(x)$

**Unfold background-subtracted data to truth:**
- Signal MC used to remove detector effects (efficiencies, resolution, scale, etc.)
- Main experimental uncertainties ⇒ JES, JER

**Compare to ME+PS or Fixed-Order predictions:**
- Multi-parton MC at LO or NLO with different matching and scale choices
- Fixed-order at NLO and NNLO ⇒ *impressive recent progress!*
Z+jets at 13 TeV

- Run 2 results by ATLAS (2017) and recently published also by CMS (2018)
- Both analyses based on electron and muon data collected in 2015:
  ⇒ 2.2 fb⁻¹ (CMS) or 3.2 fb⁻¹ (ATLAS), statistical uncertainties already tiny

- Similar ground offers maybe interesting comparisons
Z + ≥ N-jets at 13 TeV

- One of the main figures of merit for QCD predictions

- CMS systematic errors are a bit smaller (JER in particular), ATLAS extends to 7 jets

- Good agreement up to 4 jets ⇒ deviations in PS-dominated multiplicities where also exp. syst. are sizable (*NB: PS-tuning syst. are not considered in any publication*)
$H_T = \sum_{l,jets} |p_T|$\vspace{1cm}

- Noticeable differences in ME+PS ⇒ best for NLO+PS, but also LO can perform well
- Excellent agreement from NNLO predictions within prescribed uncertainties
Analysis of $Z\ p_T$ and Jet-Z-Balance

Test of $Z$ recoil against clustered and unclustered hadronic activity

- MG+PY8 FxFx, with CMS setup, performs very well
Searches and Unfolding: Z + 2 jets

- “Default” MC generators for CMS and ATLAS are NLO+PS (Sherpa 2.2 and MG FxFx)
  
  \textit{Data/MC comparison is remarkably good, although not perfect}

- However any residual trend in corners of phase space may mask a BSM signal…

- Searches (e.g. Z+2jets) now starting to explore \textit{unfolding} of signal-region selections

- Model independent test of extreme phase space \Rightarrow\ example of $S_T > 600$ GeV selection

- Simple unfolding technique (e.g. bin-by-bin unfolding) but very fast result (36 fb$^{-1}$)!
W+jets Studies at LHC

- Analysis is more challenging ⇒ experimental picture more various than Z+jets
- CMS results using 13 TeV 2015 data 2.2 fb⁻¹, jet |η|<2.4, only muon data
- ATLAS results using 8 TeV 2012 data, 20 fb⁻¹, jet |Y|<4.4, only electron data

- Nevertheless still similar enough to have a close comparison
W + N-jets Measurements

- Unfolded analysis 40 (ATLAS) 20 (CMS) distributions!

- Also for W, the “exclusive” or “inclusive” jet multiplicities are well reproduced up N~4

- Run 1 JES/JER ATLAS uncertainty larger w.r.t. Run 2, partially from use of |Y|<4.4
Collinear W Emission off high-p_T jets

Challenging phase of collinear emission of a W off a jet, accessible thanks to large statistics in W sample

- Requires presence of very high-p_T leading jet (>300-500 GeV)

- Some discrepancy at transition between collinear/standard emission ΔR(μ,j)~2.5

- Origin could be experimental (e.g. angular resolution) or due to MC radiation

Dedicated ATLAS Run 1 analysis:

2017 Result: PLB765(2017)132
W $p_T$ and $W^+/W^-$ Ratio

- Challenging to model full spectrum both at low/high $W$ $p_T$ (PS, scale, accuracy, etc.)
- Availability of both $W^+$ and $W^-$ samples, with their correlations, allows extraction of precise ratio measurements where uncertainties cancel
- Different trends in $W^+/W^-$ ⇒ Hints to sensitivity to different items, e.g. PDF sets
W+Charm Measurement

- W+c-jet can test strange-quark PDF
- Use W vs c-hadron charge correlation ⇒ Opposite-Sign (OS) - Same-Sign (SS)
- **New CMS result with 36 fb$^{-1}$!**
- Uses D-meson decay and mass reconstruction for pure selection
  \[
  D^*(2010)^\pm \rightarrow D^0 + \pi^\pm_{\text{slow}} \rightarrow K^{\mp} + \pi^\pm + \pi^\pm_{\text{slow}}
  \]
- Extrapolation factor (~10) between W+D and W+c-quarks production
- Data driven W+LF background, other bkgs and extrapolation factors based on MC
- Other results at 7 TeV: CMS PRD90(2014)032004 ATLAS JHEP05(2014)068
W+Charm PDF Analysis

- Bin-by-bin unfolded $|\eta_\mu|$ in agreement with most PDF sets
- Tension with ATLASepWZ16 PDF set where strange-quark is not suppressed

Perform full QCD analysis at NLO:

- HERA DIS, CMS W-asymmetry at 7 TeV and 8 TeV, CMS W+c at 7 TeV, and 13 TeV
- Strangeness suppression factor $R_s$ (or $r_s$):
  \[
  R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}
  \]
- In agreement with strangeness “suppression” observed in neutrino scattering experiments

NB: No parameter uncertainty shown on ATLASepWZ16
Additional PDF Studies with W+Jets

- **ATLASepWZ16 PDFs** derived using W, Z 7 TeV ATLAS data ([EPJC77(2017)367](https://link.springer.com/article/10.1140/epjc/s10052-017-5233-8))
  ⇒ Can W+jets data, and its sensitivity to PDFs, be of help?


- At NNLO, new parameterization, including W,Z 7 TeV, HERA, and W+jets 8 TeV

- **W⁺ and W⁻ W-\(p_T\) 8 TeV data shows good constraining power on high-x sea-quark**
PDF Interpretation

- New PDF set has been derived and is now public ⇒ *ATLSepWZWjet19*
- Consistency test using new/old extraction method vs with/without $W p_T$ shows importance $W+\text{jet}$ data ⇒ *greatly reduced model uncertainty!*
- $R_s$ reduced at higher $x$ (w.r.t. ATLASep2016) but still enhanced at low $x$!
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- $R_s$ reduced at higher $x$ (w.r.t. ATLASep2016) but still enhanced at low $x$!
- Comparison against CMS is not trivial (NLO vs NNLO, parameteriz., etc.)

\[ Q^2 = 1.9 \text{ GeV}^2 \]

- Tension is reduced... *probably not yet final answer about strangeness!
Conclusions and Summary

Measurements of jet production in association with W or Z boson:
- Improve understanding of perturbative QCD
- Test MC modeling for observables used in analyses and searches
- Provide an important handle to constraint proton PDFs

ATLAS and CMS are providing many fiducial cross sections and differential unfolded measurements compared to a variety of predictions and generators:
- Remarkable agreement for many distribution but none is yet perfect, nevertheless the unprecedented accuracy today available
- Some tensions are present between experiments and against predictions ⇒ can be understood thanks to better and more precise measurements
  - Stay tuned for the many more results in preparation!

A complete set of V+jets (and more) SM measurements is available at:
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
<table>
<thead>
<tr>
<th>Type of Prediction</th>
<th>MCs &amp; Calculations “label”</th>
<th>Usage &amp; Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>multi-partons (Np) LO ME+PS</td>
<td><strong>Sherpa 1.X</strong>: LO up to Np = 4</td>
<td>Wide use in ATLAS Run 1</td>
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<td><strong>Madgraph5</strong>: up to Np = 4, allows different merging schemes (e.g. CKKW-L or MLM)</td>
<td>Wide use in CMS Run 1</td>
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<td><strong>ALPGEN</strong>: up to Np = 5, MLM merging</td>
<td>Run 1 (and Run 2)</td>
</tr>
<tr>
<td>multi-parton (Np) NLO and LO ME+PS</td>
<td><strong>Madgraph5</strong>: aMC@NLO: NLO up to Np = 2, FxFx merging</td>
<td>CMS Run 2 “Standard”</td>
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<td></td>
<td><strong>Sherpa 2.X</strong>: NLO up to Np = 2, LO up to Np =4, includes PS merging</td>
<td>ATLAS Run 2 “Standard”</td>
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<td></td>
<td><strong>Powheg</strong>: NLO Np = 1</td>
<td>Tested by ATLAS and CMS</td>
</tr>
<tr>
<td>Fixed order calculation</td>
<td><strong>BlackHat+Sherpa</strong>: NLO up to Np = 5</td>
<td>Tested in Run 1 &amp; 2 (both ATLAS and CMS)</td>
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<td><strong>N-Jettiness</strong>: full NNLO QCD</td>
<td><em>Tested for first time in Run 2</em></td>
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<td>NNLO+PS</td>
<td><strong>GENEVA</strong>: NNLO+ partial N³LL + PY8</td>
<td><em>Tested for first time in Run 2</em></td>
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</tbody>
</table>
Bayesian Iterative Unfolding

Response matrix accounts for migrations using MC simulation:

\[ M_{ij} = M(R_i | T_j) \]

Conditional probability that the effect \( R_i \) is produced by the cause \( T_j \)

Extract "prediction-unbiased" probability with iterative Bayesian unfolding:

- Bayes theorem:
  \[ M(T_i | R_j) = M(R_i | T_j) P_0(T_j) / \text{Sum}_i M(R_i | T_i) P_0(T_i) \]

- Particle level MC used as initial prior, \( P_0(T_j) \), to determine a first estimate of the unfolded data distribution:
  \[ T_j = \text{Sum}_i M(T_j | R_i) R_i \]

- In each further iteration the estimator of the unfolded distribution from previous iteration is used as a new prior
Leading Jet $p_T$ in $Z+$jets at 13 TeV

ATLAS

13 TeV, 3.16 fb$^{-1}$

anti-$k_t$, jets, $R = 0.4$

$p_T^{\text{jet}} > 30$ GeV, $|y^{\text{jet}}| < 2.5$

CMS

Measurement

Data

BLACKHAT + SHERPA

SHERPA 2.2

AOLPGEN + PY6

MG5_aMC + PY8 CKKWL

MG5_aMC + PY8 FxFx

$Z/\gamma^* \rightarrow t\bar{t}$, $N_{\text{jets}} \geq 1$

$Z/\gamma^* \rightarrow t\bar{t}$, $|y^{\text{jet}}| < 2.4$

$\frac{\text{d}^2 \sigma}{\text{d}p_T^{\text{jet}} \text{d}y^{\text{jet}}} [\text{pb}/\text{GeV}]$
Different flavor scheme predictions can predict correctly only part of the distributions

- Z+b(b) Kinematics in Run I
- Unfolded differential distributions and ratio of distributions with respect to generic jets!
W+D* comparison

- Good precision of ATLAS W+D 7 TeV (JHEP05(2014)068) but not used in PDF fits

- CMS 13 TeV

W+D* systematic uncertainties

<table>
<thead>
<tr>
<th>Relative systematic uncertainty in %</th>
<th>W+D</th>
<th>W+D*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton trigger and reconstruction*</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Lepton momentum scale and resolution*</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Lepton charge misidentification</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$E_T^{\text{miss}}$ reconstruction*</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>W background estimation</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Background in $W D^{(*)}$ events</td>
<td>0.7</td>
<td>0.6</td>
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<tr>
<td>W efficiency correction</td>
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<tr>
<td>Tracking efficiency</td>
<td>2.1</td>
<td>2.2</td>
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<tr>
<td>Secondary vertex reconstruction efficiency</td>
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<td>0.4</td>
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<tr>
<td>$D^*$ isolation efficiency</td>
<td>-</td>
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<tr>
<td>Fitting procedure</td>
<td>0.8</td>
<td>0.5</td>
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<td>Signal modelling</td>
<td>1.4</td>
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<tr>
<td>Statistical uncertainty on response</td>
<td>0.2</td>
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<tr>
<td>Branching ratio</td>
<td>2.1</td>
<td>1.5</td>
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<tr>
<td>Extrapolation to fiducial region</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Integrated luminosity*</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Total</td>
<td>4.3</td>
<td>4.8</td>
</tr>
</tbody>
</table>
s-quark Suppression Comparison

- Parameterization uncertainties have large impact on ATLASepWZ16nlo (similar to ATLASepWZ19U)
- Underestimate of ATLASepWZ16nlo uncertainties in CMS comparison

Important reduction of uncertainties at high-x because of new $W-p_T$ data from ATLAS W+jets

**ATLAS Preliminary**

- $Q^2 = 1.9 \text{ GeV}^2$

CMS, this analysis

- $\mu_r^2 = 1.9 \text{ GeV}^2$

$\mu_r^2 = 1.9 \text{ GeV}^2$

CMS, HERA DIS + CMS $W + CMS W+c$

- Hessian uncertainties

- MC uncertainties

Fract. uncert.
NB: Many many caveats in this comparison!
Different parameterization, different accuracy in QCD analysis, etc.