A search for tWZ production in the Full Run 2 ATLAS dataset using events with four leptons.

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Abstract. A search for tWZ production using 139 fb^{-1} of pp collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, recorded by the ATLAS experiment at CERN, is presented. Events that contain exactly four leptons (electrons or muons) are selected. Additional criteria are applied based on the number of jets, the number of b-tagged jets and the number of Z boson candidates to define signal and control regions. The large $t\bar{t}Z$ and ZZ backgrounds are distinguished from signal by a BDT-based algorithm. Inputs to the BDT-based algorithm include, a kinematic reconstruction algorithm which reconstructs leptonically decaying top quarks and a variable constructed from the output of a BDT-based algorithm which aims to classify ℓb systems originating from top quarks. The expected signal strength is extracted via a blinded maximum-likelihood fit to multiple signal and control regions. The expected signal strength was measured as, $\mu(tWZ) = 1.91^{+0.95}_{-0.82}$, leading to an expected significance of 1.44σ. An expected upper limit on the signal strength is set to $\mu^{exp}_{up} = 1.61^{+2.35}_{-1.16}$. Furthermore, a combined blinded maximum-likelihood fit was performed across the tetralepton channel (four lepton final state) and an independent analysis of the trilepton channel (three lepton final state), to further increase the sensitivity this analysis to the tWZ cross section. The expected signal strength was measured as, $\mu(tWZ) = 1.80^{+0.70}_{-0.65}$, leading to an expected significance of 1.61σ. An expected upper limit on the signal strength is set to $\mu^{exp}_{up} = 1.43^{+2.04}_{-1.03}$.

1. Introduction

The production of a single top quark in association with a $W^{\pm}$ and Z boson (tWZ) at the CERN LHC is sensitive to both the neutral and charged electroweak couplings of the top quark as the process involves the simultaneous production of a W boson and a Z boson in association with the top quark. Due to the very large coupling of the top quark to the Higgs boson, the electroweak couplings of the top quark are a theoretically well-motivated area in which to search for the first signs of new physics [**?**, **?**] that could offer a resolution to the Hierarchy Problem [**?**, **?**]. The recent lack of signs of new physics from LHC data tells us that new physics is either very heavy, or is very weakly coupled to Standard Model (SM) particles, therefore signs of new physics might only be observed in anomalous rates of well-chosen processes. A prime example of such a process is tWZ. This has an extremely low production cross section (≈ 160 fb for $\sqrt{s} = 13$ TeV [**?**]), meaning that it is an extremely rare process and subsequently, it has never been observed by any particle physics experiment.

The latest datasets recorded by the ATLAS experiment at the CERN LHC are sufficiently large to potentially allow for an observation of tWZ production. In this analysis, the Full Run 2 dataset recorded by ATLAS is used to search for tWZ production in the tetralepton channel (tWZ with exactly four final state leptons). A kinematic reconstruction technique is used which aims to discriminate between tWZ and our most prominent background process, $t\bar{t}Z$. In addition to this, Machine Learning techniques are implemented to further isolate our tWZ signal. Backgrounds from Standard Model processes including those in which one or more leptons originate from the semileptonic decay of a heavy hadron or a photon conversion are estimated by fitting predictions from simulation to data in dedicated control regions. As this work forms the basis of an official ATLAS analysis, only blinded results are shown. A maximum likelihood fit is performed over our two tWZ signal regions and three control regions, to measure the cross section of tWZ in the tetralepton channel. In this thesis only the tetralepton channel is explored, however, the results of a combined fit that includes an entirely independent analysis of the trilepton channel is presented with no overlap of events between the regions defined for these channels.

2. tWZ

The main backgrounds for tWZ in the tetralepton channel are the production of a two tops, both in the $\ell\nu b$ [1] final state channel, together with a Z boson ($t\bar{t}Z$) and diboson production with fully leptonic final states (ZZ). In Figure 1, the Leading Order (LO) Feynman diagram for tWZ in the tetralepton channel and it's major background processes, $t\bar{t}Z$ and ZZ are shown.

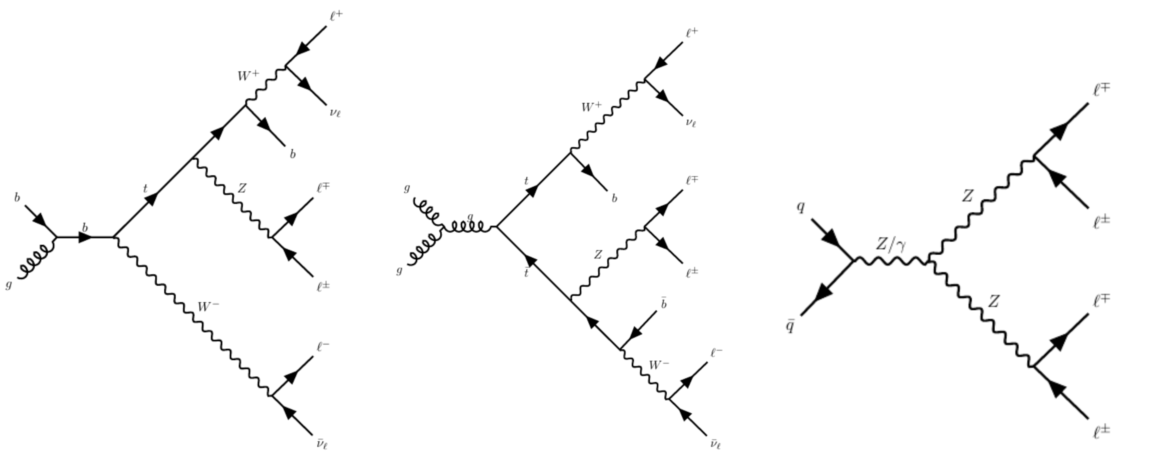

Figure 1. The LO Feynman diagrams of tWZ production in the tetralepton channel (left) and it's major backgrounds, $t\bar{t}Z$ (middle) and ZZ (right) are shown.

Prior to this analysis, only three experimental studies of tWZ in ATLAS have been performed. Two of the studies utilised the trilepton channel to search for tWZ production, whereas the third study utilised both the tri- and tetralepton channels. The first search utilised 36 fb^{-1} of ATLAS data and an upper limit on the cross section of tWZ was set at a value of ≈ 6 times the SM cross section [?]. The second search in the trilepton channel utilised 139 $^{-1}$ of ATLAS data and an expected upper limit on the cross section of tWZ was set at a value of ≈ 2.6 times the SM cross section [?]. In Section **??**, the aformentioned

[1] In this document, ℓ refers to an electron or muon, ν refers to a neutrino or anti-neutrino and b refers to a bottom quark or anti-bottom quark

analysis will be used in combination with this analysis, in order to further increase the sensitivity of the cross section of tWZ. The third study investigated the feasibility of a cross section measurement of tWZ production with CMS Run 3 data (300 fb^{-1}) [?], by utilising the trilepton and tetralepton channels. The study showed that it is possible to exclude $\mu(tWZ)$ at the 7σ significance level using 300 fb^{-1} of data. This study needs to be further investigated, since its findings seem improbable given the results obtained in this thesis. The most apparent difference between the trilepton and tetralepton channels is their branching ratios ($\frac{\Gamma_i}{\Gamma}$), with the tetralepton channel's branching ratio being much smaller than that of the trilepton channel. The tetralepton channel has a cross section times branching ratio of $\sigma^{NLO}_{(tW^{\pm}Z).Br(4\ell)} = 0.7$ fb [?], and is therefore an extremely rare process. The trilepton channel has a cross section times branching ratio of $\sigma^{NLO}_{(tW^{\pm}Z).Br(3\ell)} =$ 3.9 fb [?], which is around a factor of four larger than that of the tetralepton channel. Despite the tetralepton channel's low statistics, it is not subject to the large WZ background present in the trilepton channel [?]. The tetralepton channel has a substantial amount of ZZ background (not present in the trilepton channel), fortunately this can be easily suppressed due to the full reconstructability of the two leptonically decaying Z-bosons.

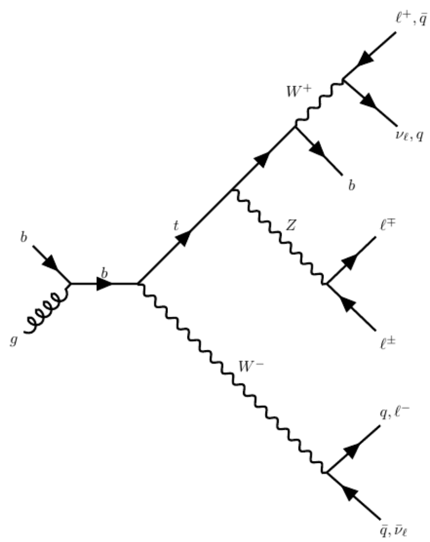

Figure 2. The LO Feynman diagrams of tWZ production in the trilepton channel is shown.

3. The search for tWZ production in the Full Run 2 ATLAS dataset using events with four leptons

3.1. Regions and Event Selection

In order to suppress potential fakes and quarkonia (low mass resonances such as J/ψ and upsilon) a requirement that all OSSF lepton pairs have an invariant mass, m_{OSSF}, greater than 10 is applied. The final state lepton charges must sum to zero. Therefore a requirement of $\sum_{i=1}^{4} charge(\ell_i) = 0$ is applied. The invariant mass of the OSSF lepton pair coming from the Z boson must equal the invariant mass of the Z boson, and noting that e,μ reconstruction and identification in the ATLAS detector has a high efficiency [?], these OSSF leptons are used to reconstruct Z bosons with relatively high confidence. A Z candidate is defined in this analysis as an OSSF lepton pair with an invariant mass, m_{OSSF}, satisfying the condition, $|m_{OSSF} - m_Z| < 30$, where $m(Z)$ is the nominal Z boson mass (91.1876 GeV [?]). This wider mass window is used in order to cover the full range of the $m(Z)$ distribution, in an attempt to increase the number of events which pass our baseline selections. Multiple Z candidates can be present in certain decay channels (e.g. $eeee$, $\mu\mu ee$, $\mu\mu\mu\mu$). In these cases, the Z candidate which has an invariant mass closest to the nominal Z boson mass is chosen.

Two tWZ SRs are defined in an attempt to suppress and constrain the ZZ background. The two tWZ SR's differ by the flavours of their leptons which don't originate from the decay of a Z-boson (non-Z leptons). The ZZ background has two Z-bosons which decay into a pair of OSSF lepton pairs, in order to mimic the tWZ signal. This is taken advantage of, to define a tWZ region enrich in ZZ background and one with a minimal ZZ background component. This is done by requiring that one of the tWZ SRs has its two non-Z leptons to have opposite flavour and the other tWZ SR is required to have its non-Z leptons to have the same flavour. These two disjoint tWZ SRs are named tWZ OF SR and tWZ SF SR respectively. It is therefore expected that the tWZ SF SR contains the majority of the ZZ background events across both tWZ SRs. In order to check the modelling of the most dominant background components in our signal region, $t\bar{t}Z$ and ZZb control regions are defined. The $t\bar{t}Z$ control region has the same requirement on the number of reconstructed Z boson candidates in the signal region (due to a commonality on the number of Z bosons present in both processes), however it is required that there are at least two jets and that exactly two of these jets are b-tagged (corresponding to the b-quark jets originating from the two top quark decays). A ZZb region is defined, as opposed to a ZZ region, since the ZZ background present in the tWZ signal region contains exactly one b-tagged jet. Therefore defining a region with ZZ plus exactly one b-jet more closely resembles the ZZ background present in the signal region. In addition to this, mis-modelling of ZZ has been seen in other analyses [**?**, **?**], further motivating the use of a ZZb control region over a ZZ CR. The ZZb CR requires exactly two Z boson candidates and exactly one b-tagged jet, resulting in an implicit requirement on the number of jets ($N_{jet} \geq 1$).

In order to constrain the fake lepton component contained within the $t\bar{t}Z$ sample, a $(tWZ)_{fake}$ CR is defined which is as similar as possible to the tWZ SRs but is enhanced in fakes. This is achieved by defining the $(tWZ)_{fake}$ CR to inherit the same selection criteria as the tWZ SRs however, in this case, a requirement of exactly 3 tight leptons and exactly 1 loose (and NOT tight) lepton is applied. Loose leptons are required in this region, since looser leptons are more likely to be fakes compared to tighter leptons. In Table 1, a summary of the final selection criteria and region definitions is shown.

Baseline selections				
$N_\ell = 4$ $p_T(\ell_1,\ell_2,\ell_3,\ell_4) > (28, 18, 10, 10)$ $p_T(jet) > 20$, $\lvert\eta(jet)\rvert < 4.5$, $jvt > 0.5$ $\lvert\eta(\ell_e)\rvert < 2.47$ excluding $1.37 < \lvert\eta(\ell_e)\rvert < 1.52$ $\lvert\eta(\ell_\mu)\rvert < 2.5$ $\sum_{i=1}^{4} charge(\ell_i) = 0$ All OSSF lepton pairs require $m_{OSSF} > 10$				
Regions				
tWZ OF SR	tWZ SF SR	$t\bar{t}Z$ CR	ZZb CR	$(tWZ)_{fake}$ CR
2*N$_\ell$(tight) = 4	2*N$_\ell$(tight) = 4	2*N$_\ell$(tight) = 4	2*N$_\ell$(tight) = 4	N$_\ell$(tight) = 3 N$_\ell$(loose and NOT tight) = 1
$N_{Zcandidate} = 1$	$N_{Zcandidate} = 1$	$N_{Zcandidate} = 1$	$N_{Zcandidate} = 2$	$N_{Zcandidate} = 1$
$N_{jet} \geq 1$	$N_{jet} \geq 1$	$N_{jet} \geq 2$	$N_{jet} \geq 1$	$N_{jet} \geq 1$
3*N$_{b-jet}$(tight) = 1	3*N$_{b-jet}$(tight) = 1	N$_{b-jet}$(tight) ≥ 1 N$_{b-jet}$(loose) ≥ 0 N$_{b-jet}$(tight) + N$_{b-jet}$(loose) = 2	3*N$_{b-jet}$(tight) = 1	3*N$_{b-jet}$(tight) = 1
Opp. Flavour non-Z leptons	Same Flavour non-Z leptons	-	-	-

Table 1. A summary of the requirements applied for selecting events in the signal and control regions is shown.

3.2. Improving signal vs background discrimination

The presence of different numbers of top quarks is a key discriminator between signal and the dominant background process, $t\bar{t}Z$. This information is aimed to be exploited by reconstructing ℓb systems as a proxy for top quarks (since, $t \to W(\to \ell\nu)b$). This is done in two ways, firstly, by implementation of a kinematic reconstruction algorithm (Two Neutrino Scanning Method) which aims to determine the likelihood of an event containing two top quarks and secondly, by implementing a Boosted Decision Tree (BDT) which is used to distinguish between ℓb systems that originate from top quarks and ℓb systems which do not originate from top quarks. In this analysis, this BDT is referred to as an *object-level* BDT. Certain variables constructed from event information show discrimination between signal and background events. This information can be exploited to discriminate between signal and background events by constructing a BDT which uses these discriminating variables for training. A BDT is implemented and is used to discriminate between events and its major backgrounds, and . Furthermore, this BDT takes information from the kinematic reconstruction algorithm and the object-level BDT in order to maximize its discriminating power. In this thesis, this BDT is referred to as an *event-level* BDT. The discriminator output from the object-level BDT can be converted to a variable which can then be used as an input to the event-level BDT.

3.2.1. Two Neutrino Scanning Method (2νSM) The difference in the number of resonant top quarks in the tWZ signal and the dominant background, $t\bar{t}Z$, is a key feature which can be exploited in order to discriminate between these two processes. In Section **??**, a BDT was implemented which exploits this information by aiming to identify ℓb systems originating from top quarks. In this section, a kinematic reconstruction algorithm (Two Neutrino Scanning Method) is implemented which exploits the same feature. The Two Neutrino Scanning Method (2νSM) algorithm[2] aims to reconstruct $t\bar{t}$ systems in the 2ℓ, 3ℓ and 4ℓ final states (e.g. 2ℓ case: $t\bar{t} \rightarrow \ell^+\nu_\ell b\ell^-\bar{\nu}_\ell\bar{b}$). The 2$\nu$SM algorithm aims to reconstruct a $t\bar{t}$ system by finding two neutrinos (ν_1 and ν_2) which are most likely to correspond to the neutrinos that originate from the decay of a $t\bar{t}$ system. This algorithm can be used in our analysis to discriminate between and , since the OSSF leptons which decay from the Z boson can be easily reconstructed and removed before inputting the event into the algorithm. The removal of the Z boson results in events that don't resemble $t\bar{t}$ systems and events that do resemble $t\bar{t}$ systems, which the algorithm is designed to distinguish between. It would then be expected that the 2νSM algorithm returns a higher score from a event (~ 1, i.e. it resembles a $t\bar{t}$ event after removal of the Z boson) and a lower score from a event (~ 0, i.e. it does not resemble a $t\bar{t}$ event after removal of the Z boson).

4. Preparing your paper

`jpconf` requires LaTeX 2ε and can be used with other package files such as those loading the AMS extension fonts `msam` and `msbm` (these fonts provide the blackboard bold alphabet and various extra maths symbols as well as symbols useful in figure captions); an extra style file `iopams.sty` is provided to load these packages and provide extra definitions for bold Greek letters.

4.1. Headers, footers and page numbers

Authors should *not* add headers, footers or page numbers to the pages of their article—they will be added by IOP Publishing as part of the production process.

4.2. `jpconf.cls` *package options*

The `jpconf.cls` class file has two options 'a4paper' and 'letterpaper':

```
\documentclass[a4paper]{jpconf}
```

or

```
\documentclass[letterpaper]{jpconf}
```

The default paper size is A4 (i.e., the default option is `a4paper`) but this can be changed to Letter by using `\documentclass[letterpaper]{jpconf}`. It is essential that you do not put macros into the text which alter the page dimensions.

[2] software tool and weights provided by Thomas McCarthy (analysis group - Max Planck Institute)

Table 2. `jpconf.cls` class file options.

Option	Description
`a4paper`	Set the paper size and margins for A4 paper.
`letterpaper`	Set the paper size and margins for US letter paper.

5. The title, authors, addresses and abstract

The code for setting the title page information is slightly different from the normal default in LaTeX but please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. The title is set in bold unjustified type using the command `\title{#1}`, where `#1` is the title of the article. The first letter of the title should be capitalized with the rest in lower case. The next information required is the list of all authors' names followed by the affiliations. For the authors' names type `\author{#1}`, where `#1` is the list of all authors' names. The style for the names is initials then surname, with a comma after all but the last two names, which are separated by 'and'. Initials should *not* have full stops. First names may be used if desired. The command `\maketitle` is not required.

The addresses of the authors' affiliations follow the list of authors. Each address should be set by using `\address{#1}` with the address as the single parameter in braces. If there is more than one address then a superscripted number, followed by a space, should come at the start of each address. In this case each author should also have a superscripted number or numbers following their name to indicate which address is the appropriate one for them.

Please also provide e-mail addresses for any or all of the authors using an `\ead{#1}` command after the last address. `\ead{#1}` provides the text Email: so `#1` is just the e-mail address or a list of emails.

The abstract follows the addresses and should give readers concise information about the content of the article and should not normally exceed 200 words. **All articles must include an abstract**. To indicate the start of the abstract type `\begin{abstract}` followed by the text of the abstract. The abstract should normally be restricted to a single paragraph and is terminated by the command `\end{abstract}`

5.1. Sample coding for the start of an article

The code for the start of a title page of a typical paper might read:

```
\title{The anomalous magnetic moment of the
neutrino and its relation to the solar neutrino problem}

\author{P J Smith$^1$, T M Collins$^2$,
R J Jones$^{3,}$\footnote[4]{Present address:
Department of Physics, University of Bristol, Tyndalls Park Road,
Bristol BS8 1TS, UK.} and Janet Williams$^3$}

\address{$^1$ Mathematics Faculty, Open University,
Milton Keynes MK7~6AA, UK}
\address{$^2$ Department of Mathematics,
Imperial College, Prince Consort Road, London SW7~2BZ, UK}
\address{$^3$ Department of Computer Science,
University College London, Gower Street, London WC1E~6BT, UK}

\ead{williams@ucl.ac.uk}
```

```
\begin{abstract}
The abstract appears here.
\end{abstract}
```

6. The text

The text of the article should should be produced using standard LaTeX formatting. Articles may be divided into sections and subsections, but the length limit provided by the conference organizer should be adhered to.

6.1. Acknowledgments

Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered Acknowledgments section immediately following the last numbered section of the paper. The command `\ack` sets the acknowledgments heading as an unnumbered section.

6.2. Appendices

Technical detail that it is necessary to include, but that interrupts the flow of the article, may be consigned to an appendix. Any appendices should be included at the end of the main text of the paper, after the acknowledgments section (if any) but before the reference list. If there are two or more appendices they will be called Appendix A, Appendix B, etc. Numbered equations will be in the form (A.1), (A.2), etc, figures will appear as figure A1, figure B1, etc and tables as table A1, table B1, etc.

The command `\appendix` is used to signify the start of the appendixes. Thereafter `\section`, `\subsection`, etc, will give headings appropriate for an appendix. To obtain a simple heading of 'Appendix' use the code `\section*{Appendix}`. If it contains numbered equations, figures or tables the command `\appendix` should precede it and `\setcounter{section}{1}` must follow it.

7. References

In the online version of *Journal of Physics: Conference Series* references will be linked to their original source or to the article within a secondary service such as INSPEC or ChemPort wherever possible. To facilitate this linking extra care should be taken when preparing reference lists.

Two different styles of referencing are in common use: the Harvard alphabetical system and the Vancouver numerical system. For *Journal of Physics: Conference Series*, the Vancouver numerical system is preferred but authors should use the Harvard alphabetical system if they wish to do so. In the numerical system references are numbered sequentially throughout the text within square brackets, like this [2], and one number can be used to designate several references.

7.1. Using BibTeX

We highly recommend the `iopart-num` BibTeX package by Mark A Caprio [1], which is included with this documentation.

7.2. Reference lists

A complete reference should provide the reader with enough information to locate the article concerned, whether published in print or electronic form, and should, depending on the type of reference, consist of:

- name(s) and initials;

- date published;
- title of journal, book or other publication;
- titles of journal articles may also be included (optional);
- volume number;
- editors, if any;
- town of publication and publisher in parentheses for *books*;
- the page numbers.

Up to ten authors may be given in a particular reference; where there are more than ten only the first should be given followed by '*et al*'. If an author is unsure of a particular journal's abbreviated title it is best to leave the title in full. The terms *loc. cit.* and *ibid.* should not be used. Unpublished conferences and reports should generally not be included in the reference list and articles in the course of publication should be entered only if the journal of publication is known. A thesis submitted for a higher degree may be included in the reference list if it has not been superseded by a published paper and is available through a library; sufficient information should be given for it to be traced readily.

7.3. Formatting reference lists

Numeric reference lists should contain the references within an unnumbered section (such as `\section*{References}`). The reference list itself is started by the code `\begin{thebibliography}{<num>}`, where `<num>` is the largest number in the reference list and is completed by `\end{thebibliography}`. Each reference starts with `\bibitem{<label>}`, where 'label' is the label used for cross-referencing. Each `\bibitem` should only contain a reference to a single article (or a single article and a preprint reference to the same article). When one number actually covers a group of two or more references to different articles, `\nonum` should replace `\bibitem{<label>}` at the start of each reference in the group after the first.

For an alphabetic reference list use `\begin{thereferences}` ... `\end{thereferences}` instead of the 'thebibliography' environment and each reference can be start with just `\item` instead of `\bibitem{label}` as cross referencing is less useful for alphabetic references.

7.4. References to printed journal articles

A normal reference to a journal article contains three changes of font (see table 3) and is constructed as follows:

- the authors should be in the form surname (with only the first letter capitalized) followed by the initials with no periods after the initials. Authors should be separated by a comma except for the last two which should be separated by 'and' with no comma preceding it;
- the article title (if given) should be in lower case letters, except for an initial capital, and should follow the date;
- the journal title is in italic and is abbreviated. If a journal has several parts denoted by different letters the part letter should be inserted after the journal in Roman type, e.g. *Phys. Rev.* A;
- the volume number should be in bold type;
- both the initial and final page numbers should be given where possible. The final page number should be in the shortest possible form and separated from the initial page number by an en rule '– ', e.g. 1203–14, i.e. the numbers '12' are not repeated.

A typical (numerical) reference list might begin

[1] Strite S and Morkoc H 1992 *J. Vac. Sci. Technol.* B **10** 1237
[2] Jain S C, Willander M, Narayan J and van Overstraeten R 2000 *J. Appl. Phys.* **87** 965
[3] Nakamura S, Senoh M, Nagahama S, Iwase N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 *Japan. J. Appl. Phys.* **35** L74
[4] Akasaki I, Sota S, Sakai H, Tanaka T, Koike M and Amano H 1996 *Electron. Lett.* **32** 1105
[5] O'Leary S K, Foutz B E, Shur M S, Bhapkar U V and Eastman L F 1998 *J. Appl. Phys.* **83** 826
[6] Jenkins D W and Dow J D 1989 *Phys. Rev.* B **39** 3317

which would be obtained by typing

```
\begin{\thebibliography}{9}
\item Strite S and Morkoc H 1992 {\it J. Vac. Sci. Technol.} B {\bf 10} 1237
\item Jain S C, Willander M, Narayan J and van Overstraeten R 2000
{\it J. Appl. Phys}. {\bf 87} 965
\item Nakamura S, Senoh M, Nagahama S, Iwase N, Yamada T, Matsushita T, Kiyoku H
and  Sugimoto Y 1996 {\it Japan. J. Appl. Phys.} {\bf 35} L74
\item Akasaki I, Sota S, Sakai H, Tanaka T, Koike M and Amano H 1996
{\it Electron. Lett.} {\bf 32} 1105
\item O'Leary S K, Foutz B E, Shur M S, Bhapkar U V and Eastman L F 1998
{\it J. Appl. Phys.} {\bf 83} 826
\item Jenkins D W and Dow J D 1989 {\it Phys. Rev.} B {\bf 39} 3317
\end{\thebibliography}
```

Table 3. Font styles for a reference to a journal article.

Element	Style
Authors	Roman type
Date	Roman type
Article title (optional)	Roman type
Journal title	Italic type
Volume number	Bold type
Page numbers	Roman type

7.5. References to Journal of Physics: Conference Series articles

Each conference proceeding published in *Journal of Physics: Conference Series* will be a separate *volume*; references should follow the style for conventional printed journals. For example:

[1] Douglas G 2004 *J. Phys.: Conf. Series* **1** 23–36

7.6. References to preprints

For preprints there are two distinct cases:

(1) Where the article has been published in a journal and the preprint is supplementary reference information. In this case it should be presented as:

[1] Kunze K 2003 T-duality and Penrose limits of spatially homogeneous and inhomogeneous cosmologies *Phys. Rev.* D **68** 063517 (*Preprint* gr-qc/0303038)

(2) Where the only reference available is the preprint. In this case it should be presented as

[1] Milson R, Coley A, Pravda V and Pravdova A 2004 Alignment and algebraically special tensors *Preprint* gr-qc/0401010

Table 4. Font styles for references to books, conference proceedings and reports.

Element	Style
Authors	Roman type
Date	Roman type
Book title (optional)	Italic type
Editors	Roman type
Place (city, town etc) of publication	Roman type
Publisher	Roman type
Volume	Roman type
Page numbers	Roman type

7.7. References to electronic-only journals

In general article numbers are given, and no page ranges, as most electronic-only journals start each article on page 1.

- For *New Journal of Physics* (article number may have from one to three digits)
  [1] Fischer R 2004 Bayesian group analysis of plasma-enhanced chemical vapour deposition data *New. J. Phys.* **6** 25
- For SISSA journals the volume is divided into monthly issues and these form part of the article number
  [1] Horowitz G T and Maldacena J 2004 The black hole final state *J. High Energy Phys.* JHEP02(2004)008
  [2] Bentivegna E, Bonanno A and Reuter M 2004 Confronting the IR fixed point cosmology with high-redshift observations *J. Cosmol. Astropart. Phys.* JCAP01(2004)001

7.8. References to books, conference proceedings and reports

References to books, proceedings and reports are similar to journal references, but have only two changes of font (see table 4).

Points to note are:

- Book titles are in italic and should be spelt out in full with initial capital letters for all except minor words. Words such as Proceedings, Symposium, International, Conference, Second, etc should be abbreviated to *Proc.*, *Symp.*, *Int.*, *Conf.*, *2nd*, respectively, but the rest of the title should be given in full, followed by the date of the conference and the town or city where the conference was held. For Laboratory Reports the Laboratory should be spelt out wherever possible, e.g. *Argonne National Laboratory Report.*
- The volume number, for example vol 2, should be followed by the editors, if any, in a form such as 'ed A J Smith and P R Jones'. Use *et al* if there are more than two editors. Next comes the town of publication and publisher, within brackets and separated by a colon, and finally the page numbers preceded by p if only one number is given or pp if both the initial and final numbers are given.

Examples taken from published papers:

[1] Kurata M 1982 *Numerical Analysis for Semiconductor Devices* (Lexington, MA: Heath)
[2] Selberherr S 1984 *Analysis and Simulation of Semiconductor Devices* (Berlin: Springer)
[3] Sze S M 1969 *Physics of Semiconductor Devices* (New York: Wiley-Interscience)
[4] Dorman L I 1975 *Variations of Galactic Cosmic Rays* (Moscow: Moscow State University Press) p 103
[5] Caplar R and Kulisic P 1973 *Proc. Int. Conf. on Nuclear Physics (Munich)* vol 1 (Amsterdam: North-Holland/American Elsevier) p 517
[6] Cheng G X 2001 *Raman and Brillouin Scattering-Principles and Applications* (Beijing: Scientific)

[7] Szytula A and Leciejewicz J 1989 *Handbook on the Physics and Chemistry of Rare Earths* vol 12, ed K A Gschneidner Jr and L Erwin (Amsterdam: Elsevier) p 133
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8. Tables and table captions

Tables should be numbered serially and referred to in the text by number (table 1, etc, **rather than** tab. 1). Each table should be a float and be positioned within the text at the most convenient place near to where it is first mentioned in the text. It should have an explanatory caption which should be as concise as possible.

8.1. The basic table format

The standard form for a table is:

```
\begin{table}
\caption{\label{label}Table caption.}
\begin{center}
\begin{tabular}{llll}
\br
Head 1&Head 2&Head 3&Head 4\\
\mr
1.1&1.2&1.3&1.4\\
2.1&2.2&2.3&2.4\\
\br
\end{tabular}
\end{center}
\end{table}
```

The above code produces table 5.

Table 5. Table caption.

Head 1	Head 2	Head 3	Head 4
1.1	1.2	1.3	1.4
2.1	2.2	2.3	2.4

Points to note are:

(1) The caption comes before the table.
(2) The normal style is for tables to be centred in the same way as equations. This is accomplished by using `\begin{center}` ... `\end{center}`.
(3) The default alignment of columns should be aligned left.
(4) Tables should have only horizontal rules and no vertical ones. The rules at the top and bottom are thicker than internal rules and are set with `\br` (bold rule). The rule separating the headings from the entries is set with `\mr` (medium rule). These commands do not need a following double backslash.

(5) Numbers in columns should be aligned as appropriate, usually on the decimal point; to help do this a control sequence `\lineup` has been defined which sets `\0` equal to a space the size of a digit, `\m` to be a space the width of a minus sign, and `\-` to be a left overlapping minus sign. `\-` is for use in text mode while the other two commands may be used in maths or text. (`\lineup` should only be used within a table environment after the caption so that `\-` has its normal meaning elsewhere.) See table 6 for an example of a table where `\lineup` has been used.

Table 6. A simple example produced using the standard table commands and `\lineup` to assist in aligning columns on the decimal point. The width of the table and rules is set automatically by the preamble.

A	B	C	D	E	F	G
23.5	60	0.53	−20.2	−0.22	1.7	14.5
39.7	−60	0.74	−51.9	−0.208	47.2	146
123.7	0	0.75	−57.2	—	—	—
3241.56	60	0.60	−48.1	−0.29	41	15

9. Figures and figure captions

Figures must be included in the source code of an article at the appropriate place in the text not grouped together at the end.

Each figure should have a brief caption describing it and, if necessary, interpreting the various lines and symbols on the figure. As much lettering as possible should be removed from the figure itself and included in the caption. If a figure has parts, these should be labelled (*a*), (*b*), (*c*), etc. Table 7 gives the definitions for describing symbols and lines often used within figure captions (more symbols are available when using the optional packages loading the AMS extension fonts).

Table 7. Control sequences to describe lines and symbols in figure captions.

Control sequence	Output	Control sequence	Output
`\dotted`	······	`\opencircle`	○
`\dashed`	- - - -	`\opentriangle`	△
`\broken`	– – –	`\opentriangledown`	▽
`\longbroken`	— — —	`\fullsquare`	■
`\chain`	— · —	`\opensquare`	□
`\dashddot`	— · · —	`\fullcircle`	●
`\full`	——	`\opendiamond`	◇

Authors should try and use the space allocated to them as economically as possible. At times it may be convenient to put two figures side by side or the caption at the side of a figure. To put figures side by side, within a figure environment, put each figure and its caption into a minipage with an appropriate width (e.g. 3in or 18pc if the figures are of equal size) and then separate the figures slightly by adding some horizontal space between the two minipages (e.g. `\hspace{.2in}` or `\hspace{1.5pc}`. To get the caption at the side of the figure add the small horizontal space after the `\includegraphics` command and then put the `\caption` within a minipage of the appropriate width aligned bottom, i.e. `\begin{minipage}[b]{3in}` etc (see code in this file used to generate figures 1–3).

Note that it may be necessary to adjust the size of the figures (using optional arguments to `\includegraphics`, for instance `[width=3in]`) to get you article to fit within your page allowance or to obtain good page breaks.

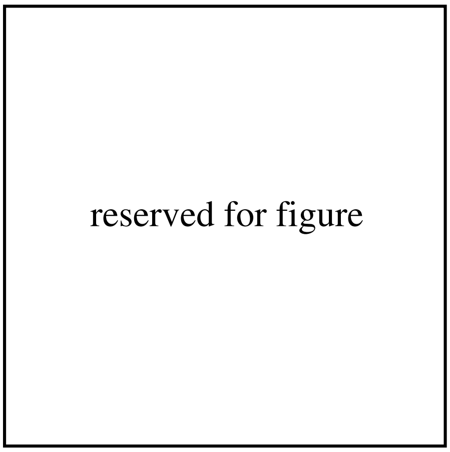

Figure 3. Figure caption for first of two sided figures.

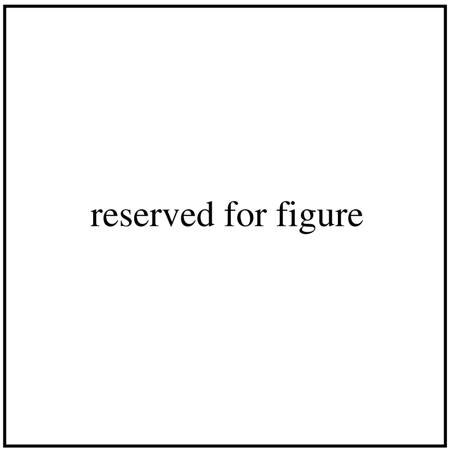

Figure 4. Figure caption for second of two sided figures.

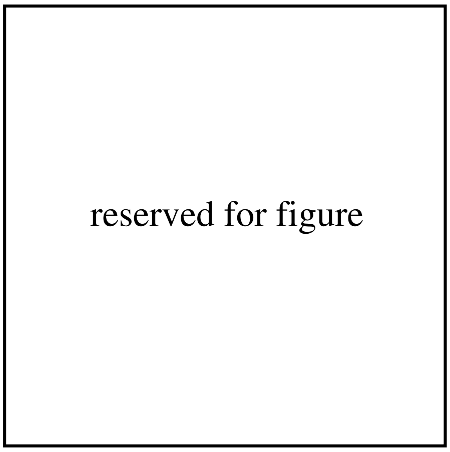

Figure 5. Figure caption for a narrow figure where the caption is put at the side of the figure.

Using the graphicx package figures can be included using code such as:

```
\begin{figure}
\begin{center}
\includegraphics{file.eps}
\end{center}
\caption{\label{label}Figure caption}
\end{figure}
```

References

[1] IOP Publishing is to grateful Mark A Caprio, Center for Theoretical Physics, Yale University, for permission to include the `iopart-num` BibTeXpackage (version 2.0, December 21, 2006) with this documentation. Updates and new releases of `iopart-num` can be found on `www.ctan.org` (CTAN).