

ASCERTAINING THE ORIGIN OF THE $l\nu l\nu$ EXCESS EVENTS AT THE LHC BY A CHANGE OF BEAM ENERGY

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A higher than predicted rate of two leptons plus missing transverse energy events, reported at the summer HEP conferences, can originate from a decay of the Higgs boson into a $WW^{(*)}$ pair, a misjudgement of the rate of SM background processes or a statistical fluctuation. In this paper we discuss a way to resolve this three-fold ambiguity.

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1. Introduction

The LHC and the Tevatron experiments are trying to close the window for the Standard Model (SM) Higgs in the low mass region, favored by the precision measurements of the SM parameters.

The question discussed here is if, and how, the LHC experiments can firmly establish the existence, or exclude, by the end of 2012, the SM Higgs boson in the mass region of 120–150 GeV/ c^2 . This mass region is of particular interest because the excess events reported at the Grenoble EPS Conference [1] can be interpreted as coming from the $H \rightarrow WW^{(*)}$ decays. Both the ATLAS and CMS collaborations reported an excess of events with respect to the SM expectation in the above mass range.

At the Lepton–Photon Conference in Mumbai, the CMS Collaboration and the ATLAS Collaboration [2] presented updated results corresponding to 1.5 fb $^{-1}$ and 1.7 fb $^{-1}$ of integrated luminosity, respectively. The statistical significance of the excess was reported to be reduced to the 2σ level (ATLAS) and to the 1σ level (CMS).

The LHC machine has reached its stable operation mode with the 50 ns bunch spacing delivering of the order of 40 pb $^{-1}$ per day. If such a performance is maintained during the pp running periods in 2011 and 2012 each experiment may collect of the order of 15 fb $^{-1}$ of integrated luminosity.

If the present excess of events represents a statistical fluctuation, the expected increase of the statistical precision in 2011 and 2012 will be largely sufficient to reject firmly the existence of Higgs boson in the discussed mass range. On the other hand, if the excess of events is confirmed with high statistics data, the following two hypothesis will remain to be resolved:

1. the excess events originate from the Higgs boson decays,
2. the excess events reflect higher than expected rate of SM background processes.

This will be difficult because the statistical errors will no longer be dominating. If the observed, N_{obs} , and the expected background and signal, N_{bgr} , N_{Higgs} , numbers of events reported by the ATLAS Collaboration at the Lepton-Photon Conference [2] for the 0 jet selection, and for $M_{\text{Higgs}} = 150 \text{ GeV}/c^2$ are scaled up to the integrated luminosity of 15 fb^{-1} and the two following assumptions are made:

1. the relative errors on the numbers of the expected SM background and Higgs events will not be improved,
2. the present excess number of observed events is genuine (representing its infinite luminosity asymptotic value),

then $N_{\text{obs}} = 618 \pm 24$, $N_{\text{bgr}} = 465 \pm 78$ and $N_{\text{Higgs}} = 300 \pm 60$. It is thus obvious that the hypothesis 2 can be confirmed only at the 2σ level and the hypothesis 1 can be tested only at the 1.5σ level. The errors on N_{bgr} and N_{Higgs} will have to be reduced by at least a factor of 3 (*i.e.* they will have to evolve with the collected luminosity L as $1/\sqrt{L}$) in order to firmly reject or to establish the existence of the SM Higgs boson. This will be anything but simple because the errors are dominated entirely by the theory and Monte Carlo modeling uncertainties [2] which give rise to irreducible errors. They may be reduced with increasing luminosity but certainly less than the experimental measurement errors, for which the $1/\sqrt{L}$ evolution reflects already a rather optimistic scenario.

In this note we shall discuss the measurement strategy capable to bypass the dominant systematic modeling uncertainties. We shall exploit the difference in the production mechanism of the background and the Higgs events and propose an observable capable to firmly identify the source of the excess events, provided that the data are taken at the LHC at two different beam energies. The aim of the strategy presented here is to ascertain the origin of the excess events (if it remains) independently of the progress in reducing the modeling and theoretical uncertainties.

2. The observable

Let us focus our attention on the 0 jet subsample of the $l\nu l\nu$ events [1]. For this subsample, the source of background events for the Higgs searches is predominantly a non-resonant production of the WW pairs, depicted in Fig. 1. The processes which dominate are the quark–antiquark collisions. Collisions of gluons contribute to the event rate at the level of $\sim 3\%$.

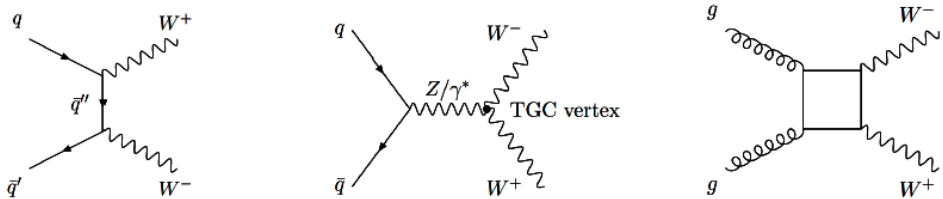


Fig. 1. The dominant non-resonant WW pair production diagrams. In the mass region studied in this paper one of the W -bosons is virtual.

If the SM Higgs boson exists, the $WW^{(*)}$ pairs are also coming from the $H \rightarrow WW^{(*)}$ decays. In the discussed mass range, the Higgs boson is produced predominantly in gluon–gluon collisions. The contribution of the quark-initiated processes (b) and (c), depicted in Fig. 2, is at the level of $\sim 10\%$.

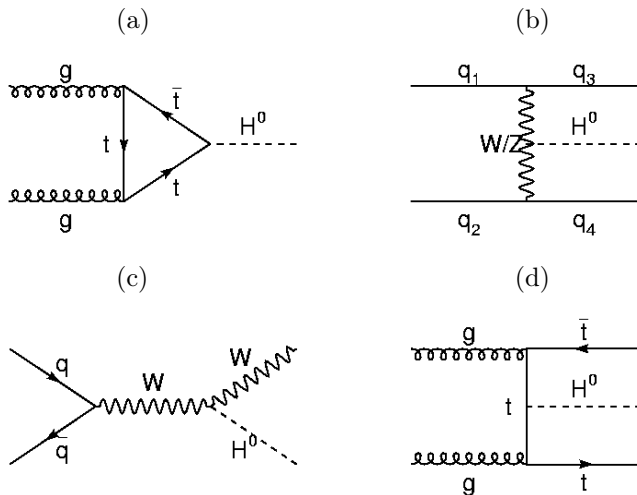


Fig. 2. The dominant Higgs production diagrams.

The relative magnitude of the Higgs and of the SM background contributions to the observed even rates could thus be established by measuring the relative strength of the gluon–gluon collision processes with respect to the

quark–antiquark ones. Of course, these processes cannot be distinguished on the event-by-event basis. However, their relative strength can be changed by modifying the centre-of-mass energy of colliding beams. This is the main idea presented in this note.

For simplicity of arguments let us consider the central (zero-rapidity) production of the $WW^{(*)}$ pairs with the invariant mass $m_0 = 150 \text{ GeV}/c^2$, in the simplified framework based on collinear, massless partons. If the centre-of-mass-energy-squared of pp collisions changes from s_0 to s_1 , the momentum fraction of partons producing exclusively the $WW^{(*)}$ pairs changes from $x_0 = \sqrt{m_0^2/s_0}$ to $x_1 = \sqrt{m_0^2/s_1}$.

If protons were composed only of gluons and sea quarks, the relative magnitude of the gluon- and quark-initiated processes could not be resolved by measuring the rates at the two s values, because the ratio of the sea quark fluxes at x_0 and x_1 is to a good approximation the same as the ratio of the gluon fluxes. This is a direct consequence of the DGLAP evolution equation. In the discussed range of $m_0^2 \gg \Lambda_{\text{QCD}}^2$ and in the LHC range of s the non-perturbative differences in the x -shape of the sea quark and gluon distributions are washed out when evolved to the $Q^2 = m_0^2$ scale.

The quark and gluon initiated processes can be resolved because of the presence of the valence quarks in the protons.

For $x \sim 10^{-2}$, corresponding at the LHC energies to the discussed mass region, the valence quark fluxes decrease with decreasing x , contrary to the sea-quark and gluon fluxes which strongly increase with decreasing x value. This is illustrated in Fig. 3, where the distributions of the valence and sea quarks are shown as a function of x at the $Q^2 = 22500 \text{ GeV}^2$ scale¹. The difference in the x -dependence of the quark and gluon/sea quark fluxes allows to change the relative proportion of the gluon and the quark initiated processes by modifying the energy of the LHC beams².

Motivated by the above considerations, we propose to use the following observable to measure the relative contribution of the gluon- and of the quark-initiated processes

$$R(s_0, s_1, m_0) = \frac{\sigma(s_1, m_0, E_{\text{jet}}^T)}{\sigma(s_0, m_0, E_{\text{jet}}^T)}, \quad (1)$$

where $\sigma(s_0, m_0, E_{\text{jet}}^T)$ and $\sigma(s_1, m_0, E_{\text{jet}}^T)$ are the integrals of the differential cross-sections, $d\sigma(m_t, s_0, m_0, E_{\text{jet}}^T)/dm_t$ and $d\sigma(m_t, s_1, m_0, E_{\text{jet}}^T)/dm_t$ integrated over the region $(0.75 \times m_0 < m_t < m_0)$ of the transverse mass, m_t , of

¹ This and all the subsequent plots showing partonic densities were made using the Durham HepData Project Tool [3].

² It is a very lucky coincidence that, for the LHC beam energies, the resolving power happens to be maximal in the mass region where the excess of events is seen.

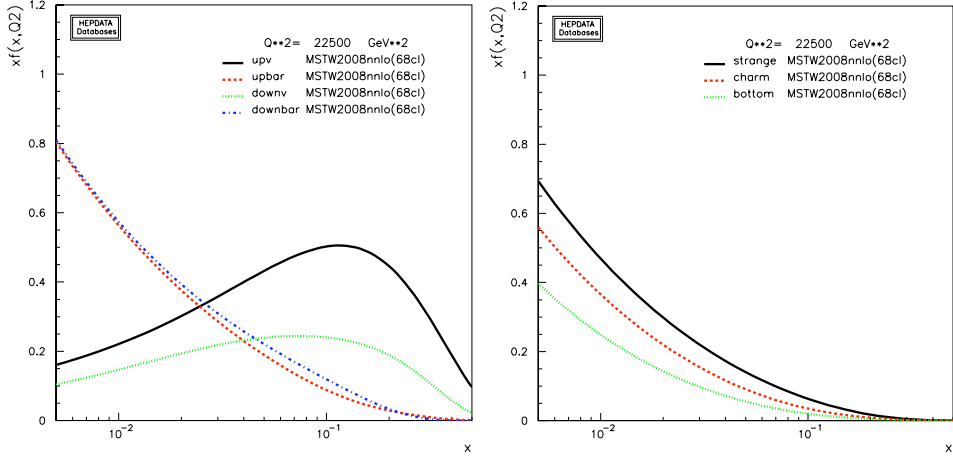


Fig. 3. The parton distribution functions of the valence and sea quarks at $Q^2 = 22500 \text{ GeV}^2$.

the two charged lepton and two neutrino system, and E_{jet}^T is the jet energy cut-off used in the selection of the 0-jet subsample events. For the quark-initiated processes, the central production of the $WW^{(*)}$ pair ($y_{WW} = 0$), $E_{\text{jet}}^T \ll m_0$, and in the absence of the higher-twists effects, $R(s_0, s_1, m_0)$ can be written in the Born approximation as

$$R(s_0, s_1, m_0) \sim R^{q\bar{q}}(s_0, s_1, m_0) = \frac{\Sigma_f q_f \left(\sqrt{m_0^2/s_1}, m_0^2 \right) \bar{q}_f \left(\sqrt{m_0^2/s_1}, m_0^2 \right)}{\Sigma_f q \left(\sqrt{m_0^2/s_0}, m_0^2 \right) \bar{q}_f \left(\sqrt{m_0^2/s_0}, m_0^2 \right)}. \quad (2)$$

For the gluon initiated processes $R(s_0, s_1, m_0)$ can be written in the Born approximation as:

$$R(s_0, s_1, m_0) \sim R^{gg}(s_0, s_1, m_0) = \frac{g^2 \left(\sqrt{m_0^2/s_1}, m_0^2 \right)}{g^2 \left(\sqrt{m_0^2/s_0}, m_0^2 \right)}. \quad (3)$$

In the above formulae $q_f(x, Q^2)$, $\bar{q}_f(x, Q^2)$ and $g(x, Q^2)$ denote the flavour f -dependent quark, antiquark and gluon distribution functions (PDFs).

The merit of measuring $R(s_0, s_1, m_0)$ is twofold.

1. From the experimental point of view, majority systematic measurement uncertainties cancel in the ratio for a stable detector, if runs taken at two different energies have similar distribution of the number of collisions per bunch-crossing, and if the s -dependence of the

effects due to co-moving partons are experimentally controlled. Such an observable is, in particular, less sensitive to the absolute scale of the lepton and jet energies. The dominant systematic error for the measured ratio reflects the uncertainty of the relative normalisation of the data samples taken at the two centre-of-mass energies. For the present method, based on the van der Meer scan [4], the expected error on the ratio will be of the order of 5%. This error can be diminished by a factor of about 3 by making use of the well-known Z production cross-section ratio, $\sigma_{\text{th}}^Z(s_1)/\sigma_{\text{th}}^Z(s_0)$, and measuring, instead of $R(s_0, s_1, m_0)$, the ratio $R_Z(s_0, s_1, m_0)$ defined as

$$R_Z(s_0, s_1, m_0) = \frac{N(s_1, m_0, E_{\text{jet}}^T)}{N(s_0, m_0, E_{\text{jet}}^T)} \times \frac{dN/dm_{ll}(s_0, m_{ll} = M_Z)}{dN/dm_{ll}(s_1, m_{ll} = M_Z)} \times \frac{\sigma_{\text{th}}^Z(s_1)}{\sigma_{\text{th}}^Z(s_0)}, \quad (4)$$

where m_{ll} is the invariant mass of the opposite charge, same flavour lepton pairs and M_Z is the Z -boson mass³.

2. The principal merit of the proposed ratio is, however, its robustness with respect to the theoretical/phenomenological modelling uncertainties. $R(s_0, s_1, m_0)$, can be directly interpreted in terms of: $R^{q\bar{q}}(s_0, s_1, m_0)$, $R^{gg}(s_0, s_1, m_0)$ and the ratio of the valence-quark to sea-quark PDFs. We have found that the sensitivity to the assumed form of the PDFs (NNPDF, ABKM, MSTW, CTEQ) [3], is reduced by at least a factor of 10 for $R^{q\bar{q}}(s_0, s_1, m_0)$ and $R^{gg}(s_0, s_1, m_0)$ with respect to the fixed s analysis. This may be easily understood by looking at Fig. 4, where the gluon and up-quark distributions are shown in the relevant x -range⁴, correspondingly. While the PDFs differ in normalisation, their ratios taken at the x_0 and x_1 values are independent of the PDF set. The sensitivity to the PDFs errors is thus restricted solely to our present understanding of the ratio of the valence to the sea quarks, which is known presently within a $\sim 5\%$ uncertainty⁵. It remains to be added that the proposed observable becomes largely insensitive to the missing higher-order QCD corrections (more precisely, to those of them that are similar for the gluon–gluon and quark–quark initiated processes).

³ In the future, the relative luminosity error could be reduced to a per-mille level if luminosity measurement method proposed in [5] is implemented.

⁴ For $m_0 = 150$ GeV and the LHC beam energies of 2.5, 3.5 and 4.5 TeV the corresponding x values are $x = 0.03, 0.021, 0.017$.

⁵ An experiment has been proposed at the CERN SPS to improve the precision of this ratio [6].

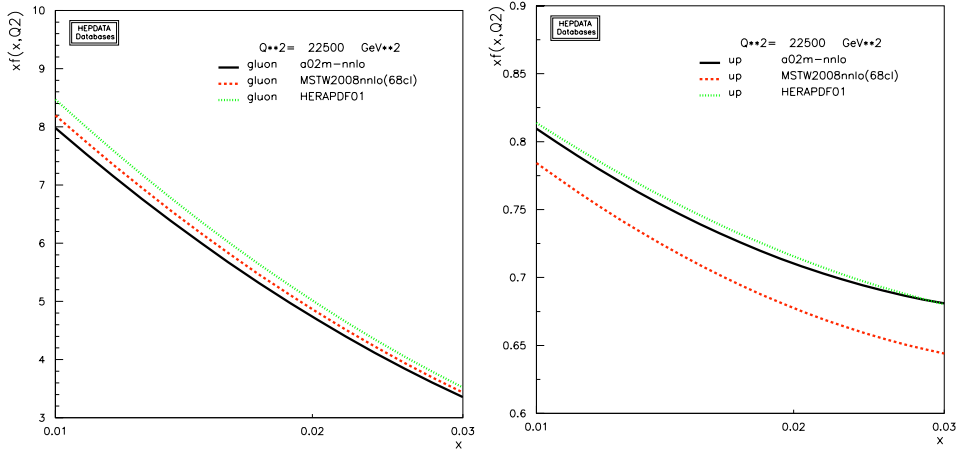


Fig. 4. The gluon and the up-quark PDF sets. Note, that the PDF ratios taken at two x values are, to a large extent, independent of PDF set.

3. LHC running scenarios and their resolving power

The minimal requirement which allows to measure the relative contribution of the gluon–gluon and quark–antiquark collision processes to the observed event rates is to collect the data at two different beam energies. We have evaluated numerically two running scenarios, each of them for the integrated luminosity of 15 fb^{-1} . In the first one 6 fb^{-1} is collected with the 3.5 TeV proton beams and 9 fb^{-1} at 2.5 TeV. The second one corresponds to 9 fb^{-1} collected with the 3.5 TeV beams and 6 fb^{-1} at 4.5 TeV.

The relative luminosity in these scenarios minimize the statistical uncertainty on the $R(s_0, s_1, m_0)$ ratio. In the following, s_0 corresponds to the present beam energy and s_1 to the reduced (increased) energy for the scenario 1 (2).

In the estimations presented in this section we have used the signal and background rates, following all the experimental cuts, in the 0-jet channel presented by the ATLAS Collaboration at the Lepton–Photon Conference [2]. The evaluation was made for the Higgs boson mass of $150 \text{ GeV}/c^2$. We have assumed further that all the $WW^{(*)}$ pairs are produced centrally and exclusively. We have neglected the small gg contribution to the $WW^{(*)}$ background and the small $q\bar{q}$ contribution to the Higgs production process. These approximations can be abandoned in a technically more advanced analysis, by including the realistic detector acceptance for the $\nu\nu$ events and by getting rid of approximations made in the presented calculations. This would be obligatory for the realistic analysis of the data but not necessary in the evaluation of the resolving power of the method presented in this note.

For the first running scenario $R^{gg}(s_0, s_1, m_0) = 0.56 \pm 0.02$, and $R^{q\bar{q}}(s_0, s_1, m_0) = 0.71 \pm 0.02$. The measurement of $R(s_0, s_1, m_0)$ by the ATLAS and CMS experiments would thus provide a model-independent, discrimination at the 2σ level⁶ between the hypothesis 1 (Higgs + SM background) and the hypothesis 2 (SM background only). This additional (with respect to the current method based on the absolute rates of events) discrimination power would be decisive to confirm or reject firmly the Higgs boson hypothesis if the current uncertainties of the expected *absolute* signal and background rates are not reduced by a factor of 3.

For the second running scenario $R^{gg}(s_0, s_1, m_0) = 1.51 \pm 0.03$ and $R^{q\bar{q}}(s_0, s_1, m_0) = 1.28 \pm 0.03$. The resolving power of the gluon against the quark-initiated processes is slightly reduced due to a smaller contribution of the valence quarks to the overall $q\bar{q}$ fluxes. The discriminating power of the $R(s_0, s_1, m_0)$ measurement between the hypothesis 1 and the hypothesis 2 stays, however, at the same level because the reduction of the resolving power of the gluon- and quark-initiated processes is compensated by the gain in the total number of both the signal and background events.

4. Outlook

The arguments presented in this note would be irrelevant, while considering the running scenarios in 2012, if the excess of events disappeared by the end of this year. If it persists, ascertaining experimentally the origin of the excess events, no matter what progress will be made in improving the precision of calculation of the signal and background rates, would certainly be one of the major tasks for the 2012 runs. In such a case an option of changing of the beam energy, proposed in this note, appears to be clearly superior with respect to continuing taking data at the current beam-energy.

The two scenarios discussed in this note, even if having comparable signal/background resolving power, are all but equivalent, as far as the safety of the machine operation is concerned. From the machine operation point of view reducing the beam energy to 2.5 TeV represents a viable technical

⁶ For the running scenarios presented above the dominant source of uncertainty on $R(s_0, s_1, m_0)$ is of statistical nature — if the current event selection procedures are maintained for the analysis of the full data sample. There is a room for an improvement here by using less restrictive experimental cuts. The optimal procedure would be to analyse $R(s_0, s_1, m_0)$ in terms of the relative yield of the gluon and quark originated processes at each stage of the event selection chain corresponding to their variable mixture. Using such a procedure the statistical errors will be reduced and a better understanding of the resolving power of the proposed method will be achieved. It has to be stressed that for such a procedure the relative luminosity uncertainty measured with the van der Meer method will become a dominant one. A remedy proposed in this paper, adequate for the discussed luminosity range, is to replace the measurement of $R(s_0, s_1, m_0)$ by a measurement of $R_Z(s_0, s_1, m_0)$.

solution. The only price to pay would be to accept a slightly diminished sensitivity of such runs to the discovery physics at the highest mass scales. This price depends upon the evolution of the machine luminosity in the year 2012. If a plateau of the instantaneous luminosity is reached by the time of collecting 6 fb^{-1} at 3.5 TeV, the impact of the expected increase of the sample of events collected by the end of 2012 at the same energy both for the searches and for the SM measurements would be marginal. In our view, a change of the beam energy would be superior with respect to continuing running present energy because of several other reasons⁷.

The option of increasing the LHC beam energy to 4.5 TeV in 2012 is another story. We are fully aware that running a 4.5 TeV proton beam before the 2013/2014 shutdown may simply be impossible because of machine safety arguments⁸. We were prompted to include in our paper the calculations for the increased beam energy by the statement of Myers at the June 2011 session of the LHCC [8]: “Following measurements of the copper stabilisers resistances during the Christmas stop, we will re-evaluate the maximum energy for 2012 (Chamonix 2012)”.

5. Conclusions

It is argued that at the LHC a change of beam energy may provide a useful tool for discriminating between production processes in cases where model uncertainties outweigh the gain from statistical error reduction. The argument is applied to the specific case of the $l\nu l\nu$ excess events observed by ATLAS and CMS at the LHC. The presented case study is a concrete example of a complementary approach to searches at the LHC which rely on the dedicated measurement procedures rather than on the specific theoretical models. Such an approach could be of use in an advanced phase of the LHC experimental programme when the “Promised Land” of discoveries, precisely chartered by the present theory paradigms, turns out to be a mirage.

⁷ The most notable gain would be to control experimentally the contribution of higher twists to the LHC observables — the domain where the theoretical calculations and modelling tools hardly exists.

⁸ We evaluated as well perhaps a more realistic scenario of collecting 8 fb^{-1} with the 3.5 TeV beams and 7 fb^{-1} at 3.97 TeV. We found that the resolution power of the quark- and the gluon-initiated processes, for this running scenario is reduced by a factor of ~ 2 . Such a running scenario, for which $s_1/s_0 = M_Z^2/M_W^2$, would fulfil a double role: in addition to the one discussed in this paper, it would be crucial for the competitive precision measurements of the W -boson mass and α_s [7].

REFERENCES

- [1] ATLAS Collaboration, Search for the Standard Model Higgs Boson in the $H \rightarrow WW^* \rightarrow l\nu l\nu$ Decay Mode with the ATLAS Detector, ATLAS-CONF-2011-111, August 15, 2011; CMS Collaboration, Search for the Higgs Boson Decaying to W^+W^* in the Fully Leptonic Final State, CMS PAS HIG-11-003, July 22, 2011.
- [2] ATLAS Collaboration, Search for the Standard Model Higgs Boson in the $H \rightarrow WW^* \rightarrow l\nu l\nu$ Decay Mode Using 1.7 fb^{-1} of Data Collected with the ATLAS Detector at $\sqrt{s} = 7 \text{ TeV}$, ATLAS-CONF-2011-134, August 24, 2011; CMS Collaboration, Search for the Higgs Boson Decaying to W^+W^- in the Fully Leptonic Final State, CMS PAS HIG-11-014.
- [3] The Durham HepData Project Tool:
<http://hepdata.cedar.ac.uk/pdf/pdf3.html>
- [4] [ATLAS Collaboration] G. Aad *et al.*, *Eur. Phys. J.* **C71**, 1630 (2011).
- [5] M.W. Krasny, J. Chwastowski, K. Slowikowski, *Nucl. Instrum. Methods Phys. Res.* **A584**, 42 (2008); M.W. Krasny, J. Chwastowski, A. Cyz, K. Slowikowski, [arXiv:1006.3858](https://arxiv.org/abs/1006.3858) [physics.ins-det]; M.W. Krasny, J. Chwastowski, A. Cyz, K. Slowikowski, Luminosity Measurement Method for the LHC: Event Selection and Absolute Luminosity Determination, to be published.
- [6] F. Dydak, M.W. Krasny, R. Voss, The Measurement of the W Mass at the LHC: Shortcuts Revisited, CERN-SPSC-2009-028/CERN-LHCC-2009-014.
- [7] M.W. Krasny, F. Fayette, W. Placzek, A. Siodmok, *Eur. Phys. J.* **C51**, 607 (2007); F. Fayette, M.W. Krasny, W. Placzek, A. Siodmok, *Eur. Phys. J.* **C63**, 33 (2009); M.W. Krasny *et al.*, *Eur. Phys. J.* **C69**, 379 (2010).
- [8] S. Myers, LHC Machine Status Report, talk at the LHCC meeting, CERN, June 2011, <http://indico.cern.ch/getFile.py/access?contribId=1&sessionId=0&resId=1&materialId=slides&confId=141891>