W/Z production cross sections in association with jets and their ratio with the ATLAS detector

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Overview

Presenting ATLAS measurements of the production cross sections of W and Z vector bosons in association with jets in various observable distributions:

- Inclusive jet multiplicity $\sigma(V + \geq N_{jets})$
- Differential cross sections $d\sigma / dp_T^{jet}$, $d\sigma / d|y^{jet}|$
- Di-jet quantities $\Delta R_{jj}$, $|\Delta y_{jj}|$, $|\Delta \phi_{jj}|$, $m_{jj}$
- Complex quantities $H_T = \Sigma p_T^{(l,v, jets)}$

All quantities defined inclusively:
less sensitive to modeling of soft component and migration effects

Measure the cross sections

- at particle level
- in the fiducial volume of the detector
- use ratios whenever possible to cancel experimental and theoretic uncertainties

- $(d\sigma/d\xi) / \sigma(V)$
- $\sigma(V + \geq n+1\ \text{jets}) / \sigma(V + \geq n\ \text{jets})$
- $\sigma(W +1\ \text{jet})/ \sigma(Z + 1\ \text{jet})$

But lets zoom out a little first ...
The Standard Model of Particle Physics

- Modern particle physics is governed by the Standard Model (SM)
- Can be formulated in a Lagrangian
- 6 quarks and 6 leptons organised in 3 families
- Forces mediated by force carriers (bosons)
- Several open questions!
  - Most eminent:
  - **Standard Model needs to be symmetric to work**
  - But observation: SM symmetry is **broken** in nature!
  - Nature of Electroweak Symmetry Breaking?
  - Higgs Mechanism?
  - SM Passes extremely precise experimental tests but many more can (and should) be done!
The Large Hadron Collider at CERN

- Goal: discover new physics at the energy frontier
- Hosts two huge general purpose detectors

Large Hadron Collider
- Located at CERN, Geneva
- 27 km circumference
- Proton-proton collisions
- Current center of mass energy: 7 TeV
- Design center of mass energy: 14 TeV (planned from 2014)
ATLAS Detector

ATLAS Collaboration
- ~ 3000 Scientists
- 174 Institutes from 38 countries

- General purpose detector
- Excellent identification of electrons, muons, jets, missing energy, ...
  - Need essentially all subdetectors for V+jets measurements
  - Slightly different acceptance for electrons and muons
LHC Data

- Presented results use 2010 data
- ATLAS recorded int. lumi: 33 – 36 pb$^{-1}$
- Well understood electron, muon and jet performance
- Relatively low collision / pile-up rates
- Up to avg. of 3 interactions per bunch crossing

- Allow cross section measurement at low jet transverse momentum
- Statistics for higher jet multiplicities / large recoil low
Outlook: LHC Data from 2011

- Next round of analyses will use 2011 data
- Int. lumi:
  - 5.2 fb\(^{-1}\) (LHC Delivered)
  - 4.69 fb\(^{-1}\) (ATLAS)
- Already events with more than 20 interactions per bunch crossing in data
- Challenging precision analyses in progress...

Example event: Z → ee with 20 pile-up interactions
Cross Sections at LHC and Tevatron

- Presenting measurements at 7 TeV center-of-mass energy in pp collisions

- Different interest and features compared to Tevatron measurements and future 14 TeV measurements:

Dominant (LO) Production mechanisms

LHC: QCD Compton process
Tevatron: Quark annihilation

- At LHC expected per 1pb\(^{-1}\) (\(\sqrt{s} = 7\) TeV)
  - \(10^4\) \(W (\rightarrow l\nu)\), \(10^3\) \(W+1\)jet (jet-\(p_T> 30\) GeV)
  - \(10^3\) \(Z (\rightarrow ll)\), \(10^2\) \(Z/\gamma^*+1\)jet (jet-\(p_T> 30\) GeV)

- Cross sections LHC ↔ Tevatron:
  - \(W (\rightarrow l\nu), Z/\gamma^* (\rightarrow ll)\):
    - cross section 4 x larger at LHC, factor 2 per jet
  - Top background:
    - 100 x larger cross section at LHC
Electroweak Measurements in ATLAS

Concentrate on dibosons and new constraints on couplings

Region of \( V+\text{jets} \) cross sections
~5 times lower per jet

ATLAS Preliminary
\[
\int L \, dt = 0.035 - 1.04 \text{ fb}^{-1}
\]
\[ \sqrt{s} = 7 \text{ TeV} \]

- Theory
- Data 2010 (~35 pb\(^{-1}\))
- Data 2011

Concentrate on dibosons and new constraints on couplings
Recent ATLAS W/Z results already take advantage of correlations between cross section measurements

Mostly from common PDF ratios

Provide some constraints on PDFs, but weak compared to W charge asymmetry results (not shown), and only “low”-Q$^2$
W + jets

• “Measurement of the production cross section for W-bosons in association with 
  jets in pp collisions using 33 pb-1 at sqrt(s) = 7 TeV with the ATLAS detector”,
  ATLAS-CONF-2011-060
  (paper in preparation)

  (33 pb⁻¹)

• “Measurement of the production cross section for W bosons in association with 
  jets in pp collisions at s√ = 7 TeV with the ATLAS detector”,

  (1.3 pb⁻¹)

Z/γ + jets

• “Measurement of the production cross section for Z/γ∗ in association with jets 
  in pp collisions at √s = 7 TeV with the ATLAS detector”,

  (35 pb⁻¹)

\[ R_{jets} = \frac{\sigma(W + 1-jet)}{\sigma(Z + 1-jet)} \]

• “A measurement of the ratio of the W and Z cross sections with exactly one 
  associated jet in pp collisions at (√s) = 7 TeV with ATLAS”,

  (35 pb⁻¹)

nb: Ratio measurement principle proposed already at Tevatron:
A look at Z+jets and W+jets Topology

Similar hadronic final state (jets)
Residual difference due to differences in available phase space (leptons, $m_\nu$)

\[ Z \rightarrow ee + 1\text{-jet} \]
\[ W \rightarrow e\nu + 1\text{-jet} \]

Some experimental systematic uncertainties / features that ...

... cancel:
- Luminosity
- Lepton identification (1\textsuperscript{st} lepton)
- HFS (see above)

... do not cancel:
- Z: Lepton identification for second lepton
- W: MET uncertainty, backgrounds

Phys. Rev. D68, 033014; April, 2003; hep-ph/030388
Example Event Display

\[ Z/\gamma^* (\rightarrow \mu\mu) + 3 \text{ jets Candidate} \]

\[ P_T^Z = 144 \text{ GeV}, m_{\mu\mu} = 79 \text{ GeV} \]
Motivation for SM Measurements

Test higher order calculations and perturbative QCD

• Can use electroweak process to “tag” events (W/Z decay has clear signature)
  • Vector boson decay products + jet $p_T$ provide high, well-defined scale
    - $H^N_T = p_T + \text{MET} + \sum p_T^{\text{jet}}$
      used in MCFM and BLACKHAT-SHERPA
  • Precise stable NNLO calculations possible
• Probe different scattering amplitudes than multijet production
  (mainly gluon jets rather than quark jets)

 Solve experimental challenges in SM environment

• Provide lepton samples
  • In presence of jets (→ eg. study isolation)
  • in extreme regions of phase space at high recoil
    - (T&P, train identification)
• Tune simulation of V+jets samples
• Jet calibration: ATLAS-CONF-2011-159 (2 Dec 2011)
• Inclusive samples for di-boson production, searches → ...
• Many extensions of the Standard Model predict particles with electroweak couplings
  • General: SUSY, $W'$, $Z'$, technicolor, Higgs, leptoquarks, …
  • Decays into electroweak gauge bosons ($W^+$, $W^-$, $Z^0$, $\gamma$) likely
    • In particular if strong quantum numbers are conserved
    • Jets always possible from ISR and in cascade decays of heavy new particles
  • $V+$jets presents irreducible background for such processes!

  • Successful discoveries in the past: **top quark** in $W+3/4$ jets channel at TeVatron (1994)
  • Of particular interest
    • $W + 2$ jet    $H \rightarrow bb$, single top production (tb)
    • $W + 6$ jet    $tt$ associated production: $ttH$, $ttW$, $ttZ$
Search example: Di-jet mass in W+jets

• CDF reported a $4.1\sigma$ excess in the dijet mass region 120-160 GeV!

• No hint of a disagreement with MC expectation in the ATLAS W+jets sample!

• The “bumphunter” algorithm finds no significant excess.

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No hint of a disagreement with MC expectation in the ATLAS W+jets sample!

The “bumphunter” algorithm finds no significant excess.

ATLAS-CONF-2011-097

ATLAS Preliminary

$\int L dt = 1.02 \text{ fb}^{-1}$

$e+\mu$, Njet = 2

$\chi^2/\text{ndf} = 78.22/81$

More search examples ...

... in ATLAS with dominating V+jets backgrounds

Monojets: Large Extra Dimensions

SUSY jets+MET +2 leptons (GMSB)

SUSY jets+MET+1lepton (mSUGRA)

Higgs $H \rightarrow WW \rightarrow l\nuqq$
In (direct) searches using $R_{jets}$

- New physics contributions to either $W$+jets or $Z$+jets result in deviation of $R_{jets}$ from Standard Model prediction.

- Setting limits on BSM model possible using fit for $R_{jets} + BSM$ to measured $R_{jets}$.

$W \rightarrow Z$ Mapping for Background Predictions using $R_{jets}$

- $R_{jets}$ can be used to predict irreducible background $Z(\rightarrow \nu \nu)$ + jets (e.g. Monojet analysis).
  - Measure $W$+jets, remove lepton and normalize $Z$+jets prediction using $R_{jets}$.
  - 10x statistics compared to directly using $Z$+jets.
  - More generally: Related to data-driven background estimations (“transfer functions”).
Measurement Principle

- Theory and experiment should join at well-defined, physically meaningful level with minimal model dependencies on anything but the process of interest

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Detector Level

- Partons (pQDC / PS)
- ME (pQCD)
- PDFs (nonpert.)

Particle Level a.k.a Hadron Level

- Fragmentation (nonpert.)
- Detector Acceptance, Reconstruction, Identification, Inefficiencies, Calibration

Parton Level

- Detector Acceptance, Reconstruction, Identification, Inefficiencies, Calibration
- Jet evolution – similar for leptons

Models:
- PYTHIA
- ALPGEN+HERWIG
- SHERPA
- MCFM
- Blackhat+SHERPA

Time
## Generator Reference

### Full Shower MCs
- Used for background simulation and estimation and unfolding of detector effects

<table>
<thead>
<tr>
<th>Generator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPGEN 2.13 + HERWIG + JIMMY</td>
<td>PHOTOS, CTEQ6L1, ATLAS MC09 tune MLM matching, pQCD normalized to NNLO</td>
</tr>
<tr>
<td>SHERPA 1.13</td>
<td>CTEQ6L1, Default UE tune CKKW matching, pQCD normalized</td>
</tr>
<tr>
<td>PYTHIA 6.4.21</td>
<td>PHOTOS, MRST 2007 LO LO MatrixElement + ISR, PS corrections PQCD normalized</td>
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</tbody>
</table>

### pQCD NLO parton level calculators
- Used for NLO predictions

<table>
<thead>
<tr>
<th>Generator</th>
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</thead>
<tbody>
<tr>
<td>MCFM 5.8</td>
<td>CTEQ6.6/CTEQ6L1 PYTHIAUE, fragmentation</td>
</tr>
<tr>
<td>SHERPA+BLACKHAT</td>
<td>CTEQ6.6M</td>
</tr>
<tr>
<td>FEWZ NNLO</td>
<td>MRST2007LO* PDF Used for pQCD normalization K-factors: 1.20 (W), 1.24 (Z) @ 5% unc.</td>
</tr>
</tbody>
</table>
Theory Status

Drell-Yan W, Z/γ*: NNLO
- FEWZ
  - R. Gavin at al., arXiv:1011.3540v1

W, Z/γ* + 1(2) jets: NLO
- MCFM

W, Z/γ* + 3 jets: NLO
- BLACKHAT+SHERPA
  - C. F. Berger et al., arXiv:1005.3728
- W + 3 jets:
- Z/γ*+ 3 jets:

W, Z/γ* + 4 jets: NLO
- Z/γ* + 4 jets:
  - Ita et al., arXiv:1108.2229
- W + 4 jets:

- Important to have NLO calculations available
- Uncertainties decrease from 50% at LO to ~15-20% at NLO
- In particular PYTHIA not expected to be precise for N_{jet}>1
- Not all NLO calculations technically available in all cases at time of analysis
A few features of recent theory ...

- Scale choice $H_T$ important because can now have hard jets $p_T^{\text{jets}} \gg p_T^{\text{V}}$
- Tevatron: $\mu = E TW$ was ok because higher than HFS sum $pt$
- Scale $\mu$ can cause negative x-section at NLO (logs do not cancel properly at large jet $ET$)

C. Berger et al., [arXiv 1009.2338]

W+4 jets at NLO

LO/NLO
Ratio under Control to High jet $pT$
Z + 4 jets Predictions

- Latest Results:
  Precise Predictions for Z + 4 Jets at Hadron Colliders
  - Probe different pdfs in $W^+/Z$ (mostly $u/u$) and $W^-/Z$ (mostly $d/u$)

Uncertainties:
- Scale: 4-14%
- PDF+$\alpha_s$: 3-8%
PDF and scale uncertainties on pQCD predictions

- $R_{jets}$ exclusively using MCFM this round
  (Looks at 1-jet only for now: no great difference from LO+PS to NLO)

- PDF uncertainties from eigenvector/eigenvalue method (error sets envelope) greatly reduced in $R_{jets}$ because cross sections go in the same direction for each error set

- Scale uncertainties:
  
  Same effect, large cancellation in $R_{jets}$
Parton-to-Particle Correction

- Reminder: MCFM and BlackHat-SHERPA are not full NLO Shower-MCs, but “just” parton level predictions
- Have to evaluate non-perturbative effects on parton level predictions
- Calculated using MC variation samples (tune variations: UE on/off...)

**Fragmentation**
- Losses: lower $p_T$ jets, less jets

**Underlying event**
- Adds energy:
  - higher $p_T$ jets, more jets

- Partial cancellation in total correction (~1-2%)
- About 10% correction at $p_T = 30$ GeV (2-5% syst. unc.)
Lepton Dressing

- Bare leptons at propagator are also not physically meaningful
- "Dress" leptons:
  Add photon 4-vectors in $\Delta R < 0.1$ around lepton to lepton 4-vector
- Mainly from FSR
- Provide clear definition where experiment and theory can meet
- Results in \( \sim 1.5\% \) acceptance correction per lepton
- Effect on cross section 2%-2.5% (Z channel)
Lepton Selection and Phase Space

Muons

- $p_T > 20$ GeV
- $|\eta| < 2.4$
- Inner Detector + Muon System
- Various quality requirements
- Track isolation

Electrons

- $|\eta| < 2.47$ excluding $1.37 < \eta < 1.52$
- em. shower shape in calorimeter
- Various quality definitions to optimise signal efficiency / background rejection ("medium", "tight")

Different acceptance requires inter/extrapolation of fiducial region for combination

Pseudorapidity distributions from inclusive analysis
Similar for negative leptons
Vector Boson Selection and Phase Space

**W**
- Exactly one lepton (veto 2\textsuperscript{nd})
- $E_{T\text{miss}} > 25$ GeV
- $M_T > 40$ GeV

**Z**
- Exactly two leptons
- Opposite charges
- $66 < M_{ll} < 116$ GeV

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**Data 2010 $\sqrt{s} = 7$ TeV**

- $W \rightarrow ev$
- QCD
- $W \rightarrow \tau v$

*Taken from inclusive $W,Z$ measurement*

- Acceptance $\sim 45\%$
- Inclusive backgrounds: $\sim 10\%$ ($W$), $\sim 2\%$ ($Z$)
Jet Selection and Phase Space

Jets
- Anti-\(k_T\) algorithm \(R = 0.4\)
- \(p_T > 20\ \text{GeV} \) (W+jets)
- \(p_T > 30\ \text{GeV} \) (Z+jets and \(R_{\text{jets}}\))
- \(|\eta| < 4.4\) (\(|\eta| < 2.8\) for \(R_{\text{jets}}\))
- lepton-jet separation \(\Delta R_{lj} > 0.5\) (0.6 for \(R_{\text{jets}}\)) (prevent distortion of jet by em. showers)

- Pileup removal using “Jet Vertex Fraction” JVF > 0.75
- Source of large systematic uncertainty in V+jets – small for \(R_{\text{jets}}\) : pile-up almost cancels
- JVF only usable in 2010 data with low pileup
- JES calibration largely MC based

Particle level definition of jets
- Use all final-state particle
  - including HF decay products
  - excluding W/Z decay products
Inclusive Jet Multiplicity (Detector Level)

- Backgrounds increasing towards higher $N_{\text{jet}}$
- EW and top taken from simulation – **QCD important at low multiplicities**
- **Top becomes important at higher jet multiplicities ($N_{\text{jet}} > 3,4$) in $W$ channel**
- Overall good agreement data / prediction
- Very similar plots for $R_{\text{jets}}$ in respective phase space
  - (Statistics not enough to cover more than 1 jet: limited by $Z$ channel)
- Inclusive bin: Can already estimate $\sigma(W) / \sigma(Z) \sim 10$

**W + jets**

**Z + jets**
QCD Background Modeling

Depending on final state use data driven method or MC estimates

- $W\rightarrow ee$  Fit data to MET distribution using QCD template
  - electron ID reversal or
  - electron selection replaced with photon
- $Z\rightarrow ee$  Loosen electron ID, normalize with dilepton-mass
- $W\rightarrow \mu\mu$  Fit MET distribution, QCD template from MC
- $Z\rightarrow \mu\mu$  directly from MC (HF dominated)

QCD template and Normalisation from data in $W+1$-jet

(from $R_{jets}$ analysis)
Bin-by-bin correction factors $U(\xi)$

$$\frac{d\sigma}{d\xi} = \frac{1}{\mathcal{L}} \frac{1}{\Delta\xi} \left( N_{\text{data}} - N_{\text{backg}} \right) \times U(\xi)$$

- $U(\xi)$ contains all trigger and reconstruction (leptons and jets) inefficiencies / resolutions
- Determined using ALPGEN simulation
  - Electron channel: $U(\xi) = 1.65$ to $1.35$
  - Muon channel: $U(\xi) = 1.16$ to $1.1$
- Systematic uncertainty: difference between ALPGEN and SHERPA derived corrections

**Bayesian Method “d’Agostini”**

- Cross check + future use
- Lower MC dependence, better statistical treatment
- More complex, need to pay attention to regularization
- This round confident in bin-by-bin results:
  - Good agreement data-MC at Detector level
  - $W/Z + \text{jets}$ measurements are systematically limited
  - Little migration: off-diagonal elements small
W/Z Ratio Correction Procedure

- $R_{jets}$ calculated from ratio of individually corrected event yields in W, Z channels
- Allows correct evaluation of statistical correlations in numerator/denominator

Jet spectrum correction directly on ratio

- Almost complete cancellation of jet resolution effects
- Remaining effects from W/Z phase space differences below ~5%
- Determined on ratio by smearing particle level jets according to JES
- Syst. Uncertainty from difference between ALPGEN and PYTHIA

$$R_{jet} = \frac{N_{\ell,W}^{\ell,V}}{N_{\ell,Z}^{\ell,V}} \times C_{jet}$$

Signal events (backgrounds subtracted)

1. $N_{sig}^{\ell,V} = \frac{N_{\ell,V}^{\ell,V}}{\epsilon_{\ell} \times \epsilon_{trig} \times C_{V}^{\ell,V}}$

2. Trigger efficiency

Lepton identification

Boson reconstruction

ATLAS Simulation

C$^\mu_{jet}$

- Jet Correction
- Syst. ⊕ Stat. Uncertainty

Muon channel

Jet $p_T$ Threshold [GeV]
Systematic Uncertainties in V+jets Measurements

- All uncertainties are calculated bin-wise in each observable

**Z+jets**

- Dominating Systematics
  - JES 8% - 20%
  - Luminosity 3.4%
  - pile-up jets ≈5%

**W+jets**

- Dominating Systematics
  - JES 12% - 22%

(from 1.3 pb-1 paper)
Systematic Uncertainties in lead. $p_T^{jet}$

$R_{jets}$:
- Systematic uncertainties substantially smaller than in V+jets individually
- In particular reduction on the jet systematic uncertainties
- Systematic uncertainties of the order of less than 5%
- Precision still statistically limited.
Inclusive Results V+jets Cross Sections

- Blackhat-Sherpa: NLO for N jets ≤ 3, LO for N jets = 4
- MCFM: NLO for N jets ≤ 3
- As expected PYTHIA underestimates rates of high multiplicites

pQCD works well
Jet Multiplicity Ratios

- Some systematic uncertainties cancel (Lumi, lepton ID, boson acceptance)
- Increased uncertainty on MCFM and Blackhat-Sherpa (in bin 3 and 4 respectively) due to LO prediction
  - Ratio roughly $\sim 25\%$ (W), $\sim 20\%$ (Z) per jet except first bin $\sim 15\%$
Cross section in leading jet $p_T$

- $W+$jets ($N_{\text{jet}} >= 1,2,3,4$)
- $Z+$jets ($N_{\text{jet}} >= 1$)
- $R_{\text{jets}}$ ($N_{\text{jet}} = 1$)

- Cross section normalised to inclusive cross section
- cancellation of lumi, partially lepton id and boson acceptance systematics

$\int \frac{d\sigma}{dp_T^{W+\text{jets}}} [pb/(GeV)]$

$\int \frac{d\sigma}{dp_T^{W+\text{2 jets}}}[pb/(GeV)]$

$\int \frac{d\sigma}{dp_T^{W+\text{3 jets}}}[pb/(GeV)]$

$\int \frac{d\sigma}{dp_T^{W+\text{4 jets}}}[pb/(GeV)]$

$\int \frac{d\sigma}{dp_T^{Z+\text{jets}}}[pb/(GeV)]$

$\int \frac{d\sigma}{dp_T^{R_{\text{jets}}}}[pb/(GeV)]$

$8.73 \pm 0.30 \text{ (stat)} \pm 0.40 \text{ (syst)}$

**$R_{\text{jets}}$**
- Syst. cancellation:
  - lumi
  - Partially lepton id
  - Mostly JES/JER, detector effects,
  - parton-to-hadron corr.
Transverse momenta of $2^{\text{nd}}$, $3^{\text{rd}}$, $4^{\text{th}}$ jet

W+jets

- Various energy scales and high multiplicities already available in 2010 data
- Data consistent with NLO pQCD prediction and with ME generators SHERPA and ALPGEN
- Not consistent with PYTHIA parton shower
Dijet Angular Distributions

Z+jets

- Probe hard parton emission at large angles
- Of interest for example for VBF topologies (Higgs searches)
- Well described by NLO pQCD predictions and SHERPA+ALGPEN ME generators
Results in More Complex Variables

- $H_T$ often scale choice – $m_{WZ}$ not good scale any more at large jet $p_T$
- Interesting for searches, also: invariant mass $m_{12}$
- Variables well described by pQCD predictions and ME generators
Combined Electron+Muon Phase Space

- Combine individual $e/\mu$ cross sections to roughly double statistics
- Minimal extrapolation to common $e/\mu$ phase space to minimizing model dependent corrections
- $V+$jets: use the BLUE (BestLinearUnbiasedEstimate) method
- $R_{jets}$: use BAT (Bayesian Analysis Toolkit)

\[
\int L dt = 36 \text{ pb}^{-1}
\]

\[
\text{anti}-k_t, \ R = 0.4, \ p_T > 30 \text{ GeV}, \ |y^\text{cm}| < 4.4
\]

\[
\sigma(W \rightarrow l\bar{l}) + 1\text{-jet} \quad \sigma(Z \rightarrow l\bar{l}) + 1\text{-jet}
\]

8.29 ± 0.18 (stat) ± 0.28 (syst)
Extrapolation to Full Phase Space

- Want remove dependence on vector boson mass from fiducial phase space definition
- Later use in searches should allow any mass for vector boson like particles
- In principle complete cancellation of jet uncertainties possible
- But interpolation uses simulation: increased uncertainties compared to fiducial region measurement

Almost recover inclusive ratio:

$$10.13 \pm 0.22 \text{ (stat)} \pm 0.45 \text{ (syst)}$$
Outlook

Many possibilities... have already 100x the statistics available

- **V+jets**: Measure at higher multiplicities, go to higher $p_T$

- **$R_{jets}$**: probe more distributions and extended phase space
  (mostly already explored by V+jets)

- Add novel distributions interesting for backgrounds. Examples:
  - $V + 2$-jets specific distributions $\rightarrow$ VBF-like signature
  - Jet vetoes / rapidity gaps
  - Event shapes, jet shapes

- Searches: Exploit precision of ratio measurements to look for deviation from SM predictions in model-independent way

- PDFs: $W+/W-$ and Z probe different pdfs – input for pdf-fits?

- Theory: Compare to shower MCs in the future

... there is still a lot of work to do in the Standard Model
Conclusions

- Presented measurements of the production cross-section for W and Z bosons in association with jets, performed with data collected in 2010
  - Inclusive cross-section as a function of jet multiplicity and its ratio
  - Differential cross-sections with respect to jet and di-jet kinematics
  - Cross-sections corrected for all detector effects and quoted in the kinematic region of the detector acceptance
  - Precision is mainly limited by systematic uncertainties
  - Data compared to predictions at LO and NLO in QCD
    - Good agreement between data and predictions from ALPGEN, SHERPA, MCFM and Blackhat-Sherpa in region probed by measurements
    - PYTHIA disagrees with data when $N_{\text{jet}} > 1$ (expected)
The Large Hadron Collider
JES Components

$0.3 < |\eta| < 0.8$

$2.1 < |\eta| < 2.8$