W/Z + Jets and W/Z + HF Production at the LHC

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Why W/Z + jets?

- Confront pQCD (very precise for EW vertices)
- Small experimental uncertainty
- Nearly background free
- But itself: background to BSM
- Study structure of the proton \( \{ f_i(x_1), f_j(x_2) \} \)
- We can’t do it without precise partonic cross-sections

![Diagram showing LO and NLO processes](image-url)
LHC data & MC samples

- Smooth operation during 2011 & 2012
- $5\text{fb}^{-1}@7\text{ TeV}, 22\text{fb}^{-1}@8\text{ TeV}$
- MC: need typically x10 more simulated luminosity
- Great challenge
  - CPU/Disk Storage
  - Complexity of MC tools

NLO fixed order calculations and (N)LO ME+PS are required to describe extremely rare events & kinematic configurations reachable with this data luminosity.
Z + jets @ 7 TeV

- Data with Z + ≥ 7 jets
- Good agreement with BlackHat + Sherpa NLO (up to ≥ 4 partons)
- MC@NLO (DY@NLO + 1 real emission + PS)
- ALPGEN/Sherpa: LO ME up to 5 partons, PS copes with the additional radiation
- Multiplicity is ~OK (within uncert.)
- Are the angular correlations and Jet $p_T$ OK for high $N_{jets}$?

more details about the MC setup in the backup
**Δφ correlations, Z + jets**

![Graphs showing Δφ correlations for Z + jets](image)

- Standalone Pythia meant to show here what PS can do
- Powheg has NLO (Z + 1-jet) + PS: gets the ≥ 3-jet picture
Leading jet $P_T$, $Z + \text{jets}$

For **inclusive**, higher order multi-parton emission is important; For **exclusive** MC@NLO (DY@NLO + 1 real emission) is OK; good agreement with NLO (BlackHat + Sherpa) in both **inclusive** & **exclusive** cases
$p_T(Z)$ and $\Sigma p_T(\text{jets}), Z + \text{jets}$

MC fails for boosted events, indicating missing higher orders (EWK/QCD?); important for searches: think of $p_T(Z)$ as MET when $Z \rightarrow \nu\nu$
Rapidity distributions, $Z + 1$-jet

Data/Theory for $|Y_Z|$ and $|Y_{\text{jet}}|$ within 5%
Rapidity differences, Z + 1-jet

Correlations ($Y_Z,Y_{jet}$) do not agree (Data/MC); Madgraph and Sherpa have different predictions; Data are more consistent with Sherpa; Differences attributed to jet matching in ME+PS
V + HF production
W + c-jet

- $\sigma(W + c\text{-jet})$ sensitive to strange content of the proton
- c-jet viable through charm mesons reconstruction

3 channels with W + c purity 80-90%
**W + c-jet**

Symmetric quark sea $\bar{s}/\bar{d} \sim 1$ is predicted from **B**

Strange suppression $\bar{s}/\bar{d} \leq 0.5$ is predicted from **A**

CMS data consistent with **A**

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MCFM (with different PDF sets)

include low E DIS data

collider only data

CMS Preliminary

5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

- MSTW08 $100.7^{+1.9}_{-2.2}$ PDF
- CT10 $109.9^{+7.7}_{-6.4}$ PDF
- NNPDF23 $98.4^{+4.2}_{-4.6}$ PDF

CMS 2011 $107.7^{+3.3}_{-6.9}$ (stat) $^{+6.9}_{-6.9}$ (sys)

CMS Preliminary

5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

- MSTW08 $0.906^{+0.017}_{-0.025}$ PDF
- CT10 $0.949^{+0.004}_{-0.004}$ PDF
- NNPDF23 $0.922^{+0.014}_{-0.014}$ PDF

CMS 2011 $0.954^{+0.025}_{-0.017}$ (stat) $^{+0.017}_{-0.017}$ (sys)
W + 1 b-jet

MCFM corrected ~30% for DPS


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Moriond QCD, 10 March 2013
First measurement of $W + 1$ b-jet differentially vs $d\sigma/dp_T$

- $N_{\text{jet}} = 1$ Data/MC increases as function of b-jet $p_T$
- Results are also provided without single top subtraction
W + 2 b-jet

Complementary phase space w.r.t. the W + 1 b-jet measurement, very good Data/Theory agreement; Important for WH with H→bb

\( N_{\text{bjets}} = 2 \) (exclusive)

\[
\sigma(W\to bb)
\]

Data (CMS) \( 0.53 \pm 0.05 \) stat \( \pm 0.1 \) sys [pb]

MCFM (MSTW08NNLO) \( 0.52 \pm 0.03 \) [pb]
Summary

- LHC delivered substantial data in 2011: MC is required to describe extreme kinematics of rare events with small cross-section
- Data/MC tension was observed in key distributions important for LHC physics searches
- Need to improve MC in order to be able to extract the smallest signals of interest at LHC

More luminosity (x 4) at 8 TeV yet to be analyzed
References

- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12002](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12002)
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12004](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12004)
  - CDS record: CMS-PAS-SMP-12-004
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12026](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12026)
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015)
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021)
  - CDS record: CERN-PH-EP-2012-357
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11012](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11012)
  - [http://dx.doi.org/10.1007/JHEP06(2012)126](http://dx.doi.org/10.1007/JHEP06(2012)126)
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/SMP12003TWiki](https://twiki.cern.ch/twiki/bin/view/CMSPublic/SMP12003TWiki)
  - [https://cdsweb.cern.ch/record/1428117](https://cdsweb.cern.ch/record/1428117)
  - CDS record: CERN-PH-EP-2013-003
MC setup (ATLAS)

- ALPGEN v2.13 + HERWIG v6.520 + JIMMY v4.31 + AUET2-CTEQ61L
- ALPGEN v2.14 + PYTHIA v6.425 + PERUGIA2011C + CTEQ61L (for sys studies)
- Sherpa v1.4.1 using MENLOPS for 0-jet bin + CT10
- MC@NLO v4.01 + HERWIG + CT10 (DY@NLO + 1 real emission)
- PHOTOS used for QED FSR both in ALPGEN + PYTHIA
- YSF for QED-FSR in Sherpa
- ALPGEN + Sherpa both ME with up to 5 partons
- FEWZ + MSTW08NNLO for NNLO DY inclusive cross sections
- BlackHat+Sherpa NLO Z + (1-4) partons + CT10 PDFs
MC setup (CMS)

- Madgraph v5.1.1.0 (ME up to 4 partons) + Pythia v6.4.24 + Z2 tune + CTEQ6L1
- Sherpa v1.3.1 (ME up to 4 partons) + CTEQ6m
- Powheg DY + 1-jet @ NLO + Pythia v6.4.24 + Z2 tune + CT10
- Pythia v6.4.24 + Z2 tune
- FEWZ for NNLO DY inclusive cross sections
- MCFM for NLO Z/W + 1-jet + CTEQ6.6M, MSTW2008, NNPDF21
Backup Slides
Z bb angular correlations

Madgraph with 4F PDFs approach gives best description of data (normalization and shape)
Madgraph with 5F PDFs underestimates collinear BB hadron production (gluon splitting)

Z+b-jets cross section also published with 2.2 fb$^{-1}$ @ 7 TeV J. HEP 06 (2012) 126
$W + 2j$

DPI signal

$W + 2j$ background

CERN-PH-EP-2012-355
Z + b jets

Z+bb cross section 10% higher than tree-level prediction by Madgraph 5F rescaled by k = 1.23; Some tensions in the description of the event dynamics
$k_T$ splitting

arXiv:1302.1415
$W + c$ (backup)
W + bb (backup)
Detector Level Spectra (CMS)

CMS, $\sqrt{s} = 7$ TeV, $L = 5.0$ fb$^{-1}$

- Data
- DY+jets
- $t\bar{t}$
- EW

$p_T^{\text{jet}} > 50$ GeV

Events / bin

Ratio data/MC

MC: Madgraph + Pythia normalized to NNLO (or NLO for $t\bar{t}$ & EW)
Detector Level Spectra (ATLAS)

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]

Events / bin

\begin{align*}
\text{MC / Data} & \approx 1.2 \\
& \approx 1 \\
& \approx 0.8
\end{align*}

\begin{align*}
N_{\text{jet}} & \geq 0 \\
& \geq 1 \\
& \geq 2 \\
& \geq 3 \\
& \geq 4 \\
& \geq 5 \\
& \geq 6 \\
& \geq 7
\end{align*}

\begin{align*}
\text{ALPGEN} & \\
\text{Sherpa} &
\end{align*}
Z + jets $\Delta\phi$ Correlations

- Multileg ME + PS is needed to describe (B)
- Powheg NLO Z + 1j ME + PS is good even for $\geq 3$-jets

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**Δφ correlations, Z+jets (boosted)**

- For boosted multijet final states $Δφ(J_i,J_j) \rightarrow$ uniform
- *Pythia* gets better at boosted topologies

![Graph showing Δφ distributions for Z+jets events at CMS, √s = 7 TeV, L = 5.0 fb⁻¹, with data and different simulations (MADGRAPH, SHERPA, POWHEG (Z+1j), PYTHIA6 (Z2)). The plots show Δφ(Z,J_i) and Δφ(J_i,J_j) distributions for Z+3-jets with $p_T(Z) > 150$ GeV. Data is compared to different simulations, and the Δφ distributions are normalized and overlaid for comparison.](image-url)
\[ N_{\text{jets}} \text{ scaling, } Z + \text{ jets} \]

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]

\[ \text{anti-}k_t \text{ jets, } R = 0.4, \]

\[ p_T^{\text{jet}} > 30 \, \text{GeV}, |y| < 4.4 \]

\[ \text{leading } p_T > 30 \, \text{GeV} \]

\[ \text{leading } p_T > 150 \, \text{GeV} \]

Both scaling patterns are anticipated from first principles \cite{JHEP1210} and are predicted from NLO and ME+PS; rather good Data/Theory; Poisson scaling typically expected in physics searches.
Subleading jets $p_T$, $Z + jets$