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Exclusive hadronic W decay: $W \to \pi\gamma$ and $W \to \pi^+\pi^+\pi^-$

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Abstract

In this talk I will present results which assess the possibility of the LHC observing the decays $W \to \pi\gamma$ and $W \to \pi^+\pi^+\pi^-$. No exclusive hadronic decay of a fundamental standard model boson has ever been observed before and, at the LHC, the huge QCD background and trigger challenges present serious difficulties in making such measurements. The latter problem can be addressed by studying Ws in a $t\bar{t}$ environment, exploiting the triggering opportunities this brings, and I discuss the use of an isolation technique – requiring single particle jets – which can help to separate signal from the QCD background. The conclusions drawn here are that while the $W \to \pi\gamma$ decay seems unlikely to be measured at the LHC, $W \to \pi^+\pi^+\pi^-$ could be observed by the end of the high luminosity run.

Keywords:

1. Introduction

[1] No exclusive hadronic decay of the fundamental standard model (SM) bosons W, Z or h, has ever been observed. As well as being very interesting probes of the strong interaction at the boundary of the perturbative and non-perturbative domains, it has been proposed that these decays could also be used to extract fundamental SM parameters, one potentially important example being the flavour on-/off- diagonal couplings of the Higgs boson to the light flavours of quark [2, 3, 4, 5, 6, 7]. In this talk I present results which asses the possibility of observing an exclusive hadronic decay of the W boson at the LHC, focusing on the decays $W \to \pi\gamma$ and $W \to \pi^+\pi^+\pi^-$.

There will be of order 10^{11} W bosons produced at the LHC, which motivates a push for a new level of precision in the known decay modes and parameters of this particle (summarised in the Particle Data Group review, [8]), including branching ratios to exclusive hadronic final states. However, for generic LHC W production,

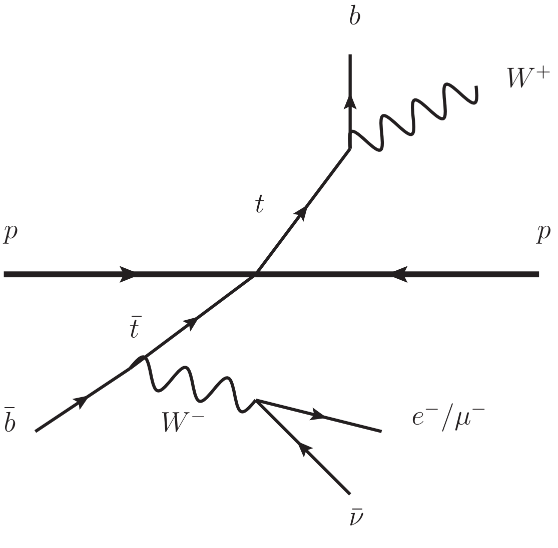

Figure 1: Top pair production in which one of the W bosons decays leptonically, providing two b-jets, a lepton, and missing energy to trigger on. The remaining W boson in the event can subsequently be studied in a relatively unbiased way.

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[1] Proceedings based on the results of Ref. [1].

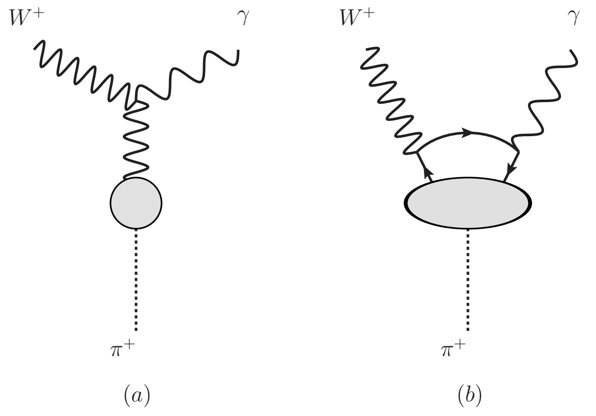

Figure 2: The decay $W \to \pi\gamma$ receives two types of contributions.

precision studies are not feasible given the trigger challenges and huge QCD background present. In [1] it was pointed out that one of the W bosons which is in the final state of $t\bar{t}$ production can be studied in a relatively unbiased way: two b-jets and the leptonic decay of one W decay can be triggered on, still leaving a further W in the event – see Fig. 1. The $t\bar{t}$ cross section is large at the LHC, and there are potentially of order 10^9 W bosons which are triggerable in this environment by the end of the high luminosity (HL) run.

Because of the huge QCD background at the LHC, exclusive hadronic decay modes of these W bosons are particularly hard to subsequently observe. The remainder of this talk is restricted to reviewing the study of the decays $W \to \pi\gamma$ and $W \to \pi^+\pi^+\pi^-$ in this $t\bar{t}$ environment, as presented in [1]. The technique studied is that of requiring single particle jets – jets which consist of a single pion (or purely photons for a 'single photon' jet). This technique exploits the fact that QCD evolution generically only very rarely produces a well isolated pion or photon. The implementation of this technique in a Monte Carlo (MC) study is described in the following section.

Before turning to the MC study, I briefly describe some theoretical aspects of these two decays.

$\underline{W^+ \to \pi^+\gamma :}$

This decay receives two different types of contributions: those of Fig. 2(a), which are proportional to

$$\langle \pi^+(p)|J_\rho(0)^W|0\rangle = \frac{f_\pi}{\sqrt{2}}\, p^\rho\,, \tag{1}$$

and those of Fig. 2(b), which involve a calculation of

$$\int d^4x e^{ik\cdot x}\langle \pi^+(p)|T[J_W^\lambda(0)J_\gamma^\mu(x)]|0\rangle\,. \tag{2}$$

The branching ratio of this decay has been previously calculated in [9, 10], and in [1] a leading order in QCD, operator product expansion (OPE) approach to the contribution of eq. 2 was used to obtain

$$\Gamma(W \to \pi\gamma) = \frac{\pi\alpha^2|V_{ud}|^2 f_\pi^2}{54 m_W \sin\theta_W^2} \sim 10^{-9}\,\mathrm{GeV}\,, \tag{3}$$

although it is emphasised that this is only an order of magnitude estimate, and that the OPE will receive important higher order corrections (see also [11]).

$\underline{W^+ \to \pi^+\pi^+\pi^- :}$

This decay mode can be generated by allowing PYTHIA [12, 13] to shower and hadronise the decay $W \to ud$. The rate at which this final state is produced by PYTHIA is approximately 1 in every 10^7 events, but the PYTHIA model[2] is constrained by LEP $Z \to$ hadrons charged multiplicity data and is subject to large errors in this extreme of the distribution. The QCD perturbative picture suggests that the decay rate for $W^+ \to \pi^+\pi^+\pi^-$ would be of the same order of magnitude as $Z \to \pi^+\pi^-\pi^0$, and given that 10^7 Z bosons were created at LEP, it is unlikely that any constraint on the latter branching ratio below 10^{-6} could be obtained[3]. From the perturbative picture it is also expected that this decay mode would be at least a factor of α_{EM} larger than the $W^+ \to \pi^+\gamma$ decay discussed above, and a branching ratio could be as high as 10^{-5} and be in no conflict with experiment.

2. Monte Carlo Study

The following MC study was undertaken to provide an estimate of the reach of the LHC in making measurement of these decay modes. A sample of $t\bar{t}$ events with one W decaying leptonically, $W^- \to e^-\bar{\nu}_e$, was generated at tree-level using Madgraph 5 [15]. Signal samples were created by forcing the decay of the other W boson to be $W^+ \to \pi^+\gamma$ or $W^+ \to \pi^+\pi^+\pi^-$ (this was done isotropically, meaning spin effects were neglected). Two background samples were also generated: the 'W-had' background, where the W decays generically hadronically, and the 'W-tau' background, where the W decays to a tau lepton, which can then further decay into a hadrons[4]. These provide the dominant backgrounds (QCD $Wb\bar{b}$ production was also considered, since when the W decays leptonically, this gives

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[2] Ref. [14] details the most recent LHC tune

[3] I am not aware of a direct search for this decay mode at LEP, nor has it been possible to infer any constraints using available LEP data.

[4] The branching ratio of a tau into a single charged pion/kaon is $\sim 12\%$ and into three charged pions/kaons is $\sim 15\%$.

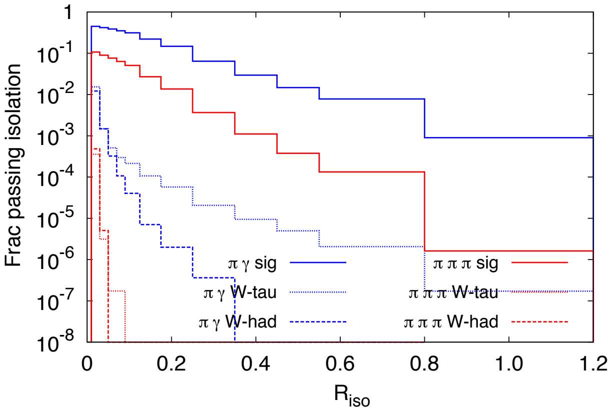

Figure 3: The fraction of signal and background events which, having passed $t\bar{t}$ selection cuts, further pass the single particle jet isolation cuts. Plotted as a function of the single particle jet parameter R_{iso}.

rise to the final state which is triggered upon. However, this background was found to be subdominant to the ones above). A separation of $\Delta R = 0.3$ was required between the lepton and a b parton in all generated events. The samples were then showered and hadronised using PYTHIA 8. Pileup was not generated.

The events are subsequently analysed as follows. Jets are constructed using FastJet [16] with the anti-kt algorithm [17] with $R = 0.4$. The cuts to select the $t\bar{t}$ events require two b-jets – jets of $p_T^j > 25\,\text{GeV}$, $|\eta_j| < 2.5$ and with a b-hadron constituent. The electron is required to have transverse momentum $p_T > 20\,\text{GeV}$ and rapidity $|\eta| < 2.5$, and a missing transverse momentum vector is constructed as the negative of the vector sum of all particles with $|\eta| < 3.6$ (excluding neutrinos), and a cut $p_T^{miss} > 30\text{GeV}$ is imposed.

If the triggering cuts are passed, single particle isolation conditions are required. All of the particles assigned to the two b-jets are first removed, and the remaining event is resent to FastJet, with a new jet parameter $R = R_{iso}$, but keeping the same jet transverse momentum and rapidity requirements as above. Then, by defining a single pion jet as a jet composed of exactly one pion, and a single photon jet as a jet which contains only photons as constituents, only the events which contain single particle jets that match the signal states (either $\pi\gamma$ or $\pi\pi\pi$) are retained. Fig.3 shows the fraction of events which, having passed the $t\bar{t}$ cuts, further pass the single particle jet requirements, as a function of the jet parameter used in the second FastJet analysis, R_{iso}. The W-had and W-tau background sample mass distributions for the $\pi\gamma$ analysis are plotted in Fig. 4, and the

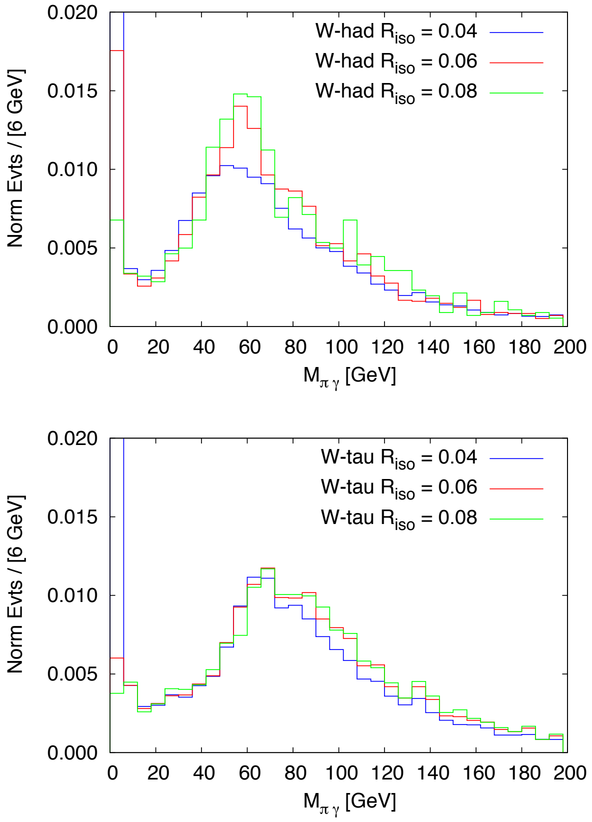

Figure 4: Background distributions of $M_{\pi\gamma}$, where π and γ are the reconstructed single particle jets, for the $W \to \pi\gamma$ analysis, shown for three values of R_{iso}. Top panel shows the W-had background; bottom panel shows the W-tau background (see text for definitions of these backgrounds).

signal invariant mass distributions are plotted in Fig. 5 – in all cases the invariant mass is built up using the single particle jets returned by FastJet.

Analysis for $W \to \pi\gamma$:

The fraction of W-had background events passing the single particle jet cuts is observed to fall considerably faster than the fraction of signal $\pi\gamma$ events as the jet parameter R_{iso} is increased (Fig. 3). However, the W-tau background does not fall as quickly – here a mechanism where the tau decays into a single pion in conjunction with a hard QED photon emission from elsewhere in the event causes the fraction to track the signal a factor of $\sim \alpha_{EM} \times BR(\tau \to \nu_\tau \pi) \sim 10^{-4}$ smaller. Events arising from this mechanism are expected to be very difficult to distinguish from signal – the tau will be well boosted in the lab frame so that, for example, secondary vertex tagging will not aid discrimination. The background invariant mass distributions shown in Fig. 4 show falling distributions across the signal region $78\,\text{GeV} \leq M_{\pi\gamma} \leq 84\,\text{GeV}$, and these remain relatively stable for the different values of R_{iso} shown. In the following estimation of LHC sensitivity, the shape of the $R_{iso} = 0.06$ distribution is assumed for both backgrounds, since it is difficult to obtain higher R_{iso} distributions with high statistics. It is also assumed that the analysis for the W^- provides a factor of two in statistics.

After a HL-LHC run, with 3 ab^{-1} of data, there are of order 10^9 $t\bar{t} \to W^\pm l^\mp \nu b\bar{b}$ events expected to pass the $t\bar{t}$ selection cuts. It is then already apparent that the order of magnitude SM result for the branching ratio $W \to \pi\gamma$ – 10^{-9} (see eq. 3) – implies that this decay is too rare to be observed with the HL-LHC data. It is nevertheless useful to estimate the smallest branching ratio which could be observed at the 3σ level, given the uncertainty in the theoretical estimates of this decay (see [1] for a more detailed discussion of these uncertainties). Using $N_{sig}/\sqrt{N_{bkg}}$ to estimate the significance, where $N_{sig\,(bkg)}$ is the number of signal (background) events with $78\,\text{GeV} \leq M_{\pi\gamma} \leq 84\,\text{GeV}$, and optimising over R_{iso}, it is found that a branching ratio of 6×10^{-7} can be observed at 3σ, using a value $R_{iso} = 0.15$. Based on this estimate, in principle the HL-LHC could better the current best limits on this decay ($< 6.4\times10^{-6}$ at 95% confidence level, obtained by CDF [18]).

Analysis for $W \to \pi\pi\pi$:

For this analysis, both backgrounds fall considerably faster than the signal as R_{iso} is increased (Fig. 3) – here tau decay into three pions does not contribute analogously to the $\pi\gamma$ case, since the decay is pencil like and the three pions exclude themselves from passing the isolation cuts. For $R_{iso} \geq 0.06$ there is no background in this MC study, which translates to a possible sensitivity for observation of this decay with a branching ratio as low as a few$\times10^{-7}$ after the HL-LHC – inside the expected standard model prediction.

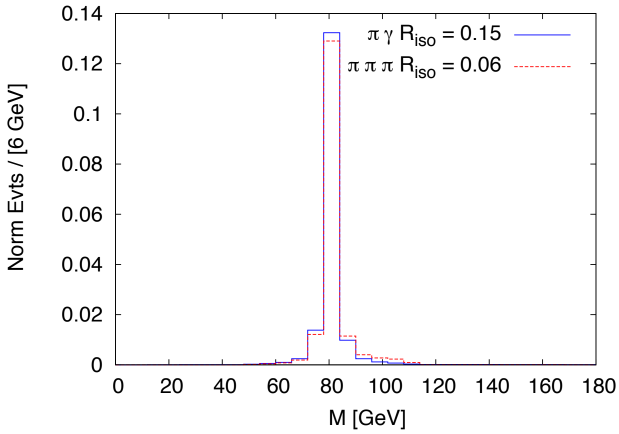

Figure 5: The distribution of the reconstructed W mass for the generated signal samples for the decay $W \to \pi\gamma$ and $W \to \pi\pi\pi$.

3. Discussion

A more detailed study that takes into account realistic detector conditions (which was beyond the scope of this work) needs to be performed. Pileup was not considered in the above, and this could present an amount of contamination so as to seriously affect the results seen here. Tracking information will be very useful for dealing with this (and also in dealing with secondary isolated pions such as those from tau decay), since the single pion tracks should be required to point to the interaction vertex (which is that flagged by the lepton on the other side of the $t\bar{t}$ event); whether this can control the amount of contamination remains to be seen after a detailed study. Further information about the background is obtained by studying events which pass the isolation cuts, but which have the wrong charge sum (determined from the charge of the lepton which tags the $t\bar{t}$ event). Additional background suppression can come from requiring the invariant mass of the signal single particle jets and one of the b-jets to be close to the top mass. It is also possible that profiling information in the electromagnetic calorimeter can be utilised to tighten the definition of the single photon jets, cutting away multiple photon events (a technique used in Higgs diphoton analyses to suppress $\pi^0 \to \gamma\gamma$ backgrounds).

With these caveats in mind, conclusions can be drawn as follows. It seems unlikely that the HL-LHC will be able to observe the decay $W \to \pi\gamma$ using the approach considered here, unless the branching ratio is significantly larger than the expected SM value. Setting a new upper limit on the decay does however appear feasible. On the other hand, the decay $W \to \pi\pi\pi$ does have potential to be measured after the HL-LHC run. This could be the first ever observation of an exclusive hadronic decay mode of a fundamental SM boson.

One interesting further avenue to pursue would be to investigate semi-exclusive hadronic measurements, $W \to PX$, in the $t\bar{t}$ environment, where X stands for anything and P is a named particle, e.g. $P = J/\psi, D^{\pm}, B_S^0 \ldots$. For generic W production at the LHC such measurements would be very challenging, but again the triggering opportunities for the $t\bar{t}$ environment as discussed here would apply. Because semi-exclusive decays have considerably larger branching ratios than fully exclusive decays, these measurements could in principle be easier, and a semi-exclusive decay table for the W boson could be built up, in parallel with the existing table for the Z boson [8].

Furthermore, precision studies in the $t\bar{t}$ environment are not limited to those of the W boson – taus (arising one ninth of the time from the W decay) and charmed hadrons (one third of the time) will be produced in similar numbers under the same triggering opportunities, as are b-hadrons (with a tagged b or $\bar{b}$ nature using the lepton sign from the associated W decay, as pointed out in Ref. [19]).

Finally, the experimental techniques honed and understood in making a measurement of W exclusive decay would be invaluable in assessing the prospects for measuring Higgs boson exclusive decays at a hadron collider, from which potential insight could be gained into off- and on- diagonal couplings of the Higgs to light quark flavours.

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