Why exclusive decays of W bosons should not be used for a mass measurement

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Abstract

The search for fully-reconstructed, hadronic vector boson decays is an ongoing part of the LHC programme, where, to date, no such decays have been observed. In addition to the intrinsic interest in the branching ratios, there is potential for a measurement of the \( W \) boson mass quite distinct from the usual methods. The radiative decay modes offer a good potential for this measurement; however, we highlight three issues with it not previously discussed: particle misidentification, partial reconstruction and the impact of interference with QCD. These issues cause shifts in the peak position of tens or hundreds of MeV/c\(^2\).

1 Introduction

Exclusive decays of \( W \) and \( Z \) bosons to hadronic final states have never been observed. Low-multiplicity final states could potentially be experimentally accessible and there are several theoretical estimates available. In particular, radiative decays of vector bosons are promising channels with many theoretical predictions \cite{1,2,3,4,5}; however, there is not universal agreement between these predictions. For example, the \( W^{\pm} \rightarrow \pi^{\pm} \gamma \) branching ratio is estimated to be of the order of \( 10^{-9} \) in Ref. \cite{1} and Ref. \cite{4}, whereas Ref. \cite{5} proposes values as high as \( 10^{-7} \).
There are experimental limits on many two-body $Z$ decays. These include radiative decays such as $\pi^0\gamma$ [6], $\eta\gamma$ and $\eta'\gamma$ [7], $\omega\gamma$ [8], $\phi\gamma$ [9], $J/\psi\gamma$ and $\Upsilon\gamma$ [10], as well as non-radiative modes such as $\pi^0\pi^0$ [6]. Preliminary limits on $W^-\rightarrow\pi^-\gamma$ at $1.5 \times 10^{-5}$ have been presented by CMS [11], following the $t\bar{t}$ selection strategy advocated in Ref. [4]. However, the total LHC $W$ cross-section is much larger, approximately 175 nb at 13 TeV according to DYNNLO 1.5 [12, 13], implying that over $5 \times 10^{11}$ $W$ bosons are expected at the HL-LHC. With a suitable trigger, this presents an interesting opportunity.

ATLAS has demonstrated a dedicated $Z\rightarrow\phi\gamma$ trigger [9], using a 35 GeV $E_T$ photon and a pair of charged tracks, with an efficiency of 80%. We assume that a similar strategy could be employed for any low-multiplicity, radiative $W$ boson decay mode. It may also be possible to record fully-hadronic events using either a $J/\psi$ decaying to muons or a modified tau-pair trigger at first level, with a tight selection on the mass in charged particles at high level.

The ATLAS and CMS detectors at the LHC achieve excellent mass resolution for decays to charged particles and isolated photons, with 1-2 GeV/c² quoted by CMS for $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ$ [14]. A nominal 1% resolution is used in this paper for decays to such particles.

This resolution suggests a measurement of the $W$ boson mass could be feasible. This measurement, however, has unrecognised difficulties from final state hadron loss and misidentification and also from EW-QCD interference.

2 Simulating Radiative Decays

Figure 1: Feynman diagrams leading to the same final state. (a) shows the electroweak radiative process of interest, whilst (b) shows an example QCD process, which will lead to interference.

The signature studied here is a $W$ boson decaying to a photon that recoils against a low-multiplicity jet. A Feynman diagram for this process is

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given in Fig. 1 (a). Fig. 1 (b) shows a QCD process leading to the same final state, which causes the interference discussed in Section 5. We generate the inclusive process, \( W \rightarrow u \bar{d} \), and focus on the decays with a hard photon in the final state, comparing the decay multiplicity for PYTHIA8 \[15, 16\] and several different Sherpa 2.2.10 configurations \[17\]. The default Sherpa cluster-fragmentation model is not expected to be reliable [F.Krauss, Personal communication] for processes with few particles in the final state, due to a mass of approximately 300 MeV/c\(^2\) assigned to the quarks. Consequently, the Lund string fragmentation model is used for all alternative Sherpa configurations. These are: only replacing the cluster-fragmentation with the Lund string fragmentation (Sherpa-Lund); additionally enabling the EW emission using the switch \texttt{CSS\_EW\_MODE=1} (Sherpa-EW-Lund); and using the hard matrix element to simulate \( W \rightarrow u \bar{d} \gamma \) (Sherpa-ME-Lund). For our purposes, the decays of \( \pi^0 \)'s and \( K^0 \)'s are switched off; otherwise, the final state particles from the generators are enumerated.

The distributions of the \( W \rightarrow u \bar{d} \) particle multiplicities produced by these generators, when requiring exactly one photon in the final state, are shown in Fig. 2 (a). At low multiplicity, PYTHIA, Sherpa-EW-Lund and Sherpa-ME-Lund, the only predictions producing hard photons, are within a factor of three of each other. This approximate agreement supports the use of the matrix-element approach, which allows for much more efficient simulation through phase space selection and the calculation of interference effects, discussed in Section 5. Sherpa-ME-Lund predicts a \( W \) branching ratio to a radiative three-body state of \((4.1 \pm 0.2) \times 10^{-8}\), with the other simulations compatible within larger statistical errors. Two-body radiative states cannot be produced by the Lund hadronization model.

In Fig. 2 (b), we show the charged-particle multiplicity for the process \( Z \rightarrow q \bar{q} \) for the same configurations outlined above. In addition, we overlay data from the ALEPH experiment \[18\]. The data does not favour any of the models and, at charged multiplicities of four or less, is not precise enough to be a definitive guide, though it hints that the true rate of extremely low multiplicity events could be lower than these simulations predict.

\section*{3 Particle Misidentification}

The particle composition of low-multiplicity events predicted by the generators is shown in Fig. 3, where exactly one photon is required from all con-
Figure 2: (a) shows the particle multiplicity for the process $W \rightarrow u \bar{d}$, with exactly one photon in the final state. (b) shows the charged-particle multiplicity for the process $Z \rightarrow q \bar{q}$, with data from the ALEPH experiment overlaid. In both figures, PYTHIA is shown in green and the predictions by the various Sherpa configurations are also shown: default Sherpa (red), Sherpa-Lund (blue), Sherpa-EW-Lund (magenta) and Sherpa-ME-Lund (dotted blue).

At very low multiplicities, the generators predict significantly different compositions. Sherpa-EW-Lund and Sherpa-ME-Lund both predict a sharp reduction in the kaon fraction, which is not seen in PYTHIA. However, only Sherpa-ME-Lund has good statistical precision when the multiplicity is less than five. In general, PYTHIA predicts fewer baryons present in the low-multiplicity states compared to both of the Sherpa configurations.

There is, therefore, considerable uncertainty about the composition of low-multiplicity states and the large LHC detectors are not able to reliably distinguish hadron species at these momenta. If the wrong species of particle is attributed to a decay, the estimated boson mass will change. For example, if $W^+ \rightarrow p\bar{p} \pi^+ \gamma$ is mistaken for $W^+ \rightarrow \pi^+ \pi^- \pi^+ \gamma$, the shift in the peak position of the $W$ boson mass is of the order 60 MeV/c^2.

4 Partial Reconstruction

Partial reconstruction refers to attempting to reconstruct a particle using a subset of the actual decay products. The example of reconstructing a $W^-$ boson using three charged tracks and a hard photon in the final state, $W^- \rightarrow h^- h^+ h^- \gamma$, as predicted by Sherpa-ME-Lund, is shown in Fig. 4.

The relatively large number of decays including additional neutral particles constitutes a major background that overlaps with the $W$ boson peak. A
Figure 3: The fractions of leptons, neutrons, kaons, protons, $\pi^0$, $\pi^\pm$ and photons predicted by (a) PYTHIA, (b) Sherpa-EW-Lund and (c) Sherpa-ME-Lund for $W\to ud$ decays with exactly one photon in the final state.

detector resolution of 1% is assumed and, even with perfect resolution, this overlap is unavoidable due to the $W$ width. These partially reconstructed events could be suppressed by vetoing on photon-like, calorimeter energy deposits, if they can be recognised. Fig 4 (b) shows the result of applying a veto at an energy of 3 GeV, corresponding approximately to the energy threshold in the ATLAS electromagnetic calorimeter in 2017 [19]. Although a large fraction of the partially reconstructed decays is removed, the surviving events form a secondary peak, which is experimentally indistinguishable from the primary.

The result of fitting a Gaussian is that the identified peak is shifted by -363±14 MeV/$c^2$, or -270±12 MeV/$c^2$ when the calorimeter cluster veto is applied. These shifts are dependant upon unknown $W$ boson decay properties and fine details of the calorimeter response. Simulation of two-body decays, such as $W\to\pi^-\gamma$ or $W\to D_s\gamma$, is not possible with this set-up; however, they will also suffer from partial reconstruction, particularly from $W\to \rho^-\gamma$ and $W\to D_s^*\gamma$. It is particularly difficult in the case of the $D_s^*$, where the dominant $D_s^*\to D_s\gamma$ decay produces a low-energy photon.

5 EW-QCD interference

Interference of the hadronic vector boson decay with the t-channel $q\bar{q}\to q\bar{q}$ QCD background has been shown to introduce an apparent reduction in
the mass of the peak $[20, 21, 22, 23]$. This comes from the change in sign of the Breit-Wigner resonance at the peak, overlaid on a continuous QCD background. The effects reported are mass shifts of hundreds of MeV/c$^2$.

For radiative final states, the LO Sherpa-ME-Lund setup is used, with the hadronization omitted to speed computation. Fig. 5 shows the mass predicted by this configuration for $W^{\pm}\rightarrow ud\gamma$ events from the EW process alone, from the QCD background process and from the coherent sum. The mass of the $ud$ system is required to be below 2 GeV/c$^2$, while that of the $ud\gamma$ is between 70 and 90 GeV/c$^2$. The predicted shift in the mass peak is $-355 \pm 24$ MeV/c$^2$, after including the detector resolution of 1%. The absolute cross-sections depend upon the upper diquark mass selection used; however, the ratio of signal-to-background and the resulting mass shift is essentially independent. The mass shift in $W^{+}\rightarrow d\pi\gamma$ is $-322 \pm 24$ MeV/c$^2$, consistent with the $W^-$ but smaller, as expected with a slightly better signal-to-background ratio.

The same effect was also studied for the second generation decays, $W^+\rightarrow cs\gamma$ and $W^-\rightarrow s\bar{c}\gamma$. For both processes, the shifts in the peak position are consistent, $-96 \pm 14$ MeV/c$^2$ and $-90 \pm 48$ MeV/c$^2$, respectively.

An exploration of interference in the fully-hadronic decay mode was also conducted. The final state $u\bar{s}s\bar{d}$ was simulated, with the $u\bar{s}$ and $s\bar{d}$ systems
Figure 5: The reconstructed mass peak in the $u\bar{d}\gamma$ system, assuming a 1% detector resolution and requiring the mass of the $u\bar{d}$ system to be below 2 GeV/$c^2$. Left: the basic distributions for the EW component (green), QCD component (red) and total (black). Right: A Gaussian fit to the EW (green) and total (black) terms to determine the mass shift.

Each separately required to have a mass below 6 GeV/$c^2$. This channel was chosen since it arises naturally in a $W$ decay and the quarks are all distinct, which allows for unique identification. The EW signal cross-section, within this (arbitrary) mass cut, is similar to the radiative process, whereas the QCD component is a factor one hundred larger, although this can be significantly suppressed by kinematic selections. The worse signal-to-background ratio makes the fully-hadronic channel much less promising than the radiative channels for LHC searches. A shift in the $W$ peak position in the fully hadronic channel of $-970 \pm 290$ MeV/$c^2$ was seen.

6 Conclusions

Radiative $W$ decays are predicted by PYTHIA8 and Sherpa for three-body and four-body states, with branching ratios of a few in $10^{-8}$. This is three orders of magnitude below the current sensitivity for the experimentally similar decay of $W^{-}\rightarrow\pi^{-}\gamma$.

It is, however, possible that exclusive hadronic vector boson decays may be observed at (HL-)LHC. Radiative decays, with a high-energy photon recoiling against a low-multiplicity hadronic system, seem to be the most promising channels. Although it might be technically feasible to trigger fully-hadronic $W$ boson decays, the poor intrinsic signal-to-background ratio means it is unlikely to be competitive with the radiative decay modes.
If a mass measurement of the $W$ boson is to be considered, three effects need to be understood and controlled: charged hadron misidentification, partial reconstruction and interference. The misidentification is the least significant of these effects, but it still produces mass shifts in the peak position of 60 MeV/$c^2$. On the other hand, partial reconstruction and interference decrease the measured mass by 100-300 MeV/$c^2$, with the precise values dependent on poorly-understood physics and details of the experimental reconstruction.

In summary, fully-reconstructed $W$ boson decays do not appear to be a promising avenue for a mass measurement.

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